DOE-EH-4.2.1.4-Interim-GENII

Rev. 1

GENII Computer Code Application Guidance for Documented Safety Analysis

Interim Report

U.S. Department of Energy

Office of Environment, Safety and Health

1000 Independence Ave., S.W.
Washington, DC 20585-2040

September 2003

INTENTIONALLY BLANK

FOREWORD

This document provides guidance to Department of Energy (DOE) facility analysts in the use of the GENII computer code for supporting Documented Safety Analysis applications. Information is provided herein that supplements information found in the GENII documentation provided by the code developer. GENII is one of six computer codes designated by the DOE Office of Environmental, Safety and Health as a toolbox code for safety analysis.

Suggestions for corrections or improvements to this document should be addressed to –

Chip Lagdon
EH-31/GTN
Office of Quality Assurance Programs
U.S. Department of Energy
Washington, D.C. 20585-2040
Phone (301) 903-4218
Email: Chip.Lagdon@hq.doe.gov

INTENTIONALLY BLANK

REVISION STATUS

Page/Section	Revision	Change
1. Entire Document	1. Interim Report	1. Original Issue

INTENTIONALLY BLANK

CONTENTS

CONTENTS (Continued)

Page

CONTENTS (Continued)

CONTENTS (Continued)

Page

TABLES

Page

FIGURES

GENII

Computer Code Application Guidance for Support of Documented Safety Analysis

EXECUTIVE SUMMARY

The Defense Nuclear Facilities Safety Board (DNFSB) issued Recommendation 2002-1 on *Quality Assurance for Safety-Related Software* in September 2002. The Recommendation identified a number of quality assurance issues for software used in the Department of Energy (DOE) facilities for analyzing hazards and designing and operating controls that prevent or mitigate potential accidents. The DOE response to the Recommendation, *Implementation Plan for Recommendation 2002-1 on Quality Assurance for Safety Software at Department of Energy Nuclear Facilities*, commits to a number of actions to improve Software Quality Assurance (SQA) in safety analysis and design software. The development and maintenance of a collection, or "toolbox," of high-use, SQA-compliant safety analysis codes is one of the major commitments. In time, the DOE safety analysis toolbox will contain a set of appropriately quality-assured, configuration-controlled, safety analysis codes, managed and maintained for DOE-broad safety basis applications. The GENII code is one of six codes designated as toolbox software.

The GENII code has two versions available. The first, Version 1.485, was subjected to strict SQA standards when it was developed. The second, Version 2, although subjected to the same SQA standards, is still undergoing final testing and is likely to require completion of quality assurance improvement measures before meeting current SQA standards. Furthermore, it has not been demonstrated that Version 2 is well suited for Documented Safety Analysis (DSA) work. Thus, GENII 1.485 is recommended over Version 2 for support of safety basis calculations. It must be noted, however, that GENII Version 1.485 should be thoroughly tested in the Windows environment before it can be unconditionally recommended, as it was developed in the Disk Operating System (DOS) environment, in which the computer memory management was different from that for Windows.

To ensure appropriate application of the designated toolbox software, the Implementation Plan has committed to sponsoring a set of code-specific documents to guide informed use of the software, and supplement the available user's manual information.

This GENII guidance report includes the following:

- Applicability information for DSA-type analysis, specifically tailored for DOE safety analysis

- Code development information and SQA background
- Appropriate regimes and code limitations
- Valid ranges of input parameters consistent with code capability and DOE safety basis applications
- Default input value recommendations for site-independent parameters

Use of the information contained here, although not ensuring correct use of GENII in each analytical context, will minimize potential user errors and further standardize the use of GENII in appropriate regimes of applicability.

This guidance report is supplemental in nature to documentation from the code developer such as the user's guide and model description. The DOE safety analyst is advised to obtain as complete set of documentation from the GENII code maintainer as is currently available.

1.0 INTRODUCTION

In January 2000, the DNFSB issued Technical Report 25 (TECH-25), *Quality Assurance for Safety-Related Software at Department of Energy Defense Nuclear Facilities* (DNFSB, 2000). TECH-25 identified issues regarding the state of SQA in the DOE Complex for software used to make safety analysis decisions and to control safety-related systems. Instances were noted in which computer codes were either inappropriately applied or were executed with incorrect input data. Of particular concern were inconsistencies in the exercise of SQA from site to site, and from facility to facility, and in the variability of guidance and training in the appropriate use of accident analysis software.

During the subsequent 2000 to 2002 period, survey information on SQA programs, processes, and procedures was collected, as well as the initial elements to a response plan. However, to expedite implementation of corrective actions in this area, the DNFSB issued Recommendation 2002-1, *Quality Assurance for Safety-Related Software at Department of Energy Defense Nuclear Facilities* (DNFSB, 2002). As part of its Recommendation to DOE, the DNFSB enumerated many of the points noted earlier in TECH-25, but noted specific concerns regarding the quality of the software used to analyze and guide safety-related decisions, the quality of the software used to design or develop safety-related controls, and the proficiency of personnel using the software.

DOE has developed a series of actions that address the DNFSB concerns, contained in the Implementation Plan for the DNFSB Recommendation, *Implementation Plan for Defense Nuclear Facilities Safety Board Recommendation 2002-1.* Two of the actions include the following:

- The identification of a set of accident analysis software that is widely used in the DOE Complex.
- Issuance of code-specific guidance reports on the use of the "toolbox" codes for DOE facility accident analysis, identifying applicable regime in accident analysis, default inputs, and special conditions for use.

Safety analysis software for the DOE "toolbox" status was designated by the DOE Office of Environment, Safety, and Health (DOE/EH) in March 2003 (DOE/EH, 2003). The supporting basis for this designation was provided by a DOE-chartered Safety Analysis Software Group in a technical report entitled, *Selection of Computer Codes for DOE Safety Analysis Applications*, dated August 2002 (see http://www.deprep.org/archive/rec/2002-1/NNSACCodes1.pdf). It includes the GENII code.

It is believed that each code designated for the toolbox can be applied to accident analysis under the precautions and recommended input parameter ranges documented in the body of the respective guidance reports. The code-specific document will be maintained and updated until a minimum qualification software package is completed.

The primary objective of this guidance report is to provide information on the use of GENII for supporting DOE safety-basis accident analysis. Specifically, the report contains the following:

- Applicability guidance for DSA-type analysis, specifically tailored for DOE safety analysis
- Appropriate regimes, recommended configurations
- Overcoming known vulnerabilities and avoiding code errors
- Valid ranges of input parameters consistent with code capability and DOE safety basis applications
- Default input value recommendations for site-independent parameters
- Citations of currently available SQA documentation

Thus, this report is intended to complement existing GENII documentation from its developer. Current GENII reports tend to be much broader in coverage of the full range of capabilities of GENII and the spectrum of inputs that might be needed depending upon the application, but lack cohesive and targeted guidance for particular applications, such as DSA accident analyses. Furthermore, the goal of this document is to identify limitations and vulnerabilities not readily found in documentation from the code developer or published elsewhere.

1.1 GENII Guidance Document

This GENII guidance document has several sections. The first section contains an introduction and background providing an overview of safe harbor software in the context of Code of Federal Regulation (CFR), Title 10, Subpart 830. More information follows on the scope and purpose of this document. The next major section is a summary description of GENII. A third section discusses applicable regimes for using GENII in performing accident analysis. Another section on default inputs and recommendations, emphasizing appropriate inputs for DOE applications, follows this section. Following this are sections on special conditions for use of the software and software limitations. Sample cases are then provided, followed by acronyms and definitions, references, and an appendix on a general overview of atmospheric dispersion and consequence analysis. This appendix is provided for the safety analyst new to this field.

1.2 Background: Overview of Toolbox Software in Context of 10 CFR 830

In the context of 10 CFR 830, the Nuclear Safety Management rule, the six computer codes designated by DOE/EH as toolbox software will be of appropriate pedigree for support of safety basis documentation. After completion of the minimum required SQA upgrade measures for a toolbox code, the safety analyst would still need to justify the specific application with the code of interest, input parameters, and user assumptions, but many SQA burdens would be reduced from current requirements. The user would need to reference the toolbox code and version, identify compliance with their organization's SQA requirements, and demonstrate that the code is being applied in the proper accident analysis context using appropriate inputs. The SQA pedigree would be sufficiently established for technical review purposes since the code is recognized as toolbox-supported.

Only six codes, out of more than one hundred software packages applied in the DOE Complex for accident analysis purposes, have been designated as "toolbox" codes. Other non-toolbox dispersion and consequence software can still be applied in the context of support safety-basis applications. However, each organization applying this category of software will need to demonstrate compliance with applicable SQA criteria, such as those applied to the toolbox software.

1.3 Scope

This GENII guidance report includes the following:

- Applicability information for DSA-type analysis, specifically tailored for DOE safety analysis
- Code development information and SQA background
- Appropriate regimes and code limitations
- Valid ranges of input parameters consistent with code capability and DOE safety basis applications
- Default input value recommendations for site-independent parameters

1.4 Purpose

The GENII code is part of the designated group of software to be placed in the DOE Safety Analysis Toolbox. Prior to being brought under configuration management in the toolbox, GENII and other designated software will be part of an SQA review. In the interim before this review process is completed, GENII can be still be applied for safety analysis purposes as long as the safety analyst understands the strengths and limitations of the software and is cognizant of the information provided in this report and documentation provided by the code developer. If it is decided that upgrades are warranted, GENII will be brought under configuration control only after this process is completed.

Use of the information contained herein will not ensure correct use of GENII in all analytical contexts. However, it should minimize potential user errors and the likelihood of use outside regimes of applicability.

1.5 Applicability

It is recognized that other computer codes besides GENII exist that perform similar type of atmospheric dispersion and radiological consequence calculations. Moreover, manual or electronic spreadsheet calculations can be a viable alternative to using a computer code for some accident analysis applications that involve releases of radiological material. The relative merits of using a different computer program or using a hand calculation for a given application is a judgment that must be made by the analyst on a case-by-case basis. The DOE has provided guidance and general recommendations in this area through the Accident Phenomenology and Consequence Methodology Evaluation Program. As part of this program, the Radiological Dispersion and Consequence Assessment (RDCA) Working Group (WG) was established to address issues and evaluate methodologies in the RDCA domain. The RDCA WG (also referred to as WG 5) issued a report that identifies and evaluates methodologies and computer codes to support RDCA applications (O'Kula, 1998).

The RDCA WG 5 report identified the GENII computer code as a recommended code with generally broad suitability to safety-basis documentation applications. In addition to code recommendations, the report also provides a broad set of recommended "best practices" for modeling radiological releases to the atmosphere.

This report builds upon the WG 5 work to provide guidance and recommendations that are targeted to the use of the GENII for atmospheric dispersion and radiological consequence calculations in the context of DSA-type applications. Specifically, the guidance is best suited for the following

- Accident analysis calculations
- Bounding analysis for final hazard categorization analysis
- Confirmatory calculations for evaluating mitigative and preventive safety controls.

2.0 SUMMARY DESCRIPTION OF THE GENII CODE

This section provides a summary form description of the GENII code followed by an overview of the use of GENII for regulatory applications, in particular, for supporting accident analysis in DSA documents. Users requiring additional background information on dispersion and consequence analysis are referred to Chapter 5 (*Atmospheric Dispersion and Consequence Modeling*) of the Nuclear Fuel Cycle Facility Accident Analysis Handbook (Nuclear Regulatory Commission [NRC], 1998) and to Appendix A of this guidance document.

2.1 GENII Summary Description[1]

The GENII computer code was developed at Pacific Northwest National Laboratory (PNNL) to provide a state-of-the art, technically peer-reviewed, documented set of programs for calculating radiation dose and risk from radionuclides released to the environment. Although the codes were initially developed at Hanford, they were designed with the flexibility to accommodate input parameters for a wide variety of generic sites.

The latest version of GENII, Version 2, incorporates the internal dosimetry models recommended by the International Commission on Radiological Protection (ICRP) and the radiological risk estimating procedures of Federal Guidance Report (FGR) 13 into updated versions of existing environmental pathway analysis models. The resulting environmental dosimetry computer codes are compiled in the GENII Environmental Dosimetry System. The earlier version, GENII 1.185, on the other hand, incorporated internal dosimetry models from earlier ICRP recommendations, namely, ICRP publications 26, 30, and 48, which are incorporated into FGR 11.

The development history of the GENII code is outlined below (Napier, 1999d):

- 1988 - Version 1, Released (ICRP-26/30/48 dosimetry)
- 1990 - Version 1.485 stabilized
- 1992 - GENII-S stochastic version
- 1998 - GENII Version 2 (ICRP-72 age-dependent dosimetry).

Table 2-1 lists summary information for GENII, Versions 1.485 and 2.0. A stochastic edition of GENII, Version 1, named GENII-S, was developed for the Waste Isolation Pilot Plant assessments by Sandia National Laboratory (Leigh et al. 1992). GENII, Version 2, is completely stochastic, using the Framework for Risk Analysis in Multimedia Environmental Systems (FRAMES) SUM[3] driver.

---

[1] Much of the information presented here can be found on the EPA website on air quality computer models, http://www.epa.gov/radiation/neshaps/models.htm.

Table 2-1. Summary Description of GENII Software – Versions 1.485 and 2.0

<table>
<tr><th>Type</th><th>Specific Information
GENII Version 1.485</th><th>Specific Information
GENII Version 2.0</th></tr>
<tr><td>Code Name</td><td colspan="2">GENII - Generalized Environmental Radiation Dosimetry Software System - Hanford Dosimetry System (Generation II)</td></tr>
<tr><td>Developing Organization and Sponsor</td><td>PNNL</td><td>PNNL for the U.S. Environmental Protection Agency (current)</td></tr>
<tr><td>Version of the Code</td><td>Version 1.485</td><td>Version 2.0</td></tr>
<tr><td>Auxiliary Codes</td><td>APPRENTICE: Interactive input processor.
ENVIN: controls input for ENV
ENV: calculates transfer and uptake
DOSE: calculates dose from all exposures
EXTDF: calculates external dose rate factors
INTDF: calculates internal dose rate factors
DITTY: calculates population exposure
MASS: Enables the mass production of GENII output using a file containing one or more nuclide groups and several input files.</td><td>Framework for Risk Analysis in Multimedia Environmental Systems (FRAMES) and Sensitivity/Uncertainty Multimedia Modeling Module (SUM^3). GENII 2 has four atmospheric codes, one surface water code, three environmental accumulation models, one exposure model, and one dose/risk model, each with its specific user-interface code.</td></tr>
<tr><td>Software Platform/Portability</td><td>Software on four DS/HD 3.5-in. (1.44 MB) diskettes in self-extracting compressed DOS files. Documentation separate (PNL-6584). Software and documentation package may be downloaded from RSICC website (see code-procurement and code-package information below).</td><td>Software and documentation on CD or download from website.</td></tr>
<tr><td>Coding and Computer</td><td>FORTRAN 77 and Quick Basic. IBM PC or compatible; Operates in a DOS environment or a DOS window in Windows 95.</td><td>FORTRAN. Requires Windows operating system (95 or later), a Pentium-class CPU, and 60 MB of disk storage (formerly 20 MB). Runs fastest with ≥ 256 MB of memory.</td></tr>
<tr><td>Technical Support</td><td>Bruce Napier
Pacific Northwest National Laboratories
P.O. Box 999
Richland, Washington 99352
509-375-3896/Phone
509-375-3896/Facsimile
Bruce.Napier@pnl.gov</td><td>Bruce Napier
Pacific Northwest National Laboratories
P.O. Box 999
Richland, Washington 99352
509-375-3896/Phone
509-375-3896/Facsimile
Bruce.Napier@pnl.gov</td></tr>
<tr><td>Code Procurement</td><td>Radiation Safety Information Computational Center (RSICC)
Oak Ridge National Laboratory
Post Office Box 2008
Bethel Valley Road
Oak Ridge, Tennessee 37831-6171
Phone: 865-574-6176; Fax: 865-241-4046
Email: pdc@ornl.gov</td><td>See Environmental Protection Agency (EPA) National Emission Standards for Hazardous Air Pollutants (NESHAPs) Website for the NESHAPS version of GENII 2, which limits the user to change certain variables:
http://www.epa.gov/radiation/neshaps/models.htm</td></tr>
<tr><td>Code Package</td><td>RSICC Code Package CCC-601 MICRO</td><td>Not available from RSICC</td></tr>
<tr><td>Contributors</td><td colspan="2">Pacific Northwest Laboratory, Richland, Washington through the Energy Science & Technology Software Center, Oak Ridge, Tennessee.
Westinghouse Hanford Engineering Development Laboratory, Richland, Washington.</td></tr>
</table>

Table 2-1. Summary Description of GENII Software (Continued)

Type	Specific Information GENII Version 1.485	Specific Information GENII Version 2.0
Documentation Supplied with Code Transmittal (Not all documents are routinely transmitted with code)	B. A. Napier, R.A. Peloquin, D. L. Strenge, and J. V. Ramsdell, *GENII - The Hanford Environmental Radiation Dosimetry Software System, Volume 1: Conceptual Representation*, PNL-6584 Vol. 1 (December 1988). B. A. Napier, R. A. Peloquin, D. L. Strenge, and J. V. Ramsdell, *GENII - The Hanford Environmental Radiation Dosimetry Software System, Volume 2: Users' Manua*l, PNL-6584 Vol. 2 (November 1988). P. D. Rittmann, *Verification Tests for the July 1993 Revision to the GENII Radionuclide and Dose Increment Libraries*, WHC-SD-WM-TI-596, Rev. 0 (October 1993).	Leigh, C. D., B. M. Thompson, J. E. Campbell, D. E. Longsine, R. A. Kennedy, and B. A. Napier. 1992. *User's Guide for GENII-S: A Code for Statistical and Deterministic Simulations of Radiation Doses to Humans from Radionuclides in the Environment*, SAND91-0561A, Sandia National Laboratories, Albuquerque, New Mexico. Napier, B. A., D. L. Strenge, J. V. Ramsdell, Jr., P.W. Eslinger, and C. F. Fosmire, 1999. *GENII Version 2 Software Design Document*, Pacific Northwest National Laboratory, Richland, Washington. Napier, B.A. 1999, *GENII Version 2 Example Calculation Descriptions*. Pacific Northwest National Laboratory, Richland Washington. Gelston, G.M., M.A. Pelton, K.J. Castleton, B.L. Hoopes, R.Y Taira, P.W. Eslinger, G. Whelan, P.D. Meyer, and B.A. Napier, 1998, *GENII Version 2 Sensitivity/Uncertainty Multimedia Modeling Module Users' Guidance*, Pacific Northwest National Laboratory, Richland, Washington.

Table 2-1. Summary Description of GENII Software (Continued)

Type	Specific Information GENII Version 1.485	Specific Information GENII Version 2.0
Nature of Problem	GENII was developed to incorporate the internal dosimetry models recommended by the ICRP into the environmental pathway analysis models used at Hanford. GENII is a coupled system of seven programs and the associated data libraries that comprise the Hanford Dosimetry System (Generation II) to estimate potential radiation doses to individuals or populations from both routine and accidental releases of radionuclides to air or water and residual contamination from spills or decontamination operations. The GENII system includes interactive menu-driven programs to assist the user with scenario generation and data input, internal and external dose factor generators, and environmental dosimetry programs. The programs analyze environmental contamination resulting from both far-field and near-field scenarios. A far-field scenario focuses outward from a source, while a near-field scenario focuses in toward a receptor. GENII can calculate annual dose, committed dose, and accumulated dose from acute and chronic releases from ground or elevated sources to air or water and from initial contamination of soil or surfaces and can evaluate exposure pathways including direct exposure via water (swimming, boating, and fishing), soil (surface and buried sources), air (semi-infinite and finite cloud geometries), inhalation pathways, and ingestion pathways. In addition, GENII can perform 10,000-years migration analyses and can be used for retrospective calculations of potential radiation doses resulting from routine emissions and for prospective dose calculations for purposes such as siting facilities, environmental impact statements, and safety analysis reports. The alternate data added in March 1995 were contributed by HEDL, and are intended to improve the treatment of decay chains for calculations of doses from contaminated soil allowed to decay for hundreds of years. Air transport calculations are largely unaffected by these changes due to the short decay times involved. In October 1996 the GENII 1.485 system was repackaged to replace the ZOO archive files with self-extracting DOS files compressed with the PKZIP utility from PKware, Inc. as some users encountered problems when reading the ZOO files.	

Table 2-1. Summary Description of GENII Software (Continued)

Type	Specific Information GENII Version 1.485	Specific Information GENII Version 2.0
Method of Solution	GENII 1.485: APPRENTICE interactively prepares a text input file for the near-term (Approximately 1 to 100 years) environmental dosimetry programs and a batch processing file to manage the file handling needed to control the operations of the five subsequent codes and prepare an output report. ENVIN controls the reading and organization of the input files for ENV, which then calculates the environmental transfer, uptake, and human exposure to radionuclides that result from the chosen scenario for the defined Source Term (ST). ENV writes the annual media concentrations and intake rates to intermediate data transfer files for use by DOSE. DOSE converts these data to radiation dose, calculating the external dose using factors generated by EXTDF and the internal dose using factors generated in INTDF. DOSE calculates the one-year dose, committed dose, cumulative dose, and maximum annual dose and prepares the normal output report of doses and optional doses by pathway and by radionuclide. EXTDF calculates the external dose-rate factors for submersion in an infinite cloud of radioactive materials, immersion in contaminated water, and direct exposure to plane or slab sources of contamination. EXTDF used the ISOSHLD point kernel integration technique whereby numerical integration is carried out over the source volume to obtain the total dose. INTDF estimates the dose equivalents in a number of target organs from the activity in a given source organ based on ICRP-30 models and biokinetic values for radionuclide residency and transport in the body. The dose equivalent in a target organ is the product of the total number of nuclear transformations of the radionuclide and the energy absorbed per gram in the target organ. This initial value problem is solved using a coupled set of differential equations. DITTY calculates long-term total population exposure based on air and water STs, atmospheric dispersion patterns, and exposed population. A straight-line cross-wind-averaged Gaussian plume model is used for the dispersion calculation, and the regional population is defined as a function of time for airborne and waterborne pathways. The time frame may be any 10,000-year period, broken into 143 periods of 70 years each. GENII 2: The FRAMES user interface is used in place of APPRENTICE and its supporting programs. The capabilities of GENII 2 are similar to GENII 1.485 but with enhancements, such as SUM^3 for stochastic evaluations, and an improved user interface.	
Restrictions or Limitations	The atmospheric model included in the code does not model the impact of terrain effects on atmospheric dispersion. The code also does not model dispersion close to the source (less than 100 meters from the source) or long-range dispersion. Maximum of 100 radionuclides, 5 shields. For GENII 1.485 there are 16 sectors and 10 distance intervals in a radial grid but only one distance and one sector can be run at a time. GENII 2 includes a 36 sector radial grid and a square grid (for puffs). The user can specify up to 10 receptor locations in the grid and GENII 2 will assign those locations to the nearest grid points.	
Run Time	The sample problems took a total of 30 minutes on an IBM PC-AT under DOS 3.3. More recent information indicates: Less than one minute for most typical runs (~ 5 s)	Machine-dependent; A few seconds for most problems.
Computer Hardware Requirements	GENII requires an IBM PC/AT or compatible computer, an 80287 math coprocessor, 640 Kbytes of random access memory, and a minimum of 5 MB on-line disk storage.	GENII Version 2 requires Windows 95, 98, NT, or 2000, using Pentium processors, and disk storage in excess of 60 Mbytes. As FRAMES and GENII make use of the memory swapping capabilities of Windows, the programs should run on any Windows compatible machine. Best performance is with machines with 256 Mbytes or more.
Computer Software Requirements	Lahey F77L (92%) and Microsoft QuickBASIC 3.0 (8%) were used to create the executables, which runs under DOS 3.1 or later. It also runs from a DOS window of	Pentium-class processor, Windows 95 or later, 60 MB disk space, preferably ≥ 256 MB memory. Does not run under DOS.

Table 2-1. Summary Description of GENII Software (Continued)

Type	Specific Information GENII Version 1.485	Specific Information GENII Version 2.0
	Windows 95. These executables were created in the early 1990s and will not run on Windows XP. The GENII and APPRENTICE source files were added to the package in the March 1995 update. APPRENTICE, which is written in Microsoft QuickBASIC 3.0, uses modules and subroutines from the Komputerwerk Modules libraries.	
Other Versions Available	GENII-S (Stochastic); GENII Version 2.0	GENII-S (Stochastic); GENII Version 1.485

2.1.1 Capabilities and Exposure Pathways

The GENII system includes the capabilities for calculating radiation doses following chronic and acute atmospheric releases. Radionuclide transport via air, water, or biological activity may be considered. Air transport options include both puff and plume models, each allow use of an effective stack height or calculation of plume rise from buoyant or momentum effects (or both). Building wake effects can be included in acute atmospheric release scenarios. The code provides risk estimates for health effects to individuals or populations; these can be obtained using the code by applying appropriate risk factors to the effective dose equivalent or organ dose. Data entry is accomplished via interactive, menu-driven user interfaces.

Default exposure and consumption parameters are provided for both the average (population) and maximum individual, however these may be modified by the user. Source term information may be entered as radionuclide release quantities for transport scenarios, or as basic radionuclide concentrations in environmental media (air, water, soil). For input of basic or derived concentrations, decay of parent radionuclides and ingrowth of radioactive decay products prior to the start of the exposure scenario may be considered. A single code run can accommodate unlimited numbers of radionuclides including the source term and any radionuclides that accumulate from decay of the parent, because the system works sequentially on individual decay chains

2.1.2 Interface System

The Version 1.485 user interface is APPRENTICE. It interfaces with other codes for input of data, computations, and output of results. The code package for Version 2.0 also provides interfaces, through the FRAMES. Both versions provide external calculations of atmospheric dispersion, geohydrology, biotic transport, and surface water transport. Target populations are identified by direction and distance (radial or square grids for Version 2) for individuals, populations, and for intruders into contained sources.

2.1.3 Dosimetry Models

GENII Version 1.485 implemented dosimetry models recommended by the ICRP in Publications 26, 30, and 48, and approved for use by DOE Order 5400.5. GENII, Version 2, implements these models plus those of ICRP Publications 56 through 72, and the related risk factors published in FGR 13. Risk factors in the form of EPA developed "slope factors" are also included. The dosimetry and risk models are considered to be "state of the art" by the international radiation protection community and have been adopted by most national and international organizations as their standard dosimetry methodology.

2.1.4 COMPONENT PROGRAMS

GENII, Version 1.485, consists of seven coupled programs (listed above) for input, processing, and output. Version 2 consists of four independent atmospheric models, one surface water model, three independent environmental accumulation models, one exposure module, and one dose/risk module, each with a specific user interface code. The computer programs are of several types: user interfaces (i.e., interactive, menu- driven programs to assist the user with scenario generation and data input), internal and external dose factor libraries, the environmental dosimetry programs, and FRAMES-supplied file-viewing routines. For maximum flexibility, the code has been divided into several interrelated, but separate, exposure and dose calculations.

2.1.5 Documented Safety Analysis Calculations

The GENII code executes consequence calculations that can be used to support applications such as site evaluations, DSAs, and environmental impact statements. Source term information may be entered as radionuclide release quantities for transport scenarios or as radionuclide concentrations in air, water, or soil media. Algorithms model transport of radioactive material through the atmosphere, surface water, and biotic activity. Atmospheric releases are modeled as plumes or as a series of puffs. The GENII code includes models for stack releases, plume rise from momentum and buoyancy effects, and building-wake influences on trajectory and dispersion. Radionuclide decay and ingrowth during plume transport are computed.

Exposure pathways include direct exposure via air, water, or soil and internal exposure through inhalation and ingestion. The tritium model also considers exposures via skin absorption. Dose Conversion Factors (DCFs) relate environmental concentrations and intakes to resultant human doses for specific exposure pathways, organs, and radionuclides.

2.2 Overview of GENII for Regulatory Applications

For documented safety analysis purposes, the consequences of interest are the centerline Total Effective Dose Equivalent (TEDE) incurred by the Maximally Exposed Offsite Individual (MOI) evaluated at the 95th percentile dose level. In general, the statistical evaluation of consequences from meteorological variability is handled in one of two ways. In the first, hourly meteorological data of wind direction, wind speed, and atmospheric stability class over a one-year period is randomly sampled. In the other (which is the only option available in GENII 1.485), a joint frequency distribution of wind direction, wind speed, and atmospheric stability class is first determined from the hourly meteorological data and then used in the calculations. GENII 1.485 can calculate the 95th percentile dose for a given distance and direction. It has to be run 16 times, once for each sector and for the site boundary for that sector. The largest of these 95th percentile values is typically given as the dose that meets the DOE Standard (STD) 3009-94, CN#2. GENII 2.0, however, cannot be used to generate 95th percentile values without considerable effort with the present version.

Accident duration is defined in terms of plume passage at the location of the dose calculation, for a period not to exceed 2 hours or 8 hours for slow-developing release scenarios (DOE, 1994). Prolonged effects, such as resuspension, need not be modeled. The acute plume model in GENII (Version 2.0 also has an acute puff model) is applicable to releases or exposures that occur over a relatively short period, such as a few hours. Thus, the acute plume model is appropriate for modeling accidental releases for DSA applications.

2.3 GENII Applications

GENII 1.485 has been applied in many safety analysis applications for determination of MOI doses. Studies using GENII include, but are not limited to those performed for:

- Safety analysis reports - Hanford site nuclear facilities, the Waste Isolation Pilot Plant
- One-year worker dose from postulated accidents - Solid Waste Material Facilities (Savannah River Site)
- EIS chronic and accident release analysis, the Mixed Oxide Fuel Fabrication Facility

As indicated in Table 2-1, GENII, Version 2.0, is EPA-sponsored, and has been applied mostly for Environmental Impact Statements (EISs) and NESHAPs compliance analyses for routine release calculations.

3.0 APPLICABLE REGIMES

The objective of this section is to present a discussion of GENII applicability from two perspectives: (1) in terms of its overall function as a key step in accident analysis; and (2) noting the phenomenological regimes in which it provides an approximate model of dispersion in the environment and the resulting radiological exposure to downwind individuals (receptors).

3.1 Overall Application in Safety Analysis

DOE evaluates and approves the operation of its nuclear facilities via the safety analysis process outlined in DOE Rule, 10 CFR 830 – Subpart B and DOE-STD-3009-94. This safety analysis process requires the development of a DSA per the Rule language and includes two key types of analyses: (1) hazard analysis and (2) accident analysis.

Hazard analysis is the cornerstone of the DOE safety analysis process and is largely a qualitative process which comprises the following

- The hazards in the facility are identified
- A spectrum of accidents are postulated for each hazard
- A qualitative evaluation of accident likelihood and consequence is made
- All preventive and mitigative systems or controls are identified along with a qualitative measure of their importance

The final product of the hazard analysis gives rise to a list of which systems or controls are important to safety and therefore are designated as safety-significant. This designation will lead to a formal commitment on the part of the facility contractor to maintain the safety function of these systems through Technical Safety Requirements (TSRs).

Accident analysis is a follow-on activity to the hazard analysis. The focus of the Design Basis Accidents (DBAs) is public exposure, and therefore, a quantitative calculation of dose to the MOI is made for each DBA. The purpose of the dose calculations is to determine if some of the safety-significant systems identified in the hazard analysis should have their safety designation raised to safety-class. The standard approach for the accident analysis is outlined below in terms of the ST and the radiological dispersion and consequence analysis phases.

3.1.1 SOURCE TERM ANALYSIS

The radiological consequences are typically established using the methods discussed in the DOE-HDBK-3010-94 (DOE, 1994a). Since the dose from the inhalation pathway will usually dominate the overall dose from most non-reactor facilities, the ST may be quantified using from the five-factor formula:

$$ST = MAR \cdot DR \cdot ARF \cdot RF \cdot LPF \tag{3-1}$$

where:

- Source term (ST) is the total quantity of respirable material released to the atmosphere during the postulated accident condition.
- Material-at-Risk (MAR) is the total quantity of radionuclides (in grams or curies of activity for each radionuclide) available to be acted on by a given physical stress.
- Damage Ratio (DR) is the fraction of the MAR actually impacted by the accident-generated conditions.
- Airborne Release Fraction (ARF) is the fraction of a radioactive material suspended in air as an aerosol and thus available for transport due to a physical stress from a specific accident condition.
- Respirable Fraction (RF) is the fraction of airborne radionuclides as particles that can be transported through air and inhaled into the human respiratory system and is commonly assumed to include particles 10-µm Aerodynamic Equivalent Diameter (AED) and less.
- Leakpath Factor (LPF) is the fraction of the radionuclides in the aerosol transported through some confinement deposition system (e.g., facility rooms, ductwork) or filtration mechanism (e.g., High Efficiency Particulate Air [HEPA] or sand filters).

For most accident analyses, the MAR is best defined as the maximum inventory that is permitted within the room, area, or facility. While it is permissible to exclude material forms that are considered to be unaffected by an accident condition from the MAR, experience suggests that for these forms the DR is usually best set to zero for the release mechanism. The overall result using either approach is the same. However, by assigning DR values to each combination of inventory form and release mechanism, there is the expectation that each credited form (e.g., a shipping package certified to withstand the postulated fire severity) is also reviewed against secondary events (e.g., building collapse initiated by a fire) and therefore, less likely to be overlooked.

The ARF and RF values presented in DOE-HDBK-3010-94 are derived from discrete experiments that typically evaluated a single release mechanism. For example, in a severe fire there may be many mechanisms occurring simultaneously. Powdered metals might be subject to entrainment by fire-induced air currents, falling because of equipment (glove box) collapse, and impact because of objects falling into the exposed fire. In addition, multiple occurrences could occur for specific mechanisms (e.g., impact of falling object on a stable powder). Aqueous solutions could be subject to boiling within the storage tank, spillage because of a tank collapse, and rapid evaporation plus splashing as the liquid sits in a diked area during the same postulated fire. Solid metals can be subject melting, dripping and burning during the same event. To accommodate multiple-mechanism events, it is common to consider the ARF and RF values for each mechanism in the ST estimate.

Just as with the (ARF·× RF) term, there can be multiple LPF terms applied to a single material form (e.g., room leakage, ventilation system deposition, or filtration system effectiveness). Thus, their cumulative effect must be accounted for. There can be interdependence between the

LPF and DR in some applications. If a shipping package is considered to leak during a fire, the leakpath effect as the material exits the packaging can be accounted for as an LPF or a DR. Based on experience, it is recommended that ST reductions related to localized conditions such as at shipping packages, and glove boxes be accounted for in the DR term. This approach allows the ST contribution from individual rooms to be readily compared. It also simplifies comparisons between the room ST and the building ST.

Based on the above discussion, Equation (1) can be generally reformatted as follows:

$$\mathrm{ST}_{\mathrm{jk}} = \sum_{\mathrm{i=1}}^{\mathrm{n_i}} \left\{ \mathrm{MAR}_{\mathrm{ij}} \cdot \mathrm{DR}_{\mathrm{ijk}} \cdot \left[\left(\mathrm{ARF} \cdot \mathrm{RF}\right)_{ijk} \cdot \left(\prod_{m=1}^{n_m} LPF_m \right)_{ijk} \right] \right\} \tag{3-2}$$

where:

- i is the MAR component in a specific form (e.g., powder, liquid)
- j is the MAR component by type (e.g., Pu_{238}, Pu_{239})
- k is the release mechanism (e.g., fire, spill)
- m is the filtration or deposition stage (successive stages)
- n is the number of parameters for the form, type, mechanism or stage based on the subscript.

Thus, the ST is usually expressed in terms of an isotopic activity distribution for each release mechanism. ST components that are associated with the same release duration can be combined, but ST components that have different release mechanisms should be kept separate to account for time-dependent variance in atmospheric dispersion for consequence assessment. Note that the LPF term is the product of the successive factors, not their sum.

Note that the DR, but not the MAR, is shown in Equation (2) as a function of the release mechanism (k subscript), based upon the recommendation above on how to best handle the interplay between the MAR and the DR. Frequently, the DR, ARF, RF, and LPF terms are specified independently of the type, and the j subscript can be dropped from these terms as applicable.

3.1.2 DISPERSION AND CONSEQUENCE ANALYSIS

Once the ST is established, the consequences to the receptors can be estimated. For fire scenarios at facilities relatively close to the site boundary, the receptor at the site boundary may be exposed to lower concentrations if plume buoyancy lofts the plume above the receptor. Under these circumstances, higher receptor exposures can be expected downwind of the site boundary as the effects of increasing downwind plume growth progressively makes plume rise effect less significant. The “touchdown” point refers to the location of maximum receptor concentration. Thus, the maximally exposed individual for a lofted plume is not at the site boundary, but rather at the touchdown point. Rather than evaluating for this point, it can be more cost effective to estimate the fire consequences as a ground level release with the maximally exposed individual at the site boundary. While the results will be higher than the plume-buoyancy credited analysis, the increase may not be significant when compared to the uncertainties in the analysis and the analysis complexity.

Typically, the off-site radiological consequences are expressed as the TEDE to the receptor at the highest exposure conditions. For most accident types, this is at, or near, the site boundary. The TEDE includes the 50-year Committed Effective Dose Equivalent (CEDE) from inhalation both during plume passage and later from resuspension, the cloudshine Effective Dose Equivalent (EDE), the groundshine EDE, and the skin absorption EDE. This TEDE calculation generally does not include the ingestion CEDE from consumption of contaminated water and foodstuffs, although in principle it could. The inhalation CEDE is usually the dominant contributor and its relationship to the ST is highlighted below.

The basic equation for the radiological consequences to an individual receptor (i.e., stationary at a specific downwind location) from the inhalation pathway during plume passage is as follows:

$$\text{Receptor Inhalation CEDE} = \text{BR} \cdot \sum_{k=1}^{n_k} \left\{ \left(\frac{\chi}{Q} \right)_k \sum_{j=1}^{n_j} \left[\text{ST}_{jk} \cdot \text{C}_j \cdot \text{IDCF}_j \right] \right\} \tag{3-3}$$

where: j, k, n are as defined in Equation 3-2 above

BR is the breathing rate of the individual exposed to the plume of released radiological material, with typical units of m^3/s.

C_j is the specific activity of isotope j, with typical units of Ci/kg if ST is in mass units (kg) and unity if ST is in activity units (Ci).

$IDCF_j$ is the Inhalation Dose Conversion Factor for unit activity uptake of isotope j, with typical units of rem/Ci.

$(\chi/Q)_k$ is the downwind dilution factor from atmospheric dispersion, which represents the time-integrated concentration at a specific downwind location that is normalized by the quantity released to the atmosphere, with typical units of s/m^3.

When the ST value is input into the GENII code, the GENII output provides the TEDE value at the requested receptor location that will include the contribution from the plume-passage inhalation CEDE as well as the contributions from resuspension inhalation CEDE, cloudshine EDE, groundshine EDE, and skin absorption EDE.

3.1.3 COMPUTER CODES FOR ACCIDENT ANALYSIS

The safety analyst may use hand calculations or computer codes to calculate ST and dispersion values. The computer codes chosen by the safety analyst fall into several categories. The categories of codes are as follows

- Radiological atmospheric dispersion codes

- Chemical atmospheric dispersion codes
- Fire modeling codes
- Leakpath analysis codes

The analyst typically applies one or more of these types of codes to calculate parameters, such as DR, LPF, and χ/Q, or to integrate over groups of these parameters. The effect of the quality of these codes on the overall safety analysis process can be evaluated qualitatively by examining the role that these parameters play in the overall safety process.

3.1.3.1 Qualitative Effect of the Codes on Safety Analysis

The gross effect of the use of computer codes can be evaluated by examining their effect on the final MOI dose values calculated as part of the accident analysis. The values chosen or calculated for each parameter in the dose equation are near the conservative tail of any distribution that would be assigned to the individual parameter. Therefore, when each parameter is multiplied using Equations 3-2 and 3-3 to obtain the dose, the conservatism in the calculation grows. If applied consistently in each phase of the process and in a reasonably bounding manner, this large conservatism in the calculation has always provided the DOE safety analysis process with sufficient margin when the doses are used to make decisions regarding safety. Even if a single value in the dose calculation were off by an order of magnitude, the resulting value would still not approach the mean value of dose if a cumulative distribution of dose also were calculated.

GENII is used to calculate the appropriate dilution factor and ultimately quantify the radiological dose. The net effect on safety then is related to GENII's input in selecting safety-class Systems, Structures, and Components (SSCs).

GENII, and other atmospheric dispersion and radiological consequence codes, are used in analyzing atmospheric dispersion and the subsequent radiological consequence of accidental releases of radioactivity from postulated accident conditions. Codes of this type of are used primarily to calculate the appropriate dilution factor for atmospheric transport of puffs or plumes and ultimately quantify the radiological dose that is received by the MOI. The 95th percentile of the distribution of doses to the MOI is the comparison point for assessment against the Evaluation Guideline (EG). Consequently, the importance of these classes of accident analysis codes on safety is related to their contribution in selecting safety-class SSCs.[2]

Appendix A to DOE-STD-3009-94 prescribes the statistical method to be used to calculate the MOI dose, which is based on the method described in Position 3 of the NRC Regulatory Guide 1.145 (NRC 1983). Given site-specific data, the 95th percentile consequence is determined from

---

[2] The selection of safety-class SSCs is an important decision, but the decision to make an SSC safety-significant is made initially in the hazard analysis. Thus, the quality of the dose value will not affect the SSC being made a safety-significant SSC and having TSR coverage, only the designation of safety-class, and therefore, possibly the pedigree of the SSC.

the distribution of meteorologically-based doses calculated for a postulated release to downwind receptors at the site boundary that would result in a dose that is exceeded 5% of the time. Appendix A to DOE-STD-3009-94 allows for variations in distance to the site boundary as a function of distance to be taken into consideration. Assuming the minimum distance to the site boundary applies in all directions is a conservative implementation.

3.2 Phenomenological Regimes of Applicability

The GENII class of atmospheric dispersion codes is based on the Gaussian model of dispersion. As such, these types of computer model are best suited for specific types of conditions. The chief phenomenological regimes for applying GENII include the following:

- Temporal regime – The use of these codes is best suited for "short" duration plumes, on the order of an hour.
- Spatial regime – The class of code also does not model dispersion close to the source (less than 100 meters from the source), especially where the influence of structures or other obstacles is still significant. Dispersion influenced by several, collocated facilities, within several hundred meters of each other should be modeled with care. Similarly, the GENII class of codes should be applied with caution at distances greater than ten to fifteen miles, especially if meteorological conditions are likely to be different from those at the source of the release. Long-range projections of dose conditions are better calculated with mesoscale, regional models that are able to account for multiple weather observations. Nevertheless, some applications may require fifty-mile or greater radius analysis to meet requirements (e.g. EISs).
- Terrain variability – Gaussian models are inherently flat-earth models, and perform best over regions of transport where there is minimal variation in terrain.
- Energetic releases – GENII does not account for releases originating from detonation type events without appreciable post-processing of boundary and initial conditions.
- Thermal buoyancy – In plumes arising from fire-related STs, the user should exercise caution with the models such as GENII that use the Briggs algorithm. The Briggs approach for accounting for sensible energy in a plume is valid for "open-field" releases (not impacted by buildings and other obstacles), or if used in combination with building wake effects.
- DCF applicability – The user should ensure that the DCFs used in GENII are applicable to the radionuclides in the ST and the physicochemical characteristics. For example, plutonium nitrates and oxides have different time scales for dosimetric effects in the body with different resulting DCFs. Thus, the appropriate lung absorption type should be used in the DCF file used in the GENII run.

4.0 INPUTS AND RECOMMENDATIONS

In principle, both versions of GENII can be used for DSA purposes. However, GENII 2 cannot be used to determine 95th percentile values of χ/Q without considerable effort. Furthermore, the full suite of subroutines for GENII 2 has not yet been completely tested (Napier, 2003). Therefore, because GENII 2 cannot yet be recommended for DSA analyses, and several DSA-type analyses have used the previous version (Section 2), the inputs and recommendations cited below are for GENII 1.485.

The GENII 1.485 computer code consists of models for atmospheric transport, surface water transport, terrestrial (i.e., plant and animal) transport, and human exposure and dosimetry. Since surface water transport and terrestrial transport are not of interest for support of a DSA, inputs associated with these models are not discussed here. The water transport and terrestrial transport models, for example, support the calculation of drinking water and food ingestion doses that are not required for DSA dose determinations.

4.1 General Code Input and Output Assumptions

A number of input parameters are unique when using GENII for a specific DSA application. Some of these parameters will be related to the source term being released or more specifically the radionuclide inventory being released. When defining the radionuclide inventory for GENII input, one must consider the activity of the inventory, under what conditions the material is being released (i.e. filtered or unfiltered conditions), and the material type being released. The material type influences the selection of CEDE IDCFs.

For DSA purposes, the consequences of interest are the centerline TEDE incurred by the MOI evaluated at the 95th percentile dose level (DOE, 1994). In GENII 1.485, each sector is evaluated independently through executing the code for each of the 16 sectors individually. The maximum value among the 95th percentile dose-level results for the 16 sectors is chosen to represent the MOI dose. Although this sector approach is not fully compliant with the guidance of Appendix A of DOE-STD-3000-94 (CN#2), it should be conservative with respect to the guidance. It is not clear, however, the extent to which the use of a Joint Frequency Distribution (JFD) by GENII 1.485 is compliant with the sampling algorithm that is prescribed by Appendix A of DOE-STD-3000-94 (CN#2) or with the basis NRC Regulatory Guide 1.145. The JFD was prepared before the prescription of DOE-STD-3009-94, Appendix A (CN#2) was promulgated and the existing JFDs may not be compliant. However, it is possible for a user to create a new JFD that is compliant.

4.2 Recommended Inputs for Specific Scenario Parameters

The user is prompted for a set of input data for a scenario when using the APPRENTICE interactive input processor. Guidance is given below for those parameters that are common to DSA applications. Other parameters are set with default values and should remain unchanged unless the user has good reason to change them. These are covered in Section 4.3.

4.2.1 SCENARIO TYPE

The user is given the choice of specifying either near-field or far-field for the scenario type. According to the user documentation, a far-field scenario is generally applicable to safety analysis applications. A typical far-field type of a scenario involves a release of radioactive material, its downwind transport, and dose impact on an individual or distributed populations. Conversely, the focus of the near-field scenario type is the dose that an individual receives at a particular location that has an external source or initial contamination.

Recommendation: The far-field scenario type is specified for most DSA applications.

4.2.2 RECEPTOR DOSE

For a far-field scenario, GENII will calculate either the dose that is received by an individual or by a distributed population.

Recommendation: The individual receptor is specified for DSA applications.

4.2.3 RELEASE TYPE

GENII models both acute and chronic releases. An acute release scenario defines an accidental, one-time release of radioactive material over a short period of time such as a few hours or less. Chronic releases occur over a longer period.

Recommendation: An acute release should be specified for DSA applications.

4.2.4 INDIVIDUAL TYPE

The individual-type input establishes a set of individual exposure parameters that are used to model inhalation, ingestion, and external exposure effects. The user specifies either average individual or maximum individual for this input. The parameter specifications for the average individual type are recommended by the user documentation for most population dose calculations.

Recommendation: The maximum individual type should be specified for DSA applications.

4.2.5 TRANSPORT PATHWAY

The GENII, Version 1.485, computer code consists of models for atmospheric air transport and surface water transport.

Recommendation: Airborne transport is specified for DSA applications.

4.2.6 EXPOSURE PATHWAYS

The GENII, Version 1.485, computer code consists of models for various exposure pathways related to inhalation, ingestion, and external exposure.

Recommendation: Ingestion exposure effects are not considered in DSA applications. Receptor doses in DSA are based on inhalation, direct shine from the plume, and ground shine from deposited material.

4.2.7 INVENTORY RADIONUCLIDES AND SOURCE TERM RELEASE QUANTITY

The number of inventory radionuclides cannot exceed 100. The user specifies the activity, in curies, of each radionuclide released over a specified release period, up to one year. For acute airborne releases, the radioactive material is effectively released over the period that is specified for the plume duration as discussed in Section 4.2.16.

Recommendation: If the number of radionuclides is greater than 100, either the inventory must be divided into groups with a maximum of 100 radionuclides each, or only those radionuclides that contribute to the overall TEDE should be retained. A useful cut-off for considering a group of radionuclides is the dose consequence contributed by one or more radionuclide is ≤ 0.1%. Below this value, the radionuclides in question can be ignored because they contribute insignificantly to the dose.

The curies released for each radionuclide of the inventory should have an appropriate amount of conservatism to account for any variability or uncertainty.

4.2.8 ATMOSPHERIC TRANSPORT AND DISPERSION CHARACTERIZATION

A cloud of released material undergoes dilution during atmospheric transport and diffusion that is characterized by the χ/Q value, which represents the time-integrated concentration at a specific downwind location, normalized by the quantity released to the atmosphere, with typical units of s/m^3. The user may specify the χ/Q value or provide a JFD of meteorological data consisting of wind speed, wind direction, and atmospheric stability.

Recommendation: If the user specifies the χ/Q value, it should represent the 95^{th} percentile χ/Q value as prescribed by Appendix A of DOE-STD-3000-94 (CN#2) with the statistical basis consistent with Regulatory Position 3 of NRC Regulatory Guide 1.145. If a JFD file of meteorological data is used, it should be developed in accordance to guidance given in the user documentation. Note that wind speeds in the JFD file should correspond to the release height of the plume. If the release takes place at or near ground level, it is common practice to base the wind speed at 10 m above ground.

When a JFD file is used, the user is prompted to specify the wind direction (i.e., one of the 16 sectors) and the site boundary distance or equivalently the distance from the source to the receptor of interest if the receptor is not at the site boundary. Regulatory Position 3 of NRC Regulatory Guide 1.145 provides instructions on how to take into consideration variations in distance to the site boundary as a function of angular direction. Each sector is evaluated independently in GENII 1.485, which requires 16 separate executions of the code for a given scenario. As discussed earlier, the maximum value among the 95th percentile dose results for the 16 sectors is chosen to represent the MOI dose.

4.2.9 SOURCE HEIGHT

With elevated plumes from a stack, the separation of the plume centerline from the ground lowers the plume concentration at ground level. The effective source height can exceed the stack height through plume rise from buoyancy or momentum effects. The user has the option of either specifying the effective source height or specifying separately the source height and plume-rise parameters that GENII will use to calculate the effective source height. Elevated releases, however, can be negated by nearby structures as the released cloud can be drawn downward and entrained behind a building into its cavity due to the aerodynamic effect of the building on the wind field in which the release occurs. The input for the height of adjacent structures is addressed in the next section and following sections address plume-rise input parameters.

Recommendation: It is generally conservative to specify a ground-level release (source height of zero) in an open field (adjacent structure height of zero) while taking no credit for plume rise effects from either momentum or buoyancy. It is recommended, however, that the analyst use judgment based on site observation and published guidance to take credit for lower ground-level concentrations that can occur with elevated releases. Site observation is necessary since the elevated release from a stack can be negated by nearby structures. In addition, the local terrain may have hills that reduce the effective stack height with respect to the ground. The source height should be conservatively estimated on the low side when there is some uncertainty or variability in its value.

4.2.10 BUILDING HEIGHT

As mentioned above, plumes from elevated discharges can be drawn downward and entrained into the wake in the wind field caused by the building. NRC Regulatory Guides 1.111 and 1.145 define a stack release condition as one in which release occurs at or above 2.5 times the height of adjacent solid structures (NRC, 1977, 1983). Releases are generally considered to be at ground level if the point of release is below the height of the facility in question and its collocated buildings. The intermediate case of releases that occur in the range between 2.5 times the height of adjacent buildings and the building height, escape the building wake under certain conditions, become completely entrained into the building wake under other conditions, or behave as a "mixture" of these types for still other conditions (NRC, 1998). Technical details of the algorithms that are used by GENII are given in Napier (1988).

The identification of adjacent structures must take into account the extent of influence that the building has on the flow field in its vicinity. The wind flow that is directly over the top of the building is entrained downward into the wake cavity. The extent of the wake cavity downwind, as measured from the lee face of the building, can range from 2.5 times the building height (H_b) to approximately 10 H_b for buildings that have large width-to-height ratios (Hanna, 1982). The wake cavity is marked by increased turbulence levels that decay progressively as a function of distance from the building. For releases from stacks not meeting the criterion of 2.5 times the height of adjacent solid structures, the combination of downward-directed entrainment into the wake cavity and increased dispersion due to high turbulence levels serve to increase ground-level concentrations above what would be observed in the absence of the building. The term downwash is frequently used to collectively describe these effects. An accepted practice by the EPA is to assume that downwash effects can influence plumes that are released from stacks that are located in the range of 2 L upwind to 5 L downwind of building, where L is the lesser of the building height or projected width (EPA, 1995).

Recommendation: It is generally conservative to specify a ground-level release (source height of zero) in an open field (adjacent structure height of zero) while taking no credit for plume rise effects from either momentum or buoyancy. It is recommended, however, that the analyst use judgment based on site observation and published guidance to take credit for lower ground-level concentrations that can occur with elevated releases. Site observation is necessary since the elevated release from a stack can be negated by nearby structures. Releases from a stack can be drawn downward and entrained behind a building into its cavity due to the aerodynamic effect of the building on the wind field in which the release occurs. Moreover, increased dispersion due to high turbulence levels serve to stretch the plume vertically (as well as horizontally), which may lead to higher ground-level concentrations especially close to the source (e.g., instead of the elevated plume simply passing over the close-in receptor, part of the plume may extend to ground-level when this increased dispersion is taken into account).

Adjacent buildings should be identified using the EPA method or an equivalent method with technical justification. Additionally, the building-height input should be conservatively estimated on the high side when used with elevated releases if there is some uncertainty or variability with its value. Conversely, the building-height input should be conservatively estimated on the low side when used with ground-level releases with no initial momentum or buoyancy.

4.2.11 PLUME RISE PARAMETERS

Just as with plumes discharged from a stack, plume rise from momentum and buoyancy effects can result in the separation of the plume centerline from the ground that lowers the plume concentration that is observed at ground level. The specific input parameters that are used for the plume rise calculations are the source exit velocity, source exit temperature, and ambient air temperature. Technical details of the algorithms that are used by GENII are given in Napier (1988).

Recommendation: The recommendation here closely parallels the one above for source height. With elevated plumes either from a stack or because of plume-rise mechanisms, the separation of the plume centerline from the ground lowers the plume concentration at ground level. Thus, the most conservative approach is generally to assume a ground-level, open-field release with no initial momentum or buoyancy. It is recommended, however, that the analyst use judgment based on site observation and published guidance to take credit for lower ground-level concentrations that can occur with elevated releases. Site observation is necessary since the elevated release can be negated by nearby structures as has been discussed above.

Specific input recommendations are given in multiple parts in order to account for the various component inputs that are needed to characterize the plume rise from buoyancy or momentum effects.

Source exit velocity – The best basis for the input would be from measurement, but for most DSA applications, the input will likely be from an external calculation. The latter can be the result of either a manual calculation or the output from another code. Plume rise from momentum effects increase with increasing stack exit velocity. The stack exit velocity should be conservatively estimated on the low side if there is some uncertainty or variability with its value.

Ambient air temperature – Statistical analysis of site-specific, meteorological measurements is the preferred approach for specifying meteorological conditions, including the ambient air temperature. Plume rise from buoyancy effects decrease with increasing ambient air temperature. The ambient air temperature should be conservatively estimated on the high side in order to address variability with its value. For air temperature, a reasonably bounding high temperature is recommended based on analysis of the site data. For example, Lazaro suggests the 95th percentile of a five-year record of daily high temperatures for the warmest month of the year (Lazaro, 1997).

Source exit temperature – The basis for the input can be measurement or external calculation. Plume rise from buoyancy effects increase with increasing effluent temperature. The effluent temperature should be conservatively estimated on the low side if there is some uncertainty or variability with its value. Buoyant plume rise is proportional to the difference between the source exit temperature and the ambient air. Ignoring buoyant plume rise is achieved by setting the source exit temperature equal to the ambient air temperature.

4.2.12 END OF INTAKE PERIOD

The time step for the GENII, Version 1.485, computer code simulations is integer years. The intake period for an acute release will be much less than one year, but one year is the minimum specification for such a release. Note that the exposure times (in hours) for external exposure from ground contamination and inhalation will be specified later, in Sections 4.2.15 and 4.2.16, respectively.

Recommendation: A specification of one for this input parameter is appropriate for DSA applications that involve accidental releases that occur over a short period.

4.2.13 DOSE COMMITMENT PERIOD

The EG for radiological releases is based on TEDE. The TEDE is the sum of the external (short-term) and the internal (committed, long-term) effective doses. When a radioactive particle is inhaled, it will cause long-term damage to the body as it remains in the body and continues to disintegrate and irradiate organs and tissues. The CEDE is the predicted dose from internal exposures over the remaining life of the individual, normally taken to be 50 years for adults.

Recommendation: The dose commitment period should be specified to be 50 years for DSA applications.

4.2.14 FRACTION OF TIME SUBMERSED IN ACUTE CLOUD

This input is used by GENII 1.485 to model acute plume exposure, and is the fraction of plume passage time spent in the plume. For chronic releases, this parameter input is set to zero.

Recommendation: A value of one for this input parameter is conservative and appropriate for DSA applications that involve acute, accidental releases that occur over a short period.

4.2.15 PERIOD OF TIME FOR SOIL CONTAMINATION EXPOSURE

This input is used by GENII 1.485 to model external exposure from ground contamination, that is, groundshine. Time is input in hours.

Recommendation: For DSA applications, accident duration is not to exceed 8 hours (DOE, 1994). Prolonged effects, such as resuspension, need not be modeled.

4.2.16 PERIOD OF TIME FOR INHALATION EXPOSURE

This input is used by GENII 1.485 to specify the receptor inhalation period in units of hours. For acute airborne releases, this value is approximately the same as the period of source term release into the atmosphere.

Recommendation: Accident duration in DSA applications is defined in terms of plume passage at the location of the dose calculation, for a period not to exceed 2 hours or 8 hours for slow-developing release scenarios (DOE, 1994). If the scenario involves release duration that is shorter than 2 hours, the scenario-specific release duration should be specified.

4.3 Recommended Inputs for Default Parameters

The following guidance is for those parameters having default values that should not be changed except for compelling reasons.

4.3.1 DEPOSITION VELOCITY

The deposition velocity represents the ratio of the ground surface contamination rate from deposition to the contaminant concentration in the plume above. Larger solid particles released in a plume will fall to the ground due to gravitational settling. Smaller particles and even some gases will deposit on ground surface elements (e.g., ground vegetation) through a variety of processes that can include chemical, biological, and physical interactions between the contaminant (particle or gas) in the plume and the ground surface elements. The GENII 1.485 code treats deposition of particles from the plume to ground surface elements in a way that mass is not conserved. Specifically, deposition velocities are applied in a standard way to deposit contaminants on the ground over the region of travel; however, this deposited material is not subtracted from the contaminants in the plume. As a result, air concentrations of contaminants and calculated CEDEs from inhalation are conservatively over-estimated.

Recommendation: In GENII 1.485, the default deposition velocity for particles is 0.001 m/s. In the context of consequence analysis, the focus is particles in the respirable size range.[3] For iodine, the deposition velocity is 0.01 m/s. A value of zero is used for noble gases. These are reasonable values and should generally be used. Data in the literature support higher deposition velocities for respirable-sized particles. In computer codes that support plume depletion from deposition (i.e., mass is conserved), the use of a higher deposition velocity generally will result in a lower receptor TEDE since the inhalation CEDE is usually the dominant contributor to the TEDE. In GENII 1.485, the use of a higher deposition velocity only creates more ground contamination and increases ground shine exposure, which generally is a small contributor to the TEDE.

4.3.2 BREATHING RATE

The inhalation CEDE that is calculated for a receptor is proportional to the assumed breathing rate.

Recommendation: The breathing rate should be set equal to the GENII 1.485 default value for acute releases of 3.3E-04 m^3/s, which represents the DOE occupational breathing rate (DOE, 1998). Note that the chronic release model in GENII 1.485, which is not recommended for DSA analysis, has a smaller default value for the breathing rate of 2.7E-04 m^3/s.

4.3.3 INHALATION DOSE CONVERSION FACTORS

DCFs relate environmental concentrations and intakes to resultant human doses for specific exposure pathways, organs, and radionuclides. Doses arise from both internal and external exposures. The internal exposures consist of inhalation (from the plume and from resuspension) and ingestion. The external exposures are from cloudshine, groundshine, and skin deposition.

For DSA purposes, the consequences of interest are the centerline TEDE incurred by the MOI evaluated at the 95th percentile dose level.

---

[3] The DOE handbook for release fractions and respirable fractions uses a broad definition of respirable range to include particles of size 10-µm AED and less (DOE, 1994a). Narrower respirable ranges have been used by the U.S. Atomic Energy Commission (up to 3.5-µm AED) and the American Conference of Governmental Industrial Hygienists (up to 2-µm AED) (DOE, 1994a).

Dose coefficients for external radiation should be based on FGR-12, which is available in both GENII 1.485 and GENII 2.0. For internal radiation, GENII 1.485 uses dose coefficients based on FGR 11[4]. GENII 2.0 offers these as well as the newer ICRP 72 recommendations[5], but these are not available in GENII 1.485.

Recommendation: Use the FGR-11 and -12 dose coefficients. The user of GENII 1.485 cannot select the newer DCFs.

Note that if the ST includes tritium oxide, its 50-year committed inhalation DCF should be increased by 50% to include the effects of skin absorption as directed by International Commission on Radiological Protection (ICRP) in their publication 30 (ICRP, 1978).

4.4 Radiological Dispersion and Consequence Analysis Recommendation

Recommendations on inputs for GENII modeling radiological dispersion and consequences and their bases are summarized in Table 4-1. In most cases, the standard practices and recommendations are site-insensitive.

---

[4] FGR 11 contains IDCFs based on weighting factors from ICRP 26 (ICRP, 1977) and organ/tissue models documented in ICRP 30 and 48 (ICRP, 1979-82, and ICRP, 1986). The IDCF values in FGR 11 are based on exposure to an adult worker and a particle size of 1.0 μm Activity Median Aerodynamic Diameter (AMAD). The AMAD signifies that fifty percent of the activity in the aerosol is associated with particles of aerodynamic diameter greater than the AMAD. The values are applied uniformly for all ages in the general public population and all release conditions.

[5] ICRP Publication 72 provides updated dosimetry for the general public, whereas ICRP 68 covers radiation workers (ICRP, 1995, 1996a, 1996b). Both include age specific models and parameters (ICRP-68/72, 2001). The IDCFs contained in these reports are based on ICRP 1990 Recommendation on radiation protection standards in Publication 60 (ICRP, 1991) and as well as the revised kinetic and dosimetric model of the respiratory tract in Publication 66 (ICRP, 1994). The inhalation DCFs in ICRP 72 are only for the CEDE and a 1.0 μm AMAD particle (ICRP, 1996a). Since the issuance of ICRP Publications 68 and 72, the ICRP has issued a compact disc with a dose coefficient database (ICRP-68/72, 2001) using the same models. However, the database gives both organ and effective dose coefficients. Additionally, the database gives the user greater flexibility by including dose coefficients for ten particle sizes and ten periods as well as six ages at exposure (ICRP-68/72, 2001).

Table 4-1. Standard Practices and Assumptions Recommended for Consequence Analysis

Model/Attribute	Recommendation/Basis
Model Basis	Gaussian plume or puff model; DOE-STD-3009-94, CN2, Appendix A.
Receptor Distances & Meteorology	• MOI: Evaluate using or conservative to 95th percentile methodology per DOE-STD-3009-94, CN2, Appendix A and NRC Regulatory Guide 1.145. • Evaluate at touchdown point for elevated or sensible energy-buoyant releases.
Dispersion Parameters (see Appendix A for a discussion of these options)	Mathematical representation of the Pasquill-Gifford curves or the equivalent (e.g., Tadmor-Gur). (Version 2.0 of GENII supports use of the dispersion coefficient set that was developed by Briggs specifically for urban conditions. Use of the rural or open country dispersion coefficients, which is the only option in Version 1.485 of GENII, generally yields conservative results)
Mixing Layer Height	Apply local site/laboratory recommendations for seasonal and time-of-day estimates for the mixing layer height.
Release Duration and Exposure	Should be consistent with accident analysis, not to not to exceed 2 hours or 8 hours for slow-developing release scenarios. Two hours: DOE-STD-3009-94, CN2, App. A; RG 1.145 (to MOI). Eight hours: DOE-STD-3009-94, CN2, App. A.
Deposition Velocity	Deposition velocity should be based on respirable-sized particles (e.g., 1 μm AED to 4 μm AED) and properties of the dispersed material if known. If the airborne particles pass through a filtration system (e.g., HEPA filters), the particles that are released to the environment and are transported to the receptor can typically be expected to be less than 1 μm AED. In GENII 1.485, the default deposition velocity for particles is 0.001 m/s. For iodine, the deposition velocity is 0.01 m/s. A value of zero is used for noble gases. Wet deposition: Not used
DCFs	ICRP-26 for metabolic model; ICRP 30/48-based: FGR 11for inhalation and ingestion DCFs and FGR 12 for external dose coefficients. (The newer DCFs are not available in GENII 1.485.)
Pathways	Primary: Inhalation; DOE-STD-3009-94, CN2, Appendix A Secondary: Cloudshine, Groundshine (Important only for criticality STs in non-reactor applications);
Breathing Rate	3.3E-04 m^3/s from DOE (1998); Note: 3.5E-04 m^3/s is used in DOE-STD-1027-92.
Dose Commitment	50-year, per definition of TEDE in DOE-STD-3009-94, CN2, Appendix A.
Evaluation Criterion	Offsite/MOI EG – 25 rem; DOE-STD-3009-94, CN2, Appendix A.
Terrain	Flat earth acceptable for most near-field and MOI estimates.
Buoyant Plume Rise	1. The conservative assumption generally is to not credit plume rise due to buoyancy, apply a short duration, and assume ground-level release in an open field. 2. More realistic result is obtained using judgment based on site observation and published guidance to take credit for lower ground-level concentrations that can occur with elevated releases. Site observation is necessary since the elevated release from a stack or buoyant plume rise can be negated by nearby structures.
Protective Actions	None. Conservatively assume no shielding by any structure or cut-off of ventilation (sheltering), or movement to avoid plume (evacuation).
Meteorological Sampling	Sampling of hourly meteorological data (not an option with GENII 1.485) or use of joint frequency of occurrence data.
Meteorological Data	At least one year of representative, qualified, hourly data. Five years is recommended by Regulatory Guide 1.194, although one year with four seasons represented can be justified.

5.0 SPECIAL CONDITIONS FOR USE

The GENII code has additional capabilities that generally are not used in standard DSA applications. For example, food ingestion doses can be calculated, but these results are not part of the DOE 3009 Appendix A requirement for safety basis dose calculations. In addition, GENII can be used to calculate population doses, but neither are these used for DSA applications.

GENII can evaluated chronic releases to air and water, and initial contamination of soil or surfaces near the point of release.

Results of these types are not needed for safety-basis dose calculations.

6.0 SOFTWARE LIMITATIONS

This section summarizes GENII software limitations in terms of past occurrences of errors and defects in various versions of the code.

Section 6.2 will be completed in the future, after results of the gap analysis (comparison of GENII with defined software standards) are made available.

6.1 Quality Assurance (QA)

The GENII code developer has indicated that both GENII versions were developed under QA plans based on the American National Standards Institute (ANSI) standard NQA-1 as implemented in the PNNL Quality Assurance Manual. The documentation accompanying the releases of both GENII 1.485 and 2.0, as well as the current air quality website for the EPA, state that all steps of code development for both versions have been documented and tested, and hand calculations have verified the code's implementation of major transport and exposure pathways for a subset of the radionuclide library. In addition, a collection of hand calculations and other verification activities is available. Additional testing is currently underway for Version 2.0.

The earlier version of GENII has been included in the International Atomic Energy Agency's VAMP project (VAlidation of Model Predictions – an acronym for the Coordinated Research Program on Validation of Models for the Transfer of Radionuclides in Terrestrial, Urban and Aquatic Environments), an international effort to compare environmental radionuclide transport models with measured environmental data. Results for test scenario CB (based on environmental measurements following the Chernobyl accident) indicated that dose estimates from GENII were comparable to, although slightly higher than, those of other participating models. The models included in the code have been validated to various degrees by additional studies, however these have not been compared directly to output from the code.

6.1.1 GENII 1.485 ISSUES

Several user experiences with GENII 1.485 should be discussed in light of potential upgrades. The following are the most significant:

- JFD – The code allows some sampling of site meteorology to provide various statistical measures of dose consequence. The sampling algorithm in this version of GENII is not fully compliant with Appendix A of DOE-STD-3000-94 (CN#2), nor with the basis NRC Regulatory Guide 1.145.
- Non-conservative plume deposition – The GENII 1.485 code allows standard deposition velocities to be used to account for dry deposition over the region of travel. However, the plume concentration is not reduced by deposition and is therefore overly conservative.
- Hydrogen equilibrium model – The tritium model in GENII assumes equilibrium is reached between tritium concentrations in air and vegetation with releases of

tritium. This is a good assumption for long-term, chronic release conditions, but may over-predict short-duration, time-dependent, release consequences.

- Food pathway modeling – In some EIS sensitivity studies, the potential population dose incurred from consumption of contaminated food is evaluated. In these cases, GENII can be used to quantify this component of dose. However, using the food ingestion dose capability, the code may over-predict the dose if one of the radionuclides is tritium (H-3) or Carbon-14. The potential exists for a limited combination of options: specifically, only for cases of acute, atmospheric release when the "food production grid" input option is used, if "food export" is chosen, and one of the input radionuclides is H-3 or C-14. Because H-3 and C-14 are handled with special specific-activity models, calculations for these two radionuclides do not have the same path through the code logic. If the above combination of options is used, the food production grid is inappropriately applied to H-3 and C-14. The total amount of food input of the full 80-km (50 mile) circle is assumed contaminated with these two radionuclides, rather than just that from the selected downwind sector. The estimated dose provided by the GENII 1.485 code is too large by factors of about 10 to 20.

The developers of GENII 1.485 have no intention at this time of making changes to the code. The code update, GENII, Version 2, is scheduled to undergo formal peer review in the immediate future, and is intended to replace GENII 1.485 after comment resolution is completed. However, unless the shortcomings of GENII 2 for DSA applications are addressed, the safety analyst is advised to use GENII 1.485 instead of GENII 2.

6.1.2 GENII 2.0 ISSUES

Current support of GENII 2.0 is from the EPA's NESHAPs office. Since its release, GENII, Version 2, has not been applied in safety analysis studies for assessment of consequences due to postulated accident releases. Most work that has been documented is for routine release assessment, or dose reconstruction studies from DOE sites. The principal shortcoming of GENII 2.0 is that it cannot be used to calculate 95th percentile dose according to DOE-STD-3009-94, Appendix A (CN#2).

6.2 Outcome of Gap Analysis

To be added at a later date.

7.0 SAMPLE CALCULATIONS

GENII 1.485 can be obtained from the Radiation Safety Information Computational Center (RSICC) at Oak Ridge. This version comes in four folders, labeled DISK01 through DISK04 (as they were originally provided on floppy disks). GENII 1.485 is operated in the DOS mode, not in Windows proper[6]. In the earlier versions of Windows (such as Windows 95 or 98), one can enter the DOS mode by clicking on "Start," then "Programs," then "MS-DOS Prompt." In the later version (such as Windows XP), one can enter the DOS mode by clicking on "Start," then "run" and type "command" in the "open" line and press "enter." If the DOS window that opens is not at the root directory (the prompt should be C:\>, assuming that "C" is the hard disk drive), type "cd C:\," which should switch to the root directory.

7.1 Installation of GENII 1.485

There are several ways one can install GENII 1.485. The following is straightforward and recommended:

1. Copy the contents of the file "DISK01" onto a blank floppy disk in drive A.

2. Open a DOS Window on drive C as described above.

3. At the C:\> prompt type "A:\genii –d," or "A:\DISK01\genii –d" if the files on the floppy disk are in a folder called "DISK01."

The latter command will install the software in the folder c:\genii.

7.2 Execution of GENII 1.485

GENII is menu driven and executed as follows:

1. Make a folder where you want to place your input and output files. This can be done using Windows or in DOS mode. If in DOS mode, use the "md" command. For

[6] Documentation with GENII 1.485 states that it can be run in a DOS window in Windows 95. However, when GENII 1.485 was developed, computers were limited to 640 KB of memory and this limitation had to be addressed during code development. Windows, however, manages memory differently than does DOS and there is a potential that unexpected problems may arise when GENII 1.485 is run in a DOS window within the Windows environment, even though this is the only way to run it on the newer computers. It will be necessary to run a number of test cases in both environments (using older [DOS] and newer [Windows] computers) and finding the results are identical before it can be stated unequivocally that GENII 1.485 functions correctly in the Windows environment.

example, if the folder name is to be SAMPLE, at the C:\> prompt type "md SAMPLE." Note that the Joint Frequency Distribution file does not have to be copied to this folder.

2. Navigate to this folder in DOS mode by typing "cd SAMPLE." The prompt should be C:\SAMPLE>.

3. At the prompt type "\genii\apprenti" (e.g., "C:\SAMPLE>\GENII\APPRENTI").

Follow the instructions given in the menu-driven prompts to input the various data. The help file can be accessed by pressing the F1 key.

The following figures are screenshots from the GENII front-end processor (Apprentice). These figures show some of the steps the user must take to generate the input file to run GENII including the execution script (batch file). Not all of the screens are shown, as there are too many possibilities to show them all here. The method is intuitive and straightforward.

Figure 7-1 is a sample of the DOS window where the front-end processor is called. The main screen for GENII is then displayed, as in Figure 7-2.

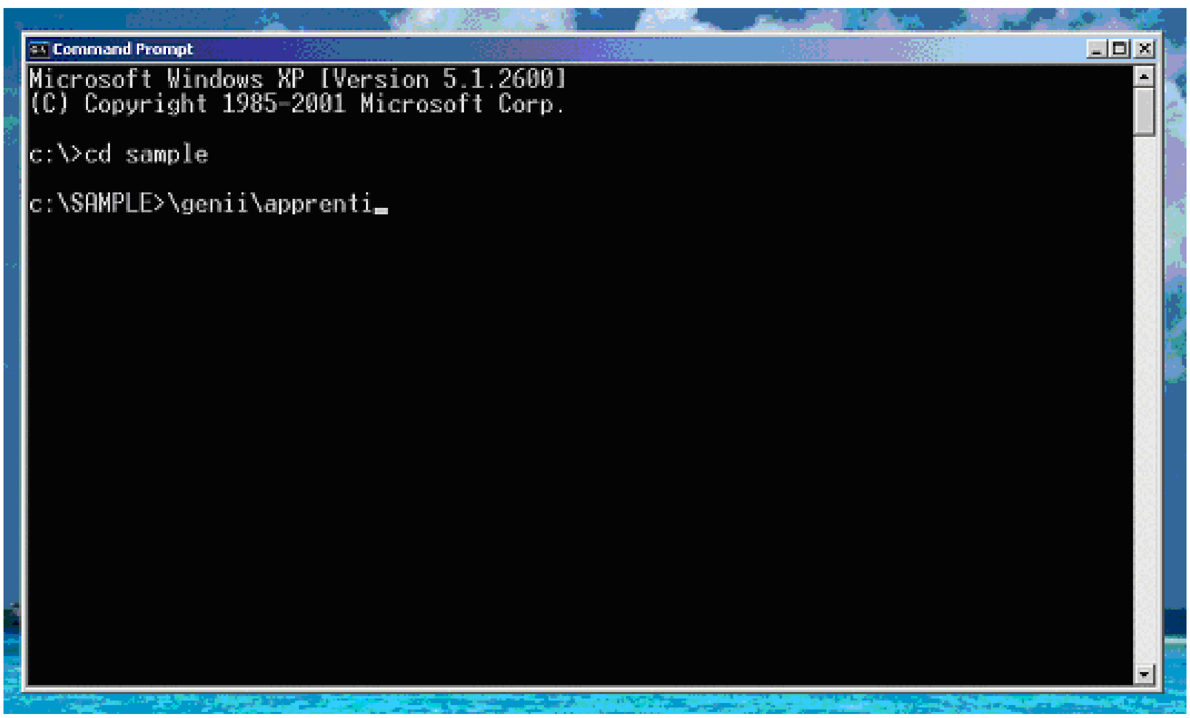

Figure 7-1. Disk Operating System Window where GENII 1.485 front-end processor (Apprentice) is called.

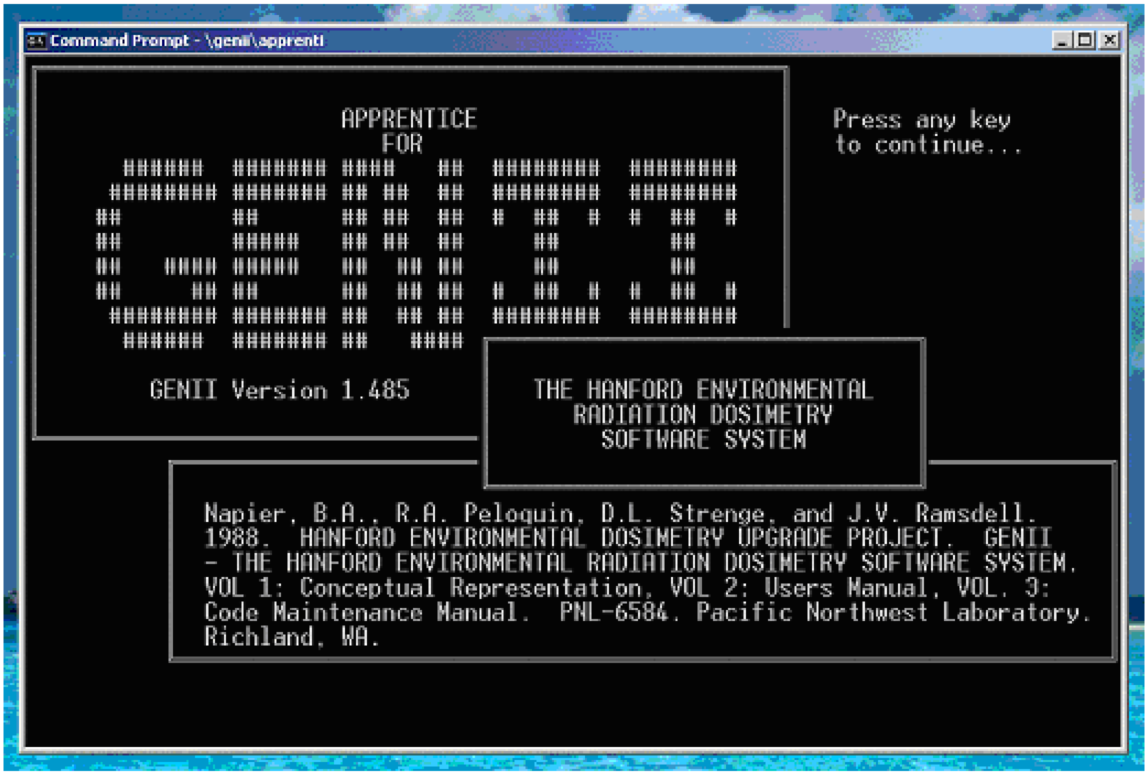

Figure 7-2. GENII 1.485 introduction screen.

Pressing any key then takes you to the first input screen, as shown in Figure 7-3. This screen allows you to input selections for individual type (average or maximum individual), scenario (far or near field), dose to population or individual, and whether the release is chronic or acute. The selections are chosen using the up- and down-arrow keys to move within a group and the left- and right-arrow keys to move between pages. Use the “enter” key to select an option. For the screen shown in Figure 7-3, the pages would be “Scenario,” “Dose to,” “Release,” “Individual Type,” and “Next,” as shown along the top of the screen. The first four are for making selections on this page, whereas “Next” navigates to the next set of selections.

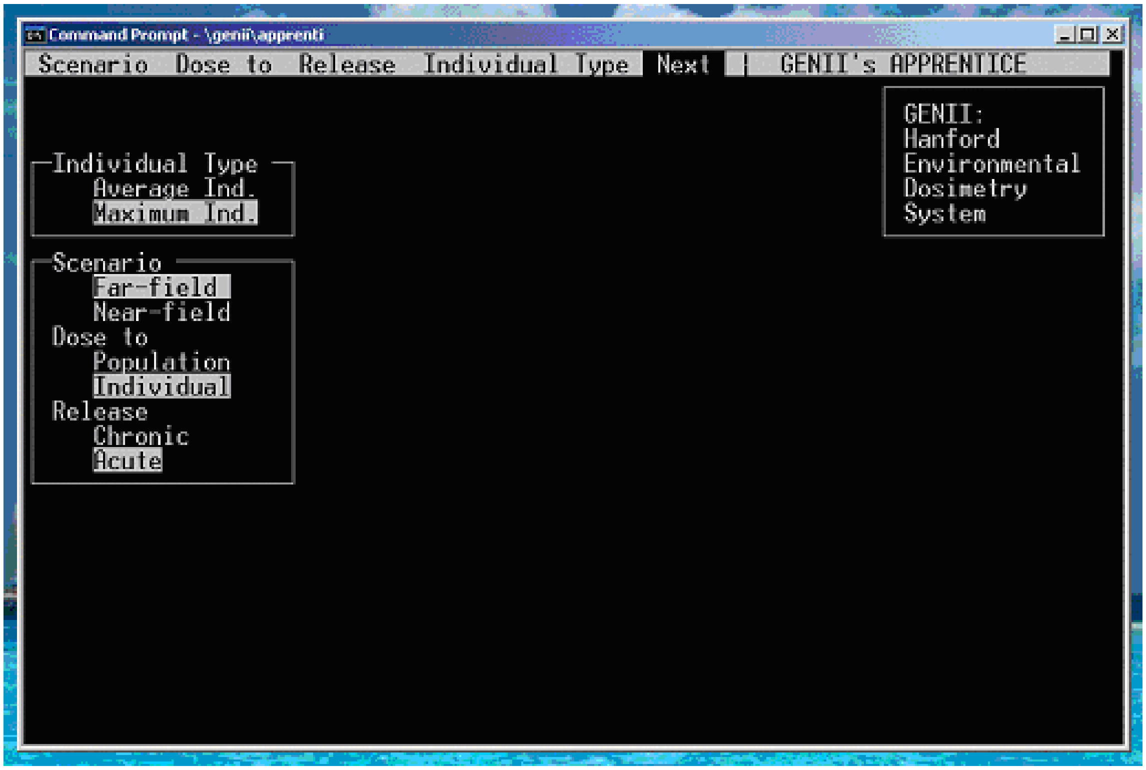

Figure 7-3. First input selection screen.

Figure 7-4 shows the types of output reports requested (annual EDE only, by radionuclide, by pathway, and screen debug), the selected transport medium (air or surface water), the selected exposure (various choices for external and internal), and inventory location for air or surface water.

Figure 7-5 is a screen view of the panel to select the radionuclides. For the screen shown, Cs-137 and Pu-239 have been chosen. The activity unit is chosen on an accompanying screen; in this case Curies (Ci) was chosen.

Figure 7-6 shows the panel where the radionuclide inventory is input. These are for the radionuclides chosen in the previous screen(s).

Figure 7-7 shows the panel where various release parameters are chosen: wind sector, location of receptor, option for release elevation, and option for building wake model. Note that only one direction and one distance can be selected for each run and that wind direction is the direction *toward* which the wind is blowing, not *from* which it is blowing (the meteorological convention).

Figures 7-8 through 7-12 show the various panels for setting exposure parameters. The figures are self-explanatory.

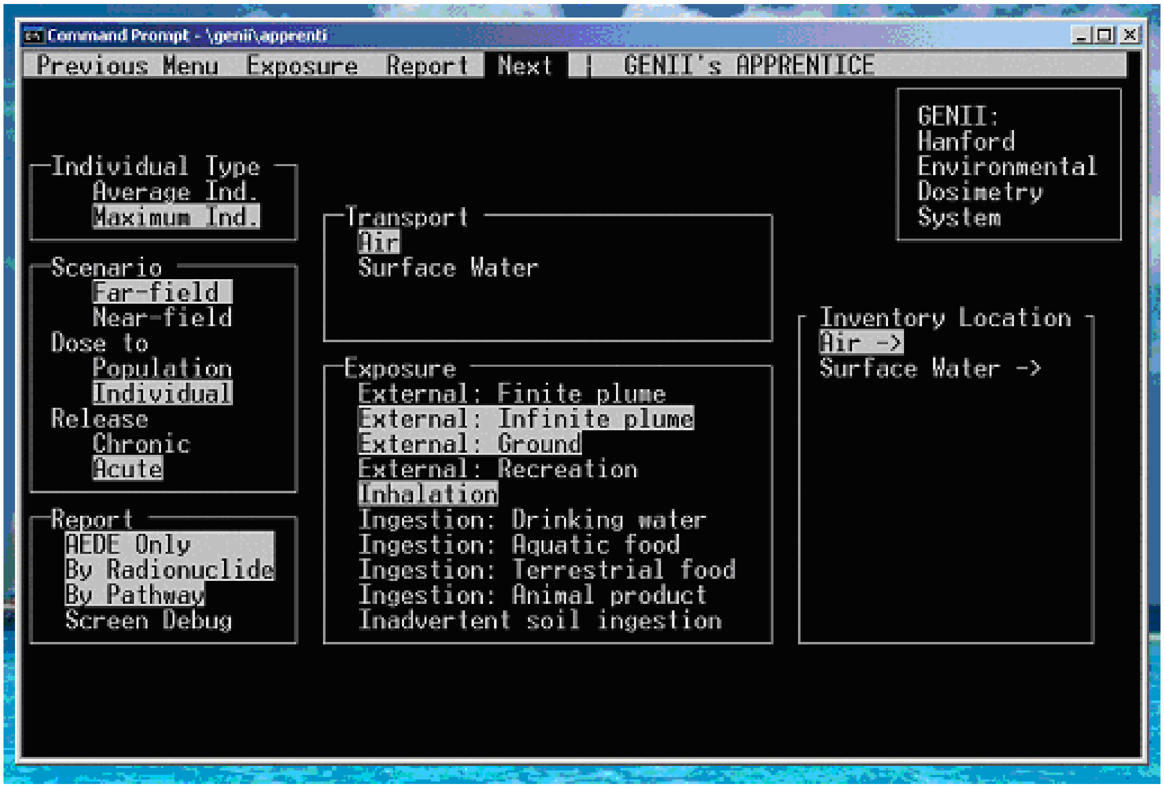

Figure 7-4. Selections of report type, transport medium, exposure types, and inventory.

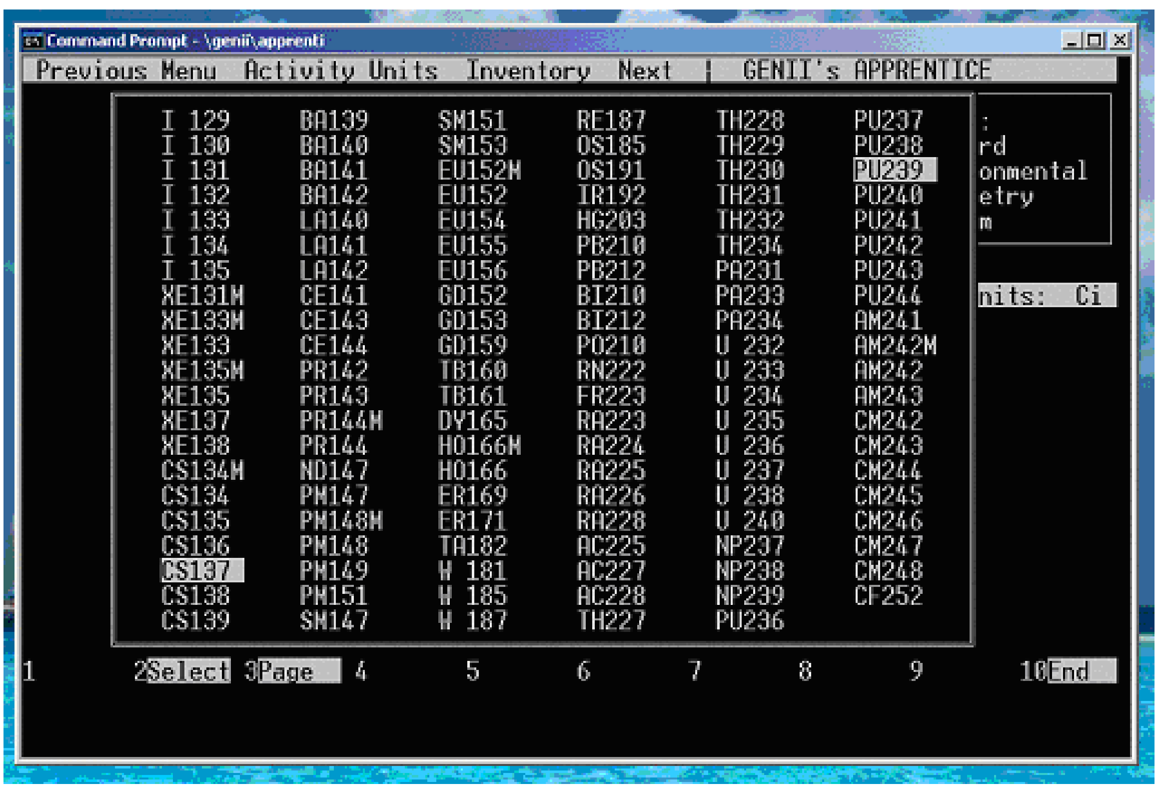

Figure 7-5. Radionuclide selection screen.

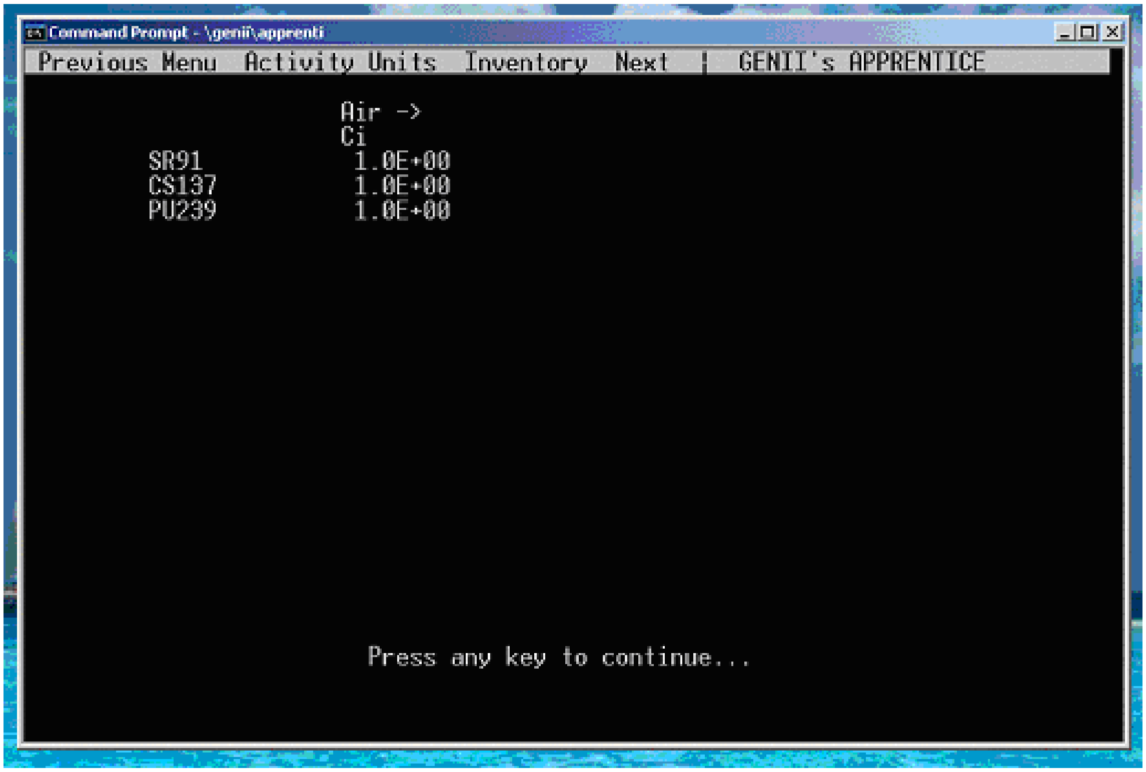

Figure 7-6. Activity specification screen for each selected radionuclide.

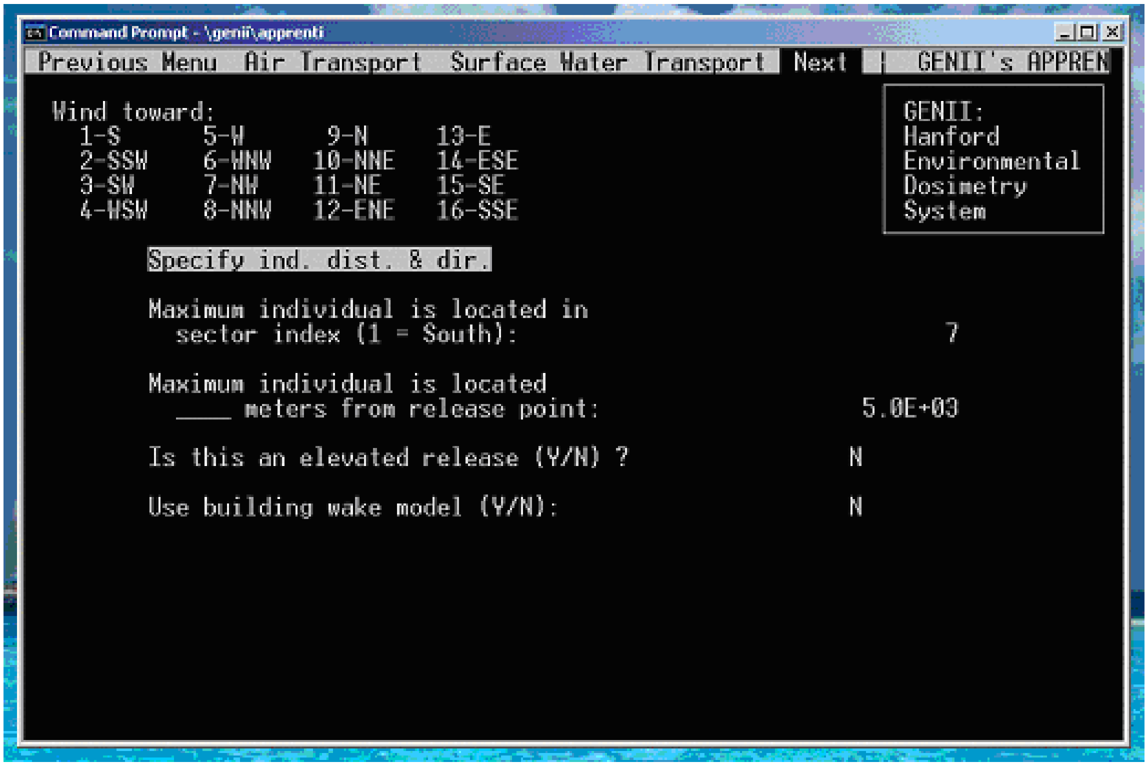

Figure 7-7. Release parameters are selected at this screen.

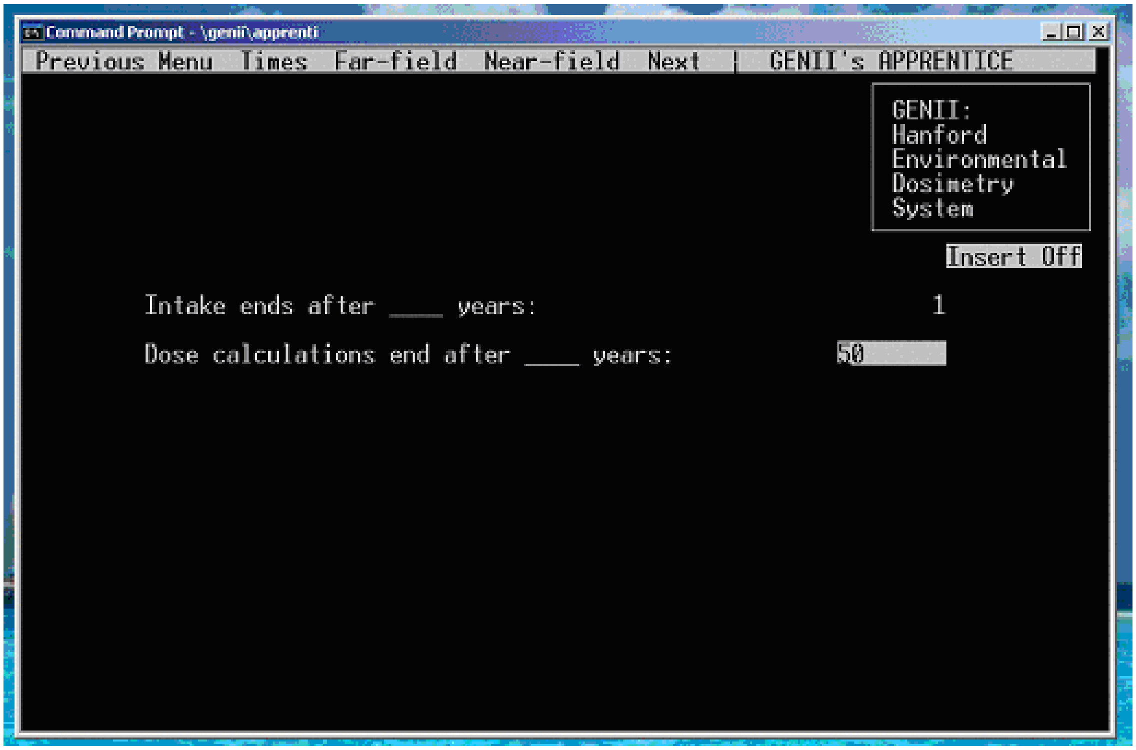

Figure 7-8. Screen for specifying durations for intake and dose calculations.

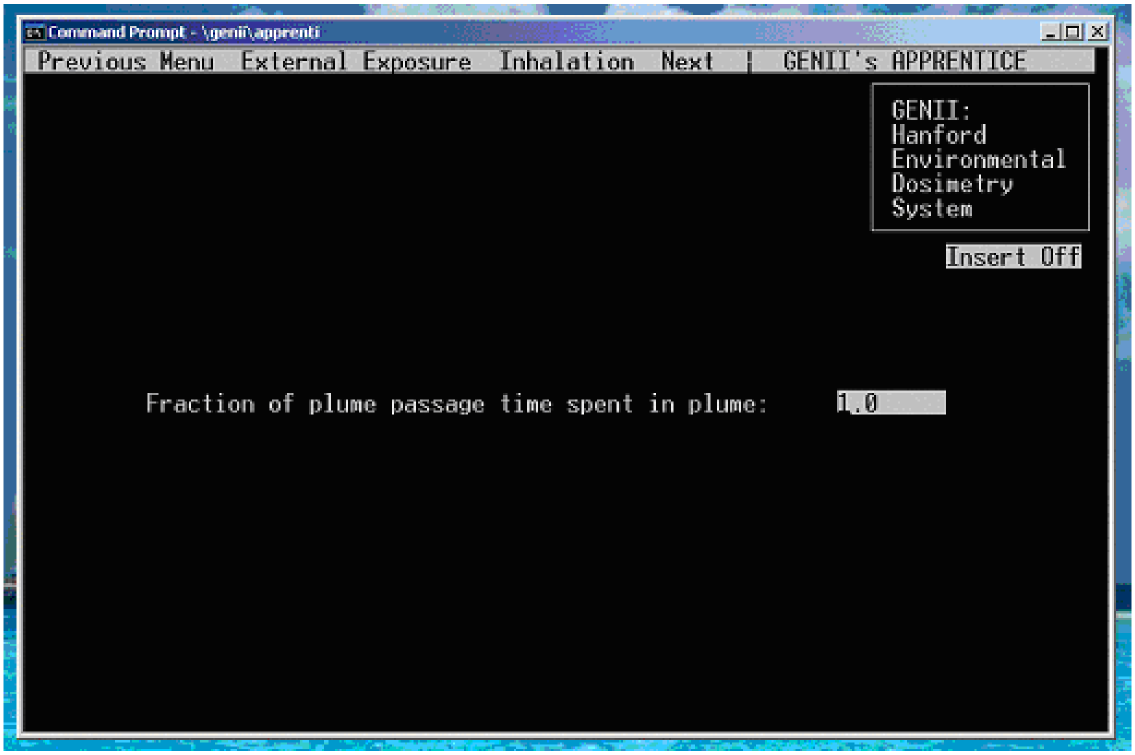

Figure 7-9. Screen for specifying fraction of plume passage time that receptor is exposed.

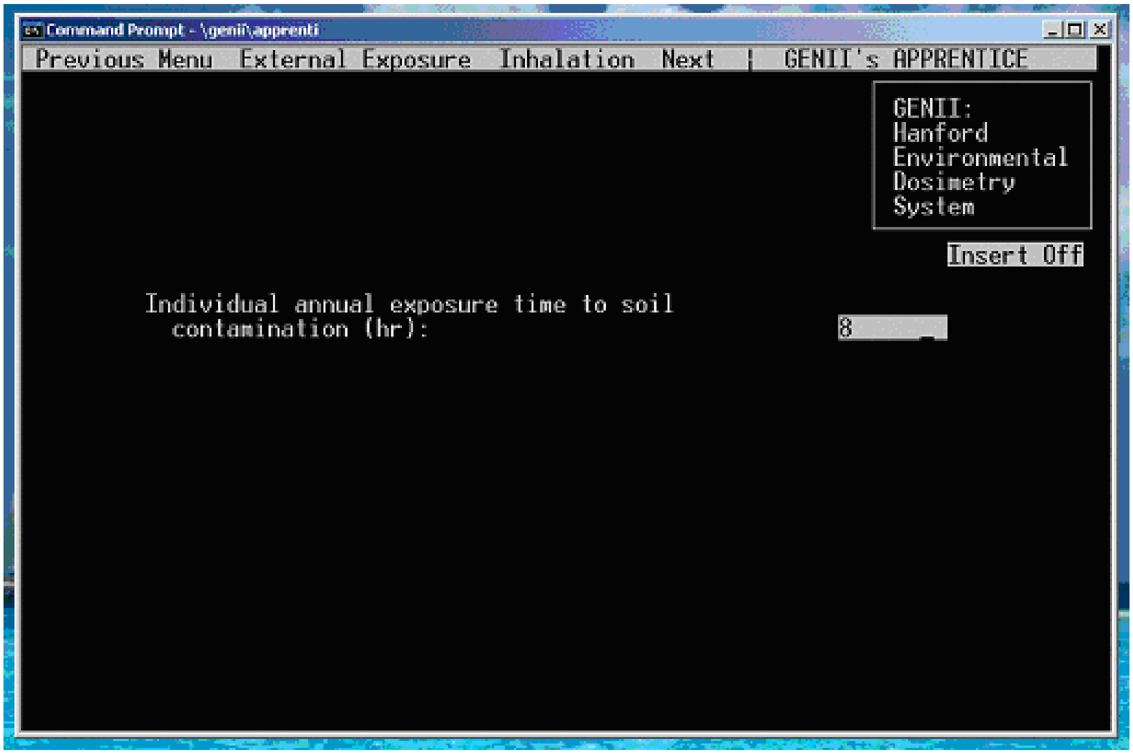

Figure 7-10. Receptor exposure time to groundshine is specified here.

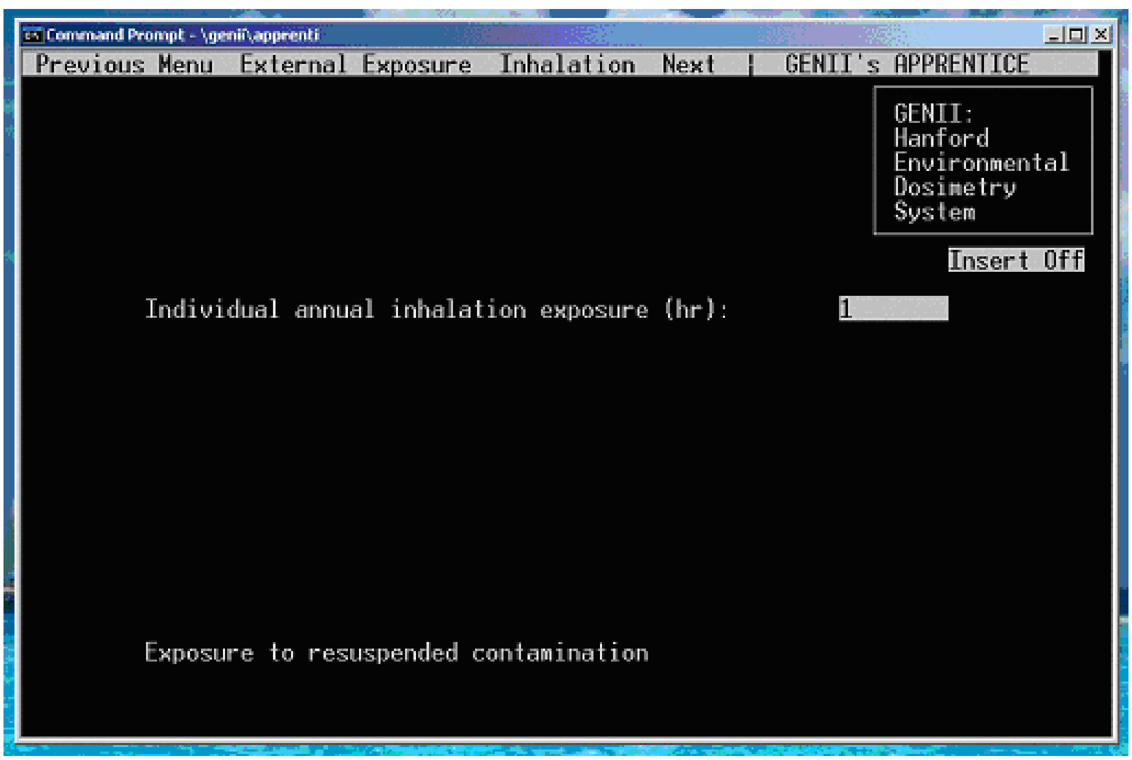

Figure 7-11. Receptor inhalation duration is specified here.

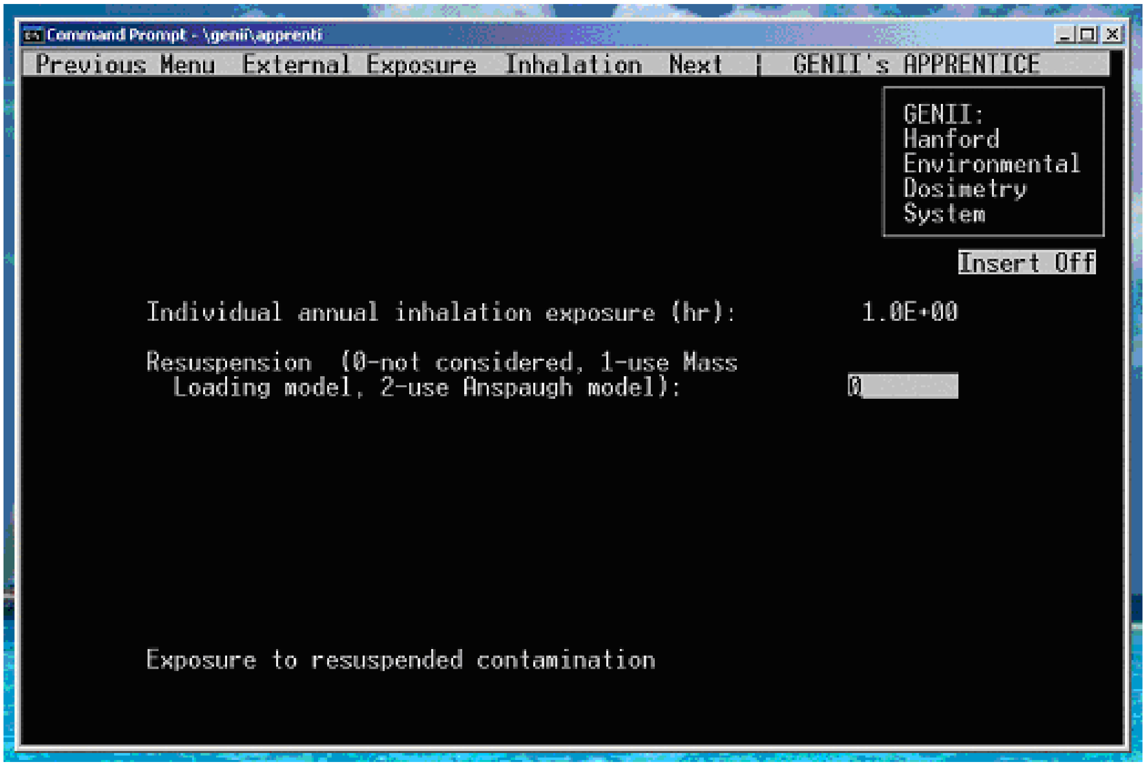

Figure 7-12. Resuspension specification

7.3 Sample Problem

A sample problem was run using a ground release of Pu-239, Sr-90, and Cs-137. The release amount was set to 1.0 Ci each. The release was over a one-hour period with external exposure from ground contamination over eight hours. The input data file generated by the GENII front-end (Apprentice) is given in Exhibit A, the output hard copy from GENII is given in Exhibit B, and the batch file generated by Apprentice is given in Exhibit C. In Exhibit B, the redundant page headers have been removed to save space.

This problem was run repeatedly for all 16-wind sectors for a receptor located 5,000 m from the release location (the 200 Area at Hanford) and used the corresponding JDF. Figure 7-13 shows the resulting Total Effective Dose Equivalent for all sectors. Note that this required GENII to be run 16 times, once for each sector for this distance.

Sectors are numbered clockwise from the south. Thus, S = 1, SSW = 2, etc. The sample problem shown in the following Exhibits are for Sector 7, that is, to the NW. The 95th percentile χ/Q (labeled E/Q in the output) for this sector at 5,000 m was 5.7×10^{-5} s/m^3.

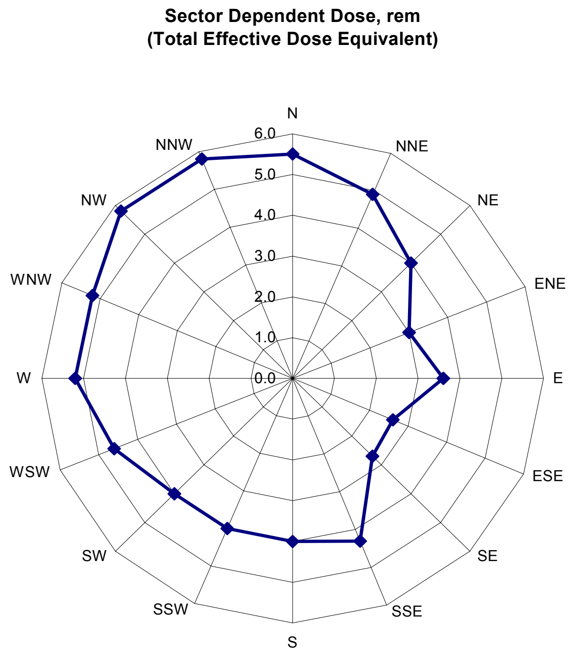

Figure 7-13. TEDE at 5 km for the example.

Various runs were made for the NW wind sector at various receptor distances and the results are given in Figure 7-14.

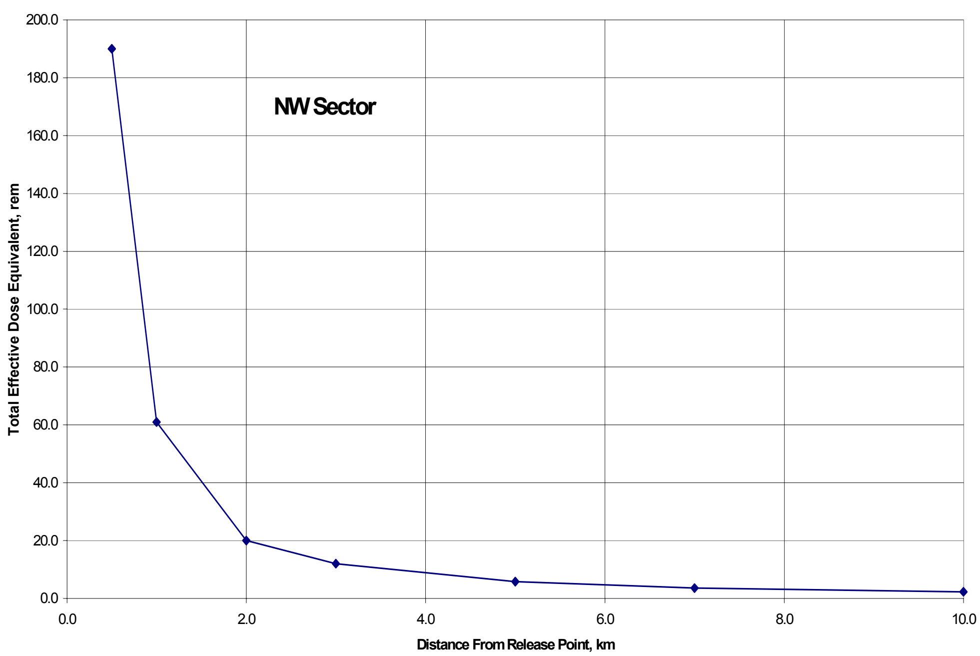

Figure 7-14. TEDE vs. distance for the NW sector for the example.

EXHIBIT A: Input file created by Apprentice for sample problem.

```
######################### Program GENII Input File ############  8 Jul 88 ####
Title: test7
       \DOE-WORK\test7.in                      Created on 10-08-2003 at 13:27
OPTIONS========================= Default =====================================
F    Near-field scenario?      (Far-field)    NEAR-FIELD: narrowly-focused
F    Population dose?         (Individual)                release, single site
T    Acute release?             (Chronic)     FAR-FIELD:  wide-scale release,
     Maximum Individual data set used                     multiple sites
                              Complete                                Complete
TRANSPORT OPTIONS============ Section   EXPOSURE PATHWAY OPTIONS===== Section
T  Air Transport                  1     F  Finite plume, external       5
F  Surface Water Transport        2     T  Infinite plume, external     5
F  Biotic Transport (near-field)  3,4   T  Ground, external             5
F  Waste Form Degradation (near)  3,4   F  Recreation, external         5
                                        T  Inhalation uptake            5,6
REPORT OPTIONS=======================   F  Drinking water ingestion     7,8
T  Report AEDE only                     F  Aquatic foods ingestion      7,8
T  Report by radionuclide               F  Terrestrial foods ingestion  7,9
T  Report by exposure pathway           F  Animal product ingestion     7,10
F  Debug report on screen               F  Inadvertent soil ingestion

INVENTORY ###################################################################

 4   Inventory input activity units: (1-pCi  2-uCi  3-mCi  4-Ci  5-Bq)
 0   Surface soil source units (1- m2  2- m3  3- kg)
     Equilibrium question goes here

     --------|----Release Terms------|----------Basic Concentrations---------|
     Use when|  transport selected   |  near-field scenario, optionally      |
     --------|-----------------------|---------------------------------------|
     Release |        Surface Buried |        Surface Deep    Ground  Surface|
     Radio-  |Air     Water   Waste  |Air     Soil    Soil    Water   Water  |
     nuclide |/yr     /yr     /m3    |/m3     /unit   /m3     /L      /L     |
     --------|------- ------- -------|------- ------- ------- ------- -------|
     SR90     1.0E+00
     CS137    1.0E+00
     PU239    1.0E+00

     --------|----Derived Concentrations-----|
     Use when|   measured values are known   |
     --------|-------------------------------|
     Release |Terres. Animal  Drink   Aquatic|
     Radio-  |Plant   Product Water   Food   |
     nuclide |/kg     /kg     /L      /kg    |
     --------|------- ------- ------- -------|

TIME ########################################################################

1    Intake ends after (yr)
50   Dose calc. ends after (yr)
0    Release ends after (yr)
0    No. of years of air deposition prior to the intake period
0    No. of years of irrigation water deposition prior to the intake period

FAR-FIELD SCENARIOS (IF POPULATION DOSE) ####################################

0          Definition option: 1-Use population grid in file POP.IN
0                             2-Use total entered on this line
```

```
NEAR-FIELD SCENARIOS ##########################################################

           Prior to the beginning of the intake period: (yr)
0            When was the inventory disposed?  (Package degradation starts)
0            When was LOIC?  (Biotic transport starts)
0          Fraction of roots in upper soil (top 15 cm)
0          Fraction of roots in deep soil
0          Manual redistribution: deep soil/surface soil dilution factor
0          Source area for external dose modification factor (m2)
TRANSPORT #####################################################################
           ====AIR TRANSPORT====================================SECTION 1=====
                   0-Calculate PM            |0       Release type (0-3)
3          Option: 1-Use chi/Q or PM value   |F       Stack release (T/F)
                   2-Select MI dist & dir    |0       Stack height (m)
                   3-Specify MI dist & dir   |0       Stack flow (m3/sec)
0          Chi/Q or PM value                 |0       Stack radius (m)
7          MI sector index (1=S)             |0       Effluent temp. (C)
5000.0     MI distance from release point (m)|0       Building x-section (m2)
T          Use jf data, (T/F) else chi/Q grid|0       Building height (m)

           ====SURFACE WATER TRANSPORT==========================SECTION 2=====
0          Mixing ratio model: 0-use value, 1-river, 2-lake
0          Mixing ratio, dimensionless
0          Average river flow rate for: MIXFLG=0 (m3/s), MIXFLG=1,2 (m/s),
0          Transit time to irrigation withdrawl location (hr)
           If mixing ratio model > 0:
0            Rate of effluent discharge to receiving water body (m3/s)
0            Longshore distance from release point to usage location (m)
0            Offshore distance to the water intake (m)
0            Average water depth in surface water body (m)
0            Average river width (m), MIXFLG=1 only
0            Depth of effluent discharge point to surface water (m), lake only

           ====WASTE FORM AVAILABILITY==========================SECTION 3=====
0          Waste form/package half life, (yr)
0          Waste thickness, (m)
0          Depth of soil overburden, m

           ====BIOTIC TRANSPORT OF BURIED SOURCE================SECTION 4=====
T          Consider during inventory decay/buildup period (T/F)?
T          Consider during intake period (T/F)?   | 1-Arid non agricultural
0          Pre-Intake site condition.............| 2-Humid non agricultural
                                                 | 3-Agricultural

EXPOSURE ######################################################################

           ====EXTERNAL EXPOSURE================================SECTION 5=====
           Exposure time:               |   Residential irrigation:
0            Plume (hr)                 | T       Consider: (T/F)
8.0          Soil contamination (hr)    | 0       Source: 1-ground water
0            Swimming (hr)              |                 2-surface water
0            Boating (hr)               | 0       Application rate (in/yr)
0            Shoreline activities (hr)  | 0       Duration (mo/yr)
0          Shoreline type: (1-river, 2-lake, 3-ocean, 4-tidal basin)
0          Transit time for release to reach aquatic recreation (hr)
1.0        Average fraction of time submersed in acute cloud (hr/person hr)

           ====INHALATION=======================================SECTION 6=====
1.0        Hours of exposure to contamination per year
0          0-No resus-  1-Use Mass Loading          2-Use Anspaugh model
0            pension      Mass loading factor (g/m3)   Top soil available (cm)
```

```
           ====INGESTION POPULATION============================SECTION 7=====
0          Atmospheric production definition (select option):
0            0-Use food-weighted chi/Q, (food-sec/m3), enter value on this line
             1-Use population-weighted chi/Q
             2-Use uniform production
             3-Use chi/Q and production grids (PRODUCTION will be overridden)
0          Population ingesting aquatic foods, 0 defaults to total (person)
0          Population ingesting drinking water, 0 defaults to total (person)
F          Consider dose from food exported out of region (default=F)

           Note below: S* or Source: 0-none, 1-ground water, 2-surface water
                                     3-Derived concentration entered above
           ==== AQUATIC FOODS / DRINKING WATER INGESTION=========SECTION 8====

F          Salt water? (default is fresh)

           USE         TRAN-  PROD-    -CONSUMPTION- |
           ?   FOOD    SIT    UCTION   HOLDUP   RATE |
           T/F TYPE    hr     kg/yr    da      kg/yr |      DRINKING WATER
           --- ------ -----  -------  ------   ----- |------------------------
           F   FISH    0.00  0.0E+00    0.00     0.0 | 0      Source (see above)
           F   MOLLUS  0.00  0.0E+00    0.00     0.0 | T      Treatment? T/F
           F   CRUSTA  0.00  0.0E+00    0.00     0.0 | 0      Holdup/transit(da)
           F   PLANTS  0.00  0.0E+00    0.00     0.0 | 0      Consumption (L/yr)

           ====TERRESTRIAL FOOD INGESTION=======================SECTION 9=====

           USE         GROW   --IRRIGATION--          PROD-    --CONSUMPTION--
           ?   FOOD    TIME   S RATE   TIME    YIELD  UCTION   HOLDUP   RATE
           T/F TYPE    da     * in/yr  mo/yr   kg/m2  kg/yr    da       kg/yr
           --- ------ -----  - -----  -----   -----  -------  ------   ------
           F   LEAF V  0.00  0   0.0   0.0      0.0  0.0E+00     0.0      0.0
           F   ROOT V  0.00  0   0.0   0.0      0.0  0.0E+00     0.0      0.0
           F   FRUIT   0.00  0   0.0   0.0      0.0  0.0E+00     0.0      0.0
           F   GRAIN   0.00  0   0.0   0.0      0.0  0.0E+00     0.0      0.0

           ====ANIMAL PRODUCTION CONSUMPTION===================SECTION 10====

           ---HUMAN---- TOTAL   DRINK   -------------STORED FEED--------------
USE        CONSUMPTION  PROD-   WATER   DIET  GROW  -IRRIGATION--        STOR-
?   FOOD   RATE  HOLDUP UCTION  CONTAM  FRAC- TIME  S RATE  TIME   YIELD AGE
T/F TYPE   kg/yr   da    kg/yr  FRACT.  TION   da   * in/yr mo/yr  kg/m3 da
--- ------ ------ ----- ------ -------- ----  ----  - ----- -----  ----- -----
F   BEEF      0.0   0.0   0.00     0.00 0.00   0.0  0   0.0  0.00   0.00   0.0
F   POULTR    0.0   0.0   0.00     0.00 0.00   0.0  0   0.0  0.00   0.00   0.0
F   MILK      0.0   0.0   0.00     0.00 0.00   0.0  0   0.0  0.00   0.00   0.0
F   EGG       0.0   0.0   0.00     0.00 0.00   0.0  0   0.0  0.00   0.00   0.0
                                         -------------FRESH FORAGE------------
    BEEF                                0.00   0.0  0   0.0  0.00   0.00   0.0
    MILK                                0.00   0.0  0   0.0  0.00   0.00   0.0
```

EXHIBIT B: Output file created by GENII 1.485 for sample problem.

```
 ------------------------------------------------------------------------------
                        GENII  Dose Calculation Program
                           (Version 1.485 3-Dec-90)
Case title:   test7
Executed on:  10/09/:3 at 10:22:18                                  Page A.  1
 ------------------------------------------------------------------------------

           This is a far-field (wide-scale release, multiple site) scenario.
           Release is acute
           Individual dose

           THE FOLLOWING TRANSPORT MODES ARE CONSIDERED
                Air

           THE FOLLOWING EXPOSURE PATHS ARE CONSIDERED:
                Infinite plume, external
                Ground, external
                Inhalation uptake

           THE FOLLOWING TIMES ARE USED:
                Intake ends after (yr):                1.0
                Dose calculations ends after (yr):    50.0

========== FILENAMES AND TITLES OF FILES/LIBRARIES USED =======================

 Input file name: \DOE-WORK\test7.in
 GENII Default Parameter Values (28-Mar-90 RAP)
 Radionuclide Master Library - Long Times  (23-July-93 PDR)
 External Dose Factors for GENII in person Sv/yr per Bq/X (8-May-90 R
 Internal Dose Increments, PNL Solubility Choices Rerun 12/3/90 PDR
 200 AREA - 0 M - Pasquill A - F (1983 - 1987 Average)

===============================================================================

           -------- ----Release Terms------
           Release          Surface Buried
           Radio-   Air     Water   Source
           nuclide   Ci/yr   Ci/yr   Ci/m3
           -------- ------- ------- -------
           SR90     1.0E+00 0.0E+00 0.0E+00
           CS137    1.0E+00 0.0E+00 0.0E+00
           PU239    1.0E+00 0.0E+00 0.0E+00

========== AIR TRANSPORT ======================================================
           Joint frequency data input.
5.0E+03    Maximum individual distance from release point (m)
7.0E+00    Maximum individual sector index (Wind Toward NW )
           Ground level release.

========== EXTERNAL EXPOSURE ==================================================
 1.0E+00   Fraction of time spent in cloud
 8.0E+00   Hours of exposure to ground contamination

========== INHALATION =========================================================
           Resuspension not considered

===============================================================================
Input prepared by:  _______________________________       Date: ______________

Input checked by:   _______________________________       Date: ______________
```

	Probability	E/Q (sec/m3)	DOQ (m2)	Travel Time (sec)	Population-Weighted E/Q (person-sec/m3)
Sector index: 7					
Distance: 5000.0					
	0.0336	6.5E-05	6.5E-07	5618.	
	0.0500	5.7E-05	5.7E-07	5618.	
	0.1000	3.2E-05	3.2E-07	5618.	
	0.2500	1.5E-05	1.5E-07	1887.	
	0.5000	5.4E-06	5.4E-08	510.	

5.7E-05 Individual E/Q

Acute release
Uptake/exposure period: 1.0
Dose commitment period: 50.0
Dose units: Rem

Organ	Committed Dose Equivalent	Weighting Factors	Weighted Dose Equivalent
Gonads	8.0E-01	2.5E-01	2.0E-01
Breast	5.9E-04	1.5E-01	8.8E-05
R Marrow	4.6E+00	1.2E-01	5.5E-01
Lung	2.2E+01	1.2E-01	2.6E+00
Thyroid	5.9E-04	3.0E-02	1.8E-05
Bone Sur	5.9E+01	3.0E-02	1.8E+00
Liver	1.1E+01	6.0E-02	6.4E-01
LL Int.	2.8E-03	6.0E-02	1.7E-04
UL Int.	1.3E-03	6.0E-02	8.0E-05
S Int.	7.8E-04	6.0E-02	4.7E-05
Stomach	6.8E-04	6.0E-02	4.1E-05
Internal Effective Dose Equivalent			5.8E+00
External Dose			7.3E-06
Annual Effective Dose Equivalent			5.8E+00
Controlling Organ:			Bone Sur
Controlling Pathway:			Inh
Controlling Radionuclide:			PU239
Total Inhalation EDE:			5.8E+00
Total Ingestion EDE:			0.0E+00

```
             Dose Commitment Year
                  1          2          3    ...
            _________________________________
Internal  : |
Intake    : |
Year:     3 |                        0.0E+00   ...
            |                           +
          2 |             0.0E+00    0.0E+00   ...              Internal
            |                +          +                       Effective
          1 | 5.6E-01 + 4.0E-01 + 3.0E-01 + ...  =  5.8E+00    Dose
                                                                Equivalent
                  ||         ||         ||
Internal                                                        Cumulative
Annual        5.6E-01 + 4.0E-01 + 3.0E-01 + ...  =  5.8E+00    Internal
Dose                                                            Dose
                  +          +          +               +
External
Annual        7.3E-06    0.0E+00    0.0E+00   ...     7.3E-06
Dose
                  ||         ||         ||              ||
Annual                                                          Cumulative
Dose          5.6E-01 + 4.0E-01 + 3.0E-01 + ...  =  5.8E+00    Dose

                                                                Maximum
                                                    5.6E-01    Annual
                                                                Dose Occurred
                                                                In Year  1
______________________________________________________________________
```

Committed Dose Equivalent by Exposure Pathway

Pathway	Lung	Stomach	S Int.	UL Int.	LL Int.	Bone Su	R Marro	Testes
Inhale	2.2E+01	6.8E-04	7.8E-04	1.3E-03	2.8E-03	5.9E+01	4.6E+00	8.0E-01
Total	2.2E+01	6.8E-04	7.8E-04	1.3E-03	2.8E-03	5.9E+01	4.6E+00	8.0E-01

Pathway	Ovaries	Muscle	Thyroid	Liver
Inhale	8.0E-01	5.9E-04	5.9E-04	1.1E+01
Total	8.0E-01	5.9E-04	5.9E-04	1.1E+01

External Dose by Exposure Pathway

Pathway	
Plume	6.6E-06
Sur Soil	7.2E-07
Total	7.3E-06

Committed Dose Equivalent by Radionuclide

Radionuclide	Lung	Stomach	S Int.	UL Int.	LL Int.	Bone Su	R Marro	Testes
SR 90	9.8E-05	2.5E-05	2.7E-05	6.7E-05	2.2E-04	4.6E-02	2.0E-02	2.3E-05
Y 90	1.1E-05	5.0E-07	1.3E-06	6.1E-06	1.5E-05	1.8E-08	1.8E-08	6.2E-10
CS 137	6.2E-04	6.1E-04	6.4E-04	6.3E-04	6.4E-04	5.7E-04	5.9E-04	6.2E-04
PU 239	2.2E+01	4.9E-05	1.1E-04	6.3E-04	1.9E-03	5.9E+01	4.6E+00	8.0E-01
Total	2.2E+01	6.8E-04	7.8E-04	1.3E-03	2.8E-03	5.9E+01	4.6E+00	8.0E-01

Radionuclide	Ovaries	Muscle	Thyroid	Liver
SR 90	2.3E-05	2.2E-05	2.3E-05	0.0E+00
Y 90	6.1E-10	6.0E-10	6.1E-10	1.8E-08
CS 137	5.8E-04	5.6E-04	5.6E-04	0.0E+00
PU 239	8.0E-01	5.8E-06	5.6E-06	1.1E+01
Total	8.0E-01	5.9E-04	5.9E-04	1.1E+01

Radio-nuclide	Inhalation Effective Dose Equivalent	Ingestion Effective Dose Equivalent	External Dose	Internal Effective Dose Equivalent	Annual Effective Dose Equivalent
SR 90	3.9E-03	0.0E+00	2.5E-09	3.9E-03	3.9E-03
Y 90	2.7E-06	0.0E+00	8.7E-09	2.7E-06	2.7E-06
CS 137	5.7E-04	0.0E+00	7.3E-06	5.7E-04	5.8E-04
PU 239	5.8E+00	0.0E+00	1.3E-09	5.8E+00	5.8E+00

EXHIBIT C: Batch file created by Apprentice for sample problem.

```
CLS
rem
rem
rem
rem
rem               GENII
rem               Hanford Environmental Dosimetry Software System
rem
rem               Pacific Northwest Laboratory
rem               Richland WA
rem
rem               Contact:  Bruce Napier (509) 375-3896
rem
 echo off
 erase  \genii\genii.in
 erase  \genii\pop.in
 erase  \genii\jointfre.in
 erase  \genii\chiq.in
 erase  \genii\foodprod.in
 erase  \genii\env.in
 erase  \genii\genii.out
 erase  \genii\env.out
 erase  \genii\genii2.out
 erase  \genii\dose.out
 copy C:\DOE-WORK\zero.ave \genii\jointfre.in
echo on
 copy \DOE-WORK\test7.in \genii\genii.in
 \genii\envin
 if errorlevel 1 goto stop1
 \genii\env
 if errorlevel 1 goto stop1
 \genii\dose
 if errorlevel 1 goto stop1
rem
 copy \genii\genii.out+ \genii\genii2.out+ \genii\dose.out \DOE-WORK\test7.out
rem
:stop1
```

8.0 ACRONYMS AND DEFINITIONS

8.1 Definitions

Selected Terms and Definitions Used in Accident and Consequence Analysis and Software Quality Assurance

Absorbed Dose (D) – The energy absorbed by matter from ionizing radiation per unit mass of irradiated material at the place of interest in that material. The absorbed dose is expressed in units of rad (or gray) (1 rad = 0.01 gray).

Committed Dose Equivalent ($H_{T,50}$) – The dose equivalent calculated to be received by a tissue or organ over a 50-year period after the intake of a radionuclide into the body. It does not include contributions from radiation sources external to the body. Committed dose equivalent is expressed in units of rem (or sievert) (1 rem = 0.01 sievert).

Committed Effective Dose Equivalent (CEDE) – The sum of the committed dose equivalents ($H_{T,50}$) over a fifty-year period to various organs or tissues in the body, each multiplied by the appropriate weighting factor (w_T) -- that is $H_{E,50} = \Sigma\, w_T\, H_{T,50}$. CEDE is applicable to exposure from internally deposited radionuclides.

Gap Analysis – Evaluation of the Software Quality Assurance attributes of specific computer software against identified criteria.

Nuclear Facility – A reactor or a nonreactor nuclear facility where an activity is conducted for or on behalf of DOE and includes any related area, structure, facility, or activity to the extent necessary to ensure proper implementation of the requirements established by 10 CFR 830. (10 CFR 830)

Gray (Gy) – Systeme' International (SI) unit of absorbed dose. One gray is equal to an absorbed dose of 1 joule per kilogram. One Gy equals 100 rad.

Maximally Exposed Offsite Individual (MOI) – A theoretical offsite receptor defined to allow dose comparison with numerical offsite evaluation guides. The MOI is located at the maximum air concentration point (ground-level) at or beyond the DOE site boundary. The latter may occur with elevated or buoyant releases that do not land within the site boundary, but reach ground level beyond the boundary (touchdown point).

Onsite Evaluation Point/Person (OEP) – A theoretical onsite receptor defined to allow dose comparison with numerical onsite evaluation guides. This point may be at a fixed distance (e.g. 100 m, 600 m, or 640 m), or located at the closest point on the facility or facility area exclusion zone. For elevated or buoyant releases that do not land within the exclusion zone, the OEP is the point beyond the exclusion zone where the maximum air concentration is located (touchdown point).

Rad – The unit of absorbed dose, equal to 0.01 Gy.

Rem – A measure of biological damage from radiation. It is the unit of dose equivalent, EDE, or CEDE. The rem is numerically equal to the absorbed dose in rad multiplied by a quality factor, distribution factor, and any other necessary modifying factor (1 rem = 0.01 sievert).

Safety Analysis and Design Software – Computer software that is not part of a SSC but is used in the safety classification, design, and analysis of nuclear facilities to ensure the following:

- Proper accident analysis of nuclear facilities
- Proper analysis and design of safety SSCs
- Proper identification, maintenance, and operation of safety SSCs

Safety Analysis Software Group (SASG) – A group of technical experts formed by the DOE Deputy Secretary in October 2000 in response to Technical Report 25 issued by the DNFSB. This group was responsible for determining the safety analysis and instrument and control (I&C) software needs to be fixed or replaced, establishing plans and cost estimates for remedial work, providing recommendations for permanent storage of the software and coordinating with the Nuclear Regulatory Commission on code assessment as appropriate.

Safety-Class Structures, Systems, and Components (Safety Class SSCs) – SSCs, including portions of process systems, whose preventive and mitigative function is necessary to limit radioactive hazardous material exposure to the public, as determined from the safety analyses. (10 CFR 830)

Safety-Significant Structures, Systems, and Components (Safety Significant SSCs) – SSCs that are not designated as safety-class SSCs, but whose preventive or mitigative function is a major contributor to defense in depth and/or worker safety as determined from safety analyses (10 CFR 830). As a general rule of thumb, SS SSC designations based on worker safety are limited to those SSCs whose failure is estimated to result in prompt worker fatalities, serious injuries, or significant radiological or chemical exposure to workers. The term "serious injuries," as used in this definition, refers to medical treatment for immediately life-threatening or permanently disabling injuries (e.g., loss of eye, loss of limb). The general rule of thumb cited above is neither an EG nor a quantitative criterion. It represents a lower threshold of concern for which an Safety Significant SSC designation may be warranted. Estimates of worker consequences for the purpose of Safety Significant SSC designation are not intended to require detailed analytical modeling. Consideration should be based on engineering judgment of possible effects and the potential added value of Safety Significant SSC designation (DOE G 420.1-1).

Safety Software – Includes both safety system software and safety analysis and design software.

Safety Structures, Systems, and Components (SSCs) – The set of safety-class SSCs and safety-significant SSCs for a given facility. (10 CFR 830)

Safety System Software – Computer software and firmware that performs a safety system function as part of a SSC that has been functionally classified as Safety Class or Safety Significant. This also includes computer software such as human-machine interface software, network interface software, programmable logic controller programming language software, and safety management databases that are not part of an SSC but whose operation or malfunction can directly affect Safety Significant and Safety Class SSC function.

Sievert (Sv) – The Systeme' Internationale (SI) unit of any of the quantities expressed as dose equivalent. The dose equivalent in sievert is equal to the absorbed dose in gray multiplied by the quality factor (1 Sv = 100 rem).

Software – Computer programs, operating systems, procedures, and possibly associated documentation and data pertaining to the operation of a computer system. (IEEE Standard 610.12-1990, *IEEE Standard Glossary of Software Engineering Terminology*])

Toolbox Codes – A small number of standard computer models (codes) supporting DOE safety analysis, having widespread use, and meeting minimum qualification standards. These codes are sufficiently verified and validated, and may be said to constitute a "safe harbor" methodology. That is to say, the analysts using these codes do not need to present additional defense as to their qualification, provided that they are sufficiently qualified to use the codes and the input parameters are valid

Total Effective Dose Equivalent (TEDE) – The sum of the deep dose equivalent (from external exposure) and the CEDE (from internal exposure). Note that the TEDE is equivalent to the EDE. For purposes of compliance, deep dose equivalent to the whole body may be used as EDE for external exposures.

Whole Body – For the purposes of external exposure, head, trunk (including male gonads), arm above and including the elbow, and the legs above and including the knee.

95th Percentile Consequence – A statistical level of consequence that is exceeded no more than five percent of the time based on site-characteristic meteorology. The offsite radiological exposure basis documented in Appendix A to DOE-STD-3009-94 and based on the method described in the NRC Regulatory Guide 1.145 (February 1983) to define the meteorological conditions assumed to be present for consequence analysis. Given site-specific data, the 95th percentile consequence is determined from the distribution of meteorologically-based doses calculated for a postulated release to a downwind receptor location that would result in a dose that is exceeded 5% of the time (based on hourly averages). The specific meteorology or dilution factor leading to this dose consequence is a function of release elevation, distance to the receptor, and (to some degree) the release duration. This consequence level is direction-independent, i.e. averaged over all 360º at the distance of interest. (See Position 3 in NRC Reg. Guide 1.145 and 5 Percent Overall Site χ/Q Value.)

99.5th Percentile, Worst-Sector Consequence – A method described in the NRC Regulatory Guide 1.145 (February 1983) to define the meteorological conditions assumed to be present for consequence analysis. Given site-specific data, the sector 99.5th percentile meteorology is the set of meteorological conditions assumed during a postulated release to a downwind receptor location that would result in a dose that is exceeded 0.5% of the time (based on a yearly average) in one of sixteen 22.5^{o} sectors. The highest of the sixteen 22.5^{o} sectors is then defined as the 99.5 Percentile, Worst-Sector Meteorology/Consequence condition.

The MOI dose consideration takes distance to the site boundary in each direction into account.

8.2 Acronyms

AED	Aerodynamic Equivalent Diameter
ALI	Annual Limit on Intake
AMAD	Activity Median Aerodynamic Diameter
AMS	American Meteorological Society
ANSI	American Nuclear Standards Institute
ARF	Airborne Release Fraction
CEDE	Committed Effective Dose Equivalent
CFR	Code of Federal Regulation
DBA	Design Basis Accident
DCF	Dose Conversion Factor
DOE	Department of Energy
DOE/EH	Department of Energy Office of Environment, Safety, and Health
DOS	Disk Operating System
DR	Damage Ratio
DSA	Documented Safety Analysis
EDE	Effective Dose Equivalent
EG	Evaluation Guideline
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
FGR	Federal Guidance Report
GEP	Good Engineering Practice
HEPA	High Efficiency Particulate Air
ICRP	International Commission on Radiological Protection
IDCF	Inhalation Dose Conversion Factor

JFD	Joint Frequency Distribution
LCF	Latent Cancer Fatality
LPF	Leakpath Factor
MAR	Material at Risk
MOI	Maximally-exposed Offsite Individual
NESHAP	National Emission Standards for Hazardous Air Pollutants
NRC	Nuclear Regulatory Commission
OEP	Onsite Evaluation Point/Person
PNNL	Pacific Northwest National Laboratory
RDCA	Radiological Dispersion and Consequence Assessment
RF	Respirable Fraction
SQA	Software Quality Assurance
SSC	Structure, System, and Component
ST	Source Term
STD	Standard
SUM^3	Sensitivity/Uncertainty Multimedia Modeling Module
TEDE	Total Effective Dose Equivalent
TSR	Technical Safety Requirement
WG	Working Group

INTENTIONALLY BLANK

9.0 REFERENCES

Briggs, 1973, G. A. Briggs*, Lift Off of Buoyant Gas Initially on the Ground*," ADTL Contribution File No. 87, November 1973. Air Resources Atmospheric Turbulence and Diffusion Laboratory NOAA, Oak Ridge, TN.

Carpenter, S.B., T.L. Montgomery, J.M. Leavitt, W.C. Colbaugh, and F.W. Thomas. 1971. "Principal plume dispersion model: TVA power plants." *Journal of the Air Pollution Control Association* 23:491-495.

DNFSB, 2000, Defense Nuclear Facilities Safety Board, *Quality Assurance for Safety-Related Software at Department of Energy Defense Nuclear Facilities*, Technical Report DNFSB/TECH-25, (January 2000).

DNFSB, 2002, Defense Nuclear Facilities Safety Board, *Recommendation 2002-1, Quality Assurance for Safety-Related Software* , (September 2002).

DOE, 1994, *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Safety Analysis Reports*, DOE-STD-3009-94, U.S. Department of Energy, Washington, DC, Change Notice 2 (April 2002).

DOE, 1994a, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities*, DOE-HDBK-3010-94, U.S. Department of Energy, Washington, DC, Change Notice 1 (January, 1999).

DOE/EH, 2003, U.S. Department of Energy (2003), *Designation of Initial Safety Analysis Toolbox Codes*, Letter, (March 28, 2003).

Eckerman 1988, K.F. Eckerman, A.B. Wolbarst, A.C.B. Richardson. *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion*. Federal Guidance Report No. 11, U.S. Environmental Protection Agency, Washington, DC, DE89-011065.

Eckerman 1993, K.F. Eckerman and J.C. Ryman. *External Exposure to Radionuclides in Air, Water, and Soil. Federal Guidance Report 12*, U.S. Environmental Protection Agency, Washington, DC, PB94-114451.

Eimutis, 1972. E.C. Eimutis and M.G. Konicek, Derivations of Continuous Functions for the Lateral and Vertical Atmospheric Dispersion Coefficients, Atm. Env.,6, pp. 859-863.

EPA, 1995*. User's Guide for the Industrial Source Complex (ISC3) Dispersion Models, Volume II – Description of Model Algorithms*, EPA-454/B-95-003b, U.S. Environmental Protection Agency, Research Triangle Park, NC, September 1995.

Gifford, 1976, F.A. Gifford, "Turbulent Diffusion Typing Schemes - a Review." *Nuclear Safety* 17:68-86.

Hanna, 1982, S.R. Hanna, G.A. Briggs, and R.P. Hosker, Handbook on Atmospheric Diffusion. DOE/TIC-11223, U.S. Department of Energy, Washington, DC, 1982.

ICRP-26, 1977. *Recommendations of the ICRP*, Annals of the ICRP 1 (#3), ICRP Publication 26, published for the International Commission for Radiological Protection by Pergamon Press, Oxford, England, 1977.

ICRP, 1978, Radiation Protection: ICRP Publication 30 Part 1 Limits for Intakes of Radionuclides by Workers, Pergamon Press, New York, NY.

ICRP-30, 1979-82. *Limits for Intakes of Radionuclides by Workers*, Annals of the ICRP 2 (#3-4), 4 (#3-4), 6 (#2-3), 7, 8 (#1-4), and 19 (#4), ICRP Publication 30, published for the International Commission for Radiological Protection by Pergamon Press, Oxford, England, 1979 - 1982.

ICRP, 1986. "The Metabolism of Plutonium and Related Elements," ICRP Publication 48 *Annals of the ICRP* Volume 16, Numbers 2-3, Pergamon Press, New York, NY.

ICRP-60, 1991. *1990 Recommendations of the International Commission of Radiological Protection*, Annals of the ICRP 21 (#1-3), ICRP Publication 60, published for the International Commission for Radiological Protection by Pergamon Press, Oxford, England, 1991.

ICRP-66, 1994. *Human Respiratory Tract Model for Radiological Protection*, Annals of the ICRP 24 (#1-3), ICRP Publication 66, published for the International Commission for Radiological Protection by Pergamon Press, Oxford, England, 1994.

ICRP, 1995. "Dose Coefficients for Intakes of Radionuclides by Workers: A Report of a Task Group of Committee 2 of the International Commission on Radiological Protection Replacement of ICRP Publication 61," ICRP Publication 68 *Annals of the ICRP* Volume 24, Number 2, Pergamon Press, New York, NY.

ICRP, 1996a. "Age-dependent Doses to the Members of the Public from Intake of Radionuclides: Part 5," ICRP Publication 72 *Annals of the ICRP* Volume 26, Number 1, Pergamon Press, New York, NY.

ICRP, 1996b. "Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 4, Inhalation Dose Coefficients," ICRP Publication 71 *Annals of the ICRP* Volume 25, Number 3, Pergamon Press, New York, NY.

ICRP-68/72, 2001. *The ICRP Database of Dose Coefficients: Workers and Members of the Public*, Version 2.0, CD-ROM of ICRP Publication 68 and 72, published for the International Commission for Radiological Protection by Pergamon Press, Oxford, England, 2000.

Lazaro, 1997, M. A. Lazaro, K. Woodward, S. R. Hanna, D.J. Hesse, J. C. Huang, J. Lewis, and C. A. Mazzola. *Model Review and Evaluation for Application in DOE Safety Basis Documentation of Chemical Accidents – Modeling Guidance for Atmospheric Dispersion and Consequence Assessment*, ANL/EAD/TM-75, Environmental Assessment Division (EAD), Argonne National Laboratory (ANL), Argonne, IL.

McElroy, 1968, J.L. McElroy and F. Pooler. *The St. Louis Dispersion Study*. U.S. Public Heath Service, National Air Pollution Control Administration, Report AP-53.

Napier, 1999a, B. A. Napier, *GENII Version 2 User's Guide*, Prepared for U.S. Environmental Protection Agency, January , 1999.

Napier, 1999b, B. A. Napier, *GENII Version 2 Example Calculation Descriptions*, Prepared for U.S. Environmental Protection Agency, January , 1999.

Napier, 1999c, B. A. Napier, D.L. Strenge, J. V. Ramsdell, Jr., P. W. Eslinger, and C. Fosmire, *GENII Version 2 Software Design Document*, Prepared for U.S. Environmental Protection Agency, January , 1999.

Napier, 2003, B. A. Napier, Communication with K.R. O'Kula.

Napier, 1999d, B. A. Napier and L. Staven, *GENII Version 2 Training Power Point Slides*, Presented at the Safety Analysis Workshop of the annual meeting of the Energy Facility Contractors Group (EFCOG), June, 1999.

NRC, 1972. *Onsite Meteorological Programs*, U.S. Nuclear Regulatory Commission Regulatory Guide 1.23 (February 1972).

NRC, 1977. *Methods for Estimating Atmospheric Transport and Dispersion of Gaseous Effluents in Routine Releases from Light-Water-Cooled Reactors*, Regulatory Guide 1.111, U.S. Nuclear Regulatory Commission, Washington, DC, 1977.

NRC, 1983. *Atmospheric Dispersion Models for Potential Accident Consequence Assessments at Nuclear Power Plants*, Regulatory Guide 1.145, U.S. Nuclear Regulatory Commission, Washington, DC, February 1983.

NRC, 1998. U.S. Nuclear Regulatory Commission, Nuclear Fuel Cycle Facility Accident Analysis Handbook, NUREG/CR-6410, Prepared by SAIC for the USNRC (1998).

O'Kula, 1998, K.R. O'Kula, J.M. East, A.H. Weber, A.V. Savino, and C.A. Mazzola, *Evaluation of Current Computer Models in the DOE Complex for SAR Analysis of Radiological Dispersion & Consequences*, WSRC-TR-96-0126, Savannah River Site, Aiken, SC.

O'Kula 2000, K.R. O'Kula and J.M. East, *Evaluating Compliance with DOE-STD-3009-94, Appendix A Requirements (U)*, 2000 American Nuclear Society/European Nuclear Society International Meeting, Washington, D.C. (November 2000).

Smith, F.B. 1961. "An Analysis of Vertical Wind-fluctuation at Heights between 500 and 5,000 Feet." *Quarterly Journal of the Royal Meteorological Society* 87(372):180-193.

Turner, 1970. D.B. Turner. Workbook of Atmospheric Dispersion Estimates. Education, and Welfare report PB-191482, U.S. Department of Health, Washington, DC (1970).

Appendices

Appendix	Subject
A	Overview of Atmospheric Dispersion and Consequence Analysis
B	Software Defect Notifications

APPENDIX A. OVERVIEW OF ATMOSPHERIC DISPERSION AND CONSEQUENCE ANALYSIS

Once the ST to the environment from a postulated accident condition has been calculated or estimated, the safety analyst must determine the concentration downwind to hypothetical receptors. A robust safety analysis will apply a sound technical basis for predicting the transport and diffusion of the airborne plume. Often this is based on a dispersion model that applies environmental data specific to the facility and site under consideration.[7]

This appendix provides an overview of atmospheric dispersion methods, focusing on Gaussian methodology, and discusses radiological consequence analysis "back end." Recommendations are provided where appropriate for specific data or assumptions.

A-1 DISPERSION METHODOLOGY & SUMMARY OF DOE-STD-3009-94, APP A

Appendix A to DOE-STD-3009-94, Change Notice 2 (CN2), specifies an EG for radiological exposure to the offsite receptor, which is to be applied in specifying SSCs (DOE, 2000). The numerical value of the EG is 25 rem, TEDE. Dose estimates to be compared to the EG are those received by a hypothetical MOI at the site boundary for an exposure period of two hours. The nominal exposure period of two hours may be extended to eight hours for release scenarios that occur over a prolonged period.

Appendix A to DOE-STD-3009-94 notes that the airborne pathway is of primary interest for nonreactor nuclear facilities. NUREG-1140, *A Regulatory Analysis on Emergency Preparedness for Fuel Cycle and Other Radioactive Material Licenses*, previously noted that, "for all materials of greatest interest for fuel cycle and other radioactive material licenses, the dose from the inhalation pathway will dominate the (overall) dose." For some types of facilities such as waste storage, the surface and groundwater pathways may be more important, but accident releases usually would be expected to develop more slowly than airborne releases.

The dose calculation references Regulatory Guide 1.145 of the NRC for determination of the five percent overall site relative concentration (χ/Q, often referred to as the dilution or dispersion factor) value at the exclusion area boundary. A straight-line Gaussian model is to be applied with one-hour averaged χ/Q values for the entire course of plume duration for a period not to exceed eight hours. Text from Section A.3.3 of Appendix A on Dose Estimation (p. A-8 to A-9) states

> The relevant factors for dose estimation are receptor location, meteorological dispersion, and dose conversion values …

The first two of these three factors are addressed below.

---

[7] The term dispersion is applied using the definition appearing as Footnote 2 in NRC Regulatory Guide 1.145 to encompass both transport (due to organized or mean airflow within the atmosphere) and diffusion (due to disorganized or random air motions) of the plume.

Dose Calculation Location. For the purposes of comparison to the EG, the comparison point is taken to be the location of a theoretical MOI standing at the site boundary. This location can also be beyond the DOE site boundary if a buoyant or elevated plume is not at ground level at the DOE site boundary. In such cases, the calculation location is taken at the point of maximum exposure, typically where the plume reaches ground level. It is DOE practice and expectation that onsite individuals, both workers and public, are protected under the Emergency Response plans and capabilities of its sites. This protection, along with implementation of defense-in-depth and worker safety philosophy, Safety Significant (and indirectly, through Safety Class) SSC designation, and DOE's safety management programs, address onsite safety. However, an annual assessment of any changes in the site boundary and potential effects on safety SSC classification should be performed in association with the required annual update of the Safety Analysis Report for a facility. Privatization and site turnover initiatives may affect these determinations.

Atmospheric Dispersion. The 95th percentile of the distribution of doses to the MOI, accounting for variations in distance to the site boundary as a function of direction, is the comparison point for assessment against the EG. The method used should be consistent with the statistical treatment of calculated χ/Q values described in Regulatory Position 3 of NRC Regulatory Guide 1.145 for the evaluation of consequences along the exclusion area boundary. The determination of distance to the site boundary should be made in accordance with the procedure outlined in position 1.2 of Regulatory Guide 1.145. NRC Regulatory Guide 1.23 describes acceptable means of generating the meteorological data upon which dispersion is based. Accident phenomenology may be modeled assuming straight-line Gaussian dispersion characteristics, applying meteorological data representing a 1-hour average for the duration of the accident. Accident duration is defined in terms of plume passage at the location of dose calculation, for a period not to exceed 8 hours. Prolonged effects, such as resuspension, need not be modeled. The accident progression should not be defined so that the MOI is not substantially exposed (i.e., using a release rate that is specifically intended to expose the MOI to only a small fraction of the total material released). The exposure period begins from the time the plume reaches the MOI.

For ground level releases, the calculated dose equates to the centerline dose at the site boundary. For elevated, thermally buoyant, or jet releases, plume touchdown may occur beyond the site boundary. As noted in the discussion of receptor location, these cases should locate the dose calculation at the point of maximum dose beyond the site boundary, which is typically at the point of plume touchdown.

Accidents with unique dispersion characteristics, such as explosions, may be modeled using phenomenon-specific codes more accurately representing the release conditions. Discussion should be provided justifying the appropriateness of the model to the specific situation. For accident phenomena defined by weather extremes, actual meteorological condition associated with the phenomena may be used for comparison to the EG.

The guidance provided herein uses the prescriptive requirements of Appendix A as a basis, and is applicable for performing DSAs compliant with Subpart B of 10 CFR 83.

Before discussing choice of a model, the key important environmental transport values are summarized.

A-1.1 Atmospheric Dispersion Parameters and Statistical Bases

Most radiological STs may be treated as neutrally buoyant. By neutrally buoyant, it is assumed that the cloud[8] of released material has approximately the same density as air. This is normally a valid assumption for radioactive releases that are gaseous in nature that contain trace amounts of very fine particulates, aerosols, and gases. As the cloud is carried downwind, it is common practice based on experimental data, to assume a Gaussian distribution in both the crosswind (lateral) and vertical directions. For continuous releases, the mean wind speed dilutes the pollutant but the downwind dispersion is negligible. As the cloud moves downwind it gets progressively larger due to lateral and vertical diffusion, and hence becomes less concentrated. If the release is of short duration (i.e., puff), the mean wind speed only acts as a transport agent and the turbulence in the downwind direction becomes more important. Accordingly, a puff is described by a three-dimension Gaussian equation.

Several meteorological parameters affect the shape and size of a neutrally buoyant cloud. These are discussed in the following sections.

A-1.2 Meteorological Parameters

Earlier it was noted that downwind dispersion of a radioactive plume might be thought of as simultaneous transport and diffusion. In simplest terms, the transport term is mostly a function of wind and direction. The diffusion of the plume is due in large part to the atmospheric turbulence in the region of transport. The following sections discuss wind speed and direction, temperature profiles, and their impact on conditions in the atmosphere.

A-1.2.1 WIND SPEED AND DIRECTION

Prevailing wind is a key determinant of the transport of the radioactive cloud. In terms of importance to accident analysis calculations, wind velocity is a vector quantity having both magnitude and direction. The wind speed at the height of the release determines both the initial diffusion of the pollutant and the travel time to reach a given downwind receptor. The initial diffusion and the plume travel are both directly proportional to the wind speed. It is also a factor in determining the magnitude of atmospheric stability. Atmospheric turbulence (i.e., mechanical turbulence) is generated when adjacent parcels of air move at different speeds or move in different directions. Thus, a change in wind speed with height above the ground, or a variation in wind direction at a given height, causes mechanical turbulence. Mechanical turbulence is also

---

[8] Cloud shall mean either a continuous (plume) or short-term release (puff).

generated when air interacts with some fixed object, such as the ground, described as roughness length, or with a building, described by aerodynamic effects such as building wake and cavity.

The horizontal wind direction at the height of the release determines the direction of transport. It does not affect the magnitude of the concentration of the pollutant within the plume. The horizontal wind direction, or more commonly, wind direction, is the first moment, or average, of a series of "instantaneous" wind direction measurements. By convention, the wind direction is 180 degrees out of phase with the downwind or transport direction.

Atmospheric turbulence is directly related to the variability of wind direction. The variability of wind direction is normally expressed in terms of the standard deviation of a series of "instantaneous" wind direction measurements over a selected observation period, normally fifteen minutes. The standard deviation, or second moment of the horizontal wind direction, σ_θ, is commonly used to characterize atmospheric turbulence by stability classes. Alternatively, the standard deviation of the vertical wind component, σ_φ, is sometimes used as a basis to describe the category of atmospheric turbulence.

A-1.2.2 VERTICAL TEMPERATURE PROFILES

In addition to wind direction variation, another technique that is used to type atmospheric turbulence is to use vertical temperature gradient measurements ($\Delta T/\Delta Z$). When a parcel of air is displaced in the vertical plane, it will expand (if rising) or contract (if sinking) to adjust its pressure to that of its surroundings. The expansion or contraction is accompanied by an adiabatic temperature change. As a parcel rises, it cools. If the surrounding air is warmer, the parcel will be heavier than its surroundings and sink back toward its original position, and its motion ceases. On the other hand, if the surrounding air is cooler, the parcel will be lighter and continue to move upward. Similarly, if the air parcel sinks, it warms up as it contracts. If the surrounding air is cooler, the parcel will be lighter and rise back toward its original position, and its motion ceases. If the surrounding air is warmer, the parcel will be heavier and continue to sink.

Thus, turbulence is suppressed if the temperature profile of the air (the so-called lapse rate) is less than adiabatic (subadiabatic), and enhanced if greater than adiabatic (superadiabatic). The adiabatic lapse rate near ground is about -9.8 °C/km (-5.4 ^{o}F/1,000 feet). Superadiabatic lapse rates are associated with unstable atmospheric conditions and labeled A, B, or C stability classes, with Class A representing the most unstable set of conditions. Subadiabatic lapse rates are associated with stable atmospheric conditions, inclusive of inversions (i.e., temperature increase with height) and labeled E, F, and G stability classes, with Class G representing the most stable conditions. Adiabatic lapse rates are associated with neutral atmospheric conditions and labeled as Class D. In practice, some sites limit the extent of classes to six, with G stability class being combined with F stability.

Thus, the vertical temperature profile affects atmospheric turbulence. The atmospheric layer near the ground is called the mixing, or the mixed layer. During daylight, the ground heats up, warming the air near the surface. The lapse rate near the surface thus becomes superadiabatic and buoyancy-driven vertical turbulence enhances in the existing mechanical turbulence due to ground roughness and wind shear. At night, the ground cools, causing the air near the surface to cool, and the lapse rate becomes subadiabatic and frequently inverted. Buoyancy-driven vertical turbulence thus suppresses the existing mechanical turbulence due to ground roughness and wind shear. At greater heights, a few hundred to a few thousand meters in altitude, the lapse rate may change. It is common for the turbulent lower atmosphere to be capped by lapse rate that is subadiabatic so that turbulent eddies rising from below are suppressed. This layer near ground is thus called the mixed layer, for this is where turbulence in the strongest due primarily to the frictional effects of the earth's surface and the convective heat transfer from the earth's surface.

A-1.2.3 ATMOSPHERIC STABILITY CLASSES

A comprehensive treatment of atmospheric dispersion is so complex that many approximations are needed to make it tractable. Since turbulence is random and chaotic, it cannot be parameterized and one must resort to empirical formulations. One early attempt to simplify the treatment of turbulence was to define atmospheric stability classes and associate a rate of lateral and vertical diffusion with each class as a function of downwind distance only. Although computations based on these stability classes provide only a rough approximation to reality, they have proved extremely useful. They are still in use, although treatments that are more accurate are available. Wind direction variability and vertical temperature difference are the most common techniques that are employed to compute stability class. Wind direction variability provides the best approximation of mechanical turbulence, while vertical temperature difference approximates the buoyancy component.

Seven stability classes (i.e., Pasquill-Gifford-Turner classes) have been defined. These classes, with the original descriptions and conditions of occurrence given by Pasquill (Turner, 1994), are:

- A: Extremely Unstable (Strong superadiabatic). Normally occurs during bright sunshine with relatively low wind speed (< 3 m/s).
- B: Moderately Unstable (Moderate superadiabatic). Normally occurs during conditions that range from bright sunshine with wind speeds in the 3 to 5 m/s range to dim sunshine with wind speeds < 2 m/s.
- C: Slightly Unstable (Slight superadiabatic). Normally occurs during conditions that range from bright sunshine with wind speeds in the 5 to 6 m/s range to dim sunshine with wind speed in the 2 to 3 m/s range.
- D: Neutral (Adiabatic). Normally occurs with moderate to dim sunshine, cloudy conditions, and at night, with wind speeds > 3 m/s. It also occurs with very strong wind speeds on either sunny or cloudy days.
- E: Slightly Stable (Slight subadiabatic with or without inversion). Normally occurs at night or early morning with some cloud cover and with wind speeds in 2 to 5 m/s range.
- F: Moderately Stable (Moderate subadiabatic with inversion). Normally occurs at night or early morning with little cloud cover and with relatively low wind speeds (< 3 m/s).

- G: Extremely Stable (Strong subadiabatic with inversion). Normally occurs at night or early morning with very light to nearly zero wind speed.

Unstable conditions result in rapid lateral and vertical diffusion of pollutants (i.e., wide plumes), whereas stable conditions result in slow lateral and vertical diffusion (i.e., narrow plumes). The latter will lead to higher air concentrations from ground-level releases.

Although Class A is not rare, it is not as common as Classes B through F. Class D is the most common stability class for many DOE sites. This is due to the large number of combinations that can result in Class D stability. For example, high-wind conditions and/or cloudy conditions during the day or at night are normally Class D. Classes E and F are the most common stability classes at night.

Note that the meteorological conditions used as a basis for DOE-STD-1027-92 Hazard Characterization, Attachment 1 are D stability and 4.5 m/s wind speed. This set of conditions is also used as a basis by chemical process industry for determining limits on chemical inventories, and is representative of most U.S. regions (29 CFR 1910.119). These are median dispersion conditions for most sites.

A-1.3 Dispersion Conditions for Accident Analysis

In calculating plume concentrations, and subsequently consequences to the receptor, both "unfavorable" and "typical" dispersion conditions are of special interest in accident analyses. For accident analysis consideration of the offsite MOI receptor, unfavorable meteorology should be based on site data. In practice, this is the dilution factor (χ/Q) that coupled with the ST would lead to doses that are exceeded less than five percent of the time. The method should be conservative or consistent to the discussion in the NRC Regulatory Guide 1.145 (Position 3) as summarized in Appendix A to DOE-STD-3009-94, CN2. The 95th percentile of the distribution of doses to the MOI, accounting for variation in distance to the site boundary as a function of direction, is the comparison basis for assessment against the EG.

The size of the data set used in the meteorological assessments should be sufficiently large that it is representative of long-term meteorological trends at most sites. Meteorological data used in accident analysis should be qualified to meet the requirements of Regulatory Guide 1.23 (NRC 1972) and representative of long-term trends. A five-year dataset is desirable, but a one-year data set can be applied under the right circumstances.[9] In lieu of site-specific meteorology, the accident analysis may use generally accepted, default stability and wind speed combinations, such as Class F stability and 1.0 m/s to 1.5 m/s wind speed, as an interim measure.

[9] In Draft Regulatory Guide DG-111, this subject is discussed as follows: "The NRC staff considers five years of hourly observations to be representative of long-term trends at most sites. With sufficient justification of its representativeness, the minimum meteorological data set is one complete year (including all four seasons) of hourly observations." (NRC 2001)

It should be noted that in the long run, site data is normally preferable over the default conditions for accident analysis.

For example, Hunter (1993) evaluated Savannah River Site data and found the 95th percentile conditions varied with release height and receptor distance. For most facility MOI distances, it was determined that 95th percentile conditions were E stability and

- 1.7 m/s wind speed for a release height between 0 m and 10 m
- 2.1 m/s wind speed for a release height of 20 m, and
- 3.0 m/s wind speed for a release height of 60-m.
- For mitigated hazard analysis, DOE has not established guidance for evaluating the mitigated benefit of SSCs. Both median statistical basis (i.e., 50th percentile) and 95th percentile bases have been applied to determine onsite receptor doses. While other measures of "typical" could be applied, each is problematic. The mean (i.e., average) and the mode (i.e., peak) of a distribution, unlike the median, are not heavily influenced by outliers (abnormally small or large values). For a bimodal distribution, which often occurs, the mean may fall between the peaks (i.e., modes) of the distribution and thus be comparatively infrequent, which could not be considered "typical." (The median could also be atypical in this sense but it has a relevant meaning.) In addition, if mode were chosen as "typical," a bimodal distribution could give two valid choices if the peaks are nearly as large.
- Evaluation of site data for determining 95th and 50th percentile conditions has historically been of two types. A JFD sampling of site hourly data sorts *all* data from high relative concentration to low relative concentration and identifies various percentile conditions by ranking the full data set. Another basis is use of a random sampling technique in which a sample of the full data is randomly selected and then typically sorted into pre-assigned consequence bins (normally chosen to find high-consequence conditions). An example of this approach is Latin Hypercube Sampling.
- JFD sampling is usually done for a standard set of release conditions (e.g., one hour duration, ground-level release). The random sampling basis is normally determined on an accident case-by-case basis. The JFD profile tends to be composed of more data points and is generally "smoother."

A-1.4 Gaussian Model for Neutrally Buoyant Plumes

The choice of a dispersion model depends on factors such as the phase of safety analysis, complexity of facility, complexity of the accident sequence, and site topography and its affect on environmental transport conditions. Simply put, the most comprehensive, realistic computer model is not the best choice for all safety analysis situations. In most situations, peer-reviewed engineering calculations and spreadsheet analyses employing a Gaussian atmospheric dispersion model are sufficient. Data requirements for such calculations are typically less demanding than for models that are more complex. Ultimately, this type of accident analysis calculation is more scrutable and technically defensible during independent review if based on the Gaussian model.

The simple, straight-line Gaussian dispersion equation is used as the basis for a majority of the models used in DOE safety analysis of accidental releases. It is the basis for radionuclide inventories defining Hazard Category 2 and 3 facilities in DOE-STD-1027-92, CN 2. And, as noted earlier, for compliance with Appendix A of DOE-STD-3009, and comparison with the EG, the Gaussian model can readily estimate time-integrated air concentrations (typical units of Ci-s/m^3 for radiological releases) at downwind locations and is recommended for most accident conditions (Figure A-1). While more sophisticated models are becoming more commonplace, especially in situations where complexities in physical or chemical properties, terrain, or nearby buildings influence the dispersion of radiological material, the data demands for these approaches may be prohibitive. However, for these situations, the basic Gaussian dispersion model can be bootstrapped to accommodate release and dispersion effects that are influenced by surface features or ST characteristics.

The user should exercise care over the distance for which the Gaussian model is applied. The American Meteorological Society (AMS) published a position paper indicating that the Gaussian model is estimated to be accurate within a factor of two for distances of 0.1 to 10 – 20 km when onsite meteorological tower data are available, and conditions are reasonably steady and horizontally homogeneous (AMS, 1978). For distances beyond 20 km and closer than 100 m, the Gaussian model should be considered to be order-of-magnitude estimates at best. Aerodynamic wakes, rough or urban terrain, dense gas effects, and dispersion under very stable conditions often render Gaussian model predictions inaccurate.

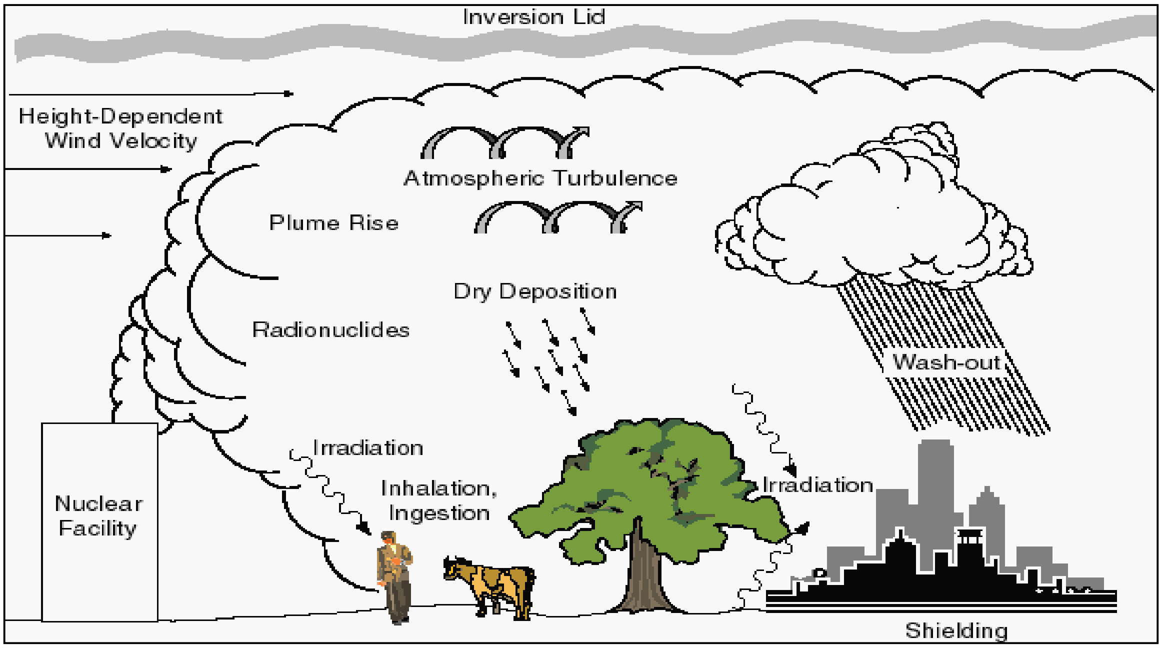

Figure A-1. Basic Processes Occurring During Accidental Release and Dose Pathways

For energetic releases, other models may be employed, as allowed under Appendix A of DOE-STD-3009-94, CN2. However, data requirements for alternative model types may preclude use to support most DSA applications. Alternative techniques have been applied to "bootstrap" a Gaussian model and thereby apply it to cases normally outside the regime of Gaussian applicability (Steele, 1998).

It is the responsibility of the analyst to make the final determination of a dispersion basis. The value of a complex, more realistic computer model with associated data demands, the requirements of the specific application, and the phase of the safety analysis must be weighed.

Recommendation:

Apply the Gaussian model as a first choice. Accident phenomenology may be modeled assuming straight-line Gaussian dispersion characteristics, applying meteorological data representing a 1-hour average for the duration of the accident.

Use other special-purpose approaches as warranted for unique release situations, e.g. detonation or blast accident scenarios. Consider appropriate modifications for addressing weather extremes, such as tornado or high-wind conditions.

Basic Gaussian Equations

Intrinsic to the assumptions underlying the Gaussian approximation of atmospheric dispersion, as a plume is transported downwind, its horizontal expansion is essentially unlimited[10]. Vertical

[10] Horizontal, or lateral, plume expansion may be somewhat limited by physical barriers, such as

expansion is limited by the earth's surface and aloft under inversion conditions. The downward expansion of the plume must obviously stop at the ground, while upward expansion may be stopped if there is a stable layer (i.e., a "cap") at the top of the mixing layer. This cap acts as a lid to rising "thermals" of air, thus restricting the range and magnitude of vertical turbulence. The plume is often considered to "reflect" off both the ground and the top of the mixing layer, causing the *vertical* profile to become increasingly uniform as the plume proceeds downwind.

The amount of atmospheric dilution and dispersion is usually expressed in terms of χ/Q, where χ is the concentration of the pollutant in air at some downwind location. For these formulations, χ represents either the instantaneous concentration (e.g., Ci/m^3 or Bq/m^3) or the time-integrated concentration (e.g., Ci-s/m^3 or Bq-s/m^3), and Q is the rate of release (e.g., Ci/s or Bq/s) of the pollutant, or total source strength (e.g., Ci or Bq) of the pollutant. The units of χ/Q are s/m^3 whether the instantaneous or time-integrated releases are considered. Thus, χ/Q is the concentration of the pollutant in air at the receptor per unit source rate, or time-integrated concentration per unit source. The actual concentration of the pollutant in air at the receptor is thus the product of χ/Q and the rate of release of the pollutant.

The Gaussian plume model (Slade, 1968), when not constrained in the vertical by the ground or the top of the mixed layer, is expressed as:

$$\frac{\chi(x,y,z,h)}{Q}=\frac{1}{2\pi u\sigma_y\sigma_z}\,e^{-y^2/2\sigma_y^2}\left[e^{-(z-h)^2/2\sigma_z^2}\right] \tag{A-1}$$

where *x* is the distance of the receptor downwind from the release point, *y* is the horizontal cross-wind distance of the receptor from the centerline of the plume, *z* is the distance of the receptor above the ground, *h* is the height of the plume centerline above the ground, σ_y is the standard deviation of the horizontal Gaussian distribution (i.e., the "half width"), σ_z is the standard deviation of the vertical Gaussian distribution (i.e., the "half thickness"), and *u* is the wind speed at 10 m height, the standard measurement height. The constant, 2π, is implicit in a Gaussian distribution, and is the product of lateral and vertical components each contributing $(2\pi)^{1/2}$. Note that the downwind distance *x* does not appear explicitly in this equation since downwind distance is an independent variable. The *x* dependence is implicit, as the σ_y and σ_z are functions of *x* only, for a given stability class. The wind speed (u) represents the direct dilution of the pollutant as soon as it is released into the atmosphere. The lateral and vertical Gaussian coefficients (σ_y, σ_z) approximate the diffusion or dispersion in the atmosphere as the plume is transported downwind.

The bracketed term in equation (A-1) defines the vertical distribution. If hazardous material released in the plume is reflected from the ground and from the top of the mixed layer, this term must be modified. This is done mathematically by adding multiple mirror STs. The bracketed term in equation (A-1) thus is replaced with:

---

buildings and topographic obstacles, but these are normally treated as special cases.

$$\left[e^{-(z-h)^2/2\sigma_z^2} + e^{-(z+h)^2/2\sigma_z^2} + \sum_{n=1}^{N}\left(e^{-(z-h-2nL)^2/2\sigma_z^2} + e^{-(z+h-2nL)^2/2\sigma_z^2} + e^{-(z-h+2nL)^2/2\sigma_z^2} + e^{-(z+h+2nL)^2/2\sigma_z^2}\right)\right] \quad \text{(A-1a)}$$

The term before the summation in expression (A-1a) is the ground reflection component since perfect reflection is assumed. The series of terms after the summation represent the perfect reflection of first the top of the plume and later the bottom of the plume on the top of the mixed layer. *L* represents the height of the top of the mixed layer and the summation is over the number (*N*) of reflections to be considered. The contribution of the summation term is minor, especially for distances close to the source and for larger values of L. The higher order terms contribute progressively less and the series is normally terminated after only a few terms. For a ground-level release (i.e., $h = 0$), the first two exponential terms become equivalent. Each of these terms subsequently becomes a value of one when the receptor is at ground level ($z = 0$). In these cases, the "2" in the denominator of equation (1) cancels out with the "2" in the numerator, if the summation term is ignored, as is often done. The maximum concentration occurs at plume centerline (i.e., $y = 0$). Thus, if the summation term is ignored, the Gaussian equation simplifies to a centerline condition:

$$\frac{\chi(x, y=0, z=0, h=0)}{Q} = \frac{1}{\pi u \sigma_y \sigma_z} \quad \text{(A-2)}$$

Strictly speaking, the numerator in the above expression is slightly greater than one because of the contribution of the summation term. Equation (A-2), which is now only a function of downwind distance of the receptor, is often used for the MOI, as the plume centerline concentration represents a conservative value.

Similarly, a puff model using a Gaussian formulation may be used for instantaneous or near-instantaneous releases of hazardous material

$$\chi(x, y, z; H) = \frac{Q_T}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\left\{\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right\} \quad \text{(A-3)}$$

where:

Q_T = total ST (Ci)

σ_x = longitudinal dispersion coefficient, representing the standard deviation of the concentration distribution in the downwind axis direction (m) (AIChE 1996).

The horizontal and vertical dispersion coefficients, σ_Y and σ_Z, required in the Gaussian dispersion equation are obtained either from site-specific meteorological measurements (standard deviations of wind angles) or indirectly through estimating an atmospheric stability class for which standard dispersion coefficients have been established. If the necessary meteorological measurements are not available, several methods for determining stability class may be used. The differences between puff and plume dispersion handled with the Gaussian dispersion equation should be taken into account when applying the model. Methods for calculating puff dispersion coefficients have been addressed by Turner (1970), Gifford (1977), and Hanna (1982). The puff dispersion equation is rarely used for radiological consequence calculations.

A-1.4.3 MIXING LAYER HEIGHT

For an evaluation of χ/Q that includes reflections from the ground and the top of the mixing layer, an estimate of the depth of the mixing layer is required. This height varies throughout the day and throughout the seasons. During clear nights, when inversions are present, the mixed layer is relatively shallow, while during sunny days the mixing layer is much deeper. The magnitude of the depth of the mixing layer can be obtained from balloon soundings or from remote sensing techniques, such as acoustic or radar soundings. In the absence of such data, regional tables can be consulted, such as those of Holzworth (1972).

Recommendation: Calculate mixing layer depth from seasonal averages and time of day (viz., day vs. night), applying archived site meteorological data. If this is not applicable, use regional data as default input values, such as from Holzworth (1972).

A-1.4.4 DISPERSION PARAMETERS

Many schemes have been proposed for establishing the magnitudes of σ_y and σ_z. Most of these are based on empirical curve fitting of data taken during experiments over flat grassland (Haugen, 1959). One commonly used curve-fitting method is that of Tadmor and Gur (1969), in which each σ is expressed as a power law:

$$\sigma = a\,x^b + c \tag{A-4}$$

where *a*, *b*, and *c* are empirical constants, given in Table A-1.

Table A-1. Fitting Constants for σ_y and σ_z - Tadmor and Gur

Curve Fitting Constant	ATMOSPHERIC STABILITY CLASS					
	A	B	C	D	E	F
a_y	0.3658	0.2751	0.2089	0.1474	0.1046	0.0722
a_z	0.00025	0.0019	0.2	0.3	0.4	0.2
b_y	0.9031	0.9031	0.9031	0.9031	0.9031	0.9031
b_z	2.094	1.098	0.911	0.516	0.305	0.18
c_y	0.0	0.0	0.0	0.0	0.0	0.0
c_z	9.6	2.0	0.0	-13.0	-34.0	-48.6

Another commonly used curve-fitting method is that of Briggs (1973), for which each σ is expressed as

$$\sigma = a\,x(1 + bx)^{-1/2} \tag{A-5}$$

where *a* and *b* are constants, given in Table A-2.

Table A-2. Fitting Constants for σ_y and σ_z from Briggs

Curve Fitting Constant	ATMOSPHERIC STABILITY CLASS					
	A	B	C	D	E	F
	Open-Country Conditions					
a_y	0.22	0.16	0.11	0.08	0.06	0.04
a_z	0.20	0.12	0.08	0.06	0.03	0.016
b_y	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
b_z	0	0	0.0002	0.0015	0.0003	0.0003
	Urban Conditions					
a_y	0.32	0.32	0.22	0.16	0.11	0.11
a_z	0.24	0.24	0.20	0.14	0.08	0.08
b_y	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
b_z	0.001	0.001	0	0.0003	0.00015	0.00015

The most commonly used curves are the Pasquill-Gifford curves based on measurements at Project Prairie Grass in the mid-1950s. They are found in Slade (1968), and are based on three-minute averaging times. An empirical formula derived the Pasquill-Gifford parameters has the following form for σ_y and σ_z , and is based on work published by Yuan (1993), where

$$\sigma_y(x) = (0.000246\ \sigma_\theta^2 + 0.00576\ \sigma_\theta\ +0.066)\ x^{\,0.9031} \qquad \text{(A-6)}$$

and

$$\sigma_z(x) = a\ x^b + c \qquad \text{(A-4)}$$

Coefficients and constants for various downwind distances and stability classes are given in Table A-3. The Tadmor-Gur and Briggs formulations, as well as others, give results that are nearly the same for some ranges and stability classes. However, they may differ by a factor of two or more for other ranges/classes. The coefficients given in these tables, and in other Gaussian models, are based on fitting curves to observational data of plumes released over flat grassland. In the case of the Briggs model, an adjustment for urban conditions has also been made. The Pasquill-Gifford formulations also specify different coefficients for different ranges of distance. It should be noted that the database underlying the empirical curve fits is valid for distances between 100 m and 1,000 m.

For distances less than about 100 m, these coefficients generally do not provide a good fit to the observations and the models are generally considered approximate. This is because the Gaussian models, with the underlying assumption of steady state, do not perform well in the near field.

In practice, the concentration at close-in receptor distances is frequently influenced by the physical presence of the facility from which the plume is released, as well as neighboring structures. Often, building wake effects are important for these smaller distances but the above coefficients ignore the enhancement of vertical turbulence from wake effects, downwashing into the wake cavity behind the building, as well as recirculation. These effects can influence concentrations and building-geometry correction factors are often applied.

Recommendation: Consult with the laboratory or site meteorology organization responsible for recording and maintaining site data, and request a best-fit set of dispersion parameters for the region of transport applicable to the analysis. As a default, apply Tadmor-Gur, Briggs, or Pasquill-Gifford dispersion parameter sets, based on site-specific and surface roughness characteristics.

Table A-3. Pasquill-Gifford Dispersion Coefficients (Eimutis, 1972)

	Coefficients				
Applicable Distance, m	**Stability Class**	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

A-1.5 Special Gaussian Modeling Considerations

A-1.5.1 PLUME MEANDER

The above expressions are for short-duration clouds released over relatively smooth terrain. However, as time passes after the initial release, larger sized eddies, mostly in the horizontal direction, may affect the cloud. Shifts in wind direction become likely with time increases since the start of release, and the cloud will tend to change direction, or meander. The meander factor is especially important for the longer duration releases. For a receptor that remains immersed in the plume for some time, meandering effectively widens the plume (i.e., increases horizontal dispersion) and thus decreases χ/Q. One formulation of the plume meander factor[11], the one attributed to Gifford (1975), is

$$\textit{meander factor} = (\textit{plume duration} / \textit{time base})^{n} \tag{A-7}$$

where the time base is typically 10 minutes and the exponent n is 0.2 for plume duration of one hour or less and 0.25 for greater duration. The σ_y is increased by this meander factor and accordingly, the plume-centerline χ/Q would accordingly be reduced by this factor. The plume meander factor is never allowed to be less than one, and the experimental basis is limited to periods no longer than 100 hours.

Example: For a two-hour release and a time base of ten minutes, the plume meander factor is $[(2 \text{ hr}) (60 \text{ min/hr}) /10 \text{ min}]^{0.25} = 1.86$.

An alternative formulation (NRC 1980) is

$$\textit{meander factor} = (2 \times \textit{plume duration})^{1/3} \tag{A-8}$$

where the plume duration is in hours (minimum of 0.5 hours). This gives results similar, but not identical, to those shown in equation (A-7).

A different type, and larger meander factor occurs under conditions that are very close to adverse meteorology for ground-level releases (i.e., very stable conditions with light wind speeds). Under such conditions, large eddies are present in the stably stratified atmosphere which augment the magnitude of the lateral turbulence. This theoretical effect was first empirically determined from tracer studies performed in the mid-1970s. After careful review of the results of the tracer study, the NRC incorporated this meander factor in Regulatory Guide 1.145 (NRC 1983), and acknowledged it in several of their atmospheric dispersion models. The Regulatory Guide does not advise using this factor for relatively higher stability classes (A, B, and C).

The embedded equations in these models can simply be described by an augmentation of the lateral turbulence:

$$\Sigma_y = M\ \sigma_y \tag{A-9}$$

where Σ_y is the augmented lateral turbulence and M is the meander factor.

The value of M increases for more stable conditions (i.e., from E to G stability class) and as wind speeds approach calm. This is exactly opposite to the aerodynamic building wake factor that is very small under these meteorological conditions, but increases significantly as the wind speeds increase and the stability class becomes neutral or slightly unstable.

---

[11] The meander factor is also called the plume expansion factor.

Recommendation: Apply the Gifford model for recalibrating the time basis of the set of dispersion parameters to the release duration of interest.

A-1.5.2 SURFACE ROUGHNESS

Surface roughness mostly affects the magnitude of vertical turbulence, and hence, vertical atmospheric dispersion. The rougher the surface, the larger the turbulent eddies that are formed when the plume encounters the earth's surface. If the terrain is not smooth, which is frequently the case, a linear scaling factor needs to be introduced to increase the effective value of σ_z. A common approach to quantifying the "roughness" factor, is based on AMS (1977) and is usually expressed as:

$$roughness\ factor = (z_1/z_0)^{0.2} \quad (z_1 \geq z_0) \tag{A-10}$$

where z_1 is the roughness length of the terrain over which the plume is passing and z_0 is the comparison standard length, normally taken as 3 cm, which represents the roughness factor associated with flat terrain. The roughness factor cannot be less than unity. Because σ_z is increased by the roughness factor, the plume-centerline χ/Q is proportionally reduced by this amount. For grasslands, the roughness length is estimated to be 10 cm. In this case, the roughness factor is $(10/3)^{0.2} = 1.27$. For terrain that includes grasslands, trees, mountains, and cities, the average roughness length commonly applied ranges from 30 cm to 100 cm. For example, if it were about 24 cm, the roughness factor would be 1.52. (Note that in the Briggs formulation of σ_y and σ_z, this roughness factor is already taken into account in that different coefficients are used for open-country and urban terrain.). McElroy and Pooler first developed "urban" dispersion coefficients in the 1960's (1968). As a rough rule of thumb, the vertical dispersion increases by one stability class for urban areas (i.e., an atmospheric condition resulting in F stability in rural environments becomes E stability in urban environments).

Recommendation: Apply a roughness correction to adjust the vertical dispersion parameterization for the region of transport that is based recommendations from the American Meteorological Society (1977).

A-1.5.3 DEPLETION PROCESSES

While atmospheric dispersion processes play the major role in determining cloud concentration, others processes exist that can remove both gases and particulates from the cloud and reinsert other radioactive species back into the atmosphere. The removal processes are dry deposition, which results from interaction of the lower portion of the plume with the ground and gravitation settling (fallout) of material from the plume, and wet deposition, or precipitation scavenging. Reinsertion of material back into the atmosphere is termed resuspension and will be discussed in more detail in the next section. These mass transfer processes are very important in determining the ultimate fate of small respirable particulates.

A-1.5.3.1 Dry Deposition

The physical characteristics of particulate and aerosol radionuclide species will tend to remove this component from a released cloud. Two common models for removal are the source model and the surface model. The source model is computationally simple, in which the rate at which material in the cloud are deposited to the ground as the product of the ground level air concentration of the materials, and the dry deposition velocity of the material (Chamberlain, 1953). This approach uniformly depletes the cloud, that is, it does not perturb the normal distribution of the concentration in the vertical direction. This assumption is valid during neutral or unstable atmospheric conditions because the constant turn-over of material in the cloud maintains uniformity, but is not as valid for stable conditions, for which the turn-over is less vigorous.

Another approach is the surface depletion method. It is computationally more complex, and depletes the source primarily at the cloud/earth interface. This model changes the material distribution in the cloud.

The parameterization of dry deposition processes is usually accomplished by the use of a deposition velocity. Deposition velocity (v_d) is a mass-transfer boundary condition at the atmosphere-ground surface interface in atmospheric dispersion and transport models. The deposition velocity is defined as a deposition flux (F_d) divided by the airborne concentration of radioactive material (χ):

$$v_d = F_d/\chi \qquad \text{(A-11)}$$

In reality, the deposition velocity is a function of the particle size. The larger the particle, the larger its deposition velocity, up to the Stokes velocity limit. From various field experiments conducted over the years, dry deposition velocities range from 0.001 – 180 cm/s for particulates, while for gases it ranges from 0.002 – 26 cm/s.

Dispersion models such as GENII permit the treatment of particle sizes and assign different deposition velocities to each of user-prescribed particle size bins. The challenge facing the analyst is to assign radioactive material into these bins that has been generated under accident conditions. More than fifty variables exist that can influence the magnitude of the rate of dry deposition removal. These are categorized into micrometeorological, depositing material, and surface variable categories.

Typically, simplifying assumptions are made, based on radionuclide species, chemical form, and whether the emitted radioactive material is filtered or non-filtered. For noble gases and tritiated hydrogen gas (HT), no deposition should be modeled. For filtered particulate releases, the deposition velocity is assumed to 0.001 m/s. This dry deposition velocity corresponds to a particle with an approximate AED of 0.2 μm to 0.4 μm (Sehemel, 1978). For unfiltered particulate releases, such as through cracks and open breaches assumed in the accident conditions, the deposition velocity is assumed to 0.01 m/s. This dry deposition velocity corresponds to a particle with an approximate AED of 2 μm to 4 μm. Tritium oxide is normally taken to have a deposition velocity of 0.005 m/s (Fallon, 1982 and Sweet, 1984).

A-1.5.3.2 Wet Deposition

Wet deposition through precipitation, depletes the plume to some degree. This phenomenon is difficult to parameterize due to its dependency on cloud physics variables which themselves vary over time and space. All types of precipitation (i.e., rain, snow, hail), passing through the plume will collect particulates and scavenge soluble gases. Wet deposition can be approximated by the following correction factor to a dispersion model:

$$D_w = exp\ (-\nu x/u) \qquad \text{(A-12)}$$

where D_w represents the wet deposition and ν represents a washout coefficient (s^{-1}), which itself is a complex function of precipitation particle-size spectrum, precipitation rate, radioactive or hazardous chemical particle-size distribution, and the solubility of the effluent. As previously, x is the downwind distance of the plume centerline from its release point, and u is the wind speed. Families of empirical curves have been developed for various rainfall rates (mm/hr) to estimate the washout coefficient. This procedure is made more complex by the spatial variability of the rainfall. Frequently, rainfall rates vary significantly within a rainfall event, and different washout coefficients may need to be applied to various segments of the plume as it travels to the receptor.

Wet deposition is not modeled in consequence calculations for either the MOI receptor, or the onsite receptors supporting Mitigated Hazard Analysis. While not applicable to deterministic safety analysis, it is usually credited as part of a site's historical data patterns in probabilistic safety assessments.

In addition to these mass-transfer processes, in-growth and decay of radioactive releases constantly occur during the transport and dispersion process. The process of in-growth and decay of radioactive isotopes in the plume is a function of the travel time and the half-life of each specific radionuclide present in the plume. In practice, this effect is appreciable for radioisotopes of half-life on the same order or shorter than the time to reach the receptor under consideration. For non-reactor facilities, an inadvertent criticality would be the primary accident type for which this factor is important.

Decay changes to the population of parent nuclide can be represented by the following factor:

$$A_i(t)/A_0 = exp(-\lambda_t t) = exp(-\lambda_t x/u) \qquad \text{(A-13)}$$

where λ_t is the decay constant of the i^{th} radionuclide species, $A_i(t)$ is its activity at time t, and A_0 its initial activity. Travel time, t, is the ratio of travel distance x, and the mean wind speed, u. Time zero ($t = 0$) is the moment of release into the environment.

Recommendation: Either the source model or surface model for depletion may be used in accident analysis. Do not model dry deposition for noble gases or tritium gas (HT or T_2). For filtered particulate releases, the deposition velocity can be taken as 0.001 m/s. For unfiltered releases, the deposition velocity is 0.01 cm/s. Tritium oxide (HTO or T_2O) has been characterized with a deposition characteristic of 0.005 m/s. Do not credit wet deposition for

DSA accident conditions. Account for decay and in-growth if the initial radionuclides involved at the start of the accident condition have half-lives shorter than the travel time to the receptor.

A-1.5.4 RESUSPENSION

Whereas deposition addresses mass-transfer from the plume to the ground surface, resuspension addresses the opposite processes. In resuspension, material that has already been deposited from the plume, or which has been on the ground for some time, is re-entrained by the wind. The particulates are reintroduced into the atmosphere and transported to a new location. While this effect can be non-negligible for DOE facilities in high-wind and environments without significant intervening vegetation, Appendix A to DOE-STD-3009-94, CN2 indicates that resuspension “need not be modeled.”

Recommendation: The analyst need not explicitly account for resuspension in the dose calculation of an accident condition for a DSA.

A-1.5.5 DEPOSITION AND REEMISSION OF TRITIUM

While dry deposition is observed for most non-noble gas radioactive species and results in diminished plume concentrations as a function of downwind transport, tritium in particular, deposits and re-emits through mechanisms that are distinct from other radionuclides. The major biophysical processes are

- Initial settling to ground
- HT conversion to HTO by soil
- HTO uptake by plants (and partial conversion to organically-bound tritium)
- HTO re-emission from soil and plant
- Uptake by vegetation root systems
- Transport into deeper soil regions.

In evaluating tritium-containing plumes in accident analysis, it is important to recognize that tritium will tend to move in the hydrogen pool throughout the environment. For tritiated water vapor, this will mean rapid uptake depending on difference in concentration. Furthermore, re-emission of tritium from soil and vegetation will take place after plume passage. The latter phenomenon usually takes place on a time scale much longer than the initial removal from the plume (O’Kula, 2001).

A-1.5.6 PLUME RISE MECHANISMS

Two physical processes can vertically propel a neutrally buoyant plume to a higher level above the ground from its initial point of release. Both of these mechanisms are collectively called plume rise. The first mechanism is termed momentum plume rise, in which the velocity of the release (i.e., efflux velocity) vertically propels the plume due to the excess momentum of the release itself. Accordingly, this is termed momentum plume rise.

The other plume rise mechanism is through buoyancy. Buoyancy plume rise occurs if the temperature of the release is warmer than the ambient air. It is also important to account for stack tip downwash of the plume under high wind speed conditions and plume downwash into the wake and cavity behind the building if the release is from a vent or small stack. A brief discussion follows on both of these plume rise components, and how they interact with forces that tend to downwash. Lastly a series of equations are identified that can be integrated into an atmospheric transport and dispersion model to account for the magnitude of these effects.

A-1.5.7 MOMENTUM RISE

The estimation of the momentum rise component requires knowledge of the efflux velocity at the point of release, the wind speed at the point of release, and the diameter of the stack from which the effluent is released. The smaller the stack diameter, the faster the efflux velocity for a given efflux. The efflux velocity is directed vertically, normally, while the wind speed is directed horizontally. Therefore, the ratio of efflux velocity to wind speed determines the initial plume rise. As the plume is transported downwind, the momentum from the efflux velocity vanishes and the wind speed bends the plume over into the horizontal plane. Any additional plume rise beyond the point of release only occurs due to plume buoyancy.

A-1.5.8 PLUME RISE AND ENTRAINMENT METHODS

NRC Regulatory Guides 1.111 and 1.145 define a “stack” release condition as one in which release occurs at or above 2.5 times the height of adjacent solid structures (NRC, 1977, 1983). Open-field, “parking lot” dispersion calculations assume non-stack releases, but with no influence of neighboring structures. Releases can be considered to be at ground level if the point of release is below the height of the facility in question and collocated buildings. The intermediate case of releases that occur in the range between 2.5 times the height of adjacent buildings and the building height is difficult to parameterize. Under some circumstances, the plume escapes the building wake; under other conditions, it becomes completely entrained into the building wake; and under still other conditions, it behaves as a “mixture” of these types (NRC, 1998). Several rules of thumb are presented in this section to guide analysis under these conditions.

The NRC guidance differs moderately from the EPA Good Engineering Practice (GEP) stack height criteria. Applying the EPA criterion, the entire effluent escapes the influence of the facility structures if the stack height is 1.5 times the height of the nearest facility structure plus either the height or width of that structure, whichever is larger. For releases from structures that meet GEP stack height criteria, and under neutral or unstable stability conditions, the amount of plume rise, h_{pr}(m), is:

$$h_{pr} = 1.44d\,(v_e/u)^{0.667}(x/d)^{0.333} - C \qquad \text{(A-14)}$$

where v_e is the efflux velocity (m/s), u is the wind speed (m/s), x is the downwind distance (m), and d is the diameter of the stack (m). This equation shows the relationship between the two opposing parameters, v_e and u. C is the downwash correction factor (m), given by:

$$C = 3[1.5 - v_e/u]d \tag{A-15}$$

Under stable (e.g., E-G stability classes) atmospheric conditions, two empirical equations are evaluated:

$$h_{pr} = 4\ (F_m/S)^{0.25} \tag{A-16a}$$

and

$$h_{pr} = 1.5(S)^{-0.1666}\ (F_m/u)^{0.333} \tag{A-16b}$$

The smaller value is chosen. In these two equations, the momentum flux is $F_m = v_e^2(0.5d)^2$, and the stability parameter is $S = g/[T(-d\theta/dz)]$. For these equations, g represents gravitational acceleration (m/s^2), T is the ambient temperature (K), and $d\theta/dz$ is the potential temperature lapse rate (K/m), which is related to the actual lapse rate.

For plume rise from non-GEP stacks or building vents, empirical relationships from field studies have been developed, where the v_e/u ratio is the driving parameter. When $v_e/u > 5$, the vertically-directed momentum flux (i.e., escape building effects) dominates the horizontally-directed wind speed (i.e., capture building effects), and the release is treated as elevated. This means that although the release emanated from a vent, it still will fully escape the aerodynamic effects of nearby buildings due to the high momentum flux coupled with low wind speed, and the GEP stack height equations apply. On the other end of the spectrum, when the v_e/u <1, the release is ground level and no plume rise occurs. Two intermediate cases were also developed from field studies. These are the partially entrained and the partially elevated cases and are expressed in terms of an entrainment coefficient, E_t. The entrainment coefficient is defined as the fraction of the plume entrained in the wake and cavity of the building.

Partially Entrained: For cases where the $1.5 \le v_e/u < 5$, a portion of the plume is entrained and the remainder of the plume remains elevated. The entrainment coefficient for this case is:

$$E_t = 0.30 - 0.06v_e/u \tag{A-17}$$

Partially Elevated: For cases where the $1 \le v_e/u < 1.5$, the entrainment coefficient is:

$$E_t = 2.58 - 1.58v_e/u \tag{A-18}$$

In both of these cases, the elevated portion of the plume is subject to plume rise, while the entrained portion of the plume is downwashed to ground level. Building wake effects are discussed in more detail in a later section.

A-1.5.9 BUOYANCY RISE

Buoyancy effects usually arise if significant sensible heat is contained in the cloud being released. For nonreactor DOE facilities, the primary sources of these cloud types are through postulated explosion or fire events. The estimation of the buoyancy component requires knowledge of the effluent and ambient temperatures at the point of release. If the effluent temperature is higher, positive (i.e., upward) buoyancy occurs, while for a cold or dense cloud, negative buoyancy will occur. The latter condition is normally associated with certain types of chemical releases, more so than for radiological releases. The stability class of the atmosphere is also very important, as it affects the magnitude of the buoyancy plume rise.

Buoyancy rise is usually calculated in two steps. The first is the initial rise and is dependent on the stability class. The second is the gradual rise and is independent of stability class. The larger of the two is then selected as representative.

Initial Plume Rise: For stability classes A – D, and buoyancy fluxes less than 55 m^4/s^3, the plume rise is given by (Briggs 1971)

$$\Delta h = 21.425\, F_b^{\,3/4}\, u^{-1} \qquad \text{(A-19a)}$$

where F_b is the buoyancy flux

$$F_b = g\, Q_h / (\pi\, C_p\, \rho_a\, T_a) \qquad \text{(A-19b)}$$

with units of [m^4/s^3]. In this equation, g is the gravitational acceleration, C_p is the specific heat of the effluent gases, ρ_a is the density of air, and T_a is the ambient air temperature.

For fluxes greater than 55 m^4/s^3, the plume rise is given by

$$\Delta h = 38.71\, F_b^{\,3/5}\, u^{-1} \qquad \text{(A-20)}$$

For stability classes E - G, the plume rise is given by (Randerson 1984)

$$\Delta h = 2.6\ [F_b / (u\, S)]^{\,1/3} \qquad \text{(A-21)}$$

In calm conditions, a better approximation is provided by

$$\Delta h = 4\ F_b^{\,1/4}\, S^{3/8} \qquad \text{(A-22)}$$

In these last two equations, S is a stability parameter with units of inverse time squared (t^{-2}).

Gradual Plume Rise: The second portion of plume rise, gradual plume rise, is applicable to unstable to neutral conditions and can be calculated from

$$\Delta h = 1.6\, F_b^{\,1/3}\, x^{2/3}\, u^{-1} \qquad \text{(A-23)}$$

The buoyancy flux from a fire is $F_b = 8.79\times10^{-6}\ \Omega$, where Ω is the rate of release of sensible energy in watts (W).

Another model is that from Mills (1987). It is based on an area (pool) fire and is more correct for facility accident analysis where the assumed fire has compromised or breached an area in the facility. The Mills method adjusts the Briggs effective release height to a lower value using

$$H_{Mills} = \{ (H_{Briggs})^3 + (R/\gamma)^3 \}^{1/3} - R/\gamma \tag{A-24}$$

where

H_{Briggs} = effective release height estimated with the Briggs approach (equation A-19)

R = radius of burning pool

G = entrainment coefficient for buoyant plume rise.

An area or full facility fire event would fall in this category.

Several significant issues exist in modeling a fire event in accident analysis and the ensuing release into the environment. These include

- Sensible heat released
- Fire plume history
- Radiological material involvement in the fire.

Sensible heat – The fraction of the heat of combustion that is not radiated is available to cause a temperature increase in the air and other gases emitted in the plume. This energy is the sensible heat that acts to effectively increase the height of release. The radiated fraction can vary with the nature of the fire, but a typical value is 0.3 – 0.4, implying a sensible heat release of 0.6 - 0.7 of the total heat released. However, for indoor fires in complex facilities, the fraction can vary with the heat being radiated to structures (walls and ceilings) becoming available for heating of air. On the other hand, plumes released into a facility tend to be cooled before escaping the structure and therefore not be as buoyant as if released outdoors.

Fire plume history – Another uncertainty that exists is the temporal nature of the fire. For the same amount of radiological material released, short duration fires will lead to larger dose than longer fires due to less crosswind meander.

Radiological material involvement – Depending on facility type and location of radiological hazards with respect to the combustible loading, the fire may have a radiological component that is evenly distributed in time, localized to certain intervals, or some combination. The radioactive release history may not match up in time with the sensible heat release.

Thus, fires represent complex phenomenology that can demand an inordinate level of precision relative to the purpose of accident analysis. While MACCS and other codes allow use of an effective height model based on sensible heat released, the uncertainties in fire duration, sensible heat, and radiological material involvement introduce a significant burden to the analyst to defend. The outcome of an even a successful defense to this level of detail may be difficult to interpret against the requirements of the accident analysis process.

Recommendation(s):

External (outdoor) fires: Determine the sensible heat fraction for well-defined fires. Credit only sensible heat fraction for the thermal buoyancy effect. Assume shortest duration consistent with fire sequence definition.

Internal (indoor fires): Assume no sensible heat release for release to environment. Assume shortest duration consistent with fire sequence definition.

If the ST analysis can defend the amount of sensible energy, the temporal history, and the spatial distribution, then this phenomenon may be modeled in the consequence analysis. If this cannot be defended adequately, then the ST from fire should be estimated using recommended five-factor methodology, and the consequent environmental model should assume a short duration fire, occurring as a ground-level release.

A-1.5.10 BUILDING WAKE EFFECTS

As shown in an earlier section, releases from vents and small stacks can be entrained behind a building into its cavity due to the aerodynamic effect of the building on the wind field in which the release occurs. Figure A-3 depicts the wake and cavity zones downwind of a nuclear facility. The downwind direction is x, the facility height is H_B, and A_B is the projected cross-sectional area of the building most influencing the flow of the plume. For most bounding, screening purposes, A_B may be assumed the surface area of the largest wall of the building nearest the receptor. To a first approximation, the extent of the cavity zone may be taken to be approximately a downwind distance of 2.5 $A_B^{0.5}$. Similarly, the wake zone may extend to roughly ten times $A_B^{0.5}$.

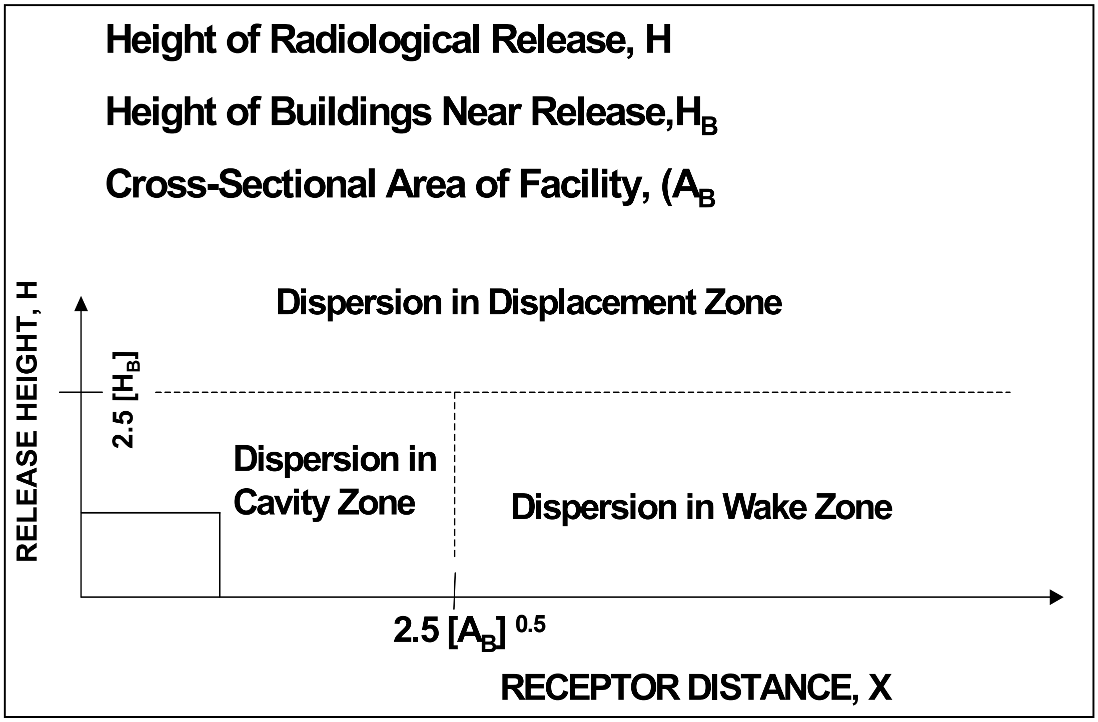

Figure A-2. Cavity and Wake Zones downwind of a Building Structure (Constant Wind Direction from Left to Right).

In order to account for aerodynamic effects of the building, the ground level dilution factor equation is modified as

$$\chi/Q = (u\,[\pi\,\sigma_y\,\sigma_z + c\,A])^{-1} \tag{A-25}$$

where *c* is the building shape factor, usually taken to be 0.5, *A* is the smallest cross-sectional area of the building, *u* is the wind speed at 10-meter height, and the σ_z is corrected for the wake effect.

This formulation is to be applied in the context of NRC Regulatory Guide 1.145 for non-stack releases, e.g., vent and other building penetrations (NRC 1983). Building wake effects tend to be appreciable under windy conditions, while the plume meander effects (discussed earlier) are more likely under light wind conditions.

An approximate form for the wake zone concentration of airborne release from a "squat" (length and width are > height) facility, up to a receptor distance of 10 building heights (10 H_B) is given by Turner (1970),

$$\chi/Q \approx 1/(u\,\pi\,\sigma'_y\,\sigma'_z) \tag{A-26}$$

where

$$\sigma'_y \;=\; 0.35\,h_w + 0.067(x - 3\,H_B),$$

$$\sigma'_z = 0.70\, h_w + 0.067(x - 3\, H_B),$$
$$h_w = 0.866\, [(Facility\ Length)^2 + (Facility\ Width)^2]^{½}.$$

The dispersion parameters for this condition are those found in EPA (1995b). The distance, x, is measured from the facility center.

For screening purposes, several empirical formulas are available for the cavity and wake zone concentrations. A suggested set is found in National Commission on Radiological Protection (1996).

A-1.5.11 EXTREME WEATHER CONDITIONS

Section A.3 of Appendix A to DOE-STD-3009-94, CN2, indicates, "For accident phenomena defined by weather extremes, actual meteorological conditions associated with the phenomena may be used for comparison to the EG." A common weather extreme that is frequently addressed in many DSAs is that due to tornadoes.

The accident analysis should at minimum consider two periods for subsequent exposure evaluation: (1) that due to meteorological conditions from the tornado impact or strike itself; and (2) a second, more prolonged period after the tornado. The latter period would account for aerodynamic re-entrainment and resuspension acting to transport radiological material from the facility into the environment. The first period would be modeled with a design basis accident dilution factor (Ψ/Q, similar to χ/Q) designated for a specific class tornado and applied for the distance from the facility to the receptor. The second period is modeled using a standard consequence model for an exposure period of no longer than eight hours, to be consistent with the time period specification discussed in Appendix A to DOE-STD-3009-94, CN2.

For the initial strike period, the appropriate Fujita scale should be applied. For most safety analyses, this is either Fujita-2 (F2) or F3. Figure A-2 shows the maximum time-integrated ground-level centerline air concentration (s/m^3) vs. downwind distance (km) for different mean translational speeds of the F2 tornado (Weber and Hunter, 1996). The consequence analysis should pick a maximum Ψ/Q for the assumed translational speed. For example, the translational speed of 7.5 m/s leads to a maximum air concentration at approximately three kilometers downwind. This exposure should be added to that obtained for that distance using the standard 95th percentile methodology to estimate the full exposure due to the event. It is possible that the standard 95th percentile methodology at the site boundary may yield a larger dose than the total dose at the maximum Ψ/Q, in which case the MOI would be considered to be at the site boundary.

Another extreme weather condition is high straight-line winds, which are not rare at some sites. High winds correspond to a stability class of D, which is the same class that occurs for median (or "typical") conditions. In this case, the χ/Q value can be scaled from the median conditions by taking ratios of wind speeds for the two conditions, as χ/Q is inversely proportional to wind speed. For example, if median conditions correspond to a wind speed of 4.5 m/s (which is common) and the high straight-line wind speed is 45 m/s (about 100 mph), the resultant χ/Q would be 10% of the median value.

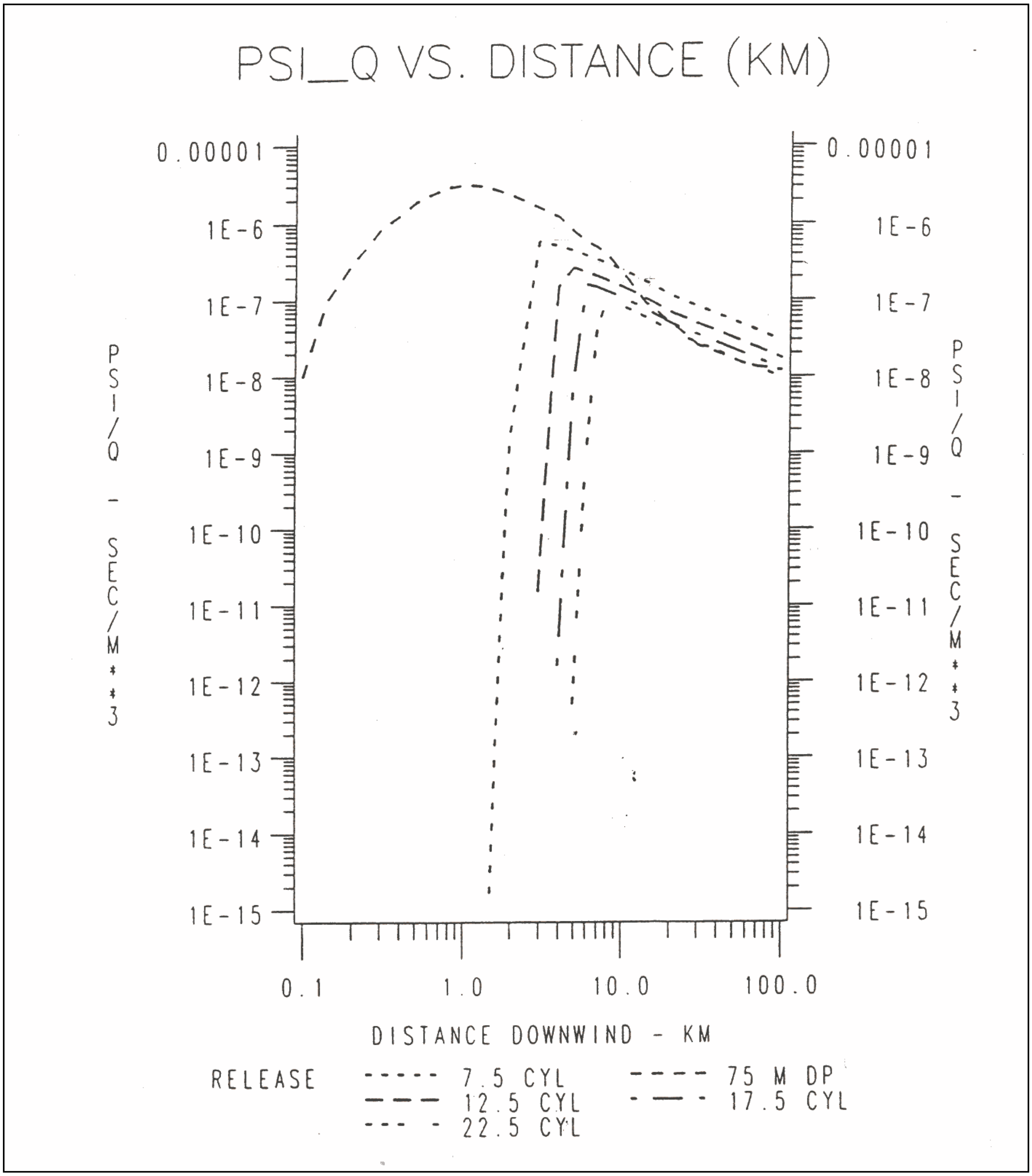

Figure A-3. The maximum time-integrated ground-level centerline air concentration (s/m^3) versus downwind distance (km) for tornado mean translational speeds from 7.5m/s to 22.5 m/s. The downdraft speed is 10 m/s and the height of the cylindrical mesocyclone is 3,500 m (from Weber and Hunter, 1996).

A-2 RADIOLOGICAL CONSEQUENCES

This section provides guidance to the safety analyst regarding evaluation of radiological doses and health risks. It discusses the different types of radiation and the effect radiation can have on the human body, its organs, and its tissues. The factors that must be considered in estimating the dose a receptor may receive following the atmospheric release of radioactive material are covered in detail. Finally, the health risks associated with radiological doses and the standards for radiation protection, in terms of allowed dose or air concentration, are discussed.

A-2.1 TYPES OF RADIOLOGICAL EXPOSURES

Radiological doses can arise from exposure to clouds of radioactive material and fallout from the cloud, and from exposure to prompt (direct) radiation from a criticality. The modes of exposure include:

- Inhalation of radioactive material (particulates and gases) in a cloud
- Inhalation of particulates from fallout that have been resuspended by traffic or by wind
- Ingestion of food products and water contaminated by fallout from the cloud
- Gamma radiation from the plume (cloudshine)[12]
- Gamma radiation from particulates deposited on the ground from fallout (groundshine)
- Skin contamination from fallout
- Prompt (direct) radiation from a criticality

Of especial concern to many DOE non-reactor facilities are inadvertent criticality events and exposure to actinide particulates. In the case of a criticality, doses arise from both the plume of fission products that may be released and from the prompt radiation. The primary contributor to dose from a criticality plume is cloudshine, although actinide particulates can also be important for an unfiltered release. Prompt radiation from a criticality is of concern only for workers located near the accident site. The distance of concern for prompt radiation depends upon the size of the criticality (number of fissions) and the amount of shielding (as from concrete walls) between the worker and the site of the criticality. On the other hand, for actinide exposure, inhalation of plutonium particulates is the primary radiological concern; cloudshine, groundshine, skin contamination, and ingestion doses are insignificant in comparison (Peterson, 1993). Inhalation of enriched uranium particulates is of lesser concern and inhalation of depleted

[12] Cloudshine also may contain a contribution from beta radiation and its attendant *bremsstrahlung* (discussed below), but this is normally minor compared to the gamma radiation.

uranium particulates are trivial by comparison (Peterson, 1995). For uranium, chemical toxicity is normally of greater concern than is the radioactivity.

A-2.2 TYPES OF RADIATION

Four types of radiation are important in accident analysis for DOE nuclear facilities: alpha (α), beta (β), gamma (γ), and neutron. The α, β, and γ radiations are emitted from atomic nuclei during radioactive disintegration (or decay) of the nucleus. The neutron radiation is emitted when a nucleus fissions (breaks into fragments), such as during an inadvertent criticality[13]. Alpha particles are energetic (fast-moving) helium nuclei – consisting of two protons, with a charge of +2[14], and two neutrons (no charge). Beta particles are energetic electrons, of charge -1, or positrons, of charge +1. They have a mass about 0.01% that of the alpha particle. Gamma radiation consists electromagnetic waves, or photons. Gamma rays have energy similar to that of X-rays, and, being photons, have neither charge nor mass. Gamma radiation typically accompanies alpha and beta radiation. Neutron radiation consists of energetic neutrons. Neutrons are particles with zero charge and mass similar to that of protons, that is, about 25% of the mass of alpha particles. When radiation strikes an organ or tissue of the body, they can deposit some or all of their energy, causing damage. The manner of energy deposition varies with the type of radiation. Some types of radiation, principally alpha and beta, deposit energy primarily by ionization. Upon striking an atom, an electron is stripped off, and the atom is said to be ionized. The two charged particles thus formed – the electron and the ion – are referred to as an ion-pair. The electron that is stripped off the atom may be sufficiently energetic that it can cause further ionization. The amount of ionization created depends upon the mass, charge, and energy of the particle. Particulate radiation (α, β, and neutron) can also deposit their energy through the dissociation of molecules and through elastic scattering, which causes heating.

Alpha-decay energy is typically on the order of several MeV (mega-electron volts)[15]. For example, plutonium, uranium, and americium all emit alpha particles with energies on the order of 5 MeV. Because an alpha particle is doubly charged and massive, it can ionize many atoms that it may encounter. For example, an alpha particle traveling through air will create on the order of 50,000 ion pairs for each centimeter it travels. Because it creates so much ionization, it deposits its energy quickly, and penetrates only a short distance into a tissue.

---

[13] Neutrons can also be produced through (α,n) reactions, in which an alpha particle strikes the nucleus of an atom, causing the emission of a neutron. This is generally not important for dose calculations as the additional dose from the neutron radiation is balanced by the decreased dose from the lost alpha particle.

[14] The basic unit of charge is that of the electron, but with a reversal of sign. The charge of an electron is -1.60×10^{-19} coulomb.

[15] An electron volt is the kinetic energy of an electron after being accelerated through an electric potential difference of one volt. It is equal to 1.60×10^{-19} joule.

Beta-decay energy is typically on the order of tens of keV to a few MeV. For example, the beta-decay energy of ^{241}Pu is 21 keV. During beta decay, the emitted electron (or positron) is accompanied by a neutrino (or anti-neutrino), with which is shares the energy. The beta-decay energy is the sum of the energies of the electron and neutrino. Thus, for ^{241}Pu, the maximum energy the electron can have is 21 keV; normally, it will have only approximately 1/3 of this. Because the beta particle is singly charged and not very massive, it cannot create nearly the amount of ionization as can an alpha particle. For example, a beta particle traveling through air will create on the order of 100 ion pairs for each centimeter it travels. In addition to causing ionization, beta particles also can be scattered elastically by atomic electrons. Because a beta particle doesn't lose its energy as rapidly as does an alpha particle, and because of elastic scattering, it can penetrate more deeply into tissue. However, it travels an irregular path in tissue because of elastic scattering. This gives rise to the emission of electromagnetic radiation called *bremsstrahlung* (German for "braking radiation"), which in turn can deposit its energy in the surrounding tissue.

The energy of a gamma ray is typically on the order of tens of keV to a few MeV. For example, the energy of one of the (several possible) gamma rays that accompanies the alpha decay of ^{239}Pu is 52 keV. A gamma photon will typically create only about one ion-pair per centimeter in air. A gamma photon can also lose its energy through Compton scattering from electrons and even from interactions with the nucleus of an atom, although the latter are minor in comparison with photoionization and Compton scattering. Gamma radiation is capable of penetrating deeply into the human body.

The energy of a fission neutron is typically on the order of a few keV to about 10 MeV. Because the neutron has no charge, it will not create many ion-pairs. It loses it energy primarily through elastic scattering. However, it can also cause nuclear transformations, especially when it has slowed (through elastic scattering) and become a "thermal" neutron. These nuclear transformations can lead to the emission of other radiation, such as α and γ. Neutron absorption through nuclear transformation is primarily by hydrogen and nitrogen in the body. Elastic scattering of neutrons is primarily by the hydrogen in the body. Like gamma radiation, neutron radiation is very penetrating.

A-2.3 RADIOACTIVITY

The *Système International d'Unités* (SI) unit of radioactivity, or simply *activity*, is the *becquerel* (*Bq*). It is equal to one disintegration per second (dps). The more commonly used, or traditional, unit of activity is the *curie* (*Ci*), and is equal to

$$1\ Ci = 3.7 \times 10^{10}\ Bq \qquad \text{(A-27a)}$$

This unit was derived from the activity of radium. The activity of one gram of ^{226}Ra was originally defined as one *Ci*. (Modern measurements, however, show that the activity of one gram of ^{226}Ra is slightly less than one *Ci*.) Conversely,

$$1\ Bq = 2.7 \times 10^{-11}\ Ci \qquad \text{(A-27b)}$$

The activity per unit mass is called *specific activity* and is measured in units such as *Bq/k*g or *Ci/g*. Thus, the specific activity of ^{226}Ra was originally defined as one *Ci/g*. The specific activity of a mixture of radionuclides is the sum, over all the radionuclides in the mixture, of the products of specific activities and mass fractions.

The activity of a sample of any given radionuclide decreases exponentially with time, providing it is not being created by the decay of another radionuclide. If N is the number of atoms of a specific type of radionuclide in a sample of material, the change in this number, dN, in a small interval of time, dt, is proportional to N and to dt. This is written

$$dN = -\lambda\, N\, dt \qquad \text{(A-28)}$$

where the negative sign is needed to show that N decreases with increasing time. The constant of proportionality, λ, is called the decay (or transformation) constant and is measured in inverse time units, such as s^{-1}. The disintegration rate, or activity (A), is given by

$$A = -dN / dt = \lambda\, N \qquad \text{(A-29)}$$

The solution to equation (A-28) is

$$N = N_0\, e^{-\lambda t} \qquad \text{(A-30)}$$

where N_0 is the number of atoms at time $t = 0$. Thus, equation (30) can be written

$$A = A_0\, e^{-\lambda t} \qquad \text{(A-31)}$$

where $A_0 = \lambda\, N_0$ is the activity at time $t=0$.

Because the decay is exponential, the time interval to decrease the number of atoms in a sample by a given factor is a constant. For example, the time to decrease by a factor of two, called the half-life ($t_{½}$), is obtained by inverting equation (A-30):

$$t_{½} = -\,(1/\lambda)\, \ln\,(\,½\, N_0 / N_0) = (1/\lambda)\, \ln\,(\,2\,) = 0.693 / \lambda \qquad \text{(A-32)}$$

The half-life of ^{239}Pu, for example, is 2.44×10^4 years and that of ^{235}U is 7.1×10^8 years. The specific activity of ^{235}U is therefore about 3×10^4 times smaller than that of ^{239}Pu, which is the reason it doesn't present as great a radiological hazard as ^{239}Pu for a given amount of material.

A-2.4 EFFECTS OF RADIATION ON THE BODY

Radiation damages the body as it deposits its energy (primarily through ionization) in organs and tissues. Because alpha radiation can be stopped by the body's epithelium (outer layer of dead skin cells), it poses no external hazard to the body; rather, its hazard is through inhalation and ingestion. Beta radiation can penetrate the skin (barely) to cause some damage; beta radiation can also damage the eye. Like alpha radiation, its damage comes principally from inhalation and ingestion, although less so than from alpha radiation. Gamma radiation and neutrons, on the other hand, cause damage as they penetrate the body directly from external sources. Material that emits gamma radiation and neutrons can, of course, be inhaled or ingested, but this is not the normal mode of exposure. Skin contamination from fallout causes tissue damage principally from β radiation.

Both short-term and long-term exposures are important. External radiation (from cloudshine, groundshine, skin contamination, or prompt radiation) typically gives a short-term, or even instantaneous dose, whereas internal radiation (from inhalation and ingestion) gives a long-term (committed) dose. A long-term dose can also arise from continual exposure to external radiation, as in a work place. If a radioactive particle is inhaled or ingested, it will cause damage as long as it remains in the body, because it contains many radioactive atoms that continue to disintegrate. If an organ or tissue is irradiated for an extended time, it can develop cancer or suffer other deleterious effects.

A-2.5 DOSE EVALUATION

The effects of exposure to ionizing radiation were originally defined in terms of the amount of ionization in air produced by gamma radiation and X-rays. The unit used was the *Roentgen* (*R*), now defined as the ratio $\Delta Q/\Delta m$, where ΔQ is the sum of all charges of one sign produced in air when all the electrons liberated by photons in a mass Δm of air are completely stopped in air. It is equal to 2.58×10^{-4} coulombs produced in one kg of air. This is equivalent to 1.61×10^{15} ion-pairs produced per kg of air or an energy deposited of 87.3 erg per gram of air (Turner, 1986). Absorption of 1 *R* of radiation in tissue corresponds to about 95 ergs per gram of tissue.

Today, dose is expressed as an absorbed dose, i.e., the amount of energy deposited in matter, or as an equivalent dose, a measure of damage done in tissue. The traditional unit of absorbed dose is the *rad* and is defined as 100 ergs absorbed in one gram of material, slightly greater than the *rep*. The newer (*SI*) unit is the *gray* (*Gy*) and is defined as one joule absorbed in one kilogram of material. Thus,

$$1 \text{ Gy} = 100 \text{ rad}$$

This definition applies to any type of radiation absorbed in any type of material.

The dose of most interest in accident analysis is the equivalent dose, as this is a measure of the biological damage. The amount of damage depends upon the type of radiation as well as the amount of energy absorbed. The equivalent dose, H_T, to a particular tissue *(T)* is equal to the absorbed dose, D_T, in that tissue times a radiation-weighting factor, w_R

$$H_T = w_R\, D_T \tag{A-33}$$

where w_R is a measure of the amount of damage done by the radiation.[16] If more than one type of radiation impacts the tissue, H_T is calculated by summing over all radiation types. Table A-4 gives the radiation weight factors (ICRP-60, 1991) for the four radiation types considered here.

[16] The definitions given here are taken from the *1990 Recommendations of the International Commission on Radiological Protection* (ICRP-60, 1991). In earlier recommendations of the ICRP, the terminology was a little different. The following

Table A-4. Radiation Weighting Factors

Type, Energy Range		Radiation Weighting Factor, w_R
Alpha	any energy	20
Beta	any energy	1
Gamma	any energy	1
Neutrons	< 10 keV	5
	10 keV to 100 keV	10
	>100 keV to 2 MeV	20
	>2 MeV to 20 MeV	10
	> 20 MeV	5

The traditional unit for equivalent dose is the *rem* (roentgen-equivalent, man). The newer (*SI*) unit is the sievert (*Sv*). The relation between them is the same as between *gray* and *rad:*

$$1 \text{ Sv} = 100 \text{ rem.}$$

The radiation-weighting factor is related to the stopping power of the material, expressed as *Linear Energy Transfer* (*LET*)

$$LET = dE / dx \tag{A-34}$$

where dE is the average energy locally imparted to the medium by a charged particle traversing the distance dx. Alpha and beta particles have high and low LET, respectively. Gamma radiation, although not a charged particle, is considered equivalent to low LET radiation. Neutrons have a moderate to high LET, depending upon their kinetic energy.

The definition of equivalent dose does not differentiate between short-term and long-term dose, or between external and internal exposure. A related term is committed equivalent dose, which is the predicted dose from internal exposures over the remaining life of the individual, normally taken to be 50 years for adults (such as workers) or 70 years for children (as in the general population); it does not include external exposures. The committed equivalent dose is thus a

---

table gives the old and new terminology. The old terminology is still in use.

Old Terminology	New Terminology
Quality Factor	Radiation Weighting Factor
Dose Equivalent	Equivalent Dose
Committed Dose Equivalent	Committed Equivalent Dose
Effective Dose Equivalent	Effective Dose
Committed Effective Dose Equivalent	Committed Effective Dose

The effective dose is not identical to the effective dose equivalent in that the organ weighting factors are slightly different (Table A-5) and the organs included in "remainder" are different. A similar statement can be made for the differences between committed effective dose and committed effective dose equivalent.

subset of the equivalent dose. This has led to some confusion as it has led some workers to use (incorrectly) equivalent dose exclusively for external radiation, apparently as a counterpoint to committed equivalent dose, which is used exclusively for internal radiation. A new term, total organ dose equivalent, is now used to indicate the sum of the external (short-term) and internal (committed, long-term) doses to *an organ or tissue* (CFR, 1991).

Doses are also calculated for the body as a whole. This is done by summing over all organs the product of an organ weighting factor and the equivalent dose for that organ. This sum is called the effective dose (formerly, the EDE – a term still used). The organ weighting factors represent the fraction of the total health risk resulting from uniform whole-body irradiation that could be attributed to that particular tissue or organ. These factors are between zero and one; their sum over all organs and tissues is one. The weighting factors for the various organs are shown in Table A-5, as taken from ICRP-60 (1991). For comparison, the ICRP-26 (1977) values are also shown, as they are still in use at many sites and laboratories.

Table A-5. Organ Weighting Factors

Organ	Organ Weighting Factor	
	ICRP-26	ICRP-60
Bladder	-	0.05
Bone Marrow (red)	0.12	0.12
Bone Surface (skeleton)	0.03	0.01
Breast	0.15	0.05
Colon	-	0.12
Esophagus	-	0.05
Gonads	0.25	0.20
Liver	-	0.05
Lung	0.12	0.12
Skin	-	0.01
Stomach	-	0.12
Thyroid	0.03	0.05
Remainder	0.30	0.05

A term similar to effective dose is committed effective dose (formerly, the CEDE, a term still used), which is the predicted dose from internal exposures over the remaining life of the individual, normally taken to be 50 years for adults, or 70 years for children. It does not include external exposures. Committed effective dose is thus a subset of effective dose. However, as with equivalent dose *cf.* committed equivalent dose, confusion has arisen in that some workers use (incorrectly) effective dose to refer to only external radiation, because committed effective dose refers only to internal radiation. A new term, total effective dose equivalent (TEDE), is now used to indicate the sum of the external (short-term) and the internal (committed, long-term) effective doses (CFR, 1991).

A-2.5.1 TYPES OF DOSE

Doses arise from both internal and external exposures, as noted above. The internal exposures consist of inhalation (from the plume and from resuspension) and ingestion. The external exposures are from cloudshine, groundshine, skin deposition, and direct (prompt) radiation from a criticality. These are discussed individually below. See the discussion earlier in this appendix for the calculation of the amount of material that falls out from a plume; this is important for the discussions of resuspension, ingestion, groundshine, and skin deposition.

A-2.5.2 UPTAKE THROUGH INHALATION

Inhalation dose from a cloud to a given organ or tissue from a given isotope (i) is the product of the amount of respirable radioactive material released (M_i), atmospheric dispersion factor (χ/Q), breathing rate (BR), and dose conversion factor (DCF_i)

$$Dose_i = M_i \times \chi/Q \times BR \times DCF_i \qquad \text{(A-35)}$$

assuming the receptor remains exposed for the duration of the plume. The total dose to the organ or tissue is the sum over all isotopes inhaled. The amount of respirable material released (M_i), called the ST, is the product of the MAR, DR, LPF), ARF, and RF. The breathing rate and dose conversion factors are discussed below and χ/Q was discussed earlier.

A-2.5.3 BREATHING RATE

The breathing rates for the various activities, as have been used in accident analyses for the past several years at many DOE sites, are given in Table A-6 (ICRP-2, 1977 and ICRP-30, 1979-82). The value used in the development of DOE-STD-1027-92 (Change Notice 1) tables is 3.5 x 10^{-4} m^3/s. ICRP-66 (1994) gives revised breathing for the "reference human"[17]. These are also listed in Table A-6. Still other breathing rates are appropriate for other individuals, such as infants, the elderly, and the infirm, and for other levels of activity (ICRP-66, 1994). The analyst needs to choose which breathing rate is appropriate for the scenario being evaluated, taking into account the possible need to be consistent with earlier analyses.

Recommendation: Based on the DOE (1998) directive, it is advised to apply the breathing rate of 3.33 x 10^{-4} m^3/s in dose calculations for DSAs.

---

[17] The reference human is male, 30 years old, height 176 cm (5 feet, 9 inches), and weight 73 kg (161 lb).

Table A-6. "Reference Human" Breathing Rates for Various Levels of Activity

Activity Level	Breathing Rate (m^3/s)
ICRP-2, ICPR-30, DOE 1998	
Chronic	2.66×10^{-4}
Light	3.33×10^{-4}
Heavy	3.47×10^{-4}
ICRP-66	
Sleep	1.25×10^{-4}
Rest, sitting	1.50×10^{-4}
Light exercise	4.17×10^{-4}
Heavy exercise	8.33×10^{-4}

A-2.5.4 BIOKINETIC MODEL AND DOSE CONVERSION FACTORS

Once radioactive material enters the lungs, it begins to migrate to other parts of the body. A portion is transferred directly to the blood and another portion to the stomach. Transfer of the material directly from the lungs into the blood depends upon where in the lungs it is deposited and how soluble it is. Material is also cleared from the lungs by means of the body's mucociliary mechanism and then swallowed, thus entering the gastro-intestinal (GI) tract. The fraction (f_1) of the material that passes from the GI tract into the blood (primarily from the small intestine) depends the solubility of the material. For some radionuclides, such as iodine, the transfer to the blood is nearly complete ($f_1 = 1.0$). For others, such as plutonium, the portion transferred to the blood is much less than 1%; the remainder is excreted. Once the material enters the blood, it can be carried to any part of the body. From there, it may preferentially target a given organ or tissue, as determined by the chemical properties of the radioactive material and the nature of the organ or tissue. For example, plutonium and americium become preferentially attached to bone surface (LANL, 1995), and tritium ultimately mixes uniformly with all tissues and organs.

The residence time of a radioactive particle in the lungs depends in part upon the solubility of the material. Three broad categories have been defined, and specify a characteristic half-time for inhaled material to clear from the pulmonary region of the lung to the blood and the gastrointestinal tract (Eckerman, 1988):

- Y: Radionuclides in insoluble compounds typically remain in the lungs for a long time; these are of Solubility Class Y (for years), also called Lung Clearance Class Y.
- W: Radionuclides in moderately soluble compounds remain in the lungs for weeks; these are of Solubility Class W (for weeks), also called Lung Clearance Class W.

- D: Radionuclides in soluble compounds remain in the lungs for only a short time; these are of Solubility Class D (for days), also called Lung Clearance Class D.

According to Federal Guidance Report #11 (EPA, 1988), plutonium compounds can be Class Y (the oxides[18]) or Class W (all other Pu compounds). There are no Class D Pu compounds. Americium compounds are only Class W. Uranium compounds can be Class Y (UO_2 and U_3O_8), Class W (UO_3, UF_4, and UCl_4), or Class D (UF_6, UO_2F_2, and $UO_2(NO_3)_2$). Fission products are of all three classes. Should these compounds be involved in a fire, their chemical nature may change. For example, a plutonium salt (as in certain residues), which is class W, may change to an oxide (class Y) in a fire. However, such conversion will probably not be complete. To be conservative, it is best to assume that the resultant chemical form is the one that gives the largest dose; in the case of plutonium salts, for example, it is conservative to assume they remain class W.

In ICRP Publication 60, the lung clearance class term was dropped in favor of the term lung absorption type. Absorption types fast (F), medium (M), and slow (S) broadly correspond to older lung clearance classes of D, W, and Y (ICRP, 1990).

A-2.5.5 DOSE CONVERSION FACTORS

The amount of biological damage that radioactive material may inflict on an organ or tissue is given by the DCF mentioned above. The DCFs take into account the migration of the radioisotope within the body, the decay of the radioisotope, and the formation of daughter isotopes that may be radioactive. For inhalation, this is typically expressed in units of Sv/Bq (or rem/Ci). This can be converted to Sv/g (or rem/g) by multiplying by the specific activity.

The older system of DCFs for a large number of radionuclides is given in Federal Guidance Report #11 (EPA, 1988). FGR 11 contains DCFs based on weighting factors from ICRP 26 (ICRP, 1977 and organ/tissue models documented in ICRP 30 and 48 (ICRP, 1979a to 1982c, and ICRP, 1986). The DCF values in FGR 11 are based on exposure to an adult worker and a particle size of 1.0 μm Activity Median Aerodynamic Diameter (AMAD).[19] The values are applied uniformly for all ages in the general public population and all release conditions.

ICRP Publication 68 provides updated dosimetry for radiation workers, while ICRP 72 covers the general public. Both include age specific models and parameters (ICRP, 1995). The DCFs contained in these reports are based on ICRP 1990 Recommendation on radiation protection standards in Publication 60 (ICRP, 1991a) and as well as the revised kinetic and dosimetric model of the respiratory tract in Publication 66 (ICRP, 1994). The inhalation DCFs in ICRP

---

[18] Plutonium hydroxides have subsequently been added to Class Y.

[19] The AMAD signifies that fifty percent of the activity in the aerosol is associated with particles of aerodynamic diameter greater than the AMAD.

Publication 68 are for the CEDE and assume either 1.0 µm or 5.0 µm AMAD particle sizes. The inhalation DCFs in ICRP 72 are only for the CEDE and a 1.0 µm AMAD particle.

A combined data set is now available from the ICRP (1999) that not only provides dosimetric information for both worker and general public populations, but extends the parameter space of the ICRP Publications 68 and 72. The combined data gives inhalation dose coefficients for ten aerosol sizes (0.001 µm to 10 µm AMAD) as well as ingestion coefficients. Effective doses and equivalent doses for all important tissues for a range of integration times (1, 7 and 30 days, 1, 5, 10, 20, 30, and 45 years) are given, together with the dose coefficients to age 70 years.

The Nuclear Regulatory Commission and at least one NRC Agreement State have granted license amendments to allow use of the newer ICRP 68/72 dosimetry. The newer data have been approved for use at least one DOE site.

A-2.5.6 INHALATION (RESUSPENSION)

Dose from resuspension inhalation is primarily of concern after plume passage. The ground concentration (GC_i) of a given isotope (i) under a plume can be calculated by the method discussed earlier, which also discusses resuspension factor (F_r) of this material. The resuspension inhalation dose to a given organ or tissue from this isotope is the product of the ground concentration, resuspension factor, breathing rate, and DCF_i for that organ and radionuclide.

$$Dose_i = GC_i \times F_r \times BR \times DCF_i \tag{A-36}$$

The total dose to the organ or tissue is the sum of the doses from all isotopes resuspended. Correction factors can also be applied, as appropriate, to account for the receptor being off-centerline (if the GC_i was calculated for plume centerline) and for shielding, such as for the receptor being indoors. Off-centerline considerations and shielding are normally of greater importance for resuspension inhalation than for plume inhalation because resuspension takes place over an extended period and the routine activities of the receptors should be taken into account. This is especially important for inhalation doses to the public. The comparative magnitude of the resuspension dose depends on the amount material deposited on the ground from the plume. If the amount is large, the resuspension inhalation dose over a period of days, weeks, or months can be as large as, or even larger than, the direct inhalation dose from the plume. For dry deposition, the size distribution of the particulates released in an accident is important; very small particles have small deposition velocities, leading to small ground concentrations. For wet deposition, particles of all sizes can be washed out by precipitation. If an accidental release of radioactive particulates occurs during a period of rain or snow, the subsequent resuspension inhalation dose will be much larger than it would be otherwise.

It is noted that the guidance in DOE-STD-3009-94, CN2, Appendix A allows the analyst to ignore resuspension.

A-2.5.7 INGESTION

Fallout of particulates from a plume may contaminate water and food supplies. The uptake of radionuclides by plants and animals, and their transfer into the food chain for humans, is a very complex process and beyond the scope of this appendix. Several models have been developed and incorporated into computer models for atmospheric dispersion and consequence assessment. Consumption of contaminated food products is not restricted to persons living near the site of an accidental release, as the food products may transported to another location for processing, and consuming in still another location. The ingestion dose must therefore be calculated separately from the other doses (from inhalation, etc.). It is not to be added to the doses from the other modes of intake unless it is clear that the receptor for the ingestion dose is the same as the receptor for the other modes of intake.

Once the amount of radioactive material ingested has been determined, the dose can be calculated by multiplying this amount by the DCF for ingestion. Tables of ingestion DCFs for a large number of radionuclides are available from both the older FGR 11/12 series as well as the ICRP 72 series. Like the inhalation DCFs, the units of the DCFs are Sv/Bq (or rem/Ci).

For calculations supporting DSA preparation, ingestion is ignored.

A-2.5.8 CLOUDSHINE

The amount of gamma radiation (and beta, if appropriate) received by a receptor from a plume of radioactive material depends upon the location of the receptor relative to the plume. The greatest dose would be received by a receptor in the plume centerline, of course, and dose conversion factors have been developed for such a receptor. The assumptions made in deriving these DCFs are that (1) the plume is uniform and semi-infinite ("semi" because the plume extends upward from the ground, but not downward) and (2) the receptor is standing upright on the ground. The dose received from a given radionuclide is the product of the concentration of the radionuclide and the DCF, integrated over the duration of the plume. The doses from all the radionuclides must then be summed. Cloudshine DCFs are expressed in units of (Sv-m^3)/(Bq-s).

The cloudshine doses calculated using the DCFs from Federal Guidance Report #12 are conservative because of the assumptions that the receptor is standing upright in a uniform, semi-infinite cloud. The plume, of course, is neither uniform nor semi-infinite, the receptor may not be at plume centerline (and the plume may even be elevated), the receptor may be sheltered, and the receptor may not be standing up. Each of these factors would tend to reduce the dose. Corrections for finite cloud size and distribution (Gaussian), and for receptor location off-centerline, are included in several computer models of atmospheric dispersion and consequence assessment. However, for typical MOI dose-to-an-individual calculations supporting DSA preparation, the effect of structural shielding is conservatively not taken into account.

A-2.5.9 GROUNDSHINE

The treatment of groundshine is similar to that of cloudshine. The amount of gamma radiation received by a receptor from radioactive material deposited on the ground (fallout) depends upon the location of receptor relative to the fallout. The greatest dose would be received by a receptor at the center of the fallout, of course, and dose conversion factors have been developed for such a receptor. The assumptions made in deriving groundshine DCFs are that (1) the material is uniformly distributed on the surface or in the soil for an infinite distance in every horizontal direction, and (2) the receptor is standing upright on the ground. The dose received from a given radionuclide is the product of the concentration of the radionuclide on (or in) the ground and the DCF, integrated over the duration of the exposure (i.e., how long the receptor is present to receive groundshine). The groundshine doses from all the radionuclides must then be summed. The concentration to be used in the calculation is either an areal concentration (Bq/m^2), if the material is only on the surface, or a volume concentration (Bq/m^3), if mixed with the soil. Groundshine DCFs are expressed in units of either ($Sv\text{-}m^2$)/(Bq-s) for surface contamination, or ($Sv\text{-}m^3$)/(Bq-s) for soil contaminated down to a specified depth.

Typically, the groundshine doses calculated using these DCFs are conservative because of the assumptions that the receptor is standing upright on a uniformly contaminated, infinite plane. The fallout, of course, is neither uniform nor infinite and the receptor may not be the middle of it. Furthermore, surface irregularities (surface roughness and uneven terrain) tend to shield the receptor, the receptor may be sheltered, and the receptor may be elevated. Each of these factors would tend to reduce the dose. Corrections for finite size and distribution of the fallout pattern, and for receptor location off-centerline, are included in several computer models of atmospheric dispersion and consequence assessment. The safety analyst may also wish to consider additional dose reduction factors associated with sheltering or surface roughness / unevenness.

In calculating groundshine doses, the time variation of the ground concentration at the receptor's location must be considered. In the early stages of plume passage, the ground concentration is increasing, the concentration reaching a peak at the end of plume passage. Resuspension of the particulates then erodes the amount of contamination. The dose received from groundshine therefore must consider not only the exposure duration of the receptor, but also the period during which the exposure is attained. Such considerations are included in several computer models of atmospheric dispersion and consequence assessment.

A-2.5.10 SKIN DEPOSITION

Doses from skin deposition are normally of short duration (a few hours) because of decontamination of the skin. The only radionuclides of importance for skin contamination are the beta emitters. Beta particles can penetrate the surface layer of dead skin cells and damage the cells directly beneath. Experiments show that for beta radiation in the 200 keV to 2 MeV range, the absorbed dose to these cells is about 0.2 rad/s for a surface contamination of 1 Ci/m^2 (Healy, 1984). Because the radiation-weighting factor for beta radiation is one (Table A-4), this equates to a dose rate of 5.4×10^{-14} ($Sv\text{-}m^2$)/(Bq-s). This dose rate must then be integrated over the duration, T, that the material is on the skin prior to decontamination to give the skin DCF

$$DCF_{skin} = 5.4\times10^{-14}\,(1 - e^{-\lambda T})\,/\,\lambda \qquad \text{(A-37)}$$

The dose to the exposed skin from a given beta-emitting isotope (i) for a receptor at (or under) plume centerline is

$$Dose_{i,skin} = AC_i \times V_d \times DCF_{skin} \times F \quad \text{(A-38)}$$

where AC_i is the ground-level air concentration of this isotope, V_d is the deposition velocity to the skin (on the order of 1 cm/s or less, depending upon the particle size distribution), and F is the fraction of the plume duration that the receptor is exposed to the plume. Correction factors need to be applied for a receptor off-centerline or sheltered. The total skin dose will be the sum of the contributions from all the beta-emitters that are deposited on the skin.

A-2.5.11 DIRECT (PROMPT) DOSE

Doses from criticalities arise from both the plume of fission products that may be released and from prompt radiation, i.e., the gamma rays and neutrons that are emitted during the brief (millisecond) energy burst(s) during the criticality spike(s). The doses from the plume of fission products are included in the discussions above and won't be repeated here.

The prompt dose depends only upon the number of fissions in the criticality, the distance to the receptor, and the amount of intervening shielding material, such as concrete. The gamma and neutron doses should be quantified using nuclear engineering principles.

Shielding is expressed in terms of the amount of intervening concrete, or the equivalent if other shielding materials are involved. In the case of gamma radiation, the dose is reduced by a factor of 2.5 for the first eight inches of concrete, a factor of 5.0 for the first foot, and a factor of 5.5 for each additional foot. For neutron radiation, the dose is reduced by a factor of 2.3 for the first eight inches of concrete, a factor of 4.6 for the first foot, and a factor of 20 for each additional foot.

Prompt dose is important for the immediate worker, i.e., one within some tens of meters from the accident, but is rarely important for persons more distant. The dose to a collocated worker at a distance of 100 m is normally small and the dose to the public is negligible.

A-2.6 Health Risks

The discussion in the following sections is added for completeness. DOE-STD-3009-94, CN2 Appendix A requires the calculation of individual doses but not health effects.

Once doses have been calculated, the corresponding health risks can be determined. This is done by multiplying doses by stochastic risk factors. Latent Cancer Fatalities (LCFs) are the health risks of most interest. The term "latent" indicates that the estimated cancer fatalities would occur sometime in the future, within the next 50 years for adult workers, or the next 70 years for the general population, which includes children. One can also calculate latent cancer occurrences (fatal plus non-fatal), genetic effects, etc., but these are not normally evaluated in safety analyses. The stochastic risk factor depends upon the type of radiation and the organ considered.

A-2.6.1 HIGH-LET RADIATION

In the case of alpha emitters, such as Pu and U, the only organs of importance for cancer risk are the lungs, liver, and bone surface (Abrahamson, 1993). The stochastic risk factors for cancer fatalities for these organs are shown in Table A-7. For these three organs, the stochastic risk factors are linear and continuous. Earlier models, based on ICRP-26 (1977), used a linear-quadratic model. The new model, based on ICRP-60 (1991), is linear but may be discontinuous for some radionuclides. The Abrahamson (1993) values (Table A-7) differ from the earlier ones (ICRP-26): the lung factor is about four times larger, the bone skeleton factor is about ten times smaller, and liver is about three times smaller than the earlier values. The values in Table A-7 are for high-LET radiation (alpha particles). Table A-7 does not give the stochastic risk factor for committed effective dose, as the total cancer risk should be calculated as the sum of the individual organ cancer risks [Σ (dose × stochastic factor)]. The other organs of the body do not contribute significantly to cancer risk from exposure to alpha radiation and have been ignored.

Table A-7. Stochastic Risk Factors for Alpha-Emitters (Abrahamson, 1993)

ORGAN	RISK FACTOR *(LCF/rem)*
Bone Surface	6.0×10^{-7}
Lungs	8.0×10^{-5}
Liver	1.5×10^{-5}

Example: Suppose a calculation of committed inhalation doses to a certain receptor from a release of plutonium gives a bone-surface dose of 0.353 rem, a lung dose of 0.112 rem, and a liver dose of 0.0787 rem; the effective dose (whole body) was 0.0351 rem. (The effective dose includes contributions from all organs, not just the three mentioned here.) For this individual, the LCF risk would therefore be $(0.353)(6.0 \times 10^{-7}) + (0.112)(8.0 \times 10^{-5}) + (0.0787)(1.5 \times 10^{-5}) = 1 \times 10^{-5}$ LCF. This means that only one person in 10^5 would die of cancer from this exposure. Note that although the bone dose is larger than the doses to the other organs, the lung dose is more important in terms of cancer risk, as seen in this example.

A-2.6.2 LOW-LET RADIATION

For low-LET radiation (beta and gamma radiation), the latent cancer risk is normally calculated from the committed effective dose, although the individual organ cancer risks could also be summed. ICRP-60 (1991) recommends using a stochastic risk factor of 5×10^{-4} LCF/rem (5×10^{-2} LCF/Sv) for the whole population, or 4×10^{-4} LCF/rem (4×10^{-2} LCF/Sv) for adult workers, based on the committed effective dose. (The factor for the public is higher than for adult workers because the public consists of a mixture of individuals with varying degrees of resistance to hazardous materials, including children, the elderly, and the infirm. This includes the cancer risk to all organs, unlike the treatment of alpha radiation, which considers only the three organs of Table A-7 to be important for cancer risk.) This ICRP-60 recommendation has been adopted by the Environmental Protection Agency for the evaluations of Environmental Assessments (EAs) (NEPA, 1993). Had this factor been used in the above example, the LCF risk to that individual would have been $(0.0351)(5 \times 10^{-4}) = 1.75 \times 10^{-5}$ LCF, or about 75% higher than obtained from using Table A-7 data. This low-LET risk factor is not recommended for alpha-emitters (high LET).

A-2.6.3 ACUTE HEALTH RISKS

Doses received in a short period (acute doses) may cause acute health risks, if large enough. A dose from gamma or neutron radiation, such as from a criticality, is the primary concern here. Table A-8 (adapted from Turner (1986)) summarizes the health effects associated with varying levels of gamma radiation.

Table A-8. Acute Radiation Effects for Gamma Radiation

DOSE (rad)	HEALTH EFFECT
0 -25	No detectable effect
25 - 100	Some biological damage; recovery probable
100 - 300	More damage; recovery probable but not assured
300 – 600	Fatalities occur in about half the population
> 600	Death expected

An acute, whole-body, gamma-ray dose of about 450 – 500 rad would probably be fatal to about half the population within about 30 days. This dose is known as LD_{50}, sometimes called $LD_{50/30}$, where “LD” means Lethal Dose. Because gamma radiation has a radiation-weighting factor of one (Table A-4) the doses in Table A-8 could also have been labeled in rem. Presumably, neutron doses (in rem) would give similar effects.

An acute dose from inhalation of plutonium or uranium, i.e., the dose received in a few hours or days, is normally very small. All of the isotopes of plutonium and uranium have half-lives of many years; therefore, the inhalation dose received by a person during the first few days following an acute exposure via the inhalation pathway will only be a small fraction of the lifetime dose. Accordingly, an acute health effect requires a very large amount of plutonium to be released. For example, in order for a person at a distance of about 2 km from the release site to get a dose large enough to cause pneumonitis (the first prompt health effect to occur), an airborne release of about 100 kg of respirable plutonium would be required (Peterson, 1993). Such a large release is extremely unlikely. Therefore, *acute* health effects need not be considered for releases of plutonium or uranium.

A-2.6.4 RADIATION PROTECTION

Radiation protection of the worker is governed by the As Low As Reasonable Achievable principle. Control of internal exposure to radionuclides is based on the limitation of the sum of current and future doses from annual intake (i.e., the CEDE) rather than of annual dose. If it is found that limits on committed dose have been exceeded for a worker, corrective actions are needed to limit further exposure.

The primary guides for worker annual exposure are 5 rem for effective dose equivalent, 50 rem to individual organs or tissues (except the lens of the eye), and 15 rem to the lens of the eye. Two types of derived guides are used to implement this. These are the Annual Limit on Intake (ALI) and the Derived Air Concentration. The ALI is the annual intake of a radionuclide that would result in a radiation dose to the reference man equal to the relevant primary guide. The Derived Air Concentration is the air concentration of a radionuclide that would result in an intake corresponding to its ALI, if breathed for a work-year (2,000 hours).

The above guidance of comparing the annual exposure limit (primary guide) with the full 50-year (or 70-year) committed effective dose received is found in several DOE and EPA documents. For dose calculations supporting DSAs, the dose should be calculated using the full fifty-year commitment, following conservative health protection and radiological practices. The newer dose conversion factor methodology and biokinetics models as described in ICRP 60, 66, and ICRP 68/72 are recommended. The older FGR guidance can be used as an alternative, should local agreements still support use of the earlier dose conversion data.

APPENDIX B. SOFTWARE DEFECT NOTIFICATIONS

The following statement is on the RSICC web site for GENII 1.485 (March 2003):

> "The potential exists for a limited combination of options: specifically, only for cases of acute, atmospheric release when the "food production grid" input option is used, if "food export" is chosen, and one of the input radionuclides is tritium or carbon-14.
>
> Because tritium and carbon-14 are handled with special specific-activity models, calculations for these two radionuclides do not have the same path through the code logic. If the above combination of options is used, the food production grid is inappropriately applied to H-3 and C-14. The total amount of food input of the full 80-km circle is assumed to be contaminated with these two radionuclides, rather than just that from the selected downwind sector. The estimated dose provided by the GENII 1.485 code is too large by factors of about 10 to 20.
>
> If the user wants to combine these options, a simple input modification can be used to obtain the appropriate answer. If the food production grid file is adjusted so that non-downwind sectors have zero production, and only the sector of interest has input data, the results should be correct.
>
> The developers of GENII 1.485 have no intention at this time of making changes to the code. The code update, GENII Version 2, is scheduled to undergo formal peer review in the immediate future, and will be replacing GENII 1.485 after comment resolution is completed."