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Technical Bases for Consequence Analyses Using MACCS (MELCOR Accident Consequence Code System)

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ABSTRACT

The use of MELCOR Accident Consequence Code System (MACCS) in regulatory applications requires that input parameters used in MACCS models have a defensible and transparent technical basis. The existing technical basis for MACCS parameters was identified and updates were developed based on current data and information. The transparent way these updates are documented provides a technical basis for updating MACCS parameters with consistent application among the MACCS user community.

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EXECUTIVE SUMMARY

This report aims to develop a comprehensive, updated summary of the technical bases for the quantification and application of MELCOR Accident Consequence Code System (MACCS) input parameters. Many MACCS users often begin with input values found in “Sample Problem A,” which was distributed with the MACCS [1] and MACCS2 [2] codes. As noted in the original MACCS user’s guide [1], “it is the responsibility of each MACCS user to ensure the appropriateness of all data in the MACCS input files which they prepare.” The summary of the technical bases for MACCS parameters in this document is intended to assist in the process of selecting appropriate MACCS parameter values. In addition, these technical bases are intended for use in reviews of analyses of the offsite radiological and economic consequences of severe accidents at nuclear facilities.

MACCS may be used for a variety of applications, and the values selected should be appropriate for the application. These values and recommendations in this report should be considered in light of the purpose of the analysis. In some cases, particularly for non-site-specific values, specific quantitative values are recommended as being generally applicable. However, many of the parameter choices are site-specific, scenario-specific, accident-specific, or a combination of these. To accommodate the need to develop an up-to-date, site- and scenario-specific parameter value, suggested processes and data sources (rather than a prescribed value) are provided as appropriate. Suggestions for which MACCS parameters may be considered “standard” (i.e., parameters that should not be changed without very good reason), “generic” (i.e., parameters that are considered reasonable generic values for most U.S. locations), or “user-defined” (i.e., parameters that should in almost all cases be evaluated and developed by the user) are provided in Appendix C.

A review was performed to identify appropriate data sources. The technical bases in WASH-1400 [3] and NUREG-1150 [4], [5] were reviewed. In addition, more recent data compilations were reviewed as potential sources of updated information. These include a series of expert elicitations conducted jointly by the U.S. Nuclear Regulatory Commission (NRC) and Commission of European Communities (CEC) in the 1990s (e.g., [6], [7]); uncertainty and sensitivity analyses conducted after NUREG-1150 (e.g., [8], [9]); MACCS parameter guidance for U.S. Department of Energy (DOE) applications [10]; and guidance for dose estimation (e.g., [11] [12]) were reviewed as potential sources of updated information. Updated recommendations developed during the State-of-the-Art Reactor Consequence Analyses (SOARCA) project (e.g., [13] [14], [15]), were also reviewed, as were the recommendations of the peer review committee that examined the SOARCA MACCS methodology [16]. Finally, additional data and information sources, such as journal articles, technical reports, and online repositories from recognized sources (e.g., U.S. census data) were also considered on a parameter specific basis. For some MACCS parameters related to protective measures and decontamination, Sandia National Laboratories (SNL) staff performed original research to develop this document. The results of that work are included in Appendices A and B.

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ABBREVIATIONS AND ACRONYMS

°	degree symbol
ARANO	Assessment of Risks of Accidents and Normal Operation
ANS	American Nuclear Society
ASME	American Society of Mechanical Engineers
AT	annual threshold
AWI	Average Wage Index
BLS	U.S. Bureau of Labor Statistics
Bq	becquerel
BRAA	Activity-Averaged Breathing Rate
BWR	boiling water reactor
°C	degrees Celsius
CAC	Codex Alimentarius Commission
CEC	Commission of the European Communities
cm	centimeter
COCO-1	Cost of Consequences Offsite model
COMIDA2	MACCS food chain preprocessor model
CONUS	Conterminous United States
COSYMA	Code System from MARIA
CPI	consumer price index
CRAC	Calculation of Reactor Accident Consequences
CY	cubic yard
DCF	dose conversion factor
DDREFA	dose and dose-rate effectiveness factor
DF	decontamination factor
DOE	U.S. Department of Energy
EAB	exclusion area boundary
EAL	emergency action level
EAS	emergency alert system
EDi	Environmental Dimensions Inc.
EPA	U.S. Environmental Protection Agency
EPZ	emergency planning zone
ETE	evacuation time estimate
FDA	Food and Drug Administration
FGR	Federal Guidance Report
FRMAC	Federal Radiological Monitoring and Assessment Center

GDP	gross domestic product
GE	general emergency
GSA	General Services Administration
GUI	graphical user interface
Gy-eq	Gray-equivalent
hr	hour
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiation Protection
IRS	U.S. Internal Revenue Service
ITRC	Interstate Technology and Regulatory Council
J	joules
JAEA	Japan Atomic Energy Association
K	degrees Kelvin
kg	kilogram
KI	potassium iodide
Km	kilometers
L	liter
lb	pound
LET	linear energy transfer
lf	linear foot
LLW	low-level waste
LWR	light-water reactor
m	meter
MACCS	MELCOR Accident Consequence Code System
MARSSIM	Multi-Agency Radiation Survey and Site Investigation Manual
MECA	Model for Economic Consequence Assessment
MeV	million electron volts
mi	mile
mm	milimeter
MOX	mixed oxide
MWd/kg	megawatt-day per kilogram
MW _{th}	megawatt thermal
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
OCONUS	Outside of Conterminous United States
OECD	Organisation for Economic Co-operation and Development
ORO	offsite response organization

PAG	protective action guide
PG	Pasquill-Gifford
PHE	Public Health England
PPE	personal protective equipment
PRA	probabilistic risk assessment
PWR	pressurized-water reactor
RBE	relative biological effectiveness
s	second
SAE	site area emergency
SCRAM	Support Center for Regulatory Atmospheric Modeling
SDA	Special Decontamination Area
SecPop	Sector Population and Economic Estimator
SNL	Sandia National Laboratories
SOARCA	State-of-the-Art Reactor Consequence Analysis
SSA	Social Security Administration
Sv	Sievert
SY	square yard
TED	total effective dose
USDA	U.S. Department of Agriculture
W	watt

1 INTRODUCTION

The MELCOR Accident Consequence Code System (MACCS) is used to perform probabilistic health and economic consequence assessments. Atmospheric dispersion and transport, wet and dry deposition, probabilistic treatment of meteorology, environmental transfer, countermeasure strategies, dosimetry, health effects, and economic impacts are addressed in the code. MACCS is used by U.S. nuclear power plant (NPP) license renewal applicants to support the plant specific evaluation of severe accident mitigation alternatives as part of the applicant's environmental report for license renewal. MACCS is also used in severe accident mitigation design alternative analyses and severe accident consequence analyses for environmental impact statements and environmental assessments for new reactor applications. The U.S. Nuclear Regulatory Commission (NRC) uses MACCS in its cost-benefit assessments supporting regulatory analyses that evaluate potential new regulatory requirements for reactors. NRC regulatory analysis guidelines recommend the use of MACCS to estimate the averted "offsite property damage" cost (benefit) and the averted offsite dose cost elements [17], [18]. A predecessor to the current version of MACCS informed NRC's requirement for a 10-mile plume-exposure-pathway emergency planning zone (EPZ). MACCS was also used in NRC's State-of-the-Art Reactor Consequence Analysis (SOARCA) project. This update supports these regulatory and research applications with updates and guidance that facilitate consistent application among MACCS users. The MACCS code has been updated over the years and was called MACCS2 for a time but given its nature with frequent updates and improvements, it is now simply called MACCS. The version used to develop this document is MACCS 3.10, which was released in March 2015.

Designed primarily as a PRA tool, MACCS can sample annual weather data and generate consequence statistics that describe the effects of weather variability at the time of a hypothetical release. MACCS can calculate consequences such as land contamination, doses to individuals and populations, numbers of health effects and individual risks, and economic losses resulting from hypothetical accidents. NPP accident property damage and cost-benefit determinations are conducted within regulatory analyses, backfit analyses, and environmental analyses [19]. MACCS is used to estimate offsite health effects and costs for these cost-benefit determinations. The treatment of offsite costs is discussed in NUREG/BR-0058, "Regulatory Analysis Guidelines of the U.S. Nuclear Regulatory Commission" [17], which describes attributes to be considered when performing a regulatory analysis including averted offsite property damage, and in NUREG/BR-0184, "Regulatory Analysis Technical Evaluation Handbook," which provides additional detailed guidance for the analysis [18]. These NRC regulatory analysis guidelines specifically recommend the use of MACCS to estimate the averted offsite property damage cost (benefit) and the offsite averted dose cost elements.

The MACCS code is divided into three modules: ATMOS, EARLY, and CHRONC. The ATMOS module performs all the calculations regarding atmospheric transport, dispersion, and deposition, as well as the radioactive decay that occurs prior to a hypothetical release and while the material is in the atmosphere. The EARLY module performs all the calculations related to the early phase of a hypothetical release. The exposure pathways considered during the early phase are cloudshine and inhalation during plume passage, groundshine from deposited materials, and inhalation of resuspended materials. Mitigative actions that can be specified for the early phase include evacuation, sheltering, use of potassium iodide (KI), and dose-dependent relocation [2]. The cost of actions implemented in the early phase is captured in the CHRONC module. The CHRONC module also simulates events that occur following the early phase, including the calculation of economic costs of the short- and long-term protective actions. CHRONC calculates the individual health effects that result from long-term external exposure to contaminated ground and from long-term inhalation of resuspended materials. Population-level health effects caused

by the consumption of contaminated food and water by individuals are also calculated in CHRONC.

Many of the parameter values initially used in MACCS were developed in the 1970's and 1980's to support early versions of consequence codes. As part of the Reactor Safety Study [3], the Calculation of Reactor Accidents Consequences (CRAC) code was developed to calculate health and economic consequences of accidental releases of radioactive material into the atmosphere. MACCS superseded CRAC and CRAC2. The original version of MACCS was based on the CRAC code and was documented in [1], [20], and [21]. MACCS was distributed with a sample problem used to illustrate the use of MACCS and to test proper operation of the code. For the most part, the parameter values in Sample Problem A are based on the comprehensive evaluation of MACCS parameter values performed for the NUREG-1150 severe accident analyses [4]. The technical bases for many of these parameters are documented in Volume 2, Part 7 of NUREG/CR-4551 [5]. Sample Problem A was updated at the time MACCS2 was released [2].

The last major review and update of MACCS parameters was conducted in support of NUREG-1150 [4], [5]. Since that time, there have been numerous updates and enhancements to the MACCS code and new information has emerged related to the parameters evaluated at the time of NUREG-1150. Many MACCS parameters were updated at the time of the SOARCA project [13], which provided new insights into severe accident progression and consequences. The ongoing decontamination activities at Fukushima are providing insights into the use and costs of decontamination techniques at large scales.

Following the publication of NUREG-1150 and the initial release of the MACCS code, a series of studies conducted jointly by the NRC and the Commission of the European Communities (CEC) in the 1990s sought to develop credible and traceable uncertainty distributions for non-site-specific input variables. Variables selected for evaluation in these expert elicitation studies were those identified to be important or significant for determining offsite consequences when using the then-new probabilistic accident consequence codes MACCS and the Code System from MARIA (COSYMA) [22]. Those expert elicitations were documented in NUREG/CR-6244 [23], NUREG/CR-6523 [24], NUREG/CR-6526 [6], NUREG/CR-6545 [25], NUREG/CR-6555 [26], and NUREG/CR-6571 [7] and were used to develop the MACCS parameter uncertainty distributions documented in NUREG/CR-7161 [27]. Another, more recent comprehensive update of parameters was included with the SOARCA project [13]. The SOARCA project developed many values for use in severe accident and consequence modeling. The values and approach to developing these values is documented in NUREG/CR-7009 [14] which provides a compilation of the parameters and inputs used in the SOARCA study. It also includes additional detail on the approaches used to developing some of the input values and methodologies applied in the SOARCA studies. Some of the parameters are site specific, but many are generally considered current best practice for a MACCS analysis. These approaches and parameters were most recently revisited in the Sequoyah SOARCA report [15], which provides updated approaches for parameter selection as well as approaches for developing uncertainty distributions for selected MACCS input parameters.

1.1 Objective

The objective of this report is to develop a comprehensive, updated summary of the technical bases for the quantification and application of MACCS input parameters. Many MACCS users often begin with input values found in "Sample Problem A" which was distributed with the MACCS [1] and MACCS2 [2] codes. As noted in [1], "it is the responsibility of each MACCS user to ensure

the appropriateness of all data in the MACCS input files which they prepare.” The summary of the technical bases for MACCS parameters in this document is intended to assist in the process of selecting and/or developing appropriate MACCS parameter values. These technical bases are intended for use in reviews of analyses of the offsite radiological and economic consequences of severe accidents at nuclear facilities.

The technical bases for recommended parameter values are provided below. In some cases, particularly for non-site-specific values, specific quantitative values are recommended. However, many of the parameter choices are site-specific, scenario-specific, accident-specific, or a combination of these. To accommodate the need to develop up-to-date, site- and scenario-specific parameter values, suggested processes and data sources (rather than a prescribed value) are provided. Suggestions for which MACCS parameters may be considered “standard” (i.e., parameters that should not be changed without very good reason), “generic” (i.e., parameters that are considered reasonable generic values for most U.S. locations), or “user-defined” (i.e., parameters that should in almost all cases be evaluated and developed by the user) are provided in Appendix C.

1.2 Scope and Limitations

The scope of the project includes a discussion of most of the input data that may be modified by the user in a MACCS run. MACCS differs from CRAC in that the values of almost all parameters used in the MACCS code may be modified by the user. This provides substantial flexibility to the user but requires the development (and justification) of significantly more input data. The flexibility afforded by MACCS extends beyond site-specific input parameters to the ability to specify non-site-specific parameters such as, but not limited to, atmospheric dispersion parameters, dose coefficients, and risk coefficients. Although the technical bases for many MACCS parameter values was documented at the time of NUREG-1150 [4] in NUREG/CR-4551 Volume 2, Part 7 [5], not all the user modifiable data were discussed in that document. For example, the technical bases for the dosimetric database, *DOSDATA.inp*, and the early and latent health effects models were provided elsewhere. In addition, code enhancements since the publication of NUREG-1150 have introduced new parameter choices. This document is intended to cover a broader set of input data than were evaluated in [5].

Multiple sources were reviewed to provide the technical bases for the parameter values and distributions found in this report. The technical bases documented in WASH-1400 [3], as well as those documented in [5] for use in NUREG-1150 [4], were reviewed to determine whether more recent technical information was available for the selection of parameter values. To assist in this review, more recent data compilations were consulted. As previously mentioned, these include a series of expert elicitations jointly conducted by the NRC and the CEC in the 1990s (e.g., [6], [7], and others); uncertainty and sensitivity analyses conducted after NUREG-1150, including [8] and the analyses documented in [9]; MACCS parameter guidance for DOE applications in [10]; and guidance for dose estimation in [12] and [11] were reviewed as potential sources of updated information. Updated recommendations developed during the SOARCA project, documented in [14], [28], [29], [14], [30], and [15] were also reviewed, as were the recommendations of the peer review committee that examined the SOARCA MACCS methodology [16]. Finally, additional data and information sources, such as journal articles, technical reports, and online repositories from recognized sources (e.g., U.S. Census data and economic data from the U.S. Bureau of Labor Statistics) were also considered on a parameter specific basis. For some MACCS parameters related to protective measures and decontamination, original research was carried out. That work is reflected in the body of the document, as well as in Appendices A and B.

This report has certain limitations. Because MACCS may be used for many different applications, the recommendations in this report should be considered in light of the purpose of each specific analysis. For example, some analyses may be focused on scenarios at relatively close ranges on the order of a few miles or less, where near-field phenomena such as plume meander, building wake effects, and plume rise may be important, and for which the region of interest is the immediate vicinity of the facility. Other analyses may be focused on assessing regional impacts, where a macroscopic average behavior over a much larger region, such as the area within 50 miles (80 km) of the facility, is of interest. Some analyses may be intended to be intentionally conservative for a particular output measure, whereas others may be intended to generate best estimates and encompass a variety of measures. The selection of a single set of recommended parameter values applicable to all possible analyses is therefore challenging. However, the summary of the technical bases provided in this document should assist the analyst in justifying the parameter choices. In all cases the analyst must understand the basis for the parameter values and should verify the applicability of any recommended values. This report is intended to provide technical information that facilitates selecting parameter values, rather than prescribing a single value or approach that is universally applicable. If appropriate, a reasonable value (or process) that is broadly applicable to a generic or unknown site is provided. The information herein may prove useful in developing specific guidance for specific applications.

A comprehensive evaluation of the parameters used by the currently recommended MACCS food chain preprocessor model (COMIDA2) was not performed for the current report. At the time of the MACCS2 development, COMIDA2 was provided as an alternative to the older MACCS food chain model and the use of COMIDA2 is the currently recommended modeling choice. MACCS is currently distributed with a sample food chain file based on the recommended values provided in Appendix A of Volume 2 of NUREG/CR-6613 [31]. The information provided in this appendix should be useful for evaluating the applicability of the generic sample food chain file for a specific analysis.

Finally, the development of the technical bases for parameters is based on the parameters typically required by the latest version of the code that was publicly available at the start of the project, which was MACCS version 3.10. Significant enhancements to the code were underway at the time of this writing, including revised limits on input parameter values, a more flexible dosimetry model, an alternative economic impact model, and an alternative atmospheric transport, dispersion, and deposition model. Recommended technical bases for parameterizing these new options are not provided in this report. Likewise, discussions of parameter values for MACCS model options that are not commonly exercised, or modeling options that have been superseded by updated approaches, but which have been retained in the interest of backward compatibility, are not included.

1.3 Report Organization and Parameter Grouping

In the original MACCS and MACCS2 documentation, parameters were grouped by the authors into data blocks of related parameters. The data blocks used in MACCS (excluding the output control data blocks) are listed in Table 1-1.

Table 1-1 Summary of MACCS and MACCS2 Data Blocks

ATMOS	EARLY
RI: Run Identification	MI: Miscellaneous
GE: Geometry	PD: Population Distribution
IS: Nuclide	OD: Organ Definition
WD: Wet Deposition	SE: Shielding and Exposure
DD: Dry Deposition	EZ: Evacuation Zone
DP: Dispersion Parameter	SR: Sheltering and Relocation
PM: Plume Meander	EF: Early Fatality
PR: Plume Rise	EI: Early Injury
WE: Wake Effects	LC: Latent Cancer
CHRONC	
M1-M5: Meteorological Sampling Specifications	CH: Long-term Exposure and Cost Data

In 2001, the NRC initiated an effort to create a Windows-based interface and framework for performing MACCS consequence analyses. The reasons for the development of this graphical user interface (GUI) were to simplify creating and modifying input files, reduce the likelihood of user errors in performing consequence analyses, enable the user to simply and conveniently account for uncertainties in input data, and displace the original batch framework with a Windows-based framework. The result of this development effort is the WinMACCS code.

With the development of the GUI for WinMACCS, parameters are organized in a tree structure to facilitate problem set-up. The highest level of the tree structure is called a main category, the second level is called a category, the third level is called a subcategory, fourth level is called a form, and under a form are one or more parameters. A summary of the categories (excluding the description, property, and output control forms) is provided in Table 1-2.

Table 1-2 WinMACCS Input Categories

ATMOS	EARLY	CHRONC
Spatial Grid	Model Basis	Shielding and Exposure
Radionuclides	Dose Model	Dose Projection
Deposition	Population by Cohort	Compensation Costs
Dispersion	Emergency Cohorts	Long-Term Protective Action
Multi-Source Term	Early Fatality	Decontamination Plan
Plume Specifications	Early Injury	Interdiction Costs
Release Descriptions	Latent Cancer	Weathering
Weather		Regional Characteristics
		Food Chain

Since the original development of WinMACCS, the American Society of Mechanical Engineers (ASME) and the American Nuclear Society (ANS) have undertaken work on the development of an industry consensus standard for offsite consequence assessment, namely a Level 3 PRA standard. As documented in [32], that effort introduced a set of eight technical elements to organize technical review of offsite consequence assessments. To facilitate the development of analysis documentation and technical review, the structure of this report is roughly based on the technical elements defined in that draft standard rather than on the code structure used by MACCS or WinMACCS. Chapter 2 provides a discussion of input parameters and data related to radionuclide release characterization. Chapter 3 provides a discussion of input parameters and data related to meteorological data and atmospheric transport, dispersion, and deposition. Chapter 4 provides a discussion of input parameters and data related to protective actions, other site data, and economic factors. Chapter 5 provides a discussion of input parameters and data related to dosimetry and health effects. Chapter 6 provides a discussion of MACCS code parameters related to conditional consequence quantification and reporting, which is largely a discussion of how to use the output control options that are available in MACCS. As an organizational convenience, the discussions are based on the MACCS parameter names rather than the WinMACCS input categories because the parameter names are the most discrete levels of input available to the user. Use of the WinMACCS GUI greatly facilitates the development of MACCS input decks, and any MACCS variable may be identified using the WinMACCS GUI. The text output produced by MACCS repeats the MACCS parameter name and its value.

1.4 Uncertainty Characterization

For each MACCS parameter discussed in this report, information is provided on the parameter name, parameter description, recommended value, uncertainty range, and supporting references. Uncertainty characterization in this document was developed based on state-of-practice where traceable uncertainty distributions are available. For the MACCS parameters that have previously been considered uncertain (e.g., in the SOARCA series of analyses [14], [30], [15]), parameter uncertainty distribution recommendations are provided. However, the uncertainty range for various MACCS parameter are listed as “not applicable” or “not available,” which indicates that within the current state-of-practice either the MACCS parameter is treated as a point-estimate or that the parameter represents a fixed selection of values within the code architecture. Alternatively, if an uncertainty range of “not available” is noted, it indicates the MACCS parameter could be considered uncertain, but no parameter uncertainty distribution is known to exist in the literature. Therefore, while the MACCS analyst could derive a parameter uncertainty distribution, no guidance is given in this document.

2 RADIONUCLIDE RELEASE CHARACTERIZATION

The development of a radiological source term is typically based on integrating the results of calculations used to develop radiological inventories such as ORIGEN [33] with the results of calculations from an accident progression code such as MELCOR [34] [35] or MAAP [36]. In the discussions that follow, emphasis is given to the processes involved when using MELCOR to develop source term information. The generation of a MACCS formatted source term from the results generated by an accident progression code may be done manually or may involve use of a preprocessor code such as MelMACCS [37] to process release information from MELCOR. In any case, the process is similar. The radionuclides to be included are identified, a radiological inventory for each is developed, the radionuclides are assigned to a set of chemical groups, and the release of each chemical group as a function of time is discretized into a set of plume segments with information related to physical release height, buoyancy, and magnitude of the released material. Such input can be developed from any accident progression code that is capable of tracking airborne releases into the environment. In some cases, simple methods can be used to estimate release fractions and timing, and this information can be translated into a MACCS source term.

2.1 Identification of Radionuclides and Development of Radionuclide Inventory

In the typical nuclear reactor core, numerous radionuclides exist in various amounts at any given time, depending on the cumulative operational history of the reactor core. This accounts for decay that has occurred in the fuel assembly during the operating cycle and fuel burnup. Using a code to estimate isotopic buildup and decay like ORIGEN [33], the radionuclide inventory can be estimated for a specified operational history. However, not all of the calculated radionuclides are significant for offsite consequences. For example, some radionuclides have half-lives on the order of seconds to minutes and decay into a stable form long before they can be released into the environment. Others, because of the characteristics of the emitted radiation or because they have a low volatility resulting in a low release fraction, do not significantly contribute to a radiological dose.

The process for identifying radionuclides to be included in a consequence analysis is discussed in WASH-1400 [3]. Sections 3.3 and 8.2.1 of Appendix VI of WASH-1400 describes a method for selecting the most important radionuclides. The methodology proposed there includes consideration of radionuclide half-life, emitted radiation type and energy, inventory, release fraction, and elemental chemistry. As part of the development of the MACCS code, Alpert et al. [38] reviewed the 500 radionuclides considered in the ORIGEN code at the time. Most of these radionuclides are not important for offsite consequences of accidents in light-water reactors (LWRs) because of their relatively small inventory, short half-life, or low radiobiological hazard. Alpert et al. [38] concluded that 60 radionuclides could be important for offsite consequence analyses of severe accidents at LWRs, as shown in Table 2-1. This list does not include some short-lived decay products that also contribute to the dose (e.g., Ba137m, the decay product of Cs-137). However, these decay products were included implicitly by adding the dose conversion factors (DCFs) for each decay product to the values of the corresponding parent, thus attributing the dose from the decay of both parent and progeny to the parent. This is a good approximation when the half-life of the decay product is very short (seconds or minutes).

Table 2-1 Radionuclides Identified as Important for Offsite Consequences of LWR Accidents

Co-58	Sr-92	Ru-103	Te-131m	Cs-136	Pr-143
Co-60	Y-90	Ru-105	Te-132	Cs-137	Nd-147
Kr-85	Y-91	Ru-106	I-131	Ba-139	Np-239
Kr-85m	Y-92	Rh-105	I-132	Ba-140	Pu-238
Kr-87	Y-93	Sb-127	I-133	La-140	Pu-239
Kr-88	Zr-95	Sb-129	I-134	La-141	Pu-240
Rb-86	Zr-97	Te-127	I-135	La-142	Pu-241
Sr-89	Nb-95	Te-127m	Xe-133	Ce-141	Am-241
Sr-90	Mo-99	Te-129	Xe-135	Ce-143	Cm-242
Sr-91	Tc-99m	Te-129m	Cs-134	Ce-144	Cm-244

Source: adapted from Table 1 of [38]

Some DCF files, including the files based on Federal Guidance Report 13 (FGR-13) [39], do not include the dose contributions from short-lived decay products that produce a significant dose. For these DCF files, such progeny must be explicitly included in the list of radionuclides to ensure proper accounting of the dose. The list of radionuclides currently used is provided in Table 2-2 and includes an additional 11 radionuclides to allow for explicit consideration of doses from progeny of the 60 radionuclides identified in [38]. Two radionuclides (Sb-127 and Sb-129), considered in WASH-1400 [3] and at the time of NUREG-1150 (as documented in [38]), were not evaluated in the SOARCA project but are included here.

Table 2-2 Currently Recommended Radionuclide List for LWR Applications

Co-58	Y-90	Ru-103	Te-132	Ba-137m	Nd-147
Co-60	Y-91m	Ru-105	I-131	Ba-139	Np-239
Kr-85	Y-91	Ru-106	I-132	Ba-140	Pu-238
Kr-85m	Y-92	Rh-103m	I-133	La-140	Pu-239
Kr-87	Y-93	Rh-105	I-134	La-141	Pu-240
Kr-88	Zr-95	Rn-106	I-135	La-142	Pu-241
Rb-86	Zr-97	Te-127	Xe-133	Ce-141	Am-241
Rb-88	Nb-95	Te-127m	Xe-135	Ce-143	Cm-242
Sr-89	Nb-97	Te-129	Xe-135m	Ce-144	Cm-244
Sr-90	Nb-97m	Te-129m	Cs-134	Pr-143	Sb-127
Sr-91	Mo-99	Te-131	Cs-136	Pr-144	Sb-129
Sr-92	Tc-99m	Te-131m	Cs-137	Pr-144m	

As described in Section 5.4 of the MACCS2 User's Guide [2], MACCS automatically accounts for decay and ingrowth of radionuclides with data supplied in the file INDEXR.DAT, supplied by the Radiation Shielding Information Center as part of the FGR-DOSE/DLC-167 data package. Some of the decay products of the radionuclides listed in Table 2-2 are very long-lived and are not significant contributors to dose. Although these radionuclides must be identified in MACCS, they may be designated as "pseudostable" to avoid the unnecessary computational expense of accounting for the negligible contribution from these radionuclides. The pseudostable radionuclides commonly associated with the radionuclides in Table 2-2 are identified in Table 2-3.

Table 2-3 Pseudostable Radionuclides Corresponding to Table 2-2

I-129	Sm-147	U-237	Nb-93m
Xe-131m	U-234	Np-237	Nb-95m
Xe-133m	U-235	Rb-87	Tc-99
Cs-135	U-236	Zr-93	Pm-147

MACCS requires an input for the activity of each radionuclide considered in the analysis. CORINV typically defines the isotopic inventory at the time of reactor shutdown, although this is not a requirement. In the MACCS frame of reference, the inventory corresponds to a time of zero. MACCS accounts for radioactive decay and ingrowth for times greater than zero. Thus, the inventory cannot be defined at a time prior to reactor shutdown because the reactor is still operating, and fission products are being formed. However, the inventory could be defined at a point in time following reactor shutdown.

The analyst should verify the time of accident initiation based on the sequence being modeled, as some sequences may be modeled with the reactor shutdown occurring at some time into the accident. The radionuclide inventory is externally derived using a code such as ORIGEN [33]. The inventory values used for Surry SOARCA, as documented in NUREG/CR-7110, Vol. 2, Rev. 1 [29], are shown in Table 2-4 below as an example. Table 2-4 values may be scaled based on the operating power level of an NPP. Alternatively, core inventories based on plant-specific calculations may be defined.

Table 2-4 Core Inventory Used for Surry SOARCA

NUCNAM	CORINV (Bq)	NUCNAM	CORINV (Bq)	NUCNAM	CORINV (Bq)
Kr-85	2.94E+16	Te-127	2.60E+17	Pu-238	8.31E+15
Kr-85m	8.07E+17	Te-127m	4.22E+16	Pu-239	9.56E+14
Kr-87	1.60E+18	Te-129	7.79E+17	Pu-240	1.17E+15
Kr-88	2.14E+18	Te-129m	1.49E+17	Pu-241	3.39E+17
Xe-133	6.07E+18	Te-131m	5.71E+17	Zr-95	4.96E+18
Xe-135	1.80E+18	Te-132	4.29E+18	Zr-97	5.00E+18
Xe-135m	1.29E+18	Te-131	2.55E+18	Am-241	3.43E+14
Cs-134	4.32E+17	Rh-105	2.90E+18	Cm-242	1.14E+17
Cs-136	1.57E+17	Ru-103	4.61E+18	Cm-244	1.13E+16
Cs-137	3.05E+17	Ru-105	3.14E+18	La-140	5.67E+18
Rb-86	5.36E+15	Ru-106	1.40E+18	La-141	5.10E+18
Rb-88	2.16E+18	Rh-103m	4.61E+18	La-142	4.92E+18
Ba-139	5.54E+18	Rh-106	1.56E+18	Nd-147	2.04E+18
Ba-140	5.37E+18	Nb-95	5.18E+18	Pr-143	4.65E+18
Sr-89	2.98E+18	Co-58	4.79E+13	Y-90	2.39E+17
Sr-90	2.27E+17	Co-60	2.65E+14	Y-91	3.93E+18
Sr-91	3.75E+18	Mo-99	5.68E+18	Y-92	4.11E+18
Sr-92	4.00E+18	Tc-99m	5.03E+18	Y-93	4.62E+18
Ba-137m	2.92E+17	Nb-97	5.24E+18	Y-91m	2.20E+18
I-131	2.78E+18	Nb-97m	4.95E+18	Pr-144	3.63E+18
I-132	4.08E+18	Ce-141	4.87E+18	Pr-144m	5.06E+16
I-133	5.76E+18	Ce-143	4.55E+18		
I-134	6.48E+18	Ce-144	3.42E+18		
I-135	5.49E+18	Np-239	5.67E+19		

Source: adapted from Appendix B of [29]

The preprocessor code MelMACCS [37] can be used to create a MACCS source term based on the results in a MELCOR plot file. This process is predicated on selecting or deriving a reactor core isotopic inventory that corresponds to the reactor modeled in the MELCOR analysis. ORIGEN is generally used to construct the mapping of the inventory by chemical class treated in MELCOR to the activities of radionuclides needed by MACCS. The result of this calculation is a value for the activity of important radionuclides in the core that is consistent with the chemical masses used in MELCOR. Though several inventories are provided as optional choices with MelMACCS, the user can provide their own inventory files. Ideally, the same ORIGEN file is used to define MELCOR masses and decay heats for each of the chemical classes in MELCOR and the inventory file needed for MelMACCS; however, this is not a requirement. Version 2 of MelMACCS includes four optional inventories that can be used to create a source term file:

- High-burnup 65 MWd/kg peak fuel rod for pressurized water reactors (PWRs) based on Sequoyah (end of cycle)
- High-burnup 65 MWd/kg peak fuel rod for boiling water reactors (BWRs) based on Peach Bottom (end of cycle)
- Medium-burnup 49 MWd/kg peak fuel rod for BWRs based on Peach Bottom (mid-cycle)
- Low-burnup 33 MWd/kg batch average based on end of cycle. Historically, this inventory is consistent with the decay heat and mass data used in older versions of MELCOR for both BWRs and PWRs.

When using MelMACCS, a reference time is defined to control the start of radionuclide decay in the MACCS calculation. Usually, this reference time is the MELCOR time when the reactor is shut down and is used to adjust the release timing to be relative to reactor shutdown. More generally, the reference time corresponds to the time for which the isotopic inventory is provided, as described above. Similar considerations are needed when using MAAP or another accident progression code to develop the source term.

Parameter Name: NUCNAM

Parameter Description: Radionuclide Names

Recommended Value: The recommended NUCNAM values are provided in Table 2-2.

Uncertainty Range: not applicable

References: [2], [14], [10], [37]

Discussion: For evaluating offsite consequences from LWR accidents, the 71 radionuclides identified in Table 2-2 are appropriate. For other applications, a different list should be evaluated, to include radionuclides that may be important for estimating doses. A useful cut-off for considering a sufficient set of radionuclides is whether the additional dose that would be contributed by the omitted radionuclides is $\leq 0.1\%$. Below this value the radionuclides in question can be ignored because they contribute insignificantly to the overall dose [10]. The standard format is for the first letter of the element abbreviation to be capitalized, followed by a hyphen and the isotope number (e.g., Cs-137).

Parameter Name: NUMISO

Parameter Description: Number of Radionuclides

Recommended Value: 71

Uncertainty Range: not applicable

References: [2], [14], [10], [37], [38]

Discussion: NUMISO defines the number of isotopes/radionuclides to be considered for evaluation (i.e., the number of isotopes defined in NUCNAM).

Parameter Name: NAMSTB

Parameter Description: List of Pseudostable Nuclides

Recommended Value: The recommended pseudostable radionuclides corresponding to the radionuclides listed by NUCNAM are listed in Table 2-3.

Uncertainty Range: not applicable

References: [14], [37]

Discussion: The number of pseudostable radionuclides included in an analysis is determined by the list of radionuclides chosen for the source term in NUCNAM. Pseudostable radionuclides shorten the decay chains of radionuclides to exclude daughter products that would not significantly contribute to the consequence associated with the total source term. The general rule is that an unstable decay product of an isotope listed under NUCNAM must either be included as an isotope (i.e., also listed under NUCNAM) or included as a pseudostable isotope (i.e., listed under NAMSTB). The standard format is for the first letter of the element abbreviation to be capitalized, followed by a hyphen and the isotope number (e.g., Xe-131m).

Parameter Name: NUMSTB

Parameter Description: Number of Defined Pseudostable Radionuclides

Recommended Value: The recommended pseudostable radionuclides corresponding to the nuclides listed by NUCNAM are listed in Table 2-3.

Uncertainty Range: not applicable

References: [14], [37]

Discussion: The number of pseudostable radionuclides included in the analysis is determined by the list of radionuclides in NAMSTB.

Parameter Name: CORINV

Parameter Description: Isotopic Inventory at Time of Reactor Shutdown

Recommended Value: Problem specific. The core inventory defined in Table 2-4, scaled for the core power level, may be used for analyses where plant specific information are not available.

Uncertainty Range: not available. Sensitivity analyses may be conducted using alternate core inventories based on different times in the operating cycle.

References: [14], [33], [37]

Discussion: The recommend approach is to use a plant-specific core inventory generated with ORIGEN [33] or to use MelMACCS with the default inventory that most closely represents the plant being analyzed. Because the inventory changes during the operating cycle, it is reasonable to perform sensitivity analyses based on different times during the operating cycle.

Parameter Name: CORSCA

Parameter Description: Linear Scaling Factor on Core Inventory

Recommended Value: Problem specific; normally 1 if a problem specific inventory has been developed.

Uncertainty Range: not available

References: [14], [40]

Discussion: If a plant-specific core inventory has been developed for the unit being analyzed, the core scaling factor should be set to 1. It should also be set to 1 when using MelMACCS with a MELCOR plot file created for the reactor that is being analyzed because MelMACCS automatically adjusts the core inventory based on the masses of each chemical class that are defined in the MELCOR calculation. The core scaling factor can be used to scale the inventory for reactors that are similar but have different thermal operating powers. For example, the analyses in NUREG-1150 [4] scaled a reference inventory by the ratio of the thermal operating power level of each individual unit to that of the reference unit. The core inventory defined in Table 2-4 is based on Units 1 and 2 at the Surry Nuclear Power Plant, both of which are Westinghouse 3-loop PWRs and have an operating power of 2,546 megawatts thermal (MW_{th}) (Table 4-1 of [29]). This inventory can be used for analyses where plant specific information is

not available by defining CORSCA to be equal to the ratio of the operating power of the reactor being evaluated to the reference operating power of 2,546 MW_{th}.

2.2 Chemical Class Assignment

Accident progression codes such as MELCOR and MAAP do not typically track the movement, or the radioactive decay, of individual radionuclides during an accident sequence, but instead track chemical classes. Assignment of chemical classes (also referred to as chemical element groups or radionuclide classes) consists of determining the number and definition of chemical classes into which the radionuclides analyzed are grouped. Since publication of the TID-14844 source term in 1962 [41], numerous studies, computer code updates, and experiments have been conducted which have expanded the understanding of radionuclide behavior during severe accidents. A summary of important studies is provided below:

- Current operating reactors were licensed using Regulatory Guide 1.3 (BWR) [42] and Regulatory Guide 1.4 (PWR) [43], which provide in-containment source terms based on release assumptions reported in TID-14844 using three chemical classes [41].
- Reactor Safety Study [3].
- The NUREG-1150 assessment of five NPPs [4] assumed nine chemical classes based on the grouping used in the Source Term Code Package [44].
- Accident Source Terms for Light-Water Nuclear Power Plants (NUREG-1465) [45].
- Accident Source Terms for Light-Water Nuclear Power Plants Using High-Burnup or MOX Fuel [46].

The Reactor Safety Study (often referred to as WASH-1400 [3]) divided radionuclides into seven chemical classes rather than the three physical classes considered in the TID-14844 source term. As part of the development of the Source Term Code Package, a set of nine chemical groups were defined as given in Table 2-5.

Table 2-5 Radionuclide Groups Defined for the Source Term Code Package

Class	Member Elements
1	Xe, Kr
2	I, Br
3	Cs, Rb
4	Te, Sb, Se
5	Sr
6	Ru, Rh, Pd, Mo, Tc, Co
7	La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y
8	Ce, Pu, Np
9	Ba

Source: [44] (adapted from Table 3.7 of [45])

These chemical classes were used as the basis for the NUREG-1150 calculations and reflect the groupings found in Sample Problem A. Further work in the 1990's on accident source terms used a modified grouping. The chemical groups defined in NUREG-1465 [45] are provided in Table 2-6.

Table 2-6 Radionuclide Groups Defined in NUREG-1465 [45]

Class	Name	Member Elements
1	Noble gases	Xe, Kr
2	Halogens	I, Br
3	Alkali Metals	Cs, Rb
4	Tellurium group	Te, Sb, Se
5	Barium, strontium	Ba, Sr
6	Noble Metals	Ru, Rh, Pd, Mo, Tc, Co
7	Lanthanides	La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y, Cm, Am
8	Cerium group	Ce, Pu, Np

Source: adapted from Table 3.8 of [45]

The chemical element grouping used in SOARCA is shown in Table 2-7 (IGROUP is equivalent to "Class" and MAXGRP is 9). Release of cesium in the form of Cs_2MoO_4 (cesium molybdate) also leads to increases in the releases of molybdenum relative to releases of other refractory metal fission products such as ruthenium and palladium. Because of this effect, the refractory metals class of radionuclides has been divided to create a special class for molybdenum [46]. Therefore, the number of chemical classes increased from the eight used in NUREG-1465 [45] to the nine chemical classes used in SOARCA [14]. The current usage in MACCS is based on updates to the MELCOR code [34, pp. RN-UG-11,12]. The noble metal group from NUREG-1465 [45] is subdivided into the platinoid group and early transition element group, yielding nine chemical groups. In addition to these groups, three additional groups typically included in MELCOR analyses, the uranium group (U/Class 10), more volatile main group (Cd/Class 11), and less volatile main group (Sn/Class 12,) were not included in SOARCA because they were determined to contain no radionuclides that are important for offsite consequences.

Table 2-7 Radionuclide Chemical Element Groups Used for Surry and Peach Bottom SOARCA

Class	Name	Representative	Member Elements
1	Noble Gas	Xe	He, Ne, Ar, Kr, Xe, Rn, H, N
2	Alkali Metals	Cs	Li, Na, K, Rb, Cs, Fr, Cu
3	Alkali Earths	Ba	Be, Mg, Ca, Sr, Ba, Ra, Es, Fm
4	Halogens	I	F, Cl, Br, I, At
5	Chalcogens	Te	O, S, Se, Te, Po
6	Platinoids	Ru	Ru, Rh, Pd, Re, Os, Ir, Pt, Au, Ni
7	Early Transition Elements	Mo	V, Cr, Fe, Co, Mn, Nb, Mo, Tc, Ta, W
8	Tetravalent	Ce	Ti, Zr, Hf, Ce, Th, Pa, Np, Pu, C
9	Trivalents	La	Al, Sc, Y, La, Ac, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Am, Cm, Bk, Cf

Source: [14]

Table 2-8 shows the chemical groups and associated isotopes modeled in SOARCA under groups 1 through 9. Based on review of [38], Table 2-2 recommends including two additional isotopes that were not treated in the SOARCA work, which are Sb-127 and Sb-129. These isotopes are associated with the cadmium group in MELCOR, which is shown as group number 10 in the table. The chemical groups and isotopes listed in Table 2-8 are the ones currently recommended to use with MACCS.

Table 2-8 Currently Recommended List of Radionuclides and Groupings Used for Consequence Assessment

Group Number (IGROUP)	Chemical Group (GRPNAM)	Radionuclides (NUCNAM)
1	Noble Gas (Xe)	Kr-85, Kr-85m, Kr-87, Kr-88, Xe-133, Xe-135, Xe-135m
2	Alkali Metals (Cs)	Rb-86, Rb-88, Cs-134, Cs-136, Cs-137
3	Alkali Earths (Ba)	Sr-89, Sr-90, Sr-91, Sr-92, Ba-137m, Ba-139, Ba-140
4	Halogens (I)	I-131, I-132, I-133, I-134, I-135
5	Chalcogens (Te)	Te-127, Te-127m, Te-129, Te-129m, Te-131, Te-131m, Te-132
6	Platinoids (Ru)	Ru-103, Ru-105, Ru-106, Rh-103m, Rh-105, Rh-106
7	Early Transition Elements (Mo)	Co-58, Co-60, Nb-95, Nb-97, Nb-97m, Mo-99, Tc-99m
8	Tetravalents (Ce)	Zr-95, Zr-97, Ce-141, Ce-143, Ce-144, Np-239, Pu-238, Pu-239, Pu-240, Pu-241
9	Trivalents (La)	Y-90, Y-91m, Y-91, Y-92, Y-93, La-140, La-141, La-142, Pr-143, Pr-144, Pr-144m, Nd-147, Am-241, Cm-242, Cm-244
10 (MELCOR Class 11)	More Volatile Main Group Metals (Cd)	Sb-127, Sb-129

Parameter Name: IGROUP

Parameter Description: Definition of Radionuclide Group Numbers

Recommended Value: Consistent with chemical group assignment used for accident progression modeling. For analyses based on MELCOR, the grouping in Table 2-8 is recommended. Current practice with MAAP uses a grouping like the one shown in Table 2-5, reflecting the fact that Cs is primarily released as CsOH, not Cs₂MoO₄.

Uncertainty Range: not applicable

References: [14], [37], [34]

Discussion: Each radionuclide is assigned to a chemical element group (e.g., noble gases.) IGROUP represents the chemical element group to which the radionuclide is assigned. Both the deposition behavior and the release fraction of a radionuclide depend on the element group to which it is assigned, and the radionuclides should therefore be grouped according to their physical and chemical properties. This grouping is typically done as part of the accident progression analysis, and the MACCS chemical groups should be defined consistently with the modeling used to develop the source term. All members of an element group have the same deposition characteristics and release fractions. The user must supply NUMISO values for this variable, one for each isotope defined in the inventory.

Parameter Name: GRPNAM

Parameter Description: Names of the Chemical Classes (Used by WinMACCS)

Recommended Value: Consistent with chemical group assignment used for accident progression modeling. For analyses based on MELCOR source terms, the abbreviation in parentheses in the second column of Table 2-8 is recommended. For analyses based on MAAP, the first elements listed in Table 2-5 are commonly used to label the chemical classes.

Uncertainty Range: not applicable

References: [14], [37], [34]

Discussion: Chemical group names are written to MELCOR plot files. MelMACCS, a software product used to convert the output from MELCOR to the input required by WinMACCS, reads the chemical group names from the MELCOR plot file. These names are translated into input images read by WinMACCS. MelMACCS writes the chemical group name information in a MACCS input file as images that are recognized by WinMACCS, but not by MACCS.

Parameter Name: MAXGRP

Parameter Description: Number of Radionuclide Groups

Recommended Value: The number of chemical groups (i.e., the maximum of the set of IGROUP values). For analyses based on MELCOR, the grouping in Table 2-8 is recommended and a value of 10 is recommended. The recommended value of MAXGRP when using MAAP is 9; the corresponding grouping is the one shown in Table 2-5.

Uncertainty Range: not applicable

References: [14], [37], [34]

Discussion: MAXGRP represents the number of chemical element groups defined in the model.

2.3 Plume Release Path Characterization

The MACCS atmospheric dispersion models require information related to the characteristics of the location from which each plume segment is released because the downwind transport of the plume is affected by the initial location of the release, the initial rise of the plume due to buoyancy effects, and spreading and trapping of the plume due to turbulence from building wakes. The models for the plume dispersion require specification of the elevation of the release (PLHITE) as well as the building height (BUILDH), initial plume horizontal dimensions (PLSIGYINIT), and initial plume vertical dimensions (PLSIGZINIT). These parameters are characteristics of the physical location of the release path. Information on the characteristics of the release path may be developed as part of the source term analysis. For example, for source terms developed by MELCOR, flow paths designated as environmental pathways are associated with specific structures and are characterized by an elevation (which may need to be adjusted to reflect the elevation with respect to grade level). MelMACCS allows a user to specify the characteristics (release height, building height, and initial plume dimensions) for each MELCOR flow path into the environment. Similar considerations are needed when the source term is developed using MAAP. Because these parameters are used to develop the treatment of atmospheric dispersion, the details of how these are reflected in MACCS are discussed in Section 3.7.

2.4 Aerosol Size Distribution

The physical and chemical form of radionuclides can strongly affect the transport of radioactivity in the atmosphere, most notably by controlling the rate at which the aerosols are depleted by dry deposition. Consequence analyses of commercial nuclear reactor units prior to SOARCA typically

used a single deposition velocity to represent all particle sizes and all radionuclide groups. In other words, all aerosols were assumed to deposit at the same velocity. However, the released radionuclides usually exhibit a range of aerosol sizes, with the deposition being different for each size. This may be captured in the analysis by defining the distribution of particle sizes for each chemical group and associating each particle size with a different deposition velocity. The deposition velocity is the value that is used in MACCS to reflect the effects of the aerosol type and size. Reactive vapors (e.g., I_2) also deposit and are commonly treated using a deposition velocity.

If MELCOR is used to develop the source term information, MelMACCS may be used to process the information provided by MELCOR to determine a set of particle size distributions, one for each chemical group. MELCOR generates a time-dependent distribution of particle sizes for each chemical group released to the environment. Because MACCS cannot account for a time-dependent distribution of particle sizes during a release, MelMACCS assigns the particle size distribution for each chemical group by integrating the aerosol masses over the entire period of the release. The particle size distribution for a given chemical group is defined by the ratio of the mass released for each particle size to the total mass released. The particle size classes are defined by an aerosol diameter range and the number of bins or sections in the MELCOR input [35]. A default logarithmic distribution of median diameter for 10 MELCOR aerosol size bins is provided in Table 2-9, which is taken from the MELCOR 2.2 Users' Guide [34].

Table 2-9 Current Default MELCOR Aerosol Size Bin Definitions

Bin Number	Mass Median Aerosol Diameter, micrometers									
	1	2	3	4	5	6	7	8	9	10
MMAD (μm)	0.15	0.29	0.53	0.99	1.8	3.4	6.4	12	22	41

Similar considerations are needed when developing an aerosol size distribution using MAAP or another accident progression code. The aerosol sizes are used to develop a set of deposition velocities. The deposition velocities are also affected by wind speed and surface roughness. MelMACCS accounts for these site-specific effects. The derivation of dry deposition velocities is discussed in Section 3.8.1.

Parameter Name: NPSGRP

Parameter Description: Number of Particle Size Groups

Recommended Value: Consistent with particle size distribution discretization (10 is the default value when MELCOR is used). When a particle size distribution is not available, a single bin can be used to represent aerosol deposition for a typical accident.

Uncertainty Range: not applicable

References: [2], [40], [37], [34]

Discussion: NPSGRP defines the number of particle size groups used in the dry deposition model. The SOARCA project implemented advancements in the MELCOR to MACCS interface using MelMACCS to provide binned particle size information for each of the radionuclide groups. When using MELCOR, the number of particle size groups are defined in the MELCOR input and can be read by MelMACCS to define the NPSGRP variable. The default value is 10 for most MELCOR analyses. However, for some consequence analyses, an aerosol size distribution may not be available or may be difficult to evaluate. In those cases, a single aerosol bin and deposition velocity may be defined, as discussed in Section 3.8.1.

Parameter Name: PSDIST

Parameter Description: Particle Size Distribution by Group

Recommended Value: Problem specific based on source term calculations.

Uncertainty Range: not available

References: [2], [40], [37], [34]

Discussion: PSDIST defines the fraction of the released activity allocated to each of the particle size (deposition velocity) groups. Each plume segment uses the same size distribution. When MELCOR is used to develop source term information, use of MelMACCS is recommended to develop a particle size distribution consistent with the MELCOR analysis. To estimate PSDIST for each chemical group and deposition velocity bin, MelMACCS considers the time from the accident initiation time (reference time for inventory in the MELCOR time frame) to the last time recorded on the MELCOR plot file. Similar considerations should be made when developing a particle size distribution with another accident progression code (e.g., MAAP). Alternatively, a single particle size group may be specified when a particle size distribution is not available. For this case, the values of PSDIST for the single size bin are unity for each chemical class.

2.5 Plume Segment Definitions

For long duration releases, when both the characteristics of release and the meteorological conditions can vary, MACCS has the capability to subdivide the release into a set of plume segments. The number of allowable plume segments in MACCS was increased to 500 with the development of WinMACCS [40]. This enhancement allows long duration releases to be divided into 1-hour plume segments. Using hourly plume segments takes maximum advantage of the hourly averaging times typically used to develop meteorological data files. This ensures that released material is transported and dispersed consistent with the meteorology, including wind direction, during the time of the release for each plume segment. The process of creating hourly plume segments can be automated when MelMACCS is used to process MELCOR source term data [37]. The following discussion is based on the use of MelMACCS; however, similar considerations can be applied when using an alternate approach.

The Gaussian plume segment model in MACCS requires information for each plume segment on the time at which the segment begins to release (PDELAY), the duration of release (PLUDUR), and the amount of material released, defined as the fraction of each chemical group that is released (RELFRC). In addition, MACCS requires the initial height of each plume segment. The downwind transport and dispersion modeling accounts for initial release height, plume rise due to buoyancy effects, and initial spreading due to building wakes.

MelMACCS includes two parameters that can be used to filter out insignificant MELCOR release paths and plume segments. The first of these causes MELCOR flow paths to be excluded when less than a specified fraction (typically 0.001) of the total release of any chemical group occurs through the flow path. This enhances computational efficiency by excluding release paths (and associated plume segments) that do not contribute significantly. The second parameter causes a plume segment to be excluded if all of the chemical groups in that segment contribute less than a user-defined portion of the total release of that chemical group (typically 0.0001 or 0.00001). While there may be multiple modeled release flow paths for any given source term, typically one or two of the flow paths contain the large majority of the release. For each important release path, the release is typically divided into approximately one-hour plume segments to be consistent with hourly meteorological data. The exact duration of a plume segment ultimately depends on the time steps that are retained in the plot file. Releases from any minor flow paths or for a

revaporation tail of the release from a major flow path(s) may occur over long time periods but may not contribute significantly. Because of their relatively small contributions, it may not be important to divide these releases into hourly plume segments. However, these long plume segments should be checked to ensure they do not have significantly larger release fractions than the hourly plume segments during the more significant periods of release. These minor plume segments can either be modeled as is, or if necessary, divided into a few plume segments to comply with the MACCS requirement that a plume segment cannot have a duration longer than 24 hours.

MACCS has two options for determining the buoyancy flux used for plume rise modeling [40]. The models for estimating the buoyancy flux are discussed in more detail in Section 3.7.3. The first method is referred to as the “Power Model” and the second method is referred to as the “Density and Flow Model.” The Power Model uses sensible heat release rate of the plume in watts (PLHEAT). The Power Model was the only model available before the development of WinMACCS and is described in NUREG/CR-6613 [2]. The Density and Flow Model can be used to account for release of gases that are lighter than air, such as hydrogen and steam, as well as releases at elevated temperatures. This approach requires the user to estimate the rate of mass release (PLMFLA) and the density of a plume segment (PLMDEN). Both of these parameters can be derived from data contained in a MELCOR plot file using MelMACCS [37].

MACCS uses a parameter known as MAXRIS to specify which plume segment is to be considered risk dominant. The selection of this plume segment is usually based on its potential for causing early fatalities. The starting time of MACCS weather trials are chosen to align the release of the risk-dominant plume segment with the selected meteorological start time of the weather sequence when the weather binning approach is used. This ensures that the weather sampling algorithms (see Section 3.2) are based on the most significant plume segment. MAXRIS is generally assigned to be the first plume segment, unless a large release is preceded by low level releases (e.g., from normal containment leakage or auxiliary building leakage). In those cases, MAXRIS should be assigned to be the first plume segment resulting from a significant environmental path (for example, from containment failure, auxiliary building failure, or from relief valves in the case of a steam generator tube rupture scenario).

To explore source term uncertainty, the SOARCA uncertainty analyses specifically avoided sampling release fractions and timing via correlated distributions. While this could be done in principle, in practice it would be very difficult to devise reasonable correlations between release fractions across the chemical groups and for each plume segment to adequately define source term uncertainty. Instead, multiple, equally-probable source terms were created by running a set of MELCOR realizations with sampled input parameters to quantify this uncertainty. While using MELCOR (or a similar source term code) to quantify uncertainty is computationally intensive, it is the best and most defensible method available.

Parameter Name: NUMREL

Parameter Description: Number of Released Plume Segments

Recommended Value: Problem specific based on plume segmentation approach

Uncertainty Range: not applicable

References: [2], [40], [37]

Discussion: NUMREL defines the number of plume segments that are released, where a constant rate of release is assumed over each plume segment. The intent of using a larger number of plume segments is to capture the time dependence of release fraction and weather variability, particularly changes in wind direction. MELCOR source terms processed through

MeIMACCS are preferred for capturing the amount of each chemical group in each aerosol bin for each plume segment. Similar evaluation of release quantities should be made when using an alternative accident progression code (e.g., MAAP).

Parameter Name: REFTIM

Parameter Description: Plume Reference Time Point

Recommended Value: A value of 0 is recommended for the MAXRIS plume segment to ensure that doses from this plume segment are not underestimated and a value of 0.5 for other plume segments to provide a best estimate.

Uncertainty Range: not applicable

References: [2], [40], [37]

Discussion: REFTIM defines the representative time point of each plume segment (e.g., 0.0=leading edge, 0.5=midpoint, 1.0=trailing edge). The characteristics of a plume are modeled as uniform along its length. This parameter allows the user to choose a representative point at which the contents of the plume are in a so-called bucket of material. The radioactive decay, dry deposition, and dispersion calculations are all performed as if the entire contents of the plume segment are located at this point. The user must supply NUMREL values of REFTIM, one for each plume segment. The choice of this parameter has no impact on wet deposition calculations since those are performed as if the entire contents of the plume are uniformly distributed along its length [2]. The value of 0 for the MAXRIS plume segment and a value of 0.5 for the other plume segments is recommended. The intent of these values is to maximize the dose estimate for the MAXRIS plume segment, where the relative timing of evacuation is critical. Using a value of 0.5 for the other plume segments is intended to be a best estimate.

Parameter Name: PDELAY

Parameter Description: Plume Segment Release Times

Recommended Value: A problem-specific value is recommended based on the source term analysis.

Uncertainty Range: not available

References: [2], [40], [37]

Discussion: The variable PDELAY specifies the start time of each plume segment in seconds from the time of the reference time for the core inventory (usually reactor shutdown). The user must supply NUMREL values for PDELAY, one for each plume segment. MACCS allows the specification of overlapping plumes (e.g., from multiple release paths that overlap in time). When MELCOR is used for the source term analysis, the use of MeIMACCS to develop the start time of each plume segment is recommended. Processing the source term to determine PDELAY and PLUDUR is facilitated with MeIMACCS, where the user can auto-insert plume segment intervals on a release fraction plot or click to insert plume segment break points to capture time-dependent variations in release fractions and other plume parameters.

Parameter Name: PLUDUR

Parameter Description: Plume Segment Durations

Recommended Value: For risk-significant plume segments, a value of approximately one hour (3,600 seconds) is recommended when hourly meteorological data are used.

Uncertainty Range: not available

References: [2], [40], [37]

Discussion: The variable PLUDUR specifies plume segment duration for each plume segment. The user must supply NUMREL values of PLUDUR, one for each plume segment. The recommended plume segment duration, PLUDUR, is typically 3,600 seconds (or a value reasonably close to this depending upon how the information from the source term is provided). This recommendation is based on site weather data usually being available on an hourly basis. Longer plume segments (that is larger values for PLUDUR) can sometimes be used for trivial releases, such as those where the segment content is a very small fraction of the total release. Shorter time segments are appropriate when release duration is less than one hour or when a very rapid, energetic release occurs over a short period. When MELCOR is used for the source term analysis, the use of MelMACCS to develop the plume segment duration is recommended. Processing a source term to determine PDELAY and PLUDUR is facilitated by MelMACCS, which allows a user to auto-insert time intervals on a release fraction plot or click to insert plume segment break points to capture time-dependent variations in the release fractions and other plume parameters.

Parameter Name: RELFRC

Parameter Description: Plume Segment Release Fractions

Recommended Value: A problem-specific value is recommended based on the source term analysis.

Uncertainty Range: not available

References: [2], [40], [37]

Discussion: RELFRC defines the release fractions for each of the plume segments and chemical element groups. The user must supply a value for RELFRC for each plume segment and chemical group. If MELCOR is used for the source term analysis, the use of MelMACCS to develop the time-dependent release fractions is recommended. Released masses for flow paths leading to the environment, which are contained in the MELCOR plot file, are used to determine the time history of fractional release for each chemical class and plume segment. The release fraction for a plume segment and chemical group is the released mass through a release path over the corresponding time interval divided by the total mass of that particular chemical group in the core inventory.

Parameter Name: APLFRC

Parameter Description: Method of Applying Release Fraction

Recommended Value: PARENT

Uncertainty Range: not applicable

References: [2], [40]

Discussion: APLFRC controls how decay products created prior to atmospheric release are treated. The options are “PARENT” or “PROGENY.” Choosing “PARENT” means each decay product is released at the same release fraction as the chemical group of the parent radionuclide; choosing “PROGENY” means each decay product is released at the same release fraction as the chemical group of the decay product. Neither option is perfect, but the better option depends on whether most of the decay occurs before release from the fuel and whether the decay involves a phase change between parent and progeny. For example, if a radionuclide is formed by decay before being released from the fuel, it is most likely released in proportion to its own chemical group, so “PROGENY” is the better option; if the decay occurs within an aerosol particle after release from fuel, then the decay product is likely to remain bound in the aerosol and be released in proportion to the “PARENT” chemical group. However,

if a decay product is volatile, as would be the case when a noble gas is formed, then the decay product is likely to be released in proportion to its own chemical group.

Generally, the recommended choice is “PARENT” because this choice is more consistent with the MELCOR and MAAP codes that are often used to construct source terms. However, depending on the type of facility considered and other aspects of the source term and its generation, “PROGENY” might be the better choice.

Parameter Name: PLMDEN

Parameter Description: Plume Segment Mass Density

Recommended Value: User-specified based on plume segment and release description

Uncertainty Range: not available

References: [2], [40], [37]

Discussion: The use of the PLMDEN variable to estimate the buoyancy flux using the recommended “Density and Flow Model” is discussed in Section 3.7.3. When MELCOR is used for a source term analysis, the use of MelMACCS to develop the density of each plume segment is recommended. The gas density can be determined for each plume segment using MelMACCS for the MACCS flow path of interest. For each time step and release path, MELCOR supplies a molecular weight in kg/mole (PLMW), a fluid temperature in degrees K (PLTEMP), and a cumulative fluid mass flow for each release path in moles (PLMFLO). This information is used to determine the plume segment average plume density (PLMDEN) [37]. The user must supply NUMREL values of PLMDEN, one for each plume segment, when the Density and Flow Model is chosen for plume buoyancy.

Parameter Name: PLMFLA

Parameter Description: Plume Segment Mass Flow Rate

Recommended Value: User-specified based on plume segment and release description

Uncertainty Range: not available

References: [2], [40], [37]

Discussion: The use of the PLMFLA variable to estimate the buoyancy flux using the recommended “Density and Flow Model” is discussed in Section 3.7.3. When MELCOR is used for a source term analysis, the use of MelMACCS to develop the gas flow rate for each plume segment is recommended. The flow rate can be determined for each plume segment using MelMACCS for the MACCS flow path of interest. MELCOR supplies a cumulative fluid mass flow for each release path in moles (PLMFLO), and an average molecular weight in kg/mole (PLMW) for each time step. Using this information, the average plume segment mass flow rate (PLMFLA), can be determined. The user must supply NUMREL values of PLMFLA, one for each plume segment, when the Density and Flow Model is chosen for plume buoyancy.

Parameter Name: PLHEAT

Parameter Description: Plume Segment Heat Contents

Recommended Value: problem specific, but applicable only when the “POWER” model is used for buoyant plume rise.

Uncertainty Range: not available

References: [2], [40], [37]

Discussion: PLHEAT defines the rate of release of sensible heat in each plume segment. The use of the PLHEAT variable to estimate the buoyancy flux using the “Power Model” is

discussed in Section 3.7.3. This quantity should be calculated as the amount of sensible heat in the plume segment divided by the duration of the plume segment. The value is used to determine the amount of buoyant plume rise that will occur. The user must supply NUMREL values of PLHEAT, one for each plume segment, when the Power Model is chosen for plume buoyancy. When MELCOR is used for the source term analysis, the use of MelMACCS to develop the heat content of each plume segment is recommended. MELCOR supplies the time-cumulative fluid enthalpy in joules (J), relative to an ambient temperature of 300 K associated with each release path. MelMACCS processes the MACCS flow path information from MELCOR to determine a plume segment rate of release in joules per second or watts. If another code is used to develop the source term, PLHEAT can be developed using Equation (2-1):

$$\dot{Q} = \dot{m} \cdot c_p \cdot (T - T_{ambient}) \quad (2-1)$$

where

\dot{Q}	=	rate of release of sensible heat in each plume segment (W)
\dot{m}	=	mass flow rate (kg/s)
c_p	=	heat capacity of air at constant pressure (J/kg/K)
T	=	temperature (K)
$T_{ambient}$	=	ambient temperature (K)

Ambient temperature is usually taken to be a constant value of 25°C (approximately 300 K). Units must be chosen so that PLHEAT is in units of watts. Notice that latent heat is not included in the equation for PLHEAT. This is because most of the time mixing with surrounding air causes the relative humidity within a plume to remain below 100% even though the plume temperature eventually approaches the ambient temperature.

Parameter Name: MAXRIS

Parameter Description: Selection of Risk Dominant Plume

Recommended Value: Problem specific based on time-dependent release fraction

Uncertainty Range: not applicable

References: [2], [40], [37]

Discussion: MAXRIS defines the risk-dominant plume segment considered in the release. When using MelMACCS, the selection of this plume may be determined after looking at the time-dependent release profile usually viewed on the release path form in the MelMACCS GUI. The choice of the MAXRIS plume segment is usually based on its potential to cause early fatalities. MAXRIS usually corresponds to the first large spike in the release fraction of a key chemical group, such as iodine.

3 ATMOSPHERIC TRANSPORT, DISPERSION, AND DEPOSITION

3.1 MACCS Meteorological File Development

Atmospheric transport modeling in MACCS requires data for wind speed, wind direction (defined in terms of compass sector the wind is blowing toward), atmospheric stability class, hourly precipitation, and diurnal (morning and afternoon) seasonal mixing heights. MACCS has several options for treating meteorological data, which include directly inputting weather data (either constant weather conditions or 120 hours of specified weather data) or sampling weather data from an external input file. The format of the MACCS site meteorological file is described in Appendix B.1 of [1] and in Appendix A.1 of [2] and is illustrated in Figure 3-1¹. Section 7 of the MACCS Users Guide [40] provides an in-depth description of MACCS meteorological files. Sampling options include the ability to specify a particular time for the start of the release, to perform sampling of data from meteorological bins defined in part by the user, or to randomly sample from each day of the weather file. The development of a site-specific weather file from meteorological observations involves balancing factors such as data availability, the degree to which hourly data are representative of long-term conditions at the site, the quality of the available meteorological data, and any local meteorological factors (such as complex terrain or the presence of large water bodies) that could affect atmospheric transport.

Met	Inpt	2012-3	day	hr	dispdsrn	WINDIR	WINDSPD	ISTAB	RNMM
			12345678901234567						
			1	1	37	137	0		
			1	2	6	147	0		
...			1	23	25	305	0		
...			1	24	26	305	0		
			5	10	45	85	0		
			5	11	45	114	0		
			5	12	7	244	0		
			5	13	8	274	0		
			5	14	7	253	0		
			5	15	5	214	0		
			5	16	4	174	0		
			5	17	63	105	0		
			5	18	9	105	0		

WINDIR	Wind direction sector #
WINDSPD	Wind speed
ISTAB	Stability Class
RNMM	Rain Rate

Figure 3-1 Sample Meteorological File Data Format

Meteorological data are typically derived from measurements from a site meteorological program conforming to ANSI/ANS-3.11-2010 or its equivalent. The data should satisfy the requirements of Regulatory Guide 1.23 [47]. At least one year's worth of weather data are necessary, preferably from a year that reasonably represents long-term weather conditions. It is common to conduct a sensitivity analysis over five or more years of meteorological data to determine the impact of the choice of year on key consequence analysis metrics, such as early and cancer fatality risk, population dose, and economic results. An example of performing such a sensitivity analysis can be found in Section 6.5.3 of the Sequoyah SOARCA report [15]. The purpose of such a sensitivity analysis is to confirm that a weather year is representative of longer term weather variability at a site.

¹ Note that wind speed in a MACCS meteorological file is given in tenths of a meter per second, and rain rate is given in hundredths of an inch.

As an alternative to performing sensitivity analyses on the choice of weather year when five or more years of high-quality onsite weather observations are not available, the characteristics of the year(s) for which data are available can be compared with records from nearby (within a 50-mile radius) weather stations. Archived data are available online from the National Centers for Environmental Information [48] for many National Weather Service Stations. Information such as the relative frequency of stability classes, wind speeds, hours of precipitation, and total precipitation can serve to judge the representativeness of the selected weather year(s) relative to long-term trends. Wind rose data can be derived from site data and compared to those from nearby weather stations to identify whether there are any significant local variations in wind patterns within the region.

Observational data at the 10-meter level are typically used to create a MACCS meteorological file. Observational data are converted to MACCS format by adjusting the units for wind speed and precipitation, adjusting the wind speed to the 10-meter equivalent, converting the wind direction from degrees to MACCS sectors, determining the stability class, and filling in any missing data.

Meteorological data consistent with Regulatory Guide 1.23 [47] will have observations at the 10 meter level. As noted in [49], “The 10-meter level is considered to be representative of the layer through which the plume is mixed when subjected to building wake effects.” Wind speeds increase with increasing height. The increase in wind speed with elevation approximately follows a power law relationship with an exponent that is a function of stability and surface roughness [50] [51], [52]. If observations are only available at elevations other than 10 meters, they should be corrected to the 10-meter level using the relationship provided in Section 4-5 of [51]. If observations are available at two different elevations at a site, site-specific values of the power law exponent used to characterize the vertical wind speed profile may be derived [52].

The user should be aware that although wind direction is defined in Regulatory Guide 1.23 [47] in terms of the direction **from** which the wind is blowing, MACCS requires that the wind direction be provided in terms of the compass sector **toward** which the wind is blowing. When performing this conversion, the user should be aware that the MACCS compass sectors are numbered beginning with 1, where sector 1 is **centered** on north. Therefore, for example, for a 64-sector meteorological file, Sector 1 (wind blowing toward north) would comprise those wind direction observations centered on 180° and with a width of 5.625° (i.e., winds blowing from 177.1875° to 182.8125°).

There are a variety of methods for estimating atmospheric stability from meteorological data. Table 1 of Regulatory Guide 1.23 [47] provides for a classification of atmospheric stability using the vertical temperature difference as measured onsite to determine Pasquill stability classes. However, a variety of alternate methods for estimating atmospheric stability are described in Section 6.4 of [52]. For example, a method developed by Turner [53], using meteorological data that are routinely collected at National Weather Service stations, is the recommended approach in [52]. Other methods described in [52] rely on estimates of solar radiation, vertical temperature difference, wind speed, and/or fluctuations of the wind elevation or azimuth. Use of the method described in Table 1 of Regulatory Guide 1.23 [47] is recommended when the necessary data is available because it is consistent with several common modifications to the Gaussian plume model.

Missing hourly data are a common occurrence even for high-quality meteorological data sets. Data recovery in excess of 90% is preferable for the data used to generate the meteorological file. If only a single hour of data are missing, they may be bridged over by averaging the surrounding hours or substituting measurements from a co-located sensor (with adjustment if

needed). If longer gaps occur, it is recommended that the data be filled in by a qualified meteorologist following the recommendations of [54] and [52].

In addition to hourly measurements, MACCS uses the mixing height to constrain vertical mixing. Mixing height can be specified in MACCS to vary as a function of the season of the year and the time of day at which the release begins by setting the flag for mixing height (MAXHGT) to the value DAY_AND_NIGHT and defining the latitude and longitude of the site (used for computing the times of sunrise and sunset.). The meteorological file specifies morning and afternoon mixing heights for four seasons (a total of eight entries). Mixing height data require upper air measurements which are only available at selected locations across the United States. Potential sources of mixing height data include [55] or the U.S Environmental Protection Agency (EPA) Support Center for Regulatory Atmospheric Modeling (SCRAM) upper air databases [56].

Parameter Name: not applicable

Parameter Description: Meteorological File Name

Recommended Value: Problem specific, usually developed based on site-specific hourly meteorological observations

Uncertainty Range: weather files from different years or observational locations may be used to evaluate the uncertainty introduced by annual or spatial variability in weather data.

References: based on site-specific sources for meteorological data; [47], [2], [55], [56]

Discussion: The name of the meteorological file is not a MACCS parameter. It is passed to the MACCS executable as a command line argument. In WinMACCS, the meteorological file is entered in the File Specification tab. The meteorological file should be developed and reviewed as discussed above. Assigning a descriptive name (i.e., including the name of the site, the year on which the data were based, and the number of sectors used in the file) may facilitate keeping track of which file was used when multiple files have been developed for a particular analysis. Although a weather file based on a single year is typically sampled to address meteorological uncertainty, multiple weather files may be developed and used to evaluate the uncertainty introduced by using a single representative weather year. The meteorological file should be evaluated to ensure that the resulting summary statistics are consistent with long-term weather data at the site.

Parameter Name: MAXHGT

Parameter Description: Flag for Mixing Height

Recommended Value: DAY_AND_NIGHT

Uncertainty Range: not applicable

References: [40]

Discussion: When MAXHGT is set to the value DAY_AND_NIGHT, both daytime and nighttime values of the mixing heights in the meteorological data file are used. MACCS estimates the mixing height value by linear interpolation between the minimum and the maximum, based on the time of day. Once the maximum mixing height is attained, it is held constant for the duration of a calculation. When MAXHGT is set to the value DAY_ONLY, MACCS uses only the maximum seasonal values, which normally correspond to the daytime values.

Parameter Name(s): LATITU, LONGIT

Parameter Description: Latitude and Longitude of Power Plant

Recommended Value: site specific

Uncertainty Range: not applicable

References: [40], other sources with information on facility location

Discussion: The site location is used to determine the time of sunrise and sunset for each day of the year. It is also used by WinMACCS when generating map files with MapGen, which allows maps to be displayed behind speed multiplier and network evacuation forms, Radial Evacuation Speed, Network Evacuation Direction, and Network Evacuation Speed.

3.2 Meteorological Sampling

The Gaussian plume segment model in MACCS relies on the use of a weather sequence, which is a sequence of successive hourly values of the weather conditions contained in a meteorological file (i.e., wind speed, wind direction, stability class, and precipitation). A weather sequence in MACCS is significantly more complex than just a point value of weather data. A weather sequence is defined by the starting hour of weather data from the meteorological data file. However, the weather sequence uses as much sequential data from the meteorological data file as required to transport all plume segments through and out of the computational grid. An overall atmospheric release (source term) may be described by up to 500 plume segments, each of which can start at a different time after the beginning of the release. Each plume segment can travel in a different direction, and it is affected by the hourly data (i.e., wind speed, stability class, and precipitation rate) taken from the weather file starting with the hour of its release from the source location and continuing until it exits the computational grid.

MACCS has several approaches for treating weather data, as described in Section 5.13 of [2]. The user can either specify a particular weather sequence or sample weather sequences from the meteorological file. Many applications of MACCS require consideration of the variability in potential weather conditions at the time of a hypothetical accident. Evaluation of this variability requires some form of sampling of meteorological data. The user has two options for sampling weather. The first method, known as weather bin sampling, is implemented by assigning the MACCS METCOD variable to be 2. Weather bin sampling is a form of importance sampling and is described in Appendix B of [20]. Because key meteorological variables that affect consequences are wind speed, stability class, intensity of precipitation, and distance a plume segment has traveled when precipitation begins, the weather binning algorithms in MACCS categorize similar sets of weather data based on these parameters. Wind direction is also a key variable that affects consequences. The assumption is that sampling within each weather bin is sufficient to adequately represent the wind rose, i.e., the likelihood of the wind blowing in each compass direction for that bin. The second method for weather sampling is known as stratified random sampling and is implemented by assigning the METCOD variable to a value of 5. In this method, a specified number of samples are selected randomly from each day of the year.

The choice of a weather sampling method involves balancing consideration of the desired accuracy with the computational time needed to complete the analyses. Hanna [57] recommends that, given the perceived complexity of the weather binning process and the increased computing power available over the last several decades, that direct use of all available weather data should be used to improve clarity in the discussion of the results. This can effectively be accomplished by using stratified random sampling (METCOD = 5) with 24 samples per day, as recommended in Chapter 4 of [10]. This approach effectively samples each hour of every day from the weather file. If this choice results in excessive computational time, the most efficient sampling method is nonuniform bin sampling, because it produces greater statistical accuracy with fewer samples than either stratified random sampling or uniform bin sampling. For the output measures examined in the SOARCA Peach Bottom uncertainty analysis, a sensitivity analysis showed that

mean results using 1,000 weather sequences were within 1 to 2% of those using all 8,760 potential sequences, while reducing the computing time by a factor of eight [30].

The weather binning process begins by determining which of the 8,760 starting hours (the number of hours in a 365-day year) belong to a rain bin, which depends on whether precipitation occurs before a plume segment travels a user-specified distance. The user specifies a set of distances (RNDSTS) and precipitation intensities (RN RATE). NRNINT is the number of rain distances and NRINTN is the number of rain intensities. These parameters allow the user to create a set of rain bins. Hours of weather data that are not included in one of the rain bins are categorized based on wind speed and stability class. Wind speed and stability class bins are fixed within MACCS and cannot be changed by the user.

The rain intensities and rain distances, used to define the rain bins, can be set with consideration of the distribution of precipitation intensity and the variation in population density with distance from the site and the evacuation boundary. Sample Problem A bin definitions are reasonable for most applications, but alternate site-specific values may also be reasonable. For example, if a population center is located within a range of distances from a site, rain distances can be chosen to ensure that precipitation over that population center will be sampled.

Bin sampling can be accomplished either with uniform or nonuniform sampling. In uniform bin sampling, the number of samples (NSMPLS) is the same for each weather bin. This approach was used in NUREG-1150 [4], with four samples per bin. However, this is not the most efficient option because some bins contain very few observations and those bins may be fully sampled; whereas, other bins contain a much larger number of observations and may be under sampled. An alternate approach is nonuniform bin sampling, which allows statistically valid estimates to be produced with significantly fewer computer time than sampling all sequences. The advantage of this sampling method is that results that may significantly affect the mean value (for example, events where heavy to moderate rainfall begins after a plume has traveled over a populated area) are sampled but properly weighted.

Nonuniform bin sampling is chosen by setting NSMPLS to zero and assigning the number of samples from each weather bin using the vector INWGHT. For each sequence, the probability (PRBMET) is defined by the bin probability divided by the number of samples chosen for the bin. The sequence probability, PRBMET, is used to weight the results for that sequence. For example, the mean value can be calculated by summing the product of the results and the respective values of PRBMET.

If the analyst chooses not to use all the available meteorological data, the weather sampling approach adopted in SOARCA is recommended. The sampling approach used in SOARCA is to assign the value of INWGHT for a particular bin to the maximum of either 10% of the observations in the bin or 12 observations. A few of the bins may contain less than 12 observations, in which case all of them are sampled. The total number of sequences in each bin can be determined by processing the meteorological file using ATMOS with the assigned rain distances and intensities and using the resulting bin classification to adjust the number of samples for each bin. This strategy results in approximately 1,000 weather trials.

The MACCS variable IRSEED is used to ensure that the random number generator produces a consistent set of weather trials among different MACCS runs, so differences between MACCS runs are due to changes in MACCS input parameters, not to the weather sampling. A set of runs with identical bin definitions (as defined by NRINTN, RN RATE, NRNINT, and RNDSTS), IRSEED and either NSMPLS (for uniform bin sampling) or INWGHT (for nonuniform bin sampling), use the same set of weather sequences.

Parameter Name: METCOD

Parameter Description: Meteorological Sampling Option Code

Recommended Value: 5 (if all weather data are to be sampled) or 2 (if nonuniform bin sampling is used)

Uncertainty Range: not applicable

References: [2], [40], [14]

Discussion: METCOD is the meteorological sampling option code and can take the following values:

- 1 - fixed start time in the weather file (day, hour),
- 2 - weather bin sampling,
- 3 - 120 hours of weather data supplied by user,
- 4 - constant weather conditions (uses boundary weather),
- 5 - stratified random sampling from equally spaced intervals.

Use of all available weather data (METCOD=5, NSMPLS=24) is recommended unless it results in excessive computational time; otherwise, the most efficient sampling method is non-uniform bin sampling (METCOD=2, NSMPLS=0).

Parameter Name: NSMPLS

Parameter Description: Number of Weather Sequences Chosen Per Bin or Day

Recommended Value: 24 (in conjunction with METCOD = 5 if all weather data are to be sampled) or 0 (in conjunction with METCOD = 2 if nonuniform bin sampling is used)

Uncertainty Range: not applicable

References: [2], [40], [14]

Discussion: Use of all available weather data (METCOD=5, NSMPLS=24) is recommended unless it results in excessive computational time; otherwise, the most efficient sampling method is non-uniform bin sampling (METCOD=2, NSMPLS=0). If METCOD = 2 (bin sampling) is selected, assigning NSMPLS =0 invokes the recommended nonuniform bin sampling with the number of samples defined by the variable INWGHT. If the user desires to sample all meteorological data, NSMPLS may be set to 24 in conjunction with METCOD 5.

Parameter Name: NRINTN

Parameter Description: Number of Rain Intensity Breakpoints

Recommended Value: 3, but alternate values may be justified on a site or analysis specific basis

Uncertainty Range: not applicable

References: [2], [40], [14], [5]

Discussion: The number of rain intensity breakpoints for binning may be justified on a site-specific basis, but the values used in the MACCS sample problem are reasonable for most analyses.

Parameter Name: RNRATE

Parameter Description: Rain Intensity Breakpoints for Weather Binning

Recommended Value: 2, 4, 6 mm/hr; alternate values may be justified on a site or analysis specific basis

Uncertainty Range: not applicable

References: [2], [40], [14], [5]

Discussion: The rain intensity breakpoints for weather binning may be justified on a site-specific basis, but the values used in the MACCS sample problem are reasonable for most analyses. NUREG-1150, as documented in Appendix A.1 of [5], used values of 2, 4, and 6 mm/hr respectively.

Parameter Name: NRNINT

Parameter Description: Number of Rain Distance Intervals

Recommended Value: 5, but alternate values may be justified on a site or analysis specific basis

Uncertainty Range: not applicable

References: [2], [40], [14], [5]

Discussion: The values used in the MACCS sample problem are reasonable for most analyses, but the number of rain distance intervals for binning may be justified on a site-specific basis. For example, NUREG-1150, as documented in Appendix A.1 of [5], used 5 rain distance intervals.

Parameter Name: RNDSTS

Parameter Description: Endpoints of Rain Distance Intervals

Recommended Value: 3.22, 5.63, 11.27, 20.92, 32.19 km; alternate values may be justified on a site or analysis specific basis

Uncertainty Range: not applicable

References: [2], [40], [14], [5]

Discussion: The endpoints of the rain distance intervals must be chosen to match the spatial endpoint distances in the array SPAEND to within 10%. The values used in the MACCS sample problem are reasonable for most analyses, but alternate values may be justified on a site-specific basis. For example, NUREG-1150, as documented in Appendix A.1 of [5], used 5 rain distance intervals (ending at 3.22, 5.63, 11.27, 20.92, and 32.19 km, respectively).

Parameter Name: NSBINS

Parameter Description: Number of Weather Bins to Sample

Recommended Value: Equal to the total number of weather bins

Uncertainty Range: not applicable

References: [2], [40], [14]

Discussion: NSBINS defines the number of bins to be sampled, up to the total number of weather bins determined by the parameters NRINTN and NRNINT. This value may be set in conjunction with INDXBN to sample only selected weather bins if the user wishes to examine the effect of specific weather bins. However, for most applications all weather bins should be sampled. If WinMACCS is used, this value is set automatically for the user to the total number of weather bins.

Parameter Name: INDXBN

Parameter Description: Index of Weather Bins to be Sampled For Nonuniform Weather Bin Sampling

Recommended Value: Set to sample all weather bins

Uncertainty Range: not applicable

References: [2], [40], [14]

Discussion: INDXBN defines the index of the bins to be sampled, up to the total number of weather bins NSBINS determined by the parameters NRINTN and NRNINT. The index for the individual user-definable rain bins may be identified by executing MACCS with the ATMOS option only and examining the section of the output file titled "METEOROLOGICAL BIN SUMMARY." This value may be set in conjunction with INWGHT to sample only selected weather bins if the user wishes to examine the effect of specific weather bins. However, for most applications all weather bins should be sampled.

Parameter Name: INWGHT

Parameter Description: Number of Samples for Each Bin Used for Nonuniform Weather Bin Sampling

Recommended Value: If nonuniform bin sampling is used, 10% of the available sequences in the bin, with a minimum value of either 12 or the number of samples in the bin.

Uncertainty Range: not applicable

References: [2], [40], [14]

Discussion: Use of the nonuniform bin sampling approach developed for the SOARCA analyses generated approximately with 1,000 samples versus all 8,760 potential sequences. The variation of the number of samples in each bin affects the total number of samples and hence both the accuracy and computational time of the final analyses. Assigning the MACCS variable RISCAT a value of "TRUE" evaluates the relative contribution of each of the weather category bins to the mean consequence values, which may be useful in choosing how many samples to draw from each bin. Alternatively, the user can assign values of INWGHT to be non-zero for only one bin in order to examine the effect of that bin on the overall results.

Parameter Name: IRSEED

Parameter Description: Seed for Random Number Generator

Recommended Value: any value between 0 and 255 can be used.

Uncertainty Range: not applicable

References: [2], [40], [14]

Discussion: Any value between 0 and 255 can be used. If a user wants to select a set of weather trials to conservatively estimate a particular MACCS output, preliminary analyses can be done with different values of IRSEED to select a value that provides a conservative estimate of a particular output for a given meteorological file, as discussed in Chapter 4 of [10]. If multiple MACCS outputs are of interest in a single analysis, it may not be possible to select a single bounding value of IRSEED that maximizes all of the outputs of interest.

3.3 Boundary Weather

MACCS has the capability to apply a user-specified set of weather conditions beyond a user-defined spatial interval, a capability known as boundary weather. The physical basis for this assumption is documented in Section 7 of Appendix VI of WASH-1400 [3], which notes that tropospheric aerosols typically have a finite residence time on the order of 2–4 days (48–96 hours) before being deposited by wet deposition. Based on the data from the six representative sites, WASH-1400 estimated that 100 hours was approximately the median travel time for a plume to travel a distance of 500 miles, and therefore considered the simplification of depositing any remaining airborne particulate radioactive material starting at 500 miles to be a

reasonable approach for accounting for the eventual fate of airborne material. Similarly, NUREG-1150 [4] chose to specify the occurrence of rain in the outermost spatial interval beyond 500 miles to prevent radioactive material from escaping consideration. Appendix A.5.3 of NUREG-1150 [4] characterizes this approach as “a special artifice of calculation...used to gradually deplete the plume of its remaining radionuclide content in particulate form and deposit it on the ground. The purpose of doing this was to provide a nearly complete accounting of the radionuclides released in particulate form from the plant” [4]. This technical rationale applied in NUREG-1150 should only be considered when the boundary weather and depleting rainfall is applied beyond 500 miles. If boundary weather is used at distances closer than 500 miles, forcing wet deposition may artificially increase consequence estimates and is not recommended.

Boundary weather is used at all distances when METCOD = 4 (constant weather) is selected. Earlier versions of MACCS read only 120 hours of weather data from the weather file. Because of the flexibility that ATMOS allows in the definition of the spatial grid, it was possible that the 120-hour sequence of weather data used in MACCS may not be enough to carry all the plume segments out to the last spatial interval, and the defined boundary weather was used for these cases. However, MACCS 3.10 treats 1,200 hours of weather data instead of 120. The only place boundary weather is currently used is therefore beyond the radius denoted by LIMSPA. Nonetheless, the user is required to specify a set of boundary weather conditions.

There are several approaches for assigning boundary weather parameters. Assignment of constant rainfall conditions at distances significantly closer than five hundred miles may not have a physical basis and is therefore not recommended for most applications. For most analyses, where results at closer distances (for example, 50-mile results) are of interest, LIMSPA may be set at the last spatial interval and boundary weather parameters may be set to default values from the sample problem or average conditions derived from the local or regional meteorological data. For example, boundary weather conditions for the mixing height, stability class, wind speed, and rainfall rate can be based on mean values of wind speed, mixing height, and precipitation rate and on the most likely stability class from the meteorological data file as long as these values are reasonably representative of the weather approximately 500 miles away (primarily toward the east since wind conditions across the U.S. are dominated by winds from the west).

Parameter Name: LIMSPA

Parameter Description: Last Interval for Measured Weather

Recommended Value: Index corresponding to final spatial interval

Uncertainty Range: not applicable

References: Section 7 of Appendix VI of [3], Appendix A.5.3 of [4]

Discussion: LIMSPA is the index of the last spatial interval for using recorded weather data from a meteorological file. It is recommended to assign LIMSPA equal to the index of last spatial interval to avoid use of constant weather conditions if observed data from a meteorological file are available, unless a very long distance (>500 mi) calculation is being performed, in which case LIMSPA may be chosen to correspond to the interval ending at approximately 500 mi.

Parameter Name: BNDMXH

Parameter Description: Boundary Weather Mixing Layer Height

Recommended Value: No recommendation

Uncertainty Range: not available

References: [55]

Discussion: BNDMXH is the mixing layer height to be used for constant weather conditions; it is not used for boundary weather. It should be chosen appropriately when a constant weather situation is evaluated. This parameter has no influence on calculations that use weather sampling, so its choice is arbitrary.

Parameter Name: BNDWND

Parameter Description: Boundary Weather Wind Speed

Recommended Value: Site-specific average OR 5 m/s

Uncertainty Range: not available

References: not available

Discussion: BNDWND is the wind speed to be used for boundary weather conditions. If LIMSPA is set at the last spatial interval and meteorological data are used, a value for this parameter is required but is unlikely to be used in the calculations. Use of either a site-specific average, a regional average, or a U.S. average of 5 m/s is generally recommended.

Parameter Name: IDBSTB

Parameter Description: Boundary Weather Stability Class Index

Recommended Value: Most likely value (mode) from site-specific data OR 4 (D stability, neutral stability conditions)

Uncertainty Range: not available

References: not available

Discussion: IDBSTB is the stability class to be used for boundary weather conditions. If LIMSPA is set at the last spatial interval and meteorological data are used, a value for this parameter is required but is not used in the calculations. Use of either a site-specific average or a default value of 4 for a neutral D stability class is generally recommended.

Parameter Name: BNDRAN

Parameter Description: Boundary Weather Rain Rate

Recommended Value: Site-specific average OR 0 mm/hr OR 5 mm/hr if the radius corresponding to LIMSPA > 500 miles.

Uncertainty Range: not applicable

References: Section 7 of Appendix VI of [3], Appendix A.5.3 of [4]

Discussion: If LIMSPA is chosen to be the last spatial interval and meteorological data are used, a value for this parameter is required but is unlikely to be used in the calculations. Use of either a site-specific average or a default 0 mm/hr is recommended. If a long distance (>500 mi) calculation is being performed, setting this value to the sample problem value of 5 mm/hr (moderate rainfall) ensures that the released aerosols are deposited after several days of transport, as discussed in Appendix VI of WASH-1400.

3.4 Wind Shift and Wind Rotation

MACCS has several options for treating changes in wind direction (wind shifts) during a release. Wind shift carries the idea of variations in wind direction. Wind shift only matters when a release is divided into multiple plume segments. The simplest Gaussian plume methods do not allow any variations in wind conditions. These methods treat the entire plume as transporting in a single

direction under constant conditions. The MACCS implementation of the Gaussian plume model is significantly more general. One of the generalizations is that plume segments can travel in different directions, depending on the directions indicated in the weather data at the time the segment is released (more precisely, when the point of the plume segment specified by REFTIM is released). For example, suppose the wind blows toward the north in the first hour and to the east in the second hour. If two plume segments are modeled, each with release duration of one hour and the second beginning immediately after the first is fully released, the first plume segment travels north. The direction of the second plume segment depends on whether wind shift is included in the calculation or not. If it is, the second plume segment travels in the direction that the weather data indicate, to the east. If it is not, both plume segments travel in the same direction, to the north. Consideration of wind shifts is the recommended modeling approach for nearly all MACCS analyses that account for more than a single plume segment.

Wind rotation is a numerical convenience for extracting more information out of a set of results without significantly increasing the amount of computational time required. A set of results is constructed for each weather sequence by considering that the wind might have blown toward each compass direction. This is equivalent to rotating the results for the weather trial around the compass, one compass sector at a time. This process creates an expanded set of results, i.e., one for each compass sector, for each weather trial. The total number of results generated by this process is the number of compass sectors (defined by the MACCS variable NUMCOR) times the number of weather trials. Probabilities for each of the rotated results are calculated by using the wind rose probabilities for the corresponding weather bin or using a user-defined wind rose (defined by the variable WINROS), depending on the wind rose option (defined by the variable OVERRID) selected by the user. The user can either use a straight-line model without wind shifts (IPLUME = 1), in which all plume segments travel in the same direction, or a wind shift model (IPLUME = 2), in which each plume segment in the release travels in the direction that the wind is blowing at the time that its representative time point (REFTIM in Section 5.11 of [2]) leaves the facility. However, when evacuation is not radially symmetric (for example, when the evacuation direction is explicitly modeled by the use of a network evacuation model or by the use of a grid element specific speed multiplier), the assumption of symmetry breaks down and rotation cannot be used. MACCS therefore has the option to treat wind shifts without rotation (IPLUME = 3), so only one result is computed per weather sequence. Furthermore, rotation should not be used when more than a few plume segments are modeled because the weather pattern may have a probability significantly different than the wind rose probability of the initial wind direction.

Parameter Name: IPLUME

Parameter Description: Wind Shift and Rotation Flag

Recommended Value: 3 (wind shift without rotation) if an asymmetric evacuation model is developed; 2 (wind shift with rotation) if a symmetric radial evacuation or no evacuation is modeled and only one or two plume segments are treated, or 1 for a straight-line model without wind shifts.

Uncertainty Range: not applicable

References: [2]

Discussion: When a network evacuation model or the spatially dependent speed multiplier model is used, WinMACCS only allows IPLUME = 3. When a single plume segment is modeled, choosing IPLUME = 1 enables centerline results to be printed. Choosing IPLUME = 2 is only reasonable when one or two plume segments are modeled and when the evacuation parameters are independent of compass direction.

Parameter Name: OVRRID

Parameter Description: Wind Rose Probabilities Flag

Recommended Value: FALSE

Uncertainty Range: not applicable

References: [2]

Discussion: When performing calculations that use rotation (IPLUME = 1 or 2), the user can override the wind rose (probability that the wind blows into a given sector determined by ATMOS from the meteorological file) and replace it with user-defined probabilities defined by the variable WINROS. The recommended approach is to use the wind rose defined by ATMOS from the meteorological data file.

3.5 Spatial Grid Definition

The spatial domain is defined within MACCS by the variable NUMRAD (the number of radial intervals), NUMCOR (the number of compass sectors), and SPAEND (the radial distance from the release point (i.e., from the center of the polar coordinate system), for each radial interval). Definition of a spatial grid for modeling involves consideration of the objectives of the analysis and the limitations of the models used by MACCS.

The analyst assigns the number of compass sectors in the spatial grid (NUMCOR). NUMCOR can be defined to be 16, 32, 48, or 64 sectors. The number of sectors must be consistent with the site file, the meteorological file, and MACCS grid definition. Within the Sector Population and Economic Estimator (SecPop) code [58], the number of compass sectors in the site file is defined by the user in the “Grid Definition” tab. The user must ensure that the number of sectors, or wind directions, in the meteorological file is consistent with the number of sectors defined in the site file and in WinMACCS. The results are computed incorrectly if the number of sectors is inconsistent between the MACCS grid definition, the site file, and the meteorological file. In older analyses, such as NUREG-1150 [4], 16 radial sectors were the only option available. Recent SOARCA analyses divided the problem areas into 64 sectors since it provides the highest degree of grid resolution available in MACCS and allows for a more realistic modeling and resolution for results. This has become the recommended choice for MACCS. This enhancement was implemented in response to the SOARCA peer review [16]. An example of the meteorological file format is provided in Figure 3-1. The wind direction sector is provided in columns 9 and 10 and is shown with a blue circle in Figure 3-1. The analyst can determine the number of sectors in the meteorological file by reviewing all the data in columns 9 and 10. A 16-sector meteorological file does not have any WINDIR greater than 16. A 64-sector meteorological file has WINDIR values greater than 48 but less than or equal to 64.

The analyst can designate up to 35 radial distances in both SecPop and MACCS. Grid spacing is typically at finer intervals close to the site, with larger intervals being more appropriate at longer distances. The grid is typically defined more finely for the EPZ and (when included) the shadow evacuation area. The spatial grid is an important element of the overall model, so time should be taken to consider site demographics, state and or local protective action guides (PAGs) and relocation information, the exclusion area boundary (EAB), and protective action recommendations. Emergency plans have actions and recommendations for the 2, 5 and 10-mile areas. Mapping applications can allow the analyst to zoom into a map of the NPP to determine the distance to the EAB as well as where the first household is in the low population zone. In addition, spatial distances called out in the results must be a spatial value designated in SPAEND.

Depending on the purpose of the analysis, there are several distances that typically need to be included when defining the radial intervals. Distances of 10 and 50 miles are typically used in current regulatory applications. The distance to the EAB should be defined so that the offsite population can be accurately located. Although the EAB is typically an irregular polygon, a single radius appropriate for the analysis (for example, the minimum distance or the most likely distance) should be selected. Intervals associated with specific measures (i.e., within one mile of the site boundary for the early fatality quantitative health objective or within 10 miles from the site for the latent cancer quantitative health objective) may be defined and distances commonly used in early phase protective action models (for example, 2, 5, and 10 miles) may be included. Also, if there is a unique feature the analyst wants to evaluate, radial distances pertinent to that feature should be included in the spatial distances. For example, if there is a large employer whose employees travel into the EPZ for work, the analyst may want to include distances that will allow the analysis to pinpoint grids that contain population specific to that large employer. Spatial intervals containing population clusters or special facilities (inside or outside the EPZ) can be defined to allow modeling of those populations. Examples of the SPAEND values used in recent analyses are given in Table 3-1.

Table 3-1 Example SPAEND Values

NUMRAD	SPAEND (mi)
1	0.10
2	0.35
3	0.65
4	1.00
5	1.35
6	2.00
7	2.50
8	3.00
9	3.50
10	5.00
11	7.00
12	10.00
13	13.00
14	15.00
15	20.00
16	25.00
17	30.00
18	40.00
19	50.00
20	70.00
21	100.00
22	150.00
23	200.00
24	350.00
25	500.00
26	1,000.00

Source: [14]

A simple and practical formula for designing a grid is based on a geometric spacing for δr as follows:

$$\delta r_n = x^n \cdot \delta r_0 \quad (3-1)$$

$$r_n = r_{n-1} + \delta r_{n-1} \quad (3-2)$$

$$r_N = \sum_{n=0}^{N-1} \delta r_n = \delta r_0 \cdot \sum_{n=0}^{N-1} x^n \quad (3-3)$$

Here,

- $r_0 = 0$ is the inner radius of first grid element (i.e., the center point of the first grid element),
- r_n is the outer radius of the n^{th} polar grid element, and
- x is a geometric factor.

The user usually needs to define $\delta r_0 = r_1$ and r_N , the outermost radius in the grid, as well as the number of rings in the grid, N . The geometric factor, x , must be defined by solving Equation (3-3), which is nonlinear. This approach can be used to define a set of subregions with boundaries that match specific distances that are important for the application. When this is done, each subregion has a different value of the geometric factor, x .

The outer limit of the analysis is defined by the maximum value of the MACCS array SPAEND. The specification of the outer grid elements depends on the level of detail desired in the reported outputs, the purpose of the analysis, and consideration of the applicability of the Gaussian plume segment model. A 50-mile radius is commonly used in cost-benefit analyses for LWR accidents based on NUREG/BR-0184 [18]. NUREG-1150 [4], as well as its supporting and supplemental analyses [59] [60], tabulated values out to 1,000 miles²; however, the use of the current MACCS atmospheric dispersion model at those great distances is subject to considerable uncertainty. Benchmarking of the results from MACCS against more complex models was performed in the analyses documented in NUREG/CR-6853 [61]. This study compared MACCS2 to ADAPT/LODI, a state-of-the-art, three-dimensional advection dispersion code. The selected site was a relatively simple terrain site in Oklahoma but the site is affected by low level nocturnal jets and occasional severe storms. Overall, the arc average and the great majority of the arc-sector average exposures and depositions calculated by MACCS were within a factor of two of the results computed by LODI [61]. Although these results were obtained at a relatively simple terrain site, they do provide a basis for use of the MACCS Gaussian plume segment model at distances of up to 100 miles. Results at distances of greater than 100 miles should be viewed with caution because the Gaussian plume segment model in MACCS was not benchmarked in [61] at distances greater than 100 miles. Several reviewers of the SOARCA project recommended caution in use of values beyond 50 miles [16].

As discussed in [10], the characteristics of Gaussian models should be considered when selecting the distances for modeling and evaluating the model results. Citing the 1977 AMS position paper on the accuracy of dispersion models [62], [10] considers the use of a Gaussian model at distances closer than 100 meters or at distances of greater than 20 km (12.5 mi) to result in concentration estimates that are accurate to within only about an order of magnitude. Based on the analyses documented in [61], use of the MACCS code to distances of up to 100 miles is considered reasonable, with due consideration of the potential uncertainties involved.

² NUREG-1150 characterizes the distances as “within 50 miles” and “entire site region.” The radius corresponding to the “entire site region” is defined in NUREG-1150 Appendix A, Section A.5.3, as 1,000 miles.

Parameter Name: NUMCOR

Parameter Description: Number of Compass Sectors in the Grid

Recommended Value: 64 if high resolution meteorological data are available, 16 otherwise.

Uncertainty Range: not applicable

References: [16], [14]

Discussion: If meteorological data are available in terms of degrees (rather than sectors) and if SecPop is used to generate a site file, the use of 64 radial sectors adds additional spatial resolution to the results without excessive data generation requirements and is recommended. Older versions of SecPop such as SECPOP2000 supported only 16 compass directions. For compatibility with MACCS models that require more compass directions, WinMACCS can create a site file that supports 32, 48, or 64 sectors from a site file that supports 16 sectors. Newer versions of SecPop allow the construction of gridded population and economic data with up to 64 radial sectors. If the available meteorological and population data are limited to the traditional 16 compass sectors, use of 16 sectors is reasonable.

Parameter Name: NUMRAD

Parameter Description: Number of Radial Spatial Intervals

Recommended Value: site specific; can be adapted from the Sample Problem A grid or the SOARCA grid

Uncertainty Range: not applicable

References: [5], [2], [14]

Discussion: There must be a minimum of 2 radii and there can be up to a maximum of 35 radii. The actual number needed depends on the desired spatial grid defined by SPAEND. Typically, MACCS models have between 25 and 30 radii. The Sample Problem A values are based on NUREG-1150 [4] values with inner intervals consistent with the Surry exclusion area distance. These values may be used as a starting point and then adjusted for the site and the region of interest under consideration for the analysis. Results from grid elements beyond 100 miles should be used with caution. Results within 100 to 500 meters from the release point should be used with consideration of the potential for building wake effects, plume meander, and dispersion parameterizations appropriate for close ranges (see Sections 3.6 and 3.7).

Parameter Name: SPAEND

Parameter Description: Radial Distances for Grid Boundaries

Recommended Value: site specific; can be adapted from the Sample Problem A grid or be based on the geometric spacing suggested earlier in this section

Uncertainty Range: not applicable

References: [5], [2], [14], [16]

Discussion: SPAEND is defined as the spatial distance from the inner to the outer radius of each grid element. The first radius can be as small as 0.05 km and there must be at least 0.1 km (0.062 miles) between consecutive radii. Additionally, the spatial designations in the site file must be within 10% of each SPAEND designation. Optimally, there should not be any difference in the intervals between the site file and MACCS SPAEND values. WinMACCS facilitates consistency by updating the definitions of SPAEND to match the values in the site file.

The Sample Problem A values are based on NUREG-1150 [4] values with inner intervals consistent with the Surry exclusion area distance. These values may be used as a starting

point and then adjusted for the site and the region of interest under consideration for the analysis. Alternatively, the geometric spacing suggested in Equations (3-1) to (3-3) can be used to define the values of SPAEND, especially when the locations of interest are significantly different than those in Sample Problem A. Results from grid elements beyond 100 miles should be used with caution. Results within 100 to 500 meters from the release point should be used with consideration of the potential for building wake effects and dispersion parameterizations appropriate for close ranges (see Sections 3.6 and 3.7).

Parameter Name: NUMFIN

Parameter Description: Number of Fine Grid Subdivisions

Recommended Value: 7

Uncertainty Range: not applicable

References: [2], [14]

Discussion: The maximum allowable value of fine grid elements defined by NUMFIN is recommended for most analyses. The primary environmental concentrations calculated in the ATMOS module include the integrated plume centerline ground level atmospheric concentration ($\text{Bq}\cdot\text{s}/\text{m}^3$) and integrated deposition (Bq/m^2) below the plume centerline. Transverse dispersion causes concentrations away from the centerline of the plume to be less than those at the plume centerline. To compute doses to individuals who are not on the plume centerline, MACCS computes an off-centerline correction factor as described in [20], Section 3.1.1 (for early phase exposure pathways) and in Section 3.2.1 (for the intermediate and late phase exposure pathways). The correction factor for the early phase exposure pathways is computed by averaging the Gaussian distribution in the crosswind direction over each fine grid, which results in a set of steps with the number of steps controlled by the MACCS variable NUMFIN. The factor is defined as the ratio of the height of the crosswind histogram at a given distance from the plume centerline to the height of the Gaussian peak. Jow et al. [20] states that the same crosswind correction factor for intermediate and late phase exposure pathways is used for both of those phases, except that the correction factors are averaged over a coarse grid in these phases. Because there is no significant computational penalty associated with using the highest resolution available, it is recommended that NUMFIN be defined with a value of seven.

3.6 Dispersion/Turbulence Parameterizations

The Gaussian plume segment model requires two spatially dependent dispersion functions, $\sigma_y(x)$ and $\sigma_z(x)$, to estimate atmospheric dispersion. These functions are represented by empirical expressions derived from field experiments (see [63] for a summary of major field experiments) based on stability class and plume travel distance. Because these experiments have been carried out over temporal scales and land-use characteristics that can be different from those of importance in the analysis, the results from these simple models are typically adjusted to account for phenomena such as plume meander (where apparent crosswind dispersion can be greater than observed in the experiments) and for surface roughness characteristics that can increase the apparent vertical dispersion relative to that measured over relatively smooth terrain.

3.6.1 Dispersion Coefficients

The method for computing dispersion coefficients in MACCS is set by assignment of the variable NUM_DIST. If NUM_DIST is set to a value between 3 and 50, it defines the dimensions of a distance-based lookup table, which allows the implementation of a wide variety of empirical or theoretical models. The value of the dispersion parameter at a specific distance is computed by

using an interpolation algorithm in conjunction with lookup table values. Use of this option allows significant flexibility in representing dispersion over a range of distances.

If NUM_DIST is not assigned or is assigned a value of zero, MACCS uses a power law relationship over the entire spatial range of the model as defined in Equations (3-4) and (3-5).

$$\sigma_y(x) = A_y \cdot \left(\frac{x}{x_0}\right)^{B_y} \quad (3-4)$$

$$\sigma_z(x) = A_z \cdot \left(\frac{x}{x_0}\right)^{B_z} \quad (3-5)$$

where x is the downwind distance and x_0 is the downwind distance scale, which is 1 m. Because the same power law parameters generally do not apply at all downwind distances — particularly for the modeling of vertical dispersion — this approach is appropriate for a narrower distance range than the lookup table approach. The analyst should evaluate the applicability of the power law parameters for the distance range of interest when selecting the power law approach. However, the power law approach facilitates conducting uncertainty analyses by minimizing the number of parameters that must be sampled and correlated.

Several parameterizations are available for estimating dispersion coefficients to be used in MACCS. Typical parameterizations used for short distances (over a distance of a few kilometers) are based on the Pasquill-Gifford (PG) dispersion curves [64] [65], which were developed from field data including the 1956 Prairie Grass diffusion experiments [66]. A variety of parameterizations are discussed in Section 2.3.3.2 of [67]. Summarizing data from [68], Table 2.8 of [67] provides dispersion coefficients for several different parameterizations for the range of stability classes. These include:

- Pasquill-Gifford [64] [65];
- Klug [69] [70] who reevaluated the results from tracer experiments that considered data from additional studies with ground level, short duration releases at low surface roughness sites, with measurements out to a few kilometers;
- Tracer experiments carried out at Brookhaven, as evaluated by [71] from elevated (108 m) releases of approximately one-hour duration over medium roughness terrain, with measurement distances out to 60 kilometers;
- Tracer experiments carried out at St. Louis, as evaluated by [72] from ground level releases of approximately one-hour duration over a relatively flat urbanized area out to distances of up to 16 kilometers; and
- Experiments at Julich Nuclear Research Center in Germany, which involved one-hour releases from three heights (50, 100, and 180 m), were conducted over farmland with medium surface roughness, and had measurements taken out to as far as 11 kilometers [68].

The Tadmor and Gur parameterization [73], as corrected by [74], of the PG curves was the basis for the power law parameters (CYSIGA, CYSIGB, CZSIGA, and CZSIGB) typically used as inputs in the original MACCS code (Table 2.2 of [20]). Because the slope of the PG curves for the vertical dispersion coefficient change with downwind distance, the Tadmor and Gur approximation uses two distances ranges (0.5–5 km and 5–50 km) to represent the vertical

dispersion coefficient. NUREG-1150 (as described in Section 2.4 of [5]) considered analytical fits to data as reflected in the Tadmor and Gur formulation as well as analytical fits from Klug and from the Julich experiments. Sprung et al. [5] recommended continued use of the Tadmor and Gur parameters because “relative to their uncertainties all of the fits are more or less equivalent and because the Tadmur (sic) and Gur fits have been used in most previous NRC consequence modeling studies”³. NUREG-1150 [4] and the original MACCS Sample Problem A used the 0.5–5 km power law representation of the Tadmor-Gur approximation. The MACCS2 Sample Problem A [2] used a lookup table implementing the 0.5–5 km power law representation of the Tadmor-Gur approximation. The coefficients for the Tadmor-Gur approximation for both the 0.5–5 km range and the 5–50 km range are provided in Table B-1 of Napier et al. [75]. It is suggested that the most practical implementation of the Tadmor-Gur approximation for ranges spanning 5 km is via a lookup table that combines the 0.5–5 km approximation with 5–50 km approximation [75]. The coefficients for the Tadmor-Gur approximations are provided in Table D-1 of Appendix D of this report.

In their review of MACCS applications at the Savannah River Site, Napier et al. [75] also considered use of the Eimutis and Konicek [76] parameterizations, noting that these are used by NRC dispersion codes such as XOQDOQ [77] and PAVAN [78]. A comparison of the Tadmor-Gur approximations to the Eimutis and Konicek formulation was conducted, with the authors indicating that the Tadmor-Gur approximations should not be applied at distances closer than 500 meters. In contrast, the Eimutis and Konicek formulation provides approximations for three downwind distance ranges: <100 m, 100-1,000 m, and >1,000 m. Both a power law (Table B-2) and a lookup table (Table B-3) formulation of the Eimutis and Konicek approximation are provided in [75]. Although the Eimutis and Konicek formulation contains coefficients for ranges closer than 100 m, concentration estimates at such close distances should only be considered approximate, as discussed in Appendix A of [10]. Building wake effects combined with very short plume travel times may result in significant uncertainties over such short distances. The validity of the MACCS code at close ranges (on the order of 100 m) is also discussed as Topical Area 7 of [75]. The coefficients for the Eimutis and Konicek approximations are provided in Table D-2 and a lookup table formulation of Eimutis and Konicek is provided in Tables D-4 and D-5 of Appendix D of this report.

Briggs [79] synthesized information from a number of experimental studies to yield parameterizations for a range of distances and land uses. The considerations for developing these curves is also discussed in [65], and an analytical formulation for the Briggs coefficients is presented in [51]. A set of lookup tables implementing both the open country and urban condition Briggs curves for use in MACCS was distributed with MACCS2 1.13. The analytical formulations for the Briggs open country approximations are provided in Table D-3 of Appendix D.

DOE [10] recommends use of the Briggs, Tadmor-Gur, or Eimutis and Konicek approximations, considering local land use and surface roughness conditions, as default approaches. Because the simple power law formulation for MACCS does not include the constant term, some of these recommended functions are most practically implemented in MACCS via a lookup table. In its review of dispersion modeling at the Savannah River Site [80], the Defense Nuclear Facilities Safety Board recommended consideration of the Briggs open country parameterization because it is based on a synthesis of data collected over a wider range of conditions and distances than the PG diffusion curves. The potential difference between these three approaches was evaluated

³ It should be noted that this observation was predicated on use of the MACCS area source model that initializes plume dimensions from any of these curves to the same dimensions at the point of release.

in Appendix A⁴ of [75], and the authors concluded that over a range of up to about 12 km all these approaches give similar results that are within the uncertainties of the dispersion models.

In the early 1990s, a joint effort of the NRC and the CEC was undertaken to develop information to support uncertainty analyses of their respective probabilistic consequence codes. The results of an expert elicitation of factors related to dispersion and deposition are documented in [23]. That study developed the technical basis for defining the plume horizontal and vertical standard deviation for a range of stability conditions, a range of surface roughness, and downwind distances ranging from 500 m to 30 km. Conversion of the elicitation data into parameters suitable for a power law formulation is documented in NUREG/CR-7161 [27], and formed the basis for the dispersion parameterization used in SOARCA [14]. Further work to refine uncertainty distributions for SOARCA was carried out and is documented in Section 5.9.6 of [15]. These distributions are recommended for uncertainty analyses.

Table 3-2 Median Value for Dispersion Coefficients from Expert Elicitation

P-G Stability Class	Sigma-y (m)		Sigma-z (m)	
	A_y	B_y	A_z	B_z
A	0.7507	0.866	0.0361	1.277
B	0.7507	0.866	0.0361	1.277
C	0.4063	0.865	0.2036	0.859
D	0.2779	0.881	0.2636	0.751
E	0.2158	0.866	0.2463	0.619
F	0.2158	0.866	0.2463	0.619

Source: as reported in [27]⁵

The values developed in NUREG-7161 [27] address the considerations identified by the Defense Nuclear Facilities Safety Board [80]. The formulation developed in [27] represents a range of experts and a range of surface roughness characteristics, and explicitly considers distances out to 30 km. In addition, the evaluation of sets of coefficients for different uncertainty levels allows for an explicit consideration of the uncertainty in dispersion coefficients for use in uncertainty analyses. Although information on uncertainty ranges may be found in [27], it is important to understand that the distributions in [27] represent uncertainty in the dispersion parameters for a relatively short period, which is a reasonable estimate of uncertainty in an individual weather sequence. If the intention of the uncertainty analysis is to generate a set of realizations in which each realization represents a mean over a large set of weather conditions, then the uncertainty is narrower, and the distributions developed in Section 5.9.6 of [15] are recommended.

For general use, including analyses where results at close ranges (<500 m) may be of interest, a lookup table based on the Eimutis and Konicek approximations to the PG curves is recommended. A lookup table formulation of the Eimutis and Konicek approximations is provided

⁴ [75] used the approximation provided by the EPA Industrial Source Complex (ISC3) model rural mode option to represent the Pasquill-Gifford curves rather than the Tadmor-Gur approximations.

⁵ Note that the same parameter values are assigned for classes A/B and for classes E/F. Use of the NUREG/CR-7161 correlations would appear to result in effectively four stability classes: unstable (A/B), slightly unstable (C), neutral (D), and stable (E/F/G).

in Table D-4 and D-5 of Appendix D. If explicit consideration of uncertainty in dispersion is desired, the use of the distributions developed in Section 5.9.6 of [15] are considered a reasonable set of dispersion coefficients to facilitate the performance of uncertainty analyses.

Parameter Name: NUM_DIST

Parameter Description: Number of Entries in the Dispersion Lookup Table

Recommended Value: Up to 50, based on the number of entries defining dispersion lookup table. Use of a lookup table based on the Eimutis and Konicek approximations to the PG curves is recommended for most analyses, but NUMDIST can also be set to 0 to implement the MACCS power law dispersion model if assessment of uncertainty is a consideration.

Uncertainty Range: not applicable

References: [2], [14], [27]

Discussion: The inclusion of a lookup table option was added with the development of MACCS2. The currently recommended approach for most analyses is to use the lookup table option to implement the Eimutis and Konicek approximations to the PG dispersion curves as discussed in Appendix D. The Briggs dispersion curves, or some other custom dispersion scheme, can also be implemented by developing a distance-based dispersion lookup table with more than three entries. If assessment of uncertainties in dispersion parameters is a consideration, the recommended value for NUMDIST is 0 which implements the power law model.

Parameter Name: DISTANCE

Parameter Description: Distances in the Dispersion Lookup Table

Recommended Value: Up to 50 distances to define the locations of the values in the dispersion table. The values provided in Tables D-4 and D-5 are recommended when uncertainty in dispersion is not evaluated.

Uncertainty Range: not applicable

References: [75], [76], Appendix D

Discussion: none.

Parameter Name(s): SIGMA_Y_A, SIGMA_Z_A, SIGMA_Y_B, SIGMA_Z_B, SIGMA_Y_C, SIGMA_Z_C, SIGMA_Y_D, SIGMA_Z_D, SIGMA_Y_E, SIGMA_Z_E, SIGMA_Y_F, SIGMA_Z_F

Parameter Description: User-Specified Tables of Sigma-y and Sigma-z as a Function of Distance

Recommended Value: The values provided in Tables D-4 and D-5 are recommended when uncertainty in dispersion is not evaluated.

Uncertainty Range: not available

References: [75], [76], Appendix D

Discussion: For most cases in which uncertainty does not need to be evaluated and when dispersion is evaluated over a broad range of distances, using a dispersion lookup table is recommended. A lookup table based on Eimutis and Konicek (provided in Table D-4 and D-5 of Appendix D) provides the best approximation over a broad distance range, <100 m to >1,000 m [75].

Parameter Name(s): CYSIGA, CYSIGB, CZSIGA, CZSIGB

Parameter Description: Linear and Exponential Coefficients for Sigma-y and Sigma-z

Recommended Value: For median values, see Table 3-2

Uncertainty Range: The distributions developed in Section 5.9.6 of [15] are recommended

References: [14], [27], [15]

Discussion: The power law dispersion model with coefficients representing the median value from the tables in NUREG/CR-7161 [27] are considered reasonable. The distributions developed in Section 5.9.6 of [15] are recommended for use in uncertainty analyses.

3.6.2 Long Range Dispersion

The approximations described in the previous subsection produce estimates of plume standard deviation (σ_y and σ_z) applicable at a range of distances from a fraction of a kilometer to some tens of kilometers (i.e., travel times on the order of an hour). Hanna [57] recommends use of a time-based dispersion model for the crosswind plume standard deviation (σ_y) at distances greater than 30 km, with a plume growing at a rate of 0.5 m/s. This recommendation is consistent with Equation 13.2 of [51]. By setting the DISPMD variable to LRTIME, MACCS has the capability to shift to a time-based dispersion model at a user-specified distance, in which the plume standard deviation is assumed to grow as a linear function of time after the specified distance. The recommended parameters are the same as those recommended by [57].

Parameter Name: DISPMD

Parameter Description: Dispersion Model Flag

Recommended Value: LRTIME

Uncertainty Range: not applicable

References: [57]

Discussion: Use of the time-based model for crosswind dispersion at distances of greater than 30 km is recommended.

Parameter Name: CYDIST

Parameter Description: Distance for Time-Based Crosswind Dispersion

Recommended Value: 30 km

Uncertainty Range: not available

References: [57], [51], [62]

Discussion: The distance at which to switch to a time-based crosswind dispersion model is subject to uncertainty. Hanna [57] recommends a distance of 30 km, and that is the recommended value for most analyses. However, it may be noted the discussion in Chapter 13 of [51], consistent with the discussion in [62], considers distances beyond 10-20 km to be long-range.

Parameter Name: CYCOEF

Parameter Description: Linear Coefficient for Time-Based Crosswind Dispersion

Recommended Value: 0.5 m/s

Uncertainty Range: Log-triangular, 0.2 to 1.25 m/s with a mode of 0.5 m/s

References: [57], [15], [51]

Discussion: A distribution to represent uncertainty for CYCOEF is described in the Sequoyah SOARCA report [15]. The recommended distribution uses 0.5 m/s as the mode and the same distribution shape as for the distance-based dispersion parameters described above, which is a log-triangular distribution with a lower bound a factor of 2.5 below the mode and an upper bound a factor of 2.5 above the mode.

3.6.3 Plume Meander

Wind shifts that occur over periods less than the averaging time of the recorded weather data (usually 1 hour) can result in an apparent dispersion that is greater than would be computed using dispersion curves based on measurements over a shorter time period, such as the PG curves. The apparent increase in crosswind dispersion can be significant under stable, low wind speed conditions. This effect is known as plume meander. Adjustment of the crosswind plume dimensions to account for plume meander can be handled a variety of ways in MACCS. The analyst may select a crosswind scaling factor YSCALE, which is constant for all distances, or from two models that explicitly treat plume meander.

The original MACCS plume meander model, currently invoked by setting the value of the MACCS parameter MNMOD to "OLD," is discussed in Section 2.9.4 of [20] and in Section 4-7 of [51]. The effect of plume meander on the crosswind dimensions of the plume are given by:

$$\sigma_y = \sigma_{ref} \left(\frac{\Delta t}{\Delta t_{ref}} \right)^m \quad (3-6)$$

where, as discussed in [20], " σ_{ref} and Δt_{ref} are the sigma value and release duration (10 minutes for the experiments that support the PG curves) of the reference plume, Δt is the release duration of the long duration release and, as recommended by Gifford, m equals 0.2 for release durations less than 1 hour and 0.25 for release durations greater than 1 hour." According to [20], the values of m have been confirmed by experiments conducted by Mueller and Reisinger [81]. As discussed in Section 9 of [75], the original MACCS plume meander model effectively accounts only for the difference in the plume sampling time. The MACCS variable TIMBAS represents Δt_{ref} in the original MACCS meander model, the variable BRKPNT is the boundary between a short- and a long-duration release, and the variables XPFAC1 and XPFAC2 represent the short- and long-duration exponents, m . It should be noted that there is a range of opinions regarding the value that should be used for Δt_{ref} when correcting the PG sigma-y curves for sampling time. The value of 10 minutes (600 seconds) traditionally used for MACCS analyses is recommended by [82] and [51] and is consistent with the sampling time used in the Prairie Grass experiments [66]. However, DOE guidance in [10] recommends a value of 3 minutes (180 seconds), a position which is supported by [83] and [84]. The use of the longer value for Δt_{ref} will result in a smaller sampling time correction factor for sigma-y, resulting in higher centerline concentrations arising from a narrower plume.

The new MACCS plume meander model is based on NUREG/CR-2260 [85] and Regulatory Guide 1.145 [49] and accounts for the observation that the amount of plume meander depends on stability class and wind speed. This model is based on empirical data from field studies conducted at Rancho Seco [86] and at the Experimental Organic Cooled Reactor test reactor building complex at the Idaho National Engineering Laboratory [87]. The model developed in NUREG/CR-2260 [85] uses factors to correct the PG σ_y values to account for plume meander and building wake effects. It should be noted that the vertical temperature lapse rate was used to determine the stability classes for developing these factors. As discussed in Regulatory Guide

1.23 [47], use of alternate stability determination methods may require the adjustment of these factors. The credit for meander diminishes beyond 800 m downwind and approaches unity at longer distances. The new MACCS plume meander model is similar to the model described in Regulatory Guide 1.145 [49] except that it is more general, and a different approach is used at distances greater than 800 m. The MACCS implementation of the Regulatory Guide 1.145 plume meander model treats plume meander beyond 800 m by using a virtual source, similar to the way an area source is treated. The meander occurs in the first 800 m downwind, creating a broader plume at that distance. Beyond 800 m, the plume gradually approaches the size that it would have had if meander had not occurred. In the MACCS implementation, the user may specify the downwind distance D beyond which the plume meander factor is no longer used. Beyond this distance, the meander factor is set to unity and location of the virtual source is adjusted to ensure continuity in the value of σ_y .

The new plume meander model is defined as follows:

$$\sigma_{ym}(x) = f_m \cdot \sigma_y(x) \quad (3-7)$$

Where $\sigma_y(x)$ is the crosswind dispersion that is evaluated without meander, $\sigma_{ym}(x)$ is the crosswind dispersion accounting for plume meander, x is the downwind distance measured from the source, and f_m is meander factor (dimensionless). Based on Regulatory Guide 1.145 [49], the meander factor is defined as follows:

$$f_m = m_i \cdot f(u) \quad (3-8)$$

where m_i is equal to 1 for stability classes A through C, 2 for stability class D, 3 for stability class E, 4 for stability class F, and $f(u)$ is a function of wind speed u (m/s) and stability given by

$$f(u) = 1 \quad u \leq u_i \quad (3-9)$$

$$f(u) = \frac{1}{m_i} \exp \left[\left(1 - \frac{\ln(u) - \ln(u_1)}{\ln(u_2) - \ln(u_1)} \right) \cdot \ln(m_i) \right] \quad u_1 < u \leq u_2 \quad (3-10)$$

$$f(u) = 1/m_i \quad u > u_2 \quad (3-11)$$

The recommended approach for analyses in which one-hour plume-segment durations are defined for risk-significant plume segments, and for which dispersion parameters based on the PG dispersion curves are used, is to set the crosswind scaling factor YSCALE to unity and to apply the Regulatory Guide 1.145 plume meander model by assigning the MACCS parameter MNMOD = "NEW." The meander model coefficients required to approximate the Regulatory Guide 1.145 plume meander model are defined by assigning the values $m_i = [1, 1, 1, 2, 3, 4]$, $u_1 = 2$ m/s, $u_2 = 6$ m/s, and $D = 800$ m. However, the analyst should note that this meander model is based on the assumption of a one-hour release (more accurately, a one-hour sampling/exposure duration) and can overestimate peak doses for release durations longer than one hour and can underestimate peak doses for release durations less than one hour.

Parameter Name: YSCALE

Parameter Description: Scale Factor for Horizontal Dispersion

Recommended Value: 1

Uncertainty Range: not applicable

References: not applicable

Discussion: The YSCALE parameter is typically not used to adjust for meander and is therefore recommended to be assigned a value of 1.

Parameter Name: MNMOD

Parameter Description: Plume Meander Model Flag

Recommended Value: NEW if dispersion parameters are based on PG curves and plume segments are approximately one hour in length, otherwise OFF or OLD

Uncertainty Range: not applicable

References: [85], [49], [14]

Discussion: If MACCS dispersion parameters are based on the PG dispersion curves and risk-significant plume segments are approximately one hour in length, the meander model consistent with the recommendations of Regulatory Guide 1.145 [49] is recommended for use with plume segment durations on the order of one hour. If other dispersion parameterizations are used, it is recommended to use either the old plume model or to turn the meander model off depending upon whether plume meander is already credited in the dispersion parameterization. The SOARCA analyses did not use a plume meander model (MNMOD = OFF). The recommended values to use with the new MACCS meander model (MNMOD=NEW) are those needed to make the model consistent with the recommendations of Regulatory Guide 1.145 [49] and should only be used when plume segment durations are on the order of one hour and dispersion parameterizations are based on PG curves.

Parameter Name: WINSP1/2

Parameter Description: Wind Speed Breakpoints for NEW Meander Model

Recommended Value: $u_1 = 2 \text{ m/s}$, $u_2 = 6 \text{ m/s}$ if MNMOD=NEW, dispersion parameterizations are based on PG curves, and plume segments are approximately one hour in length.

Uncertainty Range: not available

References: [85], [49]

Discussion: The recommended values to use with the new MACCS plume meander model (MNMOD=NEW) are consistent with the technical basis provided in [85]

Parameter Name: MN DIST

Parameter Description: Downwind Distance Breakpoint for NEW Meander Model

Recommended Value: 800 m if MNMOD=NEW, dispersion parameterizations are based on PG curves, and plume segments are approximately one hour in length.

Uncertainty Range: not available

References: [85], [49]

Discussion: The recommended values to use with the new MACCS plume meander model (MNMOD=NEW) are consistent with the technical basis provided in [85]

Parameter Name: MNDFAC

Parameter Description: Plume Meander Factor

Recommended Value: [1, 1, 1, 2, 3, 4] if MNDFAC=NEW, dispersion parameterizations are based on PG curves, and plume segments are approximately one hour in length.

Uncertainty Range: not available

References: [85], [49]

Discussion: The recommended values to use with the new MACCS plume meander model (MNDFAC=NEW) are consistent with the technical basis provided in [85].

Parameter Name: TIMBAS

Parameter Description: Time Base for Plume Expansion Factor

Recommended Value: 600 seconds (10 minutes) if MNDFAC=OLD and dispersion parameterizations are based on PG curves

Uncertainty Range: not applicable

References: [20], [82], [51], [81]

Discussion: As stated in [10], “If another set of dispersion coefficients is being used, the value should be consistent with the time-basis of those experiments.” As previously noted, there is a range of opinions regarding the value that should be used for Δt_{ref} when correcting the PG sigma-y curves for sampling time. The use of the longer (600 second) value for Δt_{ref} , which is consistent with [82] and [51], will result in a smaller sampling time correction factor for PG sigma-y values, resulting in higher centerline concentrations arising from a narrower plume.

Parameter Name: BRKPNT

Parameter Description: Breakpoint Time for Plume Meander

Recommended Value: 3,600 seconds (1 hour) if MNDFAC=OLD

Uncertainty Range: not applicable

References: [51], [20], [81]

Discussion: BRKPNT defines the time at which the exponential factor used in the old meander model switches between XPFAC1 and XPFAC2. It is typically set equal to one hour, consistent with [20] and [51].

Parameter Name: XPFAC1

Parameter Description: Exponential Factor for Short-Duration Releases.

Recommended Value: 0.2 if MNDFAC=OLD

Uncertainty Range: not available

References: [51], [20], [81]

Discussion: The exponential factor for short-duration releases (i.e., releases with a duration less than or equal to that given by the value of BRKPNT) It is typically set equal to 0.2, consistent with [20] and [51].

Parameter Name: XPFAC2

Parameter Description: Exponential Factor for Long-Duration Releases

Recommended Value: 0.25 if MNDFAC=OLD

Uncertainty Range: not available

References: [51], [20], [81]

Discussion: The exponential factor for long-duration releases (i.e., releases with a duration greater than that given by the value of BRKPNT) It is typically set equal to 0.25, consistent with [20].

3.6.4 Effect of Surface Roughness on Vertical Dispersion

The turbulence generated by surface roughness can increase vertical dispersion. This effect can be accounted for in MACCS by a multiplicative factor defined by the variable ZSCALE. As discussed in Chapter 4 of [51], σ_z is proportional z_0^p , where z_0 is the surface roughness. A value for ZSCALE can be expressed using the following equation:

$$ZSCALE = \left(\frac{z_0}{z_{0,ref}} \right)^p \quad (3-12)$$

As discussed in Chapter 4 of [51], the exponent p can range from 0.10 to 0.25 and “larger values of the exponent p are applicable to shorter distances and rougher surfaces.” Because the experiments on which the PG curves are based were over grasslands with a roughness length estimated to be 3 cm, a typical empirical correction factor recommended by DOE guidance [10] used to scale vertical dispersion uses the actual surface roughness divided by 3 cm to the 0.2 power. For example, the multiplicative factor corresponding to a 10-cm surface roughness is $(10 / 3)^{0.2} = 1.27$. A surface roughness length of 60 cm corresponds to a multiplicative ZSCALE factor of about 1.8, which was used in a surface roughness sensitivity analysis presented in Section 7.3.7 of [28]. A roughness length that accounts for forested areas is typically on the order of 100 cm, resulting in a ZSCALE correction factor of 2.0.

The preceding scaling factors are appropriately used with approximations based on the PG curves derived from the Prairie Grass experiments. Napier et al. [75] recommend a range of correction factors depending upon the downwind distance, based on an exponent of 0.2 to adjust the 0.5 to 5 km Tadmor-Gur parameter set, and an exponent of 0.1 to adjust the >5-km Tadmor-Gur parameter set. However, the Briggs approximations are based on a synthesis of a variety of land uses (and therefore roughness lengths), and the applicability of the roughness length correction factors to the Briggs dispersion formulas is unclear. As discussed in Appendix A of [75], the difference between the coefficients based on the PG curves derived from the Prairie Grass experiments, and the coefficients based on the Briggs open country equations, is minimal, with differences of only a few percent. Because the Briggs curves give very similar quantitative results to the PG curves at close ranges, Napier et al. [75] concluded that it is appropriate to apply a ZSCALE factor to the Briggs open country values at distances of less than 10 km. The selection of an appropriate average surface roughness length can be based on the land use within a few kilometers of the site, based on:

- The recommendation by Pasquill [83] that the correction should only be applied within a few kilometers of the release, and
- the observation that at longer ranges where the plume is likely to be fully vertically mixed, the effect of the ZSCALE parameter is expected to be less significant since the vertical dispersion is controlled by the mixing height rather than the sigma-z value (i.e., the plume approaches a state of uniform mixing within the mixing layer).

Surface roughness affects both vertical dispersion and dry deposition velocities. Surface roughness is not a direct input into MACCS but is used to adjust vertical dispersion coefficients when surface roughness differs from the surface roughness for which the dispersion coefficients were derived (i.e., via the ZSCALE input parameter). Table 2.3 of [20], reproduced in Table 3-3 below, provides a range of surface roughness values for typical land cover types.

Table 3-3 Approximate Surface Roughness Lengths (z_0) for Different Surfaces

Type of Surface	z_0 (cm)
Lawns	1
Tall grass, crops	10 – 15
Countryside	30
Suburbs	100
Forests	20 – 200
Cities	100 – 300

Source: Reproduced from [20]

Hansen [88] provides a discussion for the variation in roughness lengths for different land-use characteristics, including natural surfaces, agricultural lands, and urban areas. It includes a discussion of how surface roughness for natural environments may vary by the time of year. Figure 6 of [88] provides a summary of typical roughness lengths for a variety of natural, agricultural, and urban land-use categories. A more detailed table of surface roughness lengths correlated to land cover types is provided in Table A-3 of the AERSURFACE user's guide [89]. Surface roughness lengths as a function of land-use category, as implemented in the Sequoyah SOARCA analysis [15], are provided below in Table 3-4.

Table 3-4 Surface Roughness Lengths for Various Land Use Categories

Type of Land Use	z_0 (cm)
Open Water	0.03
Barren	1
Grass/Pasture	3
Developed/Open Space and Developed/Low-Intensity	5
Shrubland	5
Wetlands	5
Crops, vegetables, fruit	10
Forest	60
Developed/Medium-Intensity	70
Developed/High-Intensity	350

Source: [15]

Site-specific information on land use and land cover for use in estimating surface roughness lengths is available online from the USDA CropScape Database [90].

DOE [10] recommends basing the value used for surface roughness on "a macroscopic average for the region-of-transport and should be consistent for the environment surrounding facility in

question.” This process is discussed in somewhat more detail in [88] in the discussion regarding selection of an effective surface roughness for mesoscale modeling. However, for modeling across a range of spatial scales (for example, from the site boundary out to distances of 50 miles or greater), the region of interest may be different for the two applications of surface roughness, i.e., dispersion and deposition. As discussed in [75], the impact of surface roughness on the vertical dispersion coefficient is spatially variable, noting that “Pasquill notes that this adjustment is dependent on downwind distance (i.e., it is not a constant) and it should only be made out to “a few kilometers”, beyond which surface roughness effects are considered “tentative” [83].” However, the region of interest for dry deposition may be considerably larger, given the typically slow rate of plume depletion by dry deposition. The analyst may wish to perform a sensitivity analysis to examine how variations in land use and land cover averaged over a range of distances impact results to determine the appropriate value(s) of surface roughness to be used for dispersion and deposition.

Parameter Name: ZSCALE

Parameter Description: Scale Factor for Vertical Dispersion

Recommended Value: Derive based on surface roughness characteristics within a few kilometers of the release and an exponential factor of 0.2

Uncertainty Range: not available. A distribution could be developed from the range of values for p between 0.1 and 0.25 and local variations in surface roughness lengths.

References: [51], [75]

Discussion: The recommended approach to vertical dispersion scaling is to scale the ratio of surface roughness characteristic of the site to the surface roughness characteristic of the data used to develop the dispersion coefficients using a scaling exponent of 0.2. Based on the similarity of the coefficients from the PG curves, derived from studies with a surface roughness on the order of 3 cm, to those from the Briggs open country curves, [75] concluded that it is reasonable to apply the ZSCALE factor based on a reference roughness of 3 cm to the Briggs open country curves. The dispersion values provided in NUREG/CR-7161 [27] should be interpreted as representing a surface roughness of 3 cm; therefore, it is appropriate to scale these values with ZSCALE in the same way as one would scale dispersion values developed from Prairie Grass data, such as the Tadmor-Gur or Eimutis and Konicek approximations.

3.7 Building Wake Effects and Plume Rise

Many release paths are likely to result in releases into the aerodynamic wake created by one or more structures, including containments, control buildings, fuel handling buildings, auxiliary buildings, and turbine buildings. This introduces a number of considerations for modeling dispersion close to the source. Releases above ground level result in lower ground concentrations until the plume is mixed down to ground level, as discussed in [91]. The effective release height is a function of several characteristics of the release: the physical elevation of the point of the release, the potential for building downwash to bring an elevated plume down to ground level, and the momentum or buoyancy-driven rise of a plume above its initial release elevation. Releases into a building wake may result in significant initial dispersion, and wake effects may result in a plume released from an elevated location (but still within the wake) to be brought down closer to the ground surface, particularly at high wind speeds. Conversely, buoyant ground level releases can be elevated under low-wind speed conditions. The plume may rise above its initial release location from its initial momentum and/or buoyancy or may be trapped within a building wake. Additional discussion of source configuration considerations can be found in [92], [93], and [94].

3.7.1 Release Elevation

The release elevation, defined by the MACCS variable PLHITE, is based on the elevation of the location where the material is released into the atmosphere. This value may be obtained from the Level 2 source term analysis. However, most release paths are likely to result in releases into the building wake created by a single building or a complex of structures. Furthermore, some failure modes (such as overpressure failure) may result in uncertain release locations. Because ground level releases typically result in higher near-field concentrations, a conservative approach typically followed in DOE safety basis calculations is to model releases that are potentially affected by building wakes (usually taken as releases that are less than 2.5 times the building height) as ground level releases (PLHITE = 0 m). However, use of a ground level release may result in enhanced plume depletion near the point of release, resulting in higher concentrations close to the site but lower concentrations at longer distances. DOE [10] recommends modeling all releases as ground level releases, except for elevated releases greater than 2.5 times the building height. NUREG-1150 used either a 0 or a 10 m release height [59], and the SOARCA analyses (e.g., [28], [29], [30], and [15]) used the physical release elevations from the MELCOR source term models to initialize the height of the plume.

Parameter Name: PLHITE

Parameter Description: Plume Release Heights

Recommended Value: Actual release location is justified, particularly if results at longer ranges than the site boundary are of primary interest. For conservative estimates not accounting for the MACCS building wake model, a 0-m release height value for PLHITE can be used for releases with an initial elevation less than 2.5 times building height.

Uncertainty Range: 0 to physical release elevation

References: [10], [91], [49], [92]

Discussion: Use of a 0-m release height, or the physical release height if the release is from a tall stack, is a reasonable approach for many analyses. For analyses where results at relatively long ranges are of primary interest, use of a higher release height may result in less initial depletion, resulting in higher concentrations at longer ranges.

3.7.2 Wake Effects

The treatment of wake effects in MACCS are based on the review by Hosker [94], who describes (in Section 7.8.2.2) several approaches to treat the concentrations downwind of the recirculation region. The approach used in MACCS, as described by Sprung et al. [5] and Section 5.10 of [2], employs the virtual source approach described on pages 33-34 of [82] in which an initial plume dimension is assigned based on the characteristics of the building from which the release occurs. For the purpose of initializing plume dimensions, the plume centerline is assumed to be at ground level and in the middle of the downwind face of the building. The initial plume dimensions were defined in early versions of MACCS by entering the building dimensions and assuming that the plume concentrations at the sides and roofline of the building from which the release occurs are 10% of plume centerline concentrations (i.e., building edges are 2.15 sigma from the plume centerline), which yields initial values of the horizontal and vertical standard deviations of the Gaussian plume given by

$$\sigma_{y,init} = \frac{W_b}{4.3} \text{ and } \sigma_{z,init} = \frac{H_b}{2.15} \quad (3-13)$$

where W_b is the width (m) of the building from which release occurs and H_b is the height (m) of the building from which release occurs. As discussed in Section 2.1.2 of [5], selecting these values is uncertain because the degree of mixing is affected by the level of ambient turbulence as well as the initial failure dimensions, which are uncertain. In addition, determining the height and, especially, the width of the building from which release occurs is not always straightforward. Because wake effects can persist for some distance downwind of a structure (EPA [91] suggests a distance of five times the lesser of the width or height of the structure), a release from one part of a complex of buildings is likely to be affected by the wake generated by a nearby structure. A reactor complex is typically comprised of a set of buildings and the heights and widths of the buildings in this complex vary. In addition, the complex is irregular in shape and the apparent width depends on the direction of the wind. Use of the dimensions of the above-grade portion of the reactor containment structure, as suggested in Sprung et al. [5] is a common approach. However, Sprung et al. [5] suggested a lower limit of 10 m for both building height and width, corresponding to a lower limit of 2.3 m and 4.6 m for the initial horizontal and vertical dispersion parameters, respectively. The recommended upper limit on building height was chosen to be the height of containment, and the upper limit on building width varied widely.

The precedent of assigning initial plume dimensions based on the above-grade width and height of the reactor containment structure is considered to be a reasonable approach if building wake effects are to be credited for initial dispersion for ground level releases. However, use of the area source approach for modeling wake effects can introduce uncertainty in atmospheric concentration estimates at short distances. As discussed in Section 4.4 of [10], a more conservative approach (if the analyst does not intend to credit building wake effects) is to assign the initial plume dimensions to the minimum allowable value of 0.1 m.

In most commercial reactor analyses, releases originate within the complex defined by the containment and adjacent buildings. It is therefore considered reasonable to assign all release points from within the same building complex as having the same initial plume dimensions. However, elevated releases from a stack not subject to building downwash should generally not be diluted by wake effects and use of the minimum initial plume dimensions is recommended for stack releases that are greater than 2.5 times the building height.

Parameter Name: SIGYINIT

Parameter Description: Plume Segment Initial Sigma-y

Recommended Value: If wake effects are to be credited, site specific with $SIGYINIT = W_b/4.3$ where W_b is the width of the reactor containment structure in meters; $SIGYINIT = 0.1$ m if wake effects are not to be credited.

Uncertainty Range: Uniform, 25% to 167% of the nominal value, correlated with SIGZINIT [8]

References: [82], [92], [94], [93], [8], [2]

Discussion: Although the original MACCS building wake model is no longer hardwired in MACCS, the conceptual model is still reasonable for most applications. However, use of the area source approach for modeling wake effects can introduce uncertainty in atmospheric concentration estimates at short distances. The recommended uncertainty range is derived by normalizing the building dimensions used to define the distributions in Table 4 of [8]. Elevated releases from a stack not subject to building downwash should generally not be diluted by wake effects and use of the minimum initial plume dimensions is recommended for stack releases that are greater than 2.5 times the building height.

Parameter Name: SIGZINIT

Parameter Description: Plume Segment Initial Sigma-z

Recommended Value: If wake effects are to be credited, site specific with $SIGZINIT = H_b/2.15$, where H_b is the height of the reactor containment structure in meters; $SIGZINIT = 0.1$ m if wake effects are not to be credited.

Uncertainty Range: Uniform, 60% to 140% of the nominal value, correlated with SIGYINIT [8]

References: [82], [92], [94], [93], [8], [2]

Discussion: Although the original MACCS building wake model is no longer hardwired in MACCS, the conceptual model is still reasonable for most applications. However, use of the area source approach for modeling wake effects can introduce uncertainty in atmospheric concentration estimates at short distances. The recommended uncertainty range is derived by normalizing the building dimensions used to define the distributions in Table 4 of [8]. Elevated releases from a stack not subject to building downwash should generally not be diluted by wake effects and use of the minimum initial plume dimensions is recommended for stack releases that are greater than 2.5 times the building height.

3.7.3 Plume Liftoff

As described in Section 2.8.1 of [20], a buoyant plume segment that is released into a building wake is unable to escape from the wake when wind speeds are sufficiently high. In MACCS, escape of a buoyant plume segment from a building wake is governed by a liftoff criterion that was originally proposed by Briggs [95] and validated by experiments performed at the Warren Spring Laboratory in Great Britain [96]. The criterion states that plume rise occurs only when the wind speed at the time of release of the segment is less than a critical wind speed (u_c) that is calculated using the following formula:

$$u_c = \left[\frac{9.09F}{H_b} \right]^{\frac{1}{3}} \quad (3-14)$$

where H_b is the height of the building from which the plume is escaping (m) and F is the buoyancy flux (m^4/s^3).

The buoyancy flux F can be computed either from the sensible heat release rate or using the density and flow rate of the plume. Under standard atmospheric conditions, the sensible heat release rate \dot{Q} (in watts, calculated by dividing the sensible heat content of the plume segment by its release duration; see also Equation (2-1)) is related to the buoyancy flux, F , by the following formula:

$$F = 8.79 \cdot 10^{-6} \cdot \dot{Q} \quad (3-15)$$

To account for the release of gases that are more or less dense than air, such as hydrogen and steam, as well as releases at elevated temperatures, the plume density and mass flow rate can be used to estimate the buoyancy flux by the following formula:

$$F = \frac{g}{\pi} \left[1 - \frac{\rho}{\rho_a} \right] \frac{\dot{m}}{\rho} \quad (3-16)$$

where g is the acceleration due to gravity (9.8 m/s^2), ρ is the mass density of the plume segment (kg/m^3), ρ_a is the mass density of surrounding air at ambient conditions (1.178 kg/m^3), and \dot{m} = mass flow rate of the plume (kg/s). The user may select either option in MACCS by appropriately assigning the value of the MACCS variable PLMMOD. Use of the “Power” model estimates the buoyancy flux using the sensible heat release rate as given in Equation (3-15), whereas use of the “Density and Flow Model” estimates the buoyancy flux using the plume density and mass flow rate using Equation (3-16). The use of the Density and Flow Model in MACCS to compute the buoyancy flux is recommended to account for the potential effects of the release of steam and hydrogen during an accident.

The individual numerical coefficients used by the liftoff model are fixed in the code with no provision for their modification by the user. While it is not possible for the user to vary the individual coefficients, it is possible to modify their end results by the specification of linear scaling factors. SCLCRW is a scaling factor for the critical wind speed and is set such that values less than unity make liftoff less likely to occur. Sprung et al. [5] indicates that since the coefficient of 9.09 is uncertain by about an order of magnitude, a reasonable range for SCLCRW is approximately a factor of two.

Parameter Name: PLMMOD

Parameter Description: Flag for Plume Rise Input Option

Recommended Value: DENSITY AND FLOW (if plume density and flow rate are available), POWER (if only rate of release of sensible heat is available for individual plume segments).

Uncertainty Range: not applicable

References: [40]

Discussion: The DENSITY AND FLOW option for estimation of the buoyancy flux is available if WinMACCS is used. This model is recommended for computation of the buoyancy flux because it has the capability to consider gas density effects on buoyance when substantial amounts of hydrogen or steam could be released.

Parameter Name: BUILDH

Parameter Description: Building Height

Recommended Value: Site specific, equal to the above-grade height of the containment structure in meters.

Uncertainty Range: not applicable. Uncertainty in the liftoff model can be addressed by varying the SCLCRW parameter.

References: [95], [96]

Discussion: The BUILDH parameter in MACCS is now used only as an input to the plume liftoff model. It is recommended to set this at the above-grade height of the containment structure. Uncertainty in the liftoff model can be addressed by varying the SCLCRW parameter.

Parameter Name: SCLCRW

Parameter Description: Scaling Factor for Critical Wind Speed

Recommended Value: 1

Uncertainty Range: 0.5 to 2

References: [95], [96], [5], [2]

Discussion: Using a scaling factor of 1 is consistent with a coefficient of 9.09. This parameter may be varied for use in uncertainty analyses. As discussed in [5], “Since the coefficient 9.09 is

uncertain by something like an order of magnitude, u_c must be uncertain by about a factor of two". Using the maximum allowable value of 100 effectively turns off the entrainment model, allowing plume rise to occur regardless of wind speed.

3.7.4 Plume Rise

Once a plume is released, it may rise due to momentum or buoyancy effects. If a plume is not captured within a building wake (i.e., if liftoff occurs), MACCS models plume rise until it is terminated by one of the following conditions:

- Δh reaches the final rise height, as defined below.
- The plume centerline reaches the mixing height (height of the capping inversion layer).
- When one hour has elapsed since the plume segment was released.

Plume rise under stable conditions (stability classes E and F) is typically different than plume rise under unstable and neutral atmospheric conditions (stability classes A to D); therefore, different models are used for these two cases. In addition, alternative plume rise formulations are available for each of these cases. The recommended plume rise model, invoked by assigning the MACCS variable BRGSMD to "IMPROVED", is described below. The improved MACCS plume rise model is recommended based on an assessment that compared the final plume centerline elevation predictions for four different buoyancy models, including the mechanistic ALOFT-FT model created by the National Institute of Standards and Technology. ALOFT-FT is a flat terrain computational fluids model developed to model plume trajectory for large energy fires. It has the benefit of having successfully stood up to a significant array of field validation tests [97]. Also included in the assessment was a model developed by Carter [98]. The Carter model is one of many solutions to the standard plume trajectory differential equations. The other two models were the Briggs plume rise model [99] implemented in the original MACCS plume rise model and the improved Briggs plume rise model [100]. The assessment showed that the improved MACCS plume rise model [100] came much closer to matching the mechanistic ALOFT-FT model than the original MACCS plume rise model [99].

When atmospheric conditions are stable (stability class E or F), the following formula (adapted from [51]) is used to determine the final rise height in the improved MACCS model⁶:

$$\Delta h_{final} = 2.4 \left(\frac{F}{\bar{u}S} \right)^{1/3}, \text{ if stability class is E or F} \quad (3-17)$$

where \bar{u} is the wind speed (m/s) averaged between the initial height and the current location (x, h) and S is a stability parameter (s^{-2}) defined by assuming that the ambient temperature is 15°C and using the midpoint ambient temperature lapse rate for each stability class. Substitution of these midpoint values results in values of $5.04 \times 10^{-4} s^{-2}$ and $1.27 \times 10^{-3} s^{-2}$ for the stability parameter S for stability classes E and F, respectively. The individual numerical coefficients used by the models are fixed in the code with no provision for their modification by the user. While it is not possible for the user to vary the individual coefficients of the plume rise model, it is possible to modify the end result by specifying linear scaling factor SCLEFP for stable conditions. Briggs [99] reports that the

⁶ Note that although MACCS uses a coefficient of 2.4, there are several different values for the leading coefficient. Equation 4 of [101] gives a value of 2.9. Table 4 of [99] shows a range of values from 1.8 to 3.4 and recommends a value of 2.6, which is the value recommended in Equation 2.19 of [51]. This is the value used in the MACCS2 1.12 original plume rise model. Because the final rise height is linear with respect to the leading coefficient, adopting the more common coefficient would result in a slight increase in plume rise.

leading coefficient for plume rise under stable conditions can range from 1.8 to 3.4. With a base value of 2.4 for the improved model, this translates to a range for SCLEFP of 0.75 to 1.4.

When atmospheric conditions are neutral or unstable (stability classes A through D), plume rise is treated using the “two-thirds” law for bent over plumes [51]:

$$\Delta h(x) = \frac{1.6F^{\frac{1}{3}}x^{\frac{2}{3}}}{\bar{u}} \quad (3-18)$$

where Δh is the plume rise (m) measured from the initial release height. The final rise height is determined in the improved MACCS plume rise model using the following formulas based on the work of Briggs [100]:

$$\Delta h_{final} = \frac{38.7F^{0.6}}{\bar{u}}, \text{ if } F \geq 55 \text{ and stability class is A through D} \quad (3-19)$$

$$\Delta h_{final} = \frac{21.4F^{0.75}}{\bar{u}}, \text{ if } F < 55 \text{ and stability class is A through D} \quad (3-20)$$

The individual numerical coefficients used by this model are fixed in the code with no provision for their modification by the user. While it is not possible for the user to vary the individual coefficients, it is possible to modify the end results by specifying a linear scaling factor SCLADP for unstable and neutrally stable (stability classes A–D) conditions.

Parameter Name: BRGSMD

Parameter Description: Plume Rise Model Flag

Recommended Value: IMPROVED

Uncertainty Range: not applicable

References: [100], [99]

Discussion: The currently recommended plume rise model is invoked by selecting the “IMPROVED” plume rise model, which implements the model based on [100].

Parameter Name: SCLEFP

Parameter Description: Scaling Factor for E–F (Stable) Plume Rise

Recommended Value: 1

Uncertainty Range: 0.75 to 1.4

References: [100], [99]

Discussion: The recommended value for the plume rise scaling factor under stable conditions (SCLEFP) is 1 (i.e., no scaling). The value may be varied for sensitivity or uncertainty analysis purposes.

Parameter Name: SCLADP

Parameter Description: Scaling Factor for A–D (Unstable/Neutral) Plume Rise

Recommended Value: 1

Uncertainty Range: not available

References: [100], [99]

Discussion: The recommended value for the plume rise scaling factor under neutral and unstable conditions (SCLADP) is 1 (i.e., no scaling). The value may be varied for sensitivity or uncertainty analysis purposes.

3.8 Deposition Modeling

MACCS considers both dry and wet deposition. Each chemical group can be modeled as subject to either wet or dry deposition by assigning the DRYDEP and/or WETDEP flag to “TRUE.” If the user wishes to model species as not subject to deposition (for example, noble gases), the corresponding flags may be set to “FALSE.”

3.8.1 Dry Deposition

Dry deposition is modeled in MACCS using a source depletion method [101] [102] [103] modified to allow treatment of a particle size distribution and to account for capping of vertical expansion by an inversion lid. The source depletion method calculates the rate at which materials are deposited onto the ground as the product of the ground level air concentration of the materials and the dry deposition velocity (Equation 12.2 of [104]) of those materials. This method makes use of the simplifying assumption that deposition onto the ground does not significantly affect the air concentration near the ground. This assumption allows the plume to be treated as Gaussian when deposition occurs. In the general case, with multiple aerosol sizes each with a different deposition velocity, the ground concentration is the sum over the set of aerosol sizes of the products of the time integrated air concentrations and the deposition velocities. The mass in each radionuclide class can be distributed among several particle size groups (up to 20), with each class having a different distribution of mass among the particle size groups. The particle size distribution of each radionuclide class is specified in the release description data. Because different particle sizes can deposit at different rates, both the size distribution and the relative amounts of the radionuclide classes can vary with downwind distance.

The concentration of monodisperse aerosols at a location on the ground is the product of the integrated ground-level air concentration and the deposition velocity. It can be shown (Section 2.10.2 of [20]) that the fraction of material f_{dry} in the plume at the beginning of the time period Δt that is not removed by dry deposition during the time period can be given by

$$f_{dry} = \frac{Q}{Q_0} = e^{-\frac{v_d \cdot \Delta t}{\bar{z}}} \quad (3-21)$$

where Q_0 is the amount of radioactive material (Bq) transported into the spatial element, Q is the amount of radioactive material (Bq) transported out of the element, v_d is the deposition velocity (cm/s), Δt is the residence time (s) that the plume segment has at a location, and \bar{z} is the effective height of plume.

Dry deposition is characterized in MACCS with a set of deposition velocities, VDEPOS, corresponding to a set of aerosol size bins. Larger values of dry deposition velocity result in larger long-term doses at shorter distances and smaller doses at longer distances; the converse is also true that smaller values of dry deposition velocity result in smaller long-term doses at shorter distances and larger doses at longer distances. The dry deposition velocity is a function of the degree of turbulence in the surface boundary layer of the atmosphere, which is affected by wind speed and surface roughness, and particle size. In pp. 2-18 to 2-20 of Sprung et al. [5] the authors describe the uncertainty in deposition velocity used for NUREG-1150. In that study, a single deposition velocity was used to characterize the entire range of aerosol sizes that would be

released into the atmosphere during a reactor accident. The best estimate, based on empirical equations and physical models, was a deposition velocity of 0.3 cm/s with a reasonable range of uncertainty of 0.03 to 3 cm/s, a range of a factor of 100.

The effect of surface roughness and wind speed (which vary on a site-specific basis) on deposition velocity has been characterized in NUREG/CR-7161 [27] based on expert elicitation data from [23]. The experts provided data for two wind speeds, 2 and 5 m/s, and for three terrain types, corresponding to meadow, forest, and urban terrains. NUREG/CR-7161 [27], as revised in recent versions of MelMACCS, provides a set of correlations for estimating deposition velocity as a function of aerosol diameter, wind speed, surface roughness, and percentile representing degree of belief by the experts. The correlation has the form:

$$\ln(v_d) = a + b \cdot \ln(d_p) + c \cdot [\ln(d_p)]^2 + d \cdot [\ln(d_p)]^3 + e \cdot z_0 + f \cdot v \quad (3-22)$$

where v_d is the deposition velocity (cm/s), d_p is the aerodynamic diameter of the aerosol (μm), z_0 is the surface roughness of the terrain (m), and v is the mean wind speed (m/s). In this regression equation, surface roughness lengths of 5, 100, and 50 cm were chosen to represent meadow, forest, and urban terrains, respectively. This correlation is valid for aerosol aerodynamic diameters up to about 20 μm and surface roughness lengths up to about 100 cm. The coefficients of the correlation for the median value estimate are given in Table 3-5.

Table 3-5 Median Value Regression Coefficients for Dry Deposition Modeling⁷

a	b	c	d	e	f
-2.964	0.992	0.19	-0.072	1.061	0.169

Based on these results, the formulation for the 50th percentile correlation is as follows:

$$\begin{aligned} \ln(v_d) = & -2.964 \\ & + 0.992 \cdot \ln(d_p) + 0.190 \cdot [\ln(d_p)]^2 - 0.072 \cdot [\ln(d_p)]^3 \\ & + 1.061 \cdot z_0 \\ & + 0.169 \cdot v \end{aligned} \quad (3-23)$$

To compute deposition velocities (either by hand using Equation (3-23) or using MelMACCS), the user needs to specify a representative wind speed and surface roughness length. The recommended approach is to use an average wind speed representative of the site and a surface roughness that is representative of the region of interest for the analysis. Unlike the surface roughness correction embodied in ZSCALE, which is recommended to be estimated based on land use within a few kilometers of the site, the surface roughness for deposition velocity modeling should consider a larger area, since dry deposition is likely to be significant over longer distances than the vertical dispersion correction. Estimating a surface roughness length over a distance of 10 to 50 miles from the site may be appropriate, depending upon the purpose of the analysis.

⁷ The value of these coefficients may be viewed in the MelMACCS.ini file distributed with MelMACCS 2.01 and above.

Parameter Name: DRYDEP

Parameter Description: Dry Deposition Flag

Recommended Value: FALSE for non-depositing species (e.g., noble gases); TRUE for all other chemical groups

Uncertainty Range: not applicable

References: [2], [14]

Discussion: Standard practice is to turn off dry deposition for noble gases and model deposition for all other chemical groups.

Parameter Name: VDEPOS

Parameter Description: Dry Deposition Velocities

Recommended Value: Compute using MelMACCS or per the median value regression equation given in Equation (3-23). Alternatively, a single deposition velocity may be used to characterize the range of aerosol sizes when aerosol size distribution data are unavailable. Nominally, a deposition velocity of 0.3 cm/s is recommended when surface roughness is 10 cm and mean wind speed is about 2 m/s. This value is consistent with Section 2.5 of [5] and with the dominant or average deposition velocity discussed in Section 7.3.6.1 of [28]. If desired, this value may be adjusted to account for regional surface roughness and wind speed using Equation (3-23).

Uncertainty Range: Compute using MelMACCS. However, it is important to understand that the distributions in [27], as updated in recent versions of MelMACCS, represent uncertainty in the deposition parameters over a relatively short time period, which is a reasonable estimate of uncertainty in an individual weather sequence. If the intention of an uncertainty analysis is to generate a set of realizations in which each realization is characterized by a mean over a large set of weather conditions, then the uncertainty in deposition velocity is narrower and the methods used in Section 5.9.2 of [15] to derive a triangular distribution are recommended.

References: [23], [27], [37], [15]

Discussion: The deposition velocity should be computed using a representative (e.g., average) wind speed for the site and a characteristic surface roughness length for the region of interest. A low deposition velocity tends to increase air concentrations and therefore be conservative for analyses when inhalation pathways are dominant; whereas, a higher deposition velocity tends to increase ground concentrations at short distances and therefore is conservative when external pathways are dominant. At long enough distances from the site, larger of deposition velocities enhance the depletion of the plume (thereby reducing the effective source strength), this causes both air and ground concentrations to be lower.

3.8.2 Wet Deposition

Unlike dry deposition, which is a continuous and relatively slow process, wet deposition is not continuous and can be quite rapid. Under heavy rains, wet deposition can rapidly deplete the plume. Even under light rains, the plume is depleted much faster than by dry deposition alone. The wet deposition process can produce concentrated deposits on the ground and create what is often referred to as a hot spot (i.e., an area of higher radioactivity than the surrounding areas). While rain occurs less than 10% of the time for most of the U.S., it can significantly affect consequence calculations when it does occur.

Wet deposition is treated as a function of both rain duration and rain intensity. MACCS treats the effect of wet deposition using a source depletion approach, similar to the treatment of dry

deposition, by calculating the fraction of aerosol in a plume segment at the beginning of a time period Δt that is not removed by wet deposition during the time period. The fraction f_{wet} that remains suspended after wet deposition is [105]:

$$f_{wet} = \frac{Q}{Q_0} = e^{-C_1 \cdot \Delta t \cdot I_r \cdot C_2} \quad (3-24)$$

where Q_0 is the amount of radioactive material (Bq) transported into the spatial element, Q is the amount of radioactive material (Bq) transported out of the element, C_1 is the linear washout coefficient corresponding to the MACCS input variable CWASH1, Δt is the duration of precipitation (s) (taken in MACCS as the time(s) that the plume segment takes to cross a point in the spatial element or the duration of rain, whichever is shorter), I_r is the intensity of precipitation (mm/hr), and C_2 is the exponential washout coefficient corresponding to the MACCS input variable CWASH2. As reported in [5], Brenk and Vogt [105] recommended values of $1.2 \times 10^{-5} \text{ s}^{-1}$ and 0.5 for C_1 and C_2 , respectively. Based on reviews documented in ([106] and [107]), [5] used values of $9.5 \times 10^{-5} \text{ s}^{-1}$ and 0.8 for C_1 and C_2 , respectively. The recommended values for the linear and exponential coefficients for washout (CWASH1 and CWASH2, respectively) are based on the approach used in the SOARCA project, derived from expert elicitation data from [23]. Bixler et al. [27] provides a set of correlations based on the elicitations conducted in [23] for estimating wet deposition parameters as a function of aerosol diameter and percentile representing degree of belief by the experts. The correlation has the form

$$\ln(C_1) = a + b \cdot \ln(d_p) + c \cdot (\ln(d_p))^2 + d \cdot (\ln(d_p))^3 \quad (3-25)$$

where d_p is the aerosol diameter (μm). The best estimate for the 50th percentile correlation is as follows:

$$\begin{aligned} \ln(C_1) = & -10.875 + 1.6 \cdot \ln(d_p) + 0.122 \cdot (\ln(d_p))^2 - 0.145 \\ & \cdot (\ln(d_p))^3 \end{aligned} \quad (3-26)$$

where d_p is the aerosol diameter (μm). This correlation is valid for aerosol diameters up to about 10 μm . Because C_1 and C_2 are correlated but not in a monotonic fashion, NUREG/CR-7161 [27] recommends a single fixed value of 0.664 for C_2 . Based on these results, Table 4-1 of NUREG/CR-7161 [27] estimates the median value of the linear washout coefficient C_1 to be $1.89 \times 10^{-5} \text{ s}^{-1}$ for a 1 μm particle and the value of the exponential coefficient C_2 to be 0.664, which were the values used in SOARCA [14]. This approach was updated in Section 5.9.1 of [15], where C_1 was sampled from a log-uniform distribution ranging from 10^{-6} to 10^{-4} (where rainfall is expressed in units of mm/hr and time is expressed in units of seconds) and C_2 was assigned a value of 0.7.

Unlike dry deposition velocity, MACCS does not allow wet deposition velocity parameters to be specified as a function of particle size bins. The recommended approach is to use the median particle size to determine the washout coefficients; however, the wet deposition parameters are a source of uncertainty for which distributions are available and for which the effect of alternate particle size assumptions could be examined parametrically.

Parameter Name: WETDEP

Parameter Description: Wet Deposition Flag

Recommended Value: FALSE for non-depositing species (e.g., noble gases); TRUE for all other chemical groups

Uncertainty Range: not applicable

References: [2], [14]

Discussion: Standard practice is to turn off wet deposition for noble gases and model wet deposition for all other chemical groups.

Parameter Name: CWASH1

Parameter Description: Linear Coefficient for Washout

Recommended Value: Compute based on median particle size using median value coefficients from Table 4-1 of [27]

Uncertainty Range: Log-uniform from 10^{-6} to 10^{-4} (where rainfall is expressed in units of mm/hr and time is expressed in units of seconds)

References: [23], [27], [15]

Discussion: The recommended parameter is based on those derived from the elicitations in [23] as reported in [27]. However, it is important to understand that the distributions in [27] represent uncertainty in the wet deposition coefficient for a relatively short period, which is a reasonable estimate of uncertainty in an individual weather sequence. If the intention of an uncertainty analysis is to generate a set of realizations in which each realization is represented by a mean over a large set of weather conditions, then the uncertainty is narrower and the distributions used in Section 5.9.1 of the Sequoyah uncertainty analysis [15] are recommended.

Parameter Name: CWASH2

Parameter Description: Exponential Term for Washout

Recommended Value: 0.664 if using values derived from [27]

Uncertainty Range: if CWASH1 is sampled using [15] recommended values, set CWASH2 to 0.7

References: [23], [27], [15]

Discussion: The recommended parameter is based on those derived from the elicitations in [23] as reported in [27]. If CWASH1 is sampled using the recommendations in [15], a fixed value of 0.7 is recommended.

4 PROTECTIVE ACTION PARAMETERS, OTHER SITE DATA, AND ECONOMIC FACTORS

Protective measures are implemented routinely in the U.S. These include large scale evacuations (e.g., more than 1,000 people from more than one building) occurring approximately once every three weeks [108]. Evacuations are most often conducted by local authorities who follow their all-hazards emergency plans to shelter or evacuate the public from hazards such as train derailments, gas leaks, or wildfires. The response to these hazards includes planning, alert and notification of the public, traffic control, organized transportation, shelter facilities, and return of the public to their homes, each of which has a contribution to cost [108] [109] [110]. MACCS separates protective actions into three phases: an early phase (also known as the emergency phase), an intermediate phase, and a long-term phase.

The MACCS early phase is user defined and, to allow for delayed or prolonged releases, can be modeled with a duration of up to 40 days after accident initiation. Early phase protective actions modeled in MACCS include sheltering, evacuation, use of KI, and relocation. These actions are directed by offsite response organizations (OROs) and implemented by the public. Sheltering may be ordered for specific areas when evacuation cannot be completed prior to arrival of the plume and it may also be implemented for special facilities. Sheltering followed by evacuation is typically considered the initial protective action for the public living within the plume exposure pathway EPZ [111]. Prompt relocation of individuals outside of the evacuation zone modeled in MACCS may also be included with the same considerations that govern a recommendation for evacuation. These protective actions are modeled in MACCS in a manner that considers when such actions would occur, the duration of the actions, and the associated cost. Although sheltering and KI administration are protective measures, the costs for these actions are not included in MACCS. Sheltering, if necessary within one's own residence, place of work, or other location, would likely be short term and followed by evacuation. KI programs are administered by government agencies. The costs of activating the KI program during an event are assumed to be small in relation to other accident-related costs and are not included.

The intermediate phase follows the early phase and can be defined as lasting up to one year. Intermediate phase actions and costs apply to residents that have been evacuated or relocated and are not allowed to return after the early phase. Decontamination occurs in the long-term phase and costs are developed based on farm and non-farmland land use. Farm costs are calculated on a per hectare of farmland basis. Non-farmland costs are calculated on a per person basis and include residential, commercial, and public property, improvements to property, equipment, and possessions. By using a per person basis, the approach accounts for site-specific population densities, including the corresponding density of buildings and infrastructure. During the long-term recovery phase, three mitigative actions are defined: (1) decontamination of land and property, with temporary interdiction of land and property during the decontamination process; (2) a combination of decontamination and continued interdiction of land and property for some period of time after decontamination is complete, until the property is restored to habitability; and (3) permanent interdiction (i.e., condemnation) with removal and resettling of people [20]. Costs from the lost sales of contaminated milk and crops are also included in the economic consequences.

The protective action parameters, site data, and economic factors are implemented in the EARLY and CHRONC modules. The ATMOS module performs all the calculations with regard to atmospheric transport, dispersion, and deposition, as well as the radioactive decay that occurs prior to release and during transport through the atmosphere. The EARLY module performs all the response calculations related to the early phase. The exposure pathways considered during

this period are cloudshine, groundshine, direct inhalation, and resuspension inhalation. Mitigative actions that can be specified for the early phase include sheltering, evacuation, early relocation from areas that exceed a specified dose level, and use of KI [2] [40]. The CHRONC module simulates events that occur following the emergency phase and includes calculation of the economic costs of protective actions. CHRONC calculates the individual health effects that result from external exposure to contaminated ground and from inhalation of resuspended materials. Collective doses and health effects (i.e., not estimated on an individual risk basis) caused by the consumption of contaminated food and surface water are also calculated in CHRONC.

4.1 Site Data and Demographic Characteristics

MACCS may be run with either a uniform population density defined by the user or with a site file that contains geographically explicit distributions for population and economic data. The choice of whether to use a uniform or site-specific population distribution depends on the purpose of the analysis. Guidance on when to use a UNIFORM population distribution versus a SITE FILE is described within the input parameter descriptions below.

Parameter Name: POPFLG

Parameter Description: Population Distribution Flag

Recommended Value: FILE

Uncertainty Range: not applicable

References: [58]

Discussion: POPFLG is automatically defined by WinMACCS once the analyst has selected the Site Data Specification bullet from the Project Properties/Site Data tab. There are currently two ways to define a population distribution. One is to apply a uniform population density throughout the area, the second is to import a site file. If a site file is chosen, POPFLG is automatically assigned “FILE.” If uniform is chosen, then POPFLG is “UNIFORM.” For applications in which the population distribution is an important aspect of the analysis, the recommended approach is to develop a site file with location-specific information on population, land use, and economic values. A brief overview of methods for developing a site-specific site file using the preprocessor code SecPop is given in the following section. The SecPop user manual [58] should be consulted for more detailed information on the technical basis for the databases used in SecPop.

4.1.1 Development of a Site-Specific Site File Using SecPop

The site file used by MACCS is a formatted text file, as described in Appendix A.3 of [2], with information on the geographic distribution of population and economic data. Although the site file may be developed manually, the SecPop code [112] [58] is often used to generate the site file. The process involves developing the inputs required to generate a site file in SecPop and then manually adjusting the site file as needed. When desired, a site file can be adjusted to be highly detailed. However, the analyst should first consider the scope and goals of the model outcome. A useful source of information for site file adjustment is the site’s evacuation time estimate (ETE) report. It is recommended that site data and demographic characteristics be developed using SecPop and augmented with other sources as necessary. For example, analyses may need to assess economic and population characteristics associated with tourism or special population groups. A SecPop file may additionally be used as a starting point, and then specific data can be adjusted or added directly into the file depending on the site and model scope. Older versions of SecPop, such as SECPOP2000, only supported 16 compass directions. For compatibility with MACCS models that require more compass directions, WinMACCS can create a site file that

supports 32, 48, or 64 sectors from a site file that supports 16 sectors. The SecPop Version 4 User's Guide [58] goes into detail on how to run SecPop in order to obtain a MACCS input file (.inp file). SecPop allows the analyst to specify a location via latitude/longitude or any existing reactor within the continental U.S. At a high level, the analyst collects the inputs to SecPop, runs the code to generate a base site file, and then manually adjusts the resulting file as needed for the purposes of the analysis. The inputs to SecPop include the geographic location (latitude and longitude) of the plant, the radius of the EAB, the definition of the spatial grid, and population and economic escalators to adjust the results from the SecPop databases to a project base year.

The origin of the coordinate system in the site file is the point from which the release is modeled to occur in MACCS; all plume travel distances and population locations are relative to this point. Although the release may occur from different locations within the plant (for example, from the plant stack, from containment failure release points, or from failure of auxiliary buildings), the center of the containment, or the midpoint between the containments of a multiunit site, is a conventional location for the origin of the site file. Information on the geographic coordinates of the reactor containment structure, as well as the location of the EAB (either as a map or as a distance from the site) is typically available in the plant Safety Analysis Report. When using SecPop, the analyst should check the predefined site location against the precise location of the containment or reactor building. If the analysis involves a new unit, the location of the new construction should be used.

The EAB is frequently an irregular polygon but must be specified in SecPop as a fixed radius. The user may choose to specify the EAB radius as the minimum distance from the containment to the site boundary so that close-in offsite populations will not be inadvertently excluded by SecPop. When creating the SecPop site file, the analyst should consider the grid definition parameters (NUMCOR, NUMRAD, and SPAEND) discussed in Section 3.5. For example, if there are large employers within the EPZ, the analyst may include these locations in the grid definition. The radial distances chosen in SecPop must be within 10% of the distances used in the MACCS model; therefore, it is efficient to spend some time gathering data on the area and the desired metrics for the analysis before creating a site file. Otherwise, it is likely that a second site file will need to be created to add or adjust radial distances. A descriptive name should be used for the name of the site file. It is recommended that the name of the site file include the name of the site, the year corresponding to the projected population and economic data, and the number of compass sectors used in the file.

Population and economic statistics are based on decennial census data along with multipliers to account for population and inflation from the year of the decennial census to the desired projection year. At the time of this writing, the most recent SecPop population and economic data are from 2010 and 2012, respectively; however, older data are also included with the SecPop distribution. The analyst should check to make sure which data are being used. Scaling factors can be developed by referencing sources such as the U.S. Census [113] for the counties that comprise the region of interest and inflation calculators from the U.S. Bureau of Labor Statistics. If the base year is prior to the current year, a direct estimate of the population escalator can be computed using U.S. Census population estimates. If the project base year is in future, an annualized population growth rate can be estimated from existing data and projected forward to the desired year. An economic escalator may be obtained using consumer price index (CPI) data from the U.S. Bureau of Labor Statistics (BLS). For example, estimates of inflation based on the CPI are available from [114]. This inflation calculator uses what is known as the headline CPI, which includes costs for food and energy that contribute some volatility in the CPI. A less volatile measure of inflation involves the core CPI, which is the CPI for all items except food and energy and is also tabulated by the BLS. The core CPI was chosen to adjust values in the more recent

SOARCA work. Information to develop an escalation factor using a the core CPI may be developed using information from [115] and is the recommended method for escalating costs.

Depending on the purpose of an analysis, the site file from SecPop may be used as is or may be adjusted using a text editor or spreadsheet. The protective action scheme should be identified early in the MACCS parameter development process because many of the fundamental parameters, including the site file populations, may be different for various scenarios. Common adjustments include modifying the population to account for county-specific growth rates, addition (or subtraction) of population to adjust for special populations not reflected in the census residential data used by SecPop, and modification of economic regions to reflect user-specified data or to fill in gaps where a grid element contains no census block centroid. The extended site file produced by more recent versions of SecPop contains information on the relative proportion of a county in a specific grid element and may be useful for evaluating county specific adjustments. In sparsely populated areas, the spacing of census block centroids may be sufficiently large that some grid elements close to the site may not contain a census block centroid. These regions are identified within the site file as economic region 3. Such blocks may be reassigned to an economic region that has appropriate economic and land area values (for example, to be consistent with the county in which they are located). When manually adjusting the site file, the analyst should remember that the first sector is always *centered* on north. For example, this means that, for 16 sectors, each sector spans 22.5 degrees and the first sector starts at 348.75 degrees and end at 11.25 degrees, where 0 degrees is to the north.

A final check of the site file should include a manual inspection of the population, economic regions (both the definition and the geographic location), watershed parameters, and food chain parameters (if the original MACCS food model is used) to ensure that the file accurately reflects the site at a level of detail sufficient for the purposes of the analysis.

Parameter Name: not applicable

Parameter Description: Site File Name

Recommended Value: Problem specific. SecPop is recommended for development of the site file.

Uncertainty Range: not applicable.

References: [58], [112]

Discussion: The name of the site file is not a MACCS parameter. Rather, it is passed to the MACCS executable as a command line argument. In WinMACCS, the site file is entered in the File Specification tab. It is recommended that SecPop be used to develop a MACCS site file for sites in the continental U.S. This file can then be adjusted as necessary within a text editor.

4.2 Exposure Parameters

MACCS uses parameters for shielding, exposure, and resuspension factors to model the time-dependent reduction in groundshine doses due to weathering processes in the biosphere which determine exposure to airborne or deposited radioactive material. Shielding and exposure factors are specified separately for the EARLY and CHRONC modules but serve the same purpose. The values in CHRONC account for long-term behavior of the public and for the shielding offered by structures in which people dwell, work, and spend time. These parameters also include the factors needed to define resuspension (in EARLY and CHRONC) and the time-dependent reduction in resuspended material and external dose rate due to weathering and removal processes.

4.2.1 Shielding and Exposure Factors

Shielding and exposure factors (also termed dose-reduction factors) are specified for each dose pathway (cloudshine, groundshine, inhalation, and skin protection) in MACCS and they directly affect the doses received by individuals. These factors are based on occupancy-weighted estimates of the ratio of the protected to the unprotected (i.e., standing outdoors on a flat surface and completely unprotected from exposure to airborne and deposited radioactivity) dose. This ratio is sometimes termed the location factor. Location factors are multipliers on the dose that a person would receive if there were no shielding or protection. Thus, a location factor of one represents the limiting case of a person receiving the full dose (i.e., standing outdoors on a flat surface and completely unprotected from exposure). A location factor of zero represents the limiting case of complete protection from exposure. Because individuals may be in any of a number of locations, each of which may have a different location factor (e.g., in the upper floors of a wood-framed house, in a residential basement, in a vehicle, or outdoors), the occupancy patterns must also be considered. The typical approach to the derivation of shielding and protection factors is to estimate a weighted average factor, considering the fraction of the population that may be in each location, depending upon the activity pattern. Shielding and exposure factors are derived for normal activity, active sheltering, and evacuation for each MACCS dose pathway (i.e., inhalation, deposition onto skin, cloudshine, and groundshine), resulting in a set of 12 factors. These factors are defined for each early-phase cohort; for example, shielding factors for special populations residing in large structures, such as hospitals, may be defined to account for the additional shielding offered by such structures. The derivation of the shielding and exposure factor for use within MACCS therefore includes a calculation of the form

$$SEF_{j,k} = \sum_i w_{i,k} f_{i,j} \quad (4-1)$$

where

- i is the location of the individual (e.g., outdoors, in a vehicle, in the upper floors of a vinyl sided building, in a basement);
- j is the dose pathway (cloudshine, groundshine, inhalation, or skin deposition);
- k is the activity (normal activity, active sheltering, or evacuation);
- $SEF_{j,k}$ is the shielding and exposure factor for dose pathway j and activity k ;
- $w_{i,k}$ is the occupancy fraction (percentage of the cohort population averaged over the duration of the activity) in location i during activity k ; and
- $f_{i,j}$ is the location factor (ratio of the protected to unprotected dose) for location i and dose pathway j .

When members of a cohort behave somewhat differently, Equation (4-1) could be modified to consider population fractions of the cohort with different behaviors. This modification is more likely to be useful during the intermediate and long-term phases where the entire population is modeled with single cohort. During the early phase, the population can be represented by multiple cohorts so that averaging over multiple behaviors may not be necessary.

The basic methodology for shielding and exposure factors was developed in WASH-1400 (see Section 11.3 of [3] for more information), and was updated in Section 3.2 of Sprung et al. [5], who

derived site-specific values from information on the geographic distribution of multiunit structures and state-specific information on the fraction of newly constructed residences with basements. The results of that analysis suggested that the normal activity shielding values did not vary greatly among sites, but that the sheltering values could vary on a site-specific basis, largely because of the significant differences in the availability of basements for sheltering across different areas of the country.

4.2.1.1 Cloudshine and Groundshine Shielding

Data compilations that can be used to estimate location factors are available from a variety of sources. Location factors for groundshine (i.e., for external exposure to deposited material) were developed by Burson and Porfio [116] for WASH-1400. That analysis continues to be a commonly referenced source for location factors appropriate for LWR accidents. More recent compilations include the guidance used for assessing doses from radiological incidents and accidents (such as the FRMAC assessment manuals [11] and operational guidelines developed for use in emergency preparedness and response to a radiological dispersal device incident [12]). These values are based on a typical radionuclide spectrum from a LWR accident with limited time for decay of short-lived radioactivity. A capstone paper by Dickson and Hamby [117] developed a simplified method to estimate the building protection factor for any energy spectra.

For both cloudshine (CSFACT) and groundshine (GSHFAC) factors, considerations for estimating appropriate values include:

- Energy spectrum of the gamma radiation from the set of radionuclides creating the contamination. The tendency is for the energy to be higher during the early phase, about 1 to 1.2 MeV, and to be lower during the intermediate and long-term phases, approaching that of Cs-137, about 600 keV. This causes the protection factor to be slightly larger during the long-term phase than during the early phase.
- Deposition pattern on building walls and roof. For simplicity, it is typical to assume uniform deposition onto the ground and onto the roof. However, to conserve mass, the concentration on the roof should be reduced by the ratio of its projected area onto the ground to its actual area. If walls are assumed to be contaminated, then the total contamination on the exterior surfaces should not be more than the deposition onto a plane (in the absence of the building) would have been.
- The amount of infiltration of airborne material into the structure, which can lead to deposition onto interior surfaces and exposure sources from inside the structure.
- The type of building materials and size of the structure considered during normal activity and sheltering.
- Fraction of time a person is inside a structure that provides shielding and protection,
- Location of a person within a building during normal activity and sheltering. For example, the groundshine and cloudshine factor may depend upon whether a person shelters in the basement or is predominantly on the first or second floors.
- The size of the structure, reflecting the distance and amount of shielding material between the unprotected location and the location of the individual within the structure. Smaller structures tend to offer less protection than larger structures.

For an individual outdoors, some measure of protection from groundshine is also afforded by factors such as shielding from nearby structures and ground roughness. Burson and Porfio [116] give a range of groundshine shielding factors for an individual outdoors based on values provided for fallout sources for defense civil preparedness. Values were provided for a range of ground roughness conditions ranging from a smooth plane to a deeply plowed field. More recently, Volume I of the Federal Radiological Monitoring and Assessment Center (FRMAC) Assessment Manual [11] recommends a value of 0.82 for the groundshine shielding factor to reflect ground roughness. This value is based on measurements taken at several sites in the Ukraine following the Chernobyl accident [118] [119].

For both the derivation of cloudshine and groundshine factors, vinyl sided housing is a good surrogate for many other light construction housing types, such as wood siding, aluminum siding, or stucco. Brick siding is unique in that it offers more shielding than other housing types. The values used in MACCS represent an average across a range of occupancy patterns and structure types. Some cohorts may live or shelter in buildings with more shielding and those cohorts should have lower factors. For these cohorts, shielding factor values should be adjusted to reflect the characteristics of the cohort. For example, housing constructed of mortar filled concrete block provides substantially more shielding than brick siding because the material is about twice as thick. Also, commercial (e.g., office buildings and hospitals) and government buildings are often constructed from heavier materials, such as stone or thick concrete.

The shielding effectiveness of a structure can change over time as the radionuclide mixture and gamma-ray energy spectrum change from radionuclide migration, radioactive decay, weathering effects, and decontamination efforts. Furthermore, in some assessments the composition of radionuclides may be different from those typically assumed. Thus, the analyst may wish to develop factors designed for multiple photon energy spectra to generate a more realistic estimate of the shielding effectiveness of a particular building, particularly if the radionuclide mix may be different than that assumed for a severe accident at a LWR.

The simplified method documented in [117]⁸ can be used to assess the dose to the public from external environmental exposure pathways for any energy spectra. The method uses a DCF approach as referenced by the EPA [120] and the FRMAC Assessment Manual [11]. A series of fitted functions correlate an estimated protection factor to any photon energy up to 3.0 MeV. Functions were developed for two housing types, vinyl sided and brick, and for single- and two-story housing with and without a basement. Dickson and Hamby [117] compared the ability of the functions to estimate location factors to those presented in other study results [121] [116] [122] [123] who reported on similar structures using a variety of source terms and methods, and found they were in general agreement (see Table 6 of [117], reproduced in Figure 4-1).

⁸ Transcription errors were identified in Table C3 and C4 of [117], which provide radionuclide-specific deposition factors. A corrigendum to [117] (E D Dickson and D M Hamby 2021, "Corrigendum: Building protection- and building shielding-factors for environmental exposure to radionuclides and monoenergetic photon emissions (2016 J. Radiol. Prot. 36 579–615)", Journal of Radiological Protection 41:129-133) provides the correct radionuclide-specific deposition factors for brick-sided one-story and two-story housing units. These errors do not affect any of the numerical results provided in this report, which rely on the monoenergetic photon values provided in Tables B2, B5, A2, or A5 of [117].

Previous studies	Stickler and Auxier (1960) ^a		Burson (1975, 1977) ^b		Meckbach <i>et al</i> (1988) ^c		
	Co-60 sources		Reactor source term ^d		0.3 MeV	0.662 MeV	3.0 MeV
	Location	Wood	Concrete block	Wood, 1 and 2 story	Brick, 1 and 2 story	Pre-fabricated (wood walls, concrete roof)	
Attic	—	—	—	—	0.54	0.62	0.67
Second floor	—	—	—	—	—	—	—
First floor	0.23–0.43	0.23–0.29	—	—	0.47	0.50	0.58
Basement	0.08	0.07	0.03–0.05	0.03–0.05	0.01 ^e	0.02 ^e	0.05
Averaged	—	—	0.40	0.20	0.34	0.38	0.43

Current study	Table B2 functions		Table B5 functions		Table B5 functions		
	Co-60 source spectra ICRP 107		Reactor source term		0.3 MeV	0.662 MeV	3.0 MeV
	Location	Vinyl	Brick	Vinyl, 1 and 2 story	Brick, 1 and 2 story	Vinyl	Vinyl
Attic	—	—	—	—	—	—	—
Second floor	—	—	—	—	0.48	0.52	0.59
First floor	0.55	0.29	—	—	0.47	0.51	0.59
Basement	0.07	0.06	0.07–0.08	0.04–0.06	0.10	0.09	0.06
Averaged	0.31	0.18	0.31–0.40	0.18–0.21	0.36	0.37	0.40

^a Applied a combination of full-scale measurements and the Standard Method (Auxier *et al* 1959) to derive factors for light residential structures based on a Co-60 measurements and attenuation coefficients.

^b Provides a summary Civil Effect Test experiments and recommends a range of factors for deposited material.

^c Applied Monte Carlo methods to derive factors for a variety of residential structures based on monoenergetic photon energies. This is a prefabricated house; single-story model, wood-frame, wood primary weather barrier, cement roof, and a full basement on a concrete foundation.

^d Source term based on the U.S NRC Reactor Safety Study (NRC 1975).

^e Published basement factors are lower than those predicted by the functions presented in this study for low photon energies.

Figure 4-1 Comparison Between Other Study Results and the One- and Two-Story Function Predicted Protection Factors

Source: Table 6 of [117]⁹

Dickson and Hamby [117] also verified the functions' ability to predict factors for mixed photon energy spectra. Another series of Monte Carlo simulations were performed for a select set of radionuclides using nuclear decay data published by the ICRP in ICRP-107 [124] to develop radionuclide-specific building protection factors. These select radionuclides were selected to represent generalized exposure scenarios of 'low', 'medium', and 'high' emitted photon energy spectra. As demonstrated by Table 9 of [117], excellent agreement was achieved between the factors estimated using the functions in [117] and those computed directly using Monte Carlo methods.

Energy-dependent ground deposition location factors for deriving a groundshine shielding factor may be obtained from Tables B2 and B5 of [117]. These tables provide functions that allow the protection factor to be estimated as a function of photon energy. The functions are of the form shown in Equation (4-2) for both cloudshine and ground deposition protection factors.

⁹ Reproduced from "Building protection- and building shielding-factors for environmental exposure to radionuclides and monoenergetic photon emissions," Dickson, E. and Hamby, D., 2016, Journal of Radiological Protection, no. 36: 579-615. © IOP Publishing. Reproduced with permission. All rights reserved.

$$PF = \alpha \cdot \ln(x) + \beta \quad (4-2)$$

Where

- PF: Protection factor (ratio of indoor to outdoor dose normalized to a person standing on the ground in the absence of any nearby structures)
- α : Linear coefficient
- x : Photon energy in MeV
- β : Constant term

The coefficients for the protection factors equations are provided in Tables B2 and B5 of [117] and summarized in Table 4-1. Use of these coefficients in Equation (4-2) provide the values that should be used to develop occupancy-weighted dose-reduction factors in MACCS to be consistent with the FRCMAC [11] because these values are normalized to a person standing on the ground in the absence of any nearby structures. These values may be further modified by consideration of a ground roughness factor, discussed above.

Table 4-1 Energy-Dependent Ground Deposition Location Factor Parameters

Housing Type	Wall Barrier	Location	α	β	Source [117]
One story without basement	Vinyl	First Floor	0.0590	0.5420	Table B2
One story with basement	Vinyl	First Floor	0.0484	0.5410	Table B2
One story with basement	Vinyl	Basement	-0.0140	0.0774	Table B2
One story without basement	Brick	First Floor	0.0699	0.2799	Table B2
One story with basement	Brick	First Floor	0.0706	0.2775	Table B2
One story with basement	Brick	Basement	0.0040	0.0583	Table B2
Two story without basement	Vinyl	Second Floor	0.0395	0.5401	Table B5
Two story without basement	Vinyl	First Floor	0.0491	0.5557	Table B5
Two story with basement	Vinyl	Second Floor	0.0466	0.5378	Table B5
Two story with basement	Vinyl	First Floor	0.0491	0.5540	Table B5
Two story with basement	Vinyl	Basement	-0.0160	0.0604	Table B5
Two story without basement	Brick	Second Floor	0.0740	0.2815	Table B5
Two story without basement	Brick	First Floor	0.0905	0.2683	Table B5
Two story with basement	Brick	Second Floor	0.0740	0.2803	Table B5
Two story with basement	Brick	First Floor	0.0905	0.2668	Table B5
Two story with basement	Brick	Basement	0.0039	0.0405	Table B5

Source: adapted from Tables B2 and B5 of [117]¹⁰

¹⁰ Adapted from "Building protection- and building shielding-factors for environmental exposure to radionuclides and monoenergetic photon emissions," Dickson, E. and Hamby, D., 2016, Journal of Radiological Protection, no. 36: 579-615. © IOP Publishing. Reproduced with permission. All rights reserved.

Similarly, the coefficients for developing energy-dependent cloud immersion location factors for deriving a cloudshine shielding factor may be obtained from Tables A2 and A5 of [117]. The entries corresponding to “protection factors,” reproduced in Table 4-2 below, provide for the values that should be used to develop occupancy-weighted dose-reduction factors in MACCS to be consistent with the FRMAC [11] because these values are normalized to a person standing on the ground in the absence of any nearby structures. Unlike the ground deposition protection factors, these values should not be further modified by consideration of a ground roughness factor.

Table 4-2 Energy-Dependent Cloud Immersion Location Factor Parameters

Housing Type	Wall Barrier	Location	α	β	Source [117]
One story without basement	Vinyl	First Floor	0.0840	0.7698	Table A2
One story with basement	Vinyl	First Floor	0.0836	0.7604	Table A2
One story with basement	Vinyl	Basement	0.0871	0.4442	Table A2
One story without basement	Brick	First Floor	0.1167	0.5897	Table A2
One story with basement	Brick	First Floor	0.1187	0.5827	Table A2
One story with basement	Brick	Basement	0.0760	0.2937	Table A2
Two story without basement	Vinyl	Second Floor	0.0936	0.8741	Table A5
Two story without basement	Vinyl	First Floor	0.0821	0.7349	Table A5
Two story with basement	Vinyl	Second Floor	0.0935	0.8714	Table A5
Two story with basement	Vinyl	First Floor	0.1028	0.7217	Table A5
Two story with basement	Vinyl	Basement	0.0879	0.4035	Table A5
Two story without basement	Brick	Second Floor	0.1335	0.6201	Table A5
Two story without basement	Brick	First Floor	0.1240	0.4224	Table A5
Two story with basement	Brick	Second Floor	0.1336	0.6186	Table A5
Two story with basement	Brick	First Floor	0.1240	0.4176	Table A5
Two story with basement	Brick	Basement	0.0730	0.2070	Table A5

Source: adapted from Tables A2 and A5 of [117]¹¹

Adjustment of these location factors to account for variations in the actual location of individuals relative to different structure types requires information on occupancy patterns. In the 1990s, shielding and exposure factors were the subject of an expert elicitation [6]. In the elicitation, both the location factor (for groundshine) and occupancy patterns of the general public in seven types of locations were considered:

- inside a low shielding building (e.g., a wooden framed house)
- inside a medium shielding building (e.g., a typical brick family house)
- inside a high shielding building (e.g., a multi-story building)

¹¹ Adapted from "Building protection- and building shielding-factors for environmental exposure to radionuclides and monoenergetic photon emissions," Dickson, E. and Hamby, D., 2016, Journal of Radiological Protection, no. 36: 579-615. © IOP Publishing. Reproduced with permission. All rights reserved.

- inside the basement of a single family house
- in the basement of a multi-story building
- in a typical car on a suburban street
- in a typical bus on a suburban street

The elicitation did not specify the locations within the buildings, specific characteristics of the buildings (e.g., mass per unit area of walls, or numbers and locations of windows), deposition mechanisms, or relative deposition distributions for the various surfaces (including internal surfaces). However, estimates for these occupancy fractions for a generic U.S. location were provided by Expert “A” in Appendix C of Volume 2 of [6]. Values corresponding to the expert’s median value estimate are reproduced in Table 4-3. If desired, these estimates could be updated using, for example information from the EPA Exposure Factors Handbook [125] which has detailed information on indoor and outdoor time use.

Table 4-3 Population Fractions for a Generic U.S. Location

Median Weighted Occupancy Fractions	Outdoor/ Agricultural Workers (5%)	Indoor Workers (45%)	Non-active Adult Population (25%)	School- children (25%)
Urban (approximately 75% of US population)				
Low shielding ¹	0.34	0.34	0.44	0.37
Medium shielding ²	0.13	0.13	0.17	0.14
High shielding ³	0.14	0.33	0.23	0.28
Basement of single family house	0.03	0.03	0.03	0.04
Basement multi-story office block	0.001	0.01	0.001	0.001
Inside typical car	0.12	0.06	0.03	0.03
Inside typical bus	0.003	0.003	0.002	0.01
Outdoors	0.236	0.097	0.097	0.129
Rural (approximately 25% of US population)				
Low shielding ¹	0.40	0.40	0.53	0.44
Medium shielding ²	0.17	0.17	0.23	0.19
High shielding ³	0.04	0.25	0.13	0.17
Basement of single family house	0.03	0.03	0.03	0.04
Basement multi-story office block	0.001	0.001	0.001	0.001
Inside typical car	0.12	0.06	0.03	0.03
Inside typical bus	0.001	0.001	0.001	0.02
Outdoors	0.238	0.088	0.048	0.109

e.g., wooden framed houses

e.g., single brick family house

e.g., multi-story office block

Source: derived from median values reported in response to Question 13 by Expert “A”, pp. C32-C34 of [6]

A representative average protection factor can be developed based on a protection factor for a specific location (i.e., a “location factor”), an adjustment for the ground-level surface roughness, and a location weighting for the average time that people spend occupying a location. Based on the deposition protection factor functions in Table B2 from [117] and a photon energy of 0.6617 MeV, this report uses location factors of 0.52, 0.25, and 0.07 for a low-shielded building, a medium-shielded building, and a basement, respectively. The low-shielded building assumes a single-story vinyl-sided house with basement. The medium-shielded building assumes a single-story brick house with basement. The basement location factor value is a simple average resulting from the equations for basements in the previous two buildings. A high-shielded building is a category that includes multi-story apartments and office complexes and is assumed to have the same location factor as a basement. Location factors of 0.65 and 0.55 for a typical car and bus, respectively, are based on median values from Table 3.16 of [5]. A ground-level surface roughness factor of 0.82 is applied to most locations. It is not applied to multi-story buildings or basements, as the value assumes a surface roughness view factor to a ground-level receptor.

The normal activity location weightings are weighted averages derived from the four population subsets (i.e., agricultural and other outdoor workers, indoor workers, non-active adult population, and schoolchildren) for both urban and rural residents provided in NUREG/CR-6526 [6] as summarized in Table 4-3. Evacuation location weightings are based on [5]. There are two sets of sheltering location weightings, both of which are based on modification of the normal activity weighting. The first is for cohorts following a “shelter-in-place” order. This uses the following assumptions.

- All people in a building during normal activity remain in that building.
- The remaining people enter their residence (58%, 25%, and 17% for low, medium, and high-shielded buildings, respectively, according to [6]).
- 42% of single-family homes (i.e., low and medium-shielded) have basements [126], which are occupied if available.

The second set of sheltering location weightings is for cohorts that are preparing for evacuation (i.e., mobilizing). These mobilization location weightings use the following assumptions:

- Half of the people that are in high-shielded buildings that are not their residence (e.g., office buildings, shops) and all people that are outside during normal activity return to their residence, while the rest prepare to evacuate from where they are.
- In single-family homes, time is equally split between the first floor (active preparation) and the basement, if available. The basement is where children wait while others prepare and where other people may also wait in order to evacuate as a family unit, if family members are not initially together.
- Transportation does not change from normal activity, as some people travel to bring their family together.

The resulting values are summarized in Table 4-4. The location-weighted groundshine protection factors for an average person engaging in different activities based on Equation (4-1) are shown in the final column under “Weighted”.

Table 4-4 Location Factors and Weightings for the Groundshine Protection Factors

Location	Low shielded building	Medium shielded building	High-shielded building	Basement	Car	Bus	Outside	Weighted
Location Factor (Cs-137)	0.52	0.25	0.07	0.07	0.65	0.55	1.00	n/a
Ground-level Surface Roughness	0.82	0.82	1.00	1.00	0.82	0.82	0.82	n/a
Adjusted Location Factor ¹	0.43	0.21	0.07	0.07	0.53	0.45	0.82	n/a
Normal Activity Location Weighting	0.39	0.15	0.26	0.033	0.06	0.005	0.10	<u>0.34</u>
Shelter-in-place Location Weighting	0.29	0.12	0.29	0.30	-	-	-	<u>0.19</u>
Mobilizing Location Weighting	0.30	0.13	0.20	0.31	0.06	0.01	-	<u>0.22</u>
Evacuation Location Weighting					0.90	0.10		<u>0.52</u>

¹ adjusted for the ground-level surface roughness factor

The location factors and occupancy fractions reported in [6] were postprocessed by Gregory et al. [9] to yield a set of parameter distributions for the groundshine factor. The geographic region is not specified, but it appears that this is consistent with a generic site based on discussions of the use of U.S.-average occupancy fractions. As discussed in Section 5.9.3 of [15], the distributions provided by [9] may be used to perform uncertainty analyses. For members of the general public and for a generic site, the values provided in Table 4.11 of [9], reproduced in Table 4-5 below, facilitate uncertainty analyses. As noted in [15], “These distributions are intended to be used for the general public, but are not appropriate for populations in large, institutional facilities, such as hospitals.”

Table 4-5 Generic Groundshine Shielding Factor

Quantile	Normal Activity	Sheltering	Evacuation
0	5.3E-02	1.5E-02	8.3E-02
0.01	6.8E-02	2.2E-02	1.3E-01
0.05	9.5E-02	3.5E-02	1.8E-01
0.15	1.3E-01	4.7E-02	2.4E-01
0.25	1.5E-01	6.4E-02	2.8E-01
0.50	2.2E-01	1.0E-01	4.0E-01
0.75	3.0E-01	1.7E-01	5.5E-01
0.85	3.5E-01	2.0E-01	6.4E-01
0.95	4.2E-01	2.5E-01	7.6E-01
0.99	4.9E-01	2.9E-01	8.7E-01
1	5.5E-01	3.3E-01	9.4E-01

Source: adopted from Table 4.11 of [9]

CSFACT is the set of cloudshine shielding factors for normal, evacuation, and sheltering activities. These values were not assessed in the expert elicitation documented in [6]. Accordingly, Gregory et al. [9] referenced values from an earlier sensitivity and uncertainty analysis by Helton et al. [8] that was based on the analyses in [5]. The following recommended values for the general public for a generic site are from Table 4 of [8], see Table 4-6 below:

Table 4-6 Generic Cloudshine Factor

Quantile	Normal Activity	Sheltering	Evacuation
Lower Bound	0.60	0.50	0.9
Upper Bound	0.95	0.70	1.0
Point Estimate	0.75	0.60	0.95

Source: adopted from Table 4 of [8]

The point estimate values in Table 4-5 are considered reasonable recommended values for the general public for a generic site. Further information on the derivation of these values can be obtained from [5].

Parameter Name: GSHFAC

Parameter Description: Groundshine Shielding Factors

Recommended Values: for a generic site and for the general public, normal, 0.34; evacuation, 0.52; sheltering-in-place, 0.19; mobilizing, 0.22. Site and/or cohort specific values may be derived. Dose-reduction factors for cohorts sheltering in high-shielding buildings may be adjusted downward from these recommended values.

Uncertainty Range: Table 4-5, based on Table 4.11 of [9]

References: [9], [6], [15]

Discussion: GSHFAC is the set of groundshine factors for normal, evacuation, and sheltering activities during the early phase. For members of the general public and for a generic site, the values provided in Table 4-3 are appropriate. These may be adjusted for site-specific building

and occupancy characteristics if desired. The values for normal activity and sheltering may vary by cohort because they are based on the robustness of the buildings or facilities in which the cohort resides or shelters. Special facilities, such as hospitals or schools, provide greater shielding than single family dwellings. Cohort specific values may be derived with consideration of the location factors and occupancy fractions appropriate for the cohort. A site-specific value for sheltering by the general public may be based on the recommendations in [5], taking into account the similarity of the site to one of the sites in that document, or derived based on updated information for location factors and occupancy fractions.

Parameter Name: LGSHFAC

Parameter Description: Long-Term Groundshine Protection Factor

Recommended Value: 0.34

Uncertainty Range: Use normal activity values from Table 4-5

References: [9], [6], [15]

Discussion: LGSHFAC is the groundshine factor used for the intermediate and long-term phases. Generally, this parameter is chosen to be the same as GSHFAC for normal activity during the early phase. Consideration may be given to reducing this value to account for the generally lower energy radiation associated with Cs-137 or increasing it due to potential deposition of contaminated soil and dust on interior surfaces. Older versions of MACCS assumed that the long-term shielding and exposure factors in the intermediate- and long-term phases are identical with those for normal activity during the early phase. This is still a reasonable assumption that is commonly used. However, there are some reasons why the factors could be different for these phases. One basic difference is in potential equilibration between the exterior and interior of buildings. The usual assumption in estimating these factors for the early phase is that the exterior is contaminated but the interior is clean. This may be a reasonable assumption for the short term but may be less reasonable for the long term. Even for the short term, air exchange between the interior and exterior of a house or other building can cause some level of contamination to the interior. Ventilation systems in a home or other building would gradually introduce contaminants into the interior, which in turn would affect the shielding and exposure factors. By allowing a distinction between short-term and long-term shielding and exposure factors, MACCS can be used to evaluate possible time dependencies of these factors.

Parameter Name: CSFACT

Parameter Description: Cloudshine Shielding Factors

Recommended Values: for a generic site and for the general public, normal activity, 0.75; evacuation, 0.95; active sheltering, 0.60. Site and/or cohort specific values may be derived.

Uncertainty Range: Table 4-6, based on Table 4 of [8]

References: [8], [5]

Discussion: The values for normal activity and sheltering may vary by cohort because they are based on the robustness of the buildings or facilities in which the cohort resides or shelters. Special facilities, such as hospitals or schools, may provide greater shielding than single family dwellings. Cohort specific values may be derived with consideration of the location factors and occupancy fractions appropriate for the cohort. A site-specific value for sheltering by the general public may also be based on the recommendations in [5], taking into account the similarity of the site to one of the sites in that document, or derived based on updated information for location factors and occupancy fractions.

4.2.1.2 Inhalation and Skin Protection

The inhalation (PROTIN) and skin deposition (SKPFAC) factors are both based on the ratio of the time integrated airborne concentration in the protected location to the time integrated ground level outdoor air concentration. These may be derived using a simple, single- or multi-compartment model. Considerations for determining appropriate values for inhalation and skin protection factors include:

- Air tightness of building or structure. Modern homes are often built to high levels of air tightness.
- Integrity of building or structure. For example, windows may be closed, open, or even broken because of an earthquake. These factors may change over the course of a year; for example, windows are more likely to be open during warm weather and closed during the heating season.
- Air exchange with the exterior through heating, ventilation, and air conditioning systems or from open windows and doors. Because a measure of ventilation is needed for structures due to indoor air quality and moisture control concerns, forced ventilation may be used to ensure the appropriate level of ventilation during normal activity. Such ventilation may be shut off during periods of active sheltering.

Because there is always some air exchange between the indoor and outdoor air, the duration of cloud passage may also be important, with longer times of cloud passage resulting in a smaller difference between interior and exterior concentrations. If the air within the structure is assumed to be well mixed (i.e., the structure is modeled as a single ventilation compartment or the rate of exchange between compartments is high), the location within the building is not as important as with protection from sources outside the building. Information relevant to ventilation modeling for indoor air quality assessments are summarized in Chapter 19 of [125]. Values appropriate for active sheltering should consider the potential for shutdown of forced ventilation systems, in which case the ventilation of the structure would be due to pressure differentials between the interior and exterior of the structure due to wind.

The technical bases for the inhalation (PROTIN) and skin deposition (SKPFAC) factors were considered in the elicitation documented in [6]. These values were postprocessed by Gregory et al. [9] to yield a set of parameter distributions. These distributions were further evaluated in Section 5.9.3 of [15] for use in the SOARCA project, which recommended a somewhat narrower distribution than that provided in [9]. In addition, the recommended point value (0.98) for the evacuation inhalation protection factor was based on [127]. The resulting distributions are shown in Table 4-7.

Table 4-7 Recommended Generic Inhalation Protection Factor

Quantile	Evacuation*	Normal Activity	Sheltering
0	0.9	0.34	0.098
0.5	N/A	0.46	0.25
1	1	0.90	0.70
Point Values	0.98	0.46	0.25

*Evacuation PROTIN distribution modeled as a uniform PDF between 0.9 and 1.0

Source: adopted from Table 5-15 of [15]

Parameter Name: PROTIN

Parameter Description: Inhalation Protection Factor

Recommended Values: Recommended point values for a generic site and for the general public—normal value of 0.46; evacuation value of 0.98; sheltering value of 0.25.

Uncertainty Range: Table 4-7, based on Table 5-15 of [15]

References: [6], [9], [127], [15]

Discussion: PROTIN is the set of inhalation protection factors for normal, evacuation, and sheltering activities. The technical bases for these values was considered in the elicitation documented in [6]. For members of the general public and for a generic site, the median values provided in Table 4-7 for normal activity, adopted from Table 5-15 of [15], are appropriate. Site and/or cohort specific values may be derived. For example, special facilities, such as hospitals, may provide greater filtration and protection from outside air than single family dwellings.

Parameter Name: LPROTIN

Parameter Description: Long-Term Inhalation Protection Factor

Recommended Value: 0.46

Uncertainty Range: Normal activity values from Table 4-7, based on Table 5-15 of [15]

References: [6], [9], [15]

Discussion: LPROTIN is the inhalation protection factor used in the CHRONC module for the intermediate- and long-term phases. It is comparable to PROTIN, which is used for the early phase. Generally, this parameter is chosen to be the same as PROTIN for normal activity during the early phase.

Parameter Name: SKPFAC

Parameter Description: Skin Deposition Protection Factor

Recommended Values: for a generic site and for the general public, normal, 0.46; evacuation, 0.98; sheltering, 0.25

Uncertainty Range: Table 4-7, based on Table 5-15 of [15]

References: [6], [9], [127], [15]

Discussion: SKPFAC is the set of skin protection factors for normal, evacuation, and sheltering activities. Considerations for skin protection factor are the same as those for inhalation protection factor, because both are based on the ratio of the interior to exterior time integrated air concentration. Accordingly, it is recommended the values used for PROTIN also be used for SKPFAC.

4.2.1.3 Breathing Rates

Inhalation dose is proportional to breathing rate (BRRATE). Although the breathing rate can vary by age, gender, and activity, for most analyses an age, gender, and activity-averaged breathing rate is recommended for all three activities and for all cohorts for consistency with the inhalation dose factors. A value of 0.000266 m³/s was recommended by Sprung et al. [5] and is consistent with a population- and activity-averaged breathing rate. Breathing rate was also examined in the NRC-CEC expert elicitation on internal dosimetry [7] and was postprocessed by Gregory et al. [9] to obtain the distribution shown in Table 4-8.

Table 4-8 Breathing Rates

Quantile	Breathing Rate (m ³ /s)
0%	9.22E-05
5%	1.38E-04
50%	2.19E-04
95%	3.93E-04
100%	5.90E-04

Source: adopted from Table 4.11 of [9]

Regulatory Guides 1.195 [128] and 1.183 [129] suggest a recommended value of 3.5×10^{-4} m³/s for the breathing rate during the first eight hours of an accident, a recommended value of 1.8×10^{-4} m³/s from 8 to 24 hours following the accident, and a recommended value of 2.3×10^{-4} m³/s thereafter. In contrast, the FRMAC Assessment Manual [11] recommends a value of 4.2×10^{-4} m³/s based on the adult male light exercise breathing rate for assessing doses from the passing cloud, with a note stating that "This calculation uses the light exercise breathing rate rather than the activity averaged breathing rate (BRAA) because it is assumed that the individual will be actively seeking to exit the plume." For longer term resuspension exposures, the FRMAC recommended value for estimating resuspension inhalation exposures is based on the activity-averaged breathing rate of 2.56×10^{-4} m³/s for an adult male based on Table B.16B of [130].

The value recommended by Sprung et al. [5] of 2.66×10^{-4} m³/s is consistent with a population- and activity-averaged breathing rate and is recommended for most analyses. The values in Table 4-8 from [9] will facilitate uncertainty analyses. Additional compilations of data on activity, age, and gender distributions of breathing rates include [130] as well as Chapter 6 of [125].

Parameter Name: BRRATE

Parameter Description: Breathing Rate

Recommended Value: 2.66×10^{-4} m³/s

Uncertainty Range: The distribution in Table 4-8 may be used for uncertainty analyses

References: [5], [9], [7]

Discussion: The value recommended by [5] of 2.66×10^{-4} m³/s is consistent with a population- and activity-averaged breathing rate and is recommended for most analyses. The values in Table 4-8, taken from [9], will facilitate uncertainty analyses. Additional compilations of data on activity, age, and gender distributions of breathing rates include [130] as well as Chapter 6 of [125].

Parameter Name: LBRRATE

Parameter Description: Long-Term Breathing Rate

Recommended Value: 2.66×10^{-4} m³/s

Uncertainty Range: The distribution in Table 4-8 may be used for uncertainty analyses

References: [5], [9], [7]

Discussion: LBRRATE is the CHRONC parameter for breathing rate and the value of this parameter is used during the intermediate and long-term phases. It is comparable to BRRATE,

which is the breathing rate used during the early phase and is normally chosen to be the same as the value for normal activity.

4.2.2 Resuspension Factors

Resuspension is often modeled using a resuspension factor approach, as described in [104] and [131]. To account for the time dependence of resuspension factors as a function of time since initial deposition, a multi-term, exponentially decaying model is often used. MACCS uses a single-term model for early phase resuspension weathering and a three-term model for resuspension weathering in the intermediate and long-term phases modeled in CHRONC. The MACCS variable RESCON represents the early phase resuspension leading coefficient (m^{-1}), and RWCOEF represents the leading coefficients (m^{-1}) in the long-term resuspension model in CHRONC. The MACCS variable RESHAF is the EARLY resuspension half-life(s), and TRWHLF are the resuspension half-lives in the long-term resuspension model in CHRONC. The formulation for the multi-term resuspension model in CHRONC is given by Equation (4-3):

$$C(t) = \sum_i RWCOEF \cdot e^{-\frac{\ln(2)}{TRWHLF}t} \quad (4-3)$$

Many commonly used resuspension models use a leading coefficient of 10^{-5} or $10^{-6} m^{-1}$, so the use of a value of $10^{-4} m^{-1}$ for the early phase in MACCS is intended to be at the conservative end of the range to account for the effect of heavy traffic during emergency phase evacuation and relocation. The early phase parameters for RESCON and RESHAF recommended by [5] are chosen to represent mechanical resuspension by vehicles. The RESHAF value of 2.11 days causes $0.0001 m^{-1}$ to decay in one week to $0.00001 m^{-1}$, the value used in the first term of the long-term resuspension equation (RWCOEFF) used in CHRONC.

For resuspension in the CHRONC model, TRWHLF is the set of half-lives used in the intermediate and long-term resuspension weathering equation. The traditional set of coefficients and half-lives go back to the recommendations in [5] based on the review in [104]. A recent paper by Maxwell and Anspaugh [131] evaluates several resuspension models against a large set of resuspension data from Chernobyl, the Nevada Test Site, and wind tunnel experiments. The model proposed by Maxwell and Anspaugh [131] is the recommended resuspension model in [11] and considered by the authors to be the most defensible model so far. This model, given in equation 15 of [131], has three terms; the first two terms are exponentially decaying, and the third represents the long-term constant resuspension factor of $10^{-9} m^{-1}$. The third term cannot be represented precisely with the MACCS model but setting the corresponding half-life to the maximum allowable value ($10^{10} s$, or 317 years) reasonably represents a constant value over the duration of a typical 50-yr MACCS calculation. Maxwell and Anspaugh [131] recommend that a multiplicative coefficient of $4.2^{\pm 1}$ be used to represent the uncertainty (interpreted as a geometric standard deviation) in this model.

Parameter Name: RESCON

Parameter Description: Emergency Phase Resuspension Coefficient

Recommended Value: $0.0001 m^{-1}$

Uncertainty Range: Section 4.3 of [9] provides information that may be used to develop an uncertainty distribution for RESCON.

References: [131], [5]

Discussion: The recommended resuspension factor for early phase resuspension is based on the value used in [5] and is larger than typical to account for increased resuspension associated with vehicular traffic associated with evacuation and relocation. Section 4.3 of [9] provides information that may be used to develop an uncertainty distribution for RESCON.

Parameter Name: RESHAF

Parameter Description: Emergency Phase Resuspension Concentration Half-Life

Recommended Value: 182,000 s (2.11 d)

Uncertainty Range: Uniform distribution between 80,000 s and 240,000 s [9].

References: [131], [5], [9]

Discussion: The recommended resuspension half-life for early phase resuspension is based on the value used in [5] and is used to ensure that the early phase resuspension is consistent with the initial value recommended by [131] at the end of one week, the typical duration of the early phase. Section 4.3 of [9] recommends a uniform distribution between 80,000 s and 240,000 s for RESHAF.

Parameter Name: NRWTRM

Parameter Description: Number of Terms in Long-Term Resuspension Weathering Equation

Recommended Value: 3

Uncertainty Range: not applicable

References: [131]

Discussion: Three terms are recommended to represent the resuspension model given by Equation 15 of [131].

Parameter Name: RWCOEF

Parameter Description: Long-Term Resuspension Factor Coefficients

Recommended Value: 10^{-5} m^{-1} , $7 \cdot 10^{-9} \text{ m}^{-1}$, and 10^{-9} m^{-1}

Uncertainty Range: a multiplicative coefficient of $4.2^{\pm 1}$ may be used to represent the uncertainty (interpreted as a geometric standard deviation) in this model.

References: [131]

Discussion: The three values for RWCOEF (10^{-5} m^{-1} , $7 \cdot 10^{-9} \text{ m}^{-1}$, and 10^{-9} m^{-1}) are selected to represent the terms given by Equation 15 of [131].

Parameter Name: TRWHLF

Parameter Description: Long-Term Resuspension Weathering Half-Lives

Recommended Value: 856,000 s, 29,900,000 s, and 10^{10} s

Uncertainty Range: not available

References: [131]

Discussion: The three values for TRWHLF (856,000 s, 29,900,000 s, and 10^{10} s) are selected to represent the terms given by Equation 15 of [131]. The final term in that expression is a constant, which is implemented by setting the third value of TRWHLF to the maximum value allowed by MACCS.

4.2.3 Groundshine Weathering Factors

The reduction of the external dose rate due to the migration of material that deposits onto the soil is modeled using a two-term, first-order removal model. For groundshine, the effect of weathering on reducing external doses is based on the model developed by [132]. The form is given by Equation (4-4):

$$C(t) = \sum_i GWCOEFF_i \cdot e^{-\frac{\ln(2)}{GWHLF}t} \quad (4-4)$$

That study examined the time-dependent external exposure from a deposition of Cs-137 on several experiments with different soil types, and found that the results could be fit with a two-term model, with approximately 63% of the dose rate decaying with a half-life of about seven months, and approximately 37% of the dose rate decaying with a much longer half-life (approximately 92 years). The values recommended in [5] consider additional data and recommend that a two-term model be used with half decaying with a weathering half-life of 6 months and half decaying with a weathering half-life of 90 years. A more recent review of the literature is described in [118], based on evaluations following the Chernobyl accident [119]. That model includes a two-compartment model with a “fast” weathering compartment (effective half-life of 1.5 years) and a “slow” weathering compartment (effective half-life of 50 years), with relative fractions of 40% and 60%, respectively. The currently recommended values correspond to this newer work.

Parameter Name: NGWTRM

Parameter Description: Number of Terms in Long-Term Groundshine Weathering Equation

Recommended Value: 2

Uncertainty Range: not applicable

References: [118], [119], [5]

Discussion: NTWTRM defines the number of terms in the groundshine weathering equation as determined by the specific model used to define GWCOEF and TGWHLF. A two-term model was recommended in [5], [118], and [119].

Parameter Name: GWCOEF

Parameter Description: Long-Term Groundshine Coefficients

Recommended Value: 0.4; 0.6

Uncertainty Range: not available. Information in [119] may be used to develop an uncertainty range.

References: [118], [119], [118]

Discussion: GWCOEF is the set of groundshine weathering equation linear coefficients for each term (the number of terms is NGWTRM). Anspaugh et al. [118] and Likhtarev et al. [119] recommend values of 40% and 60% for the “fast” and “slow” fraction.

Parameter Name: TGWHLF

Parameter Description: Long-Term Groundshine Weathering Half-Lives

Recommended Value: 47,000,000 s (1.5 yr); 1,580,000,000 s (50 yr)

Uncertainty Range: not available. Information in [119] may be used to develop an uncertainty range.

References: [118], [119], [118]

Discussion: TGWHLF represents the set of groundshine half-lives in the CHRONC module for each term (the number of terms is NGWTRM). Anspaugh et al. [118] and Likhtarev et al. [119] recommend values of 1.5 years and 50 years for the “fast” and “slow” fraction.

4.3 Early Phase Duration and Protective Actions

MACCS input parameters related to emergency response and evacuation are typically developed from information in the site-specific ETE and offsite emergency plans. ETEs prepared in accordance with NRC guidance [133] include detailed demographic information on population segments and include measures of effectiveness useful to develop the response timing for the start of sheltering, the start of evacuation, and travel speeds. The offsite emergency response plans describe evacuation, sheltering, and for states that implement KI programs, administration of KI. Population characteristics are assessed and population groups that mobilize or respond uniquely are identified as cohorts (e.g., schools vs. general public).

Parameter Name: ENDEMP

Parameter Description: Time Duration for the Early Phase

Recommended Value: 7 days, unless modeling delayed and/or prolonged releases

Uncertainty Range: not applicable

References: [14]

Discussion: ENDEMP defines the duration of the early phase. MACCS calculates the dose accrued in each grid element starting with the arrival of the first plume segment at that location and continuing for the period defined by ENDEMP, which can last for up to 40 days. ENDEMP should be defined to be long enough to allow all released plume segments to exit the problem area. Currently, the recommended value for ENDEMP is seven days since that is considered a reasonable period of time to allow the population to take any necessary protective actions, for the plant to be able to terminate the release, and allow all released plumes to exit the analysis grid [14]. The modeling of delayed and/or prolonged releases may require ENDEMP to be extended beyond one week to ensure adequate time for all plume segments to be released and to exit the analysis grid after all releases have ended.

4.3.1 Evacuation and Sheltering

Supplement 3 to NUREG-0654 [111] provides criteria for protective action recommendations (PARs). Emergency classification schemes, generally consistent with industry-wide guidance such as [134], are required as part of the plant-specific emergency plan [135]. These schemes define emergency action levels (EALs), which define a “pre-determined, site-specific, observable threshold for a plant condition that places the plant in an emergency class.” These emergency classification schemes may be used to determine when an emergency class defined in Appendix I of [135], such as a Site Area Emergency (SAE) or General Emergency (GE), may be reached and a protective action recommendation to shelter or evacuate issued. At many sites, early protective actions are implemented for select populations in response to declaration of an Alert or SAE. For example, if an Alert is declared in the evening, some offsite emergency plans require that schools not be open on the following day. In response to an SAE declaration, many offsite emergency plans call for the sounding of sirens, and many also identify evacuation of schools. An early decision in setting up a MACCS analysis is the specific scenario to be implemented in the

model. The scenario is selected for each specific analysis. The scenario should be identified early in the process because many of the fundamental parameters, including the site file populations, may be different. In summer scenarios, the weather is often good and schools are closed, but there may be additional transients at local tourist areas or working on farms. Winter scenarios mean that schools are open, which challenges OROs with additional evacuation details. The accident-specific details include timing of EAL declarations and source term effects.

Building upon the analyses conducted for the review of the criteria for protective action recommendations documented in [127], a state-of-the-art approach for the representation of MACCS emergency response parameters was developed for the SOARCA project. More population segments (cohorts) were modeled at greater level of detail than had previously been done. SNL and NRC staff worked with the licensees to understand the EAL classification timing for each accident sequence in SOARCA. The EAL classification together with FEMA exercise report data were used to establish response timelines. This approach provided a realistic timing of alert, notification, and response activities [14]. The process established in the SOARCA documentation provides a basis from which an analysis can be structured if a high level of resolution in the modeling of early phase protective actions is desired.

4.3.1.1 Defining Evacuation Cohorts

Cohorts represent population groups that mobilize or respond differently from other population groups. Cohorts can be based on the population segments included in the site's ETE, which are described in guidance (Appendix 4 of [135], [133]). These cohorts may be established to represent members of the public who may evacuate early, evacuate late, refuse to evacuate, and those who evacuate from areas not under an evacuation order (i.e., a shadow evacuation). Use of multiple cohorts allows for more realistic analyses and provides the ability to identify risk at a more discrete level. MACCS allows up to 20 cohorts. Consideration should be given to establishing separate cohorts for populations that may evacuate late or shelter (for example, the evacuation tail or institutional populations that may require additional time for mobilization) and thus be at risk for exposure to a released plume. However, there is not much benefit in defining cohorts with little difference in response characteristics. Likewise, there is little benefit in defining multiple cohorts that would complete evacuation well before arrival of the first plume segment at their location, since they would receive no exposures. At the time SOARCA was initiated, use of more than three cohorts had not been implemented, and there was uncertainty regarding computer run time needed for a larger number of cohorts. It was decided that a maximum of 6 cohorts would be used to reduce run times. More recent analyses have suggested that additional cohorts do not lead to excessive run times; however, additional cohorts do require the development of additional input data to characterize those cohorts. Examples of cohorts may include:

- General public, which may be segmented into multiple cohorts to represent realistic mobilization of evacuees onto the roadway network, including a tail to represent the last portion of the general public evacuation;
- Schools, if the scenario is during a school session;
- Special facilities (e.g., nursing homes, hospitals, prisons, or jails);
- Seasonal transient populations (e.g., visitors to beaches, amusement parks, or summer camps);

- Transit-dependent populations;
- Shadow evacuees; and
- Non-evacuees.

A shadow evacuation occurs when people outside of any officially declared evacuation zone leave without having been instructed to do so [108]. Shadow evacuations are considered because the additional traffic generated has the potential to impede an evacuation of the EPZ and because shadow evacuees represent members of the public who have left the area early and would not receive a dose during the remainder of the early phase. Consideration of the effect of a shadow evacuation on the time to evacuate the EPZ is generally considered in a site's ETE and should be considered when developing the evacuation speeds used by MACCS. It is estimated that 20 percent of the public would evacuate from the shadow evacuation areas [136] [133]. NRC has formalized guidance regarding analysis of shadow evacuations establishing a 20% contribution to a distance of 15 miles from a reactor site (i.e., 5 miles beyond the EPZ) [133].

Conversely, a small fraction of the public may refuse to evacuate when an evacuation order has been given. This has been recognized since the time of WASH-1400, where it is stated that "Civil Defense personnel have observed a minority of approximately 5% who stay behind and never evacuate, but the concept of such a nonparticipating minority is not resolvable from the analyses performed" [3]. In NUREG-1150 [4], this was changed to 0.5%, with the rationale that:

The plants that were studied in NUREG-1150 have detailed and well-maintained emergency plans, which also have provisions for evacuating from special facilities within the EPZ. Because an evacuation is preplanned, it is expected to be nearly complete. The preplanned evacuation should be distinguished from unplanned and impromptu evacuations prompted by transportation accidents involving toxic chemicals, accidents at chemical plants, or natural disasters. The specific value used (0.5%) was derived from an actual use of a nuclear emergency plan (for a nearby chemical accident) [4].

This concept of a very small non-evacuating fraction is consistent with more recent research [108], [137]. A 0.5% value was used for this cohort in SOARCA [14]. This value is also supported by discussions with response agencies. Since the publication of those studies, research on a Graniteville South Carolina train accident evacuation found that 5,400 people evacuated and 12 refused (corresponding to a 0.2% non-evacuee rate) [138]. In an after-action study, a survey of evacuees found that 98.4 percent of the public evacuated in response to the Graniteville chemical spill [138]. Thus, 1.6 percent of the public did not evacuate. Considering that the EPZ has a siren system and tone alert radios to alert the public, and the EPZ population receives emergency response information at least annually and is largely aware of what is expected during a response [136], the response from within an EPZ should be expected to be more efficient than the ad hoc evacuation for Graniteville. Therefore, a non-evacuating fraction of 0.5% continues to be considered a reasonable estimate for the fraction of the general public that may refuse to evacuate.

An example of individual cohorts that may be used in an analysis is provided in Table 4-9. The distribution of these cohorts among the populations defined in the site file is described in the following sections.

Table 4-9 Cohort Examples

Cohort #	Cohort Name
1	Schools
2	Special Medical Facilities
3	Transit Dependent
4	0-10 mi Early General Pop
5	0-10 mi Middle General Pop
6	0-10 mi Tail General Pop
7	10-15 mi Shadow
8	Non-Evac

Once the cohorts have been identified, the analyst has several methods available in MACCS to model the way multiple cohorts are distributed across the spatial grid and how output results are combined. Within the Site Data tab of the Project Properties Menu there is drop down menu for “Results Weighting Factor.” The *Results Weighting Factor* selection defines the MACCS variable WTNAME, which determines the way multiple-cohort results are combined. If a site file is imported, there are three weighting options: PEOPLE, TIME, and SUMPOP. If the site data are uniformly distributed across the grid, there are two weighting factor options: PEOPLE and TIME.

Until recent versions of MACCS, PEOPLE was the recommended weighting factor method. With this method the analyst determines the weight fraction of each cohort that make up the grid. A model that uses PEOPLE uses the same set of cohort weighting factors for every grid element. The SUMPOP option provides a much more versatile way to assign the cohort fractions over the spatial grid. If SUMPOP is selected, the user must specify the source of the site file by choosing a *Predefined Site File* or *Create from Existing Site File*. If a predefined site file is selected, the user is required to link to an existing site file which must have one population defined for each evacuation cohort. One option is to create the site file manually, but this process can be time-consuming and error-prone. The recommended option is to create a SUMPOP site file from an existing site file using WinMACCS. WinMACCS allows the analyst to create up to 90 different cohort fractions using a set of defined cohorts and apply these specific cohort fractions to each spatial grid element. The ability to define SUMPOP cohorts was enhanced with the development of WinMACCS, which allows the user to define populations (consisting of fractions of each of the cohorts) using a GUI. As a result, creating a base site file using SecPop and then using SUMPOP as the weighting factor method is now the preferred option.

The first step to create a SUMPOP site file is to create a base site file as described previously. The next step, which creates a SUMPOP site file using WinMACCS, is to open the category Early/Population by Cohort/Populations and define the various population distributions that exist at the site. A population distribution is a combination of the set of cohorts that exists in one or more grid elements. Figure 4-2 below provides an example of a completed SUMPOP population distribution for a site. In this example, the eight cohorts defined in Table 4-9 are shown in the columns in Figure 4-2. Each row is one set of cohort weighting fractions, and all the weighting fractions in each row included in the population distribution function should normally, but are not required to, sum to 100%.

Enter Comments	Pop 1 is school weighted, Pop 2 is medical/special weighted, Pop 3 is 0-10 mile general sans schools and general, Pop 4 is 10-15 mile shadow, and Pop 5 is 15 - 1000 mile nonevac							
<input style="border: 1px solid black; padding: 2px 10px; margin-right: 10px;" type="button" value="Save"/> <input style="border: 1px solid black; padding: 2px 10px;" type="button" value="Cancel"/>								
N_POP_DIST (-) 5								
POP_DIST(-)								
	COHORT 1	COHORT 2	COHORT 3	COHORT 4	COHORT 5	COHORT 6	COHORT 7	COHORT 8
Population 1	0.3934	0.	0.0115	0.2976	0.2381	0.0545	0.	0.
Population 2	► 0.	0.342	0.0124	0.3228	0.2582	0.0646	0.	0.
Population 3	0.	0.	0.0188	0.4875	0.39	0.0975	0.	0.0063
Population 4	0.	0.	0.	0.	0.	0.	0.2	0.8
Population 5	0.	0.	0.	0.	0.	0.	0.	1.
*								

Figure 4-2 Example SUMPOP Population Distributions

After the population distributions have been defined, a label (DIST_LABEL) and single character symbol (DIST_SYMB) are chosen for each population. The symbol character may be a letter or a numeric or symbolic character (Figure 4-3). The spatial grid form facilitates the assignment of populations, identified by this symbol DIST_SYMB defined on the *Population Labels* form, to grid elements (Figure 4-3). After this form is saved, each *Population* form for every defined cohort is updated. Before the MACCS simulation is run, a new site file is constructed based on each of the *Population* forms. This site file is created to be compatible with the MACCS SUMPOP option and includes a separate population for each cohort.

	DIST_SYMB	DIST_LABEL
Population^ 1	► S	0-10 Schools
Population 2	►	0-10 Med Nursing
Population 3	G	0-10 General Pop
Population 4	2	10-15 Shadow
Population 5	3	0-1000 Nonevac
*		

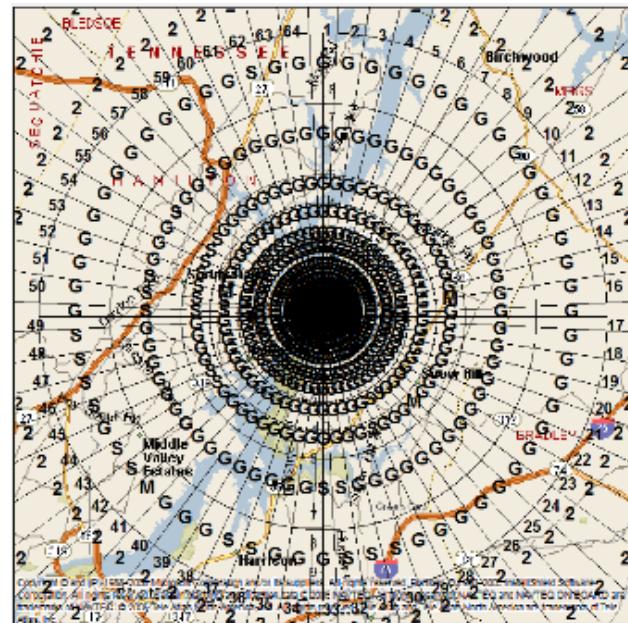


Figure 4-3 Example SUMPOP Labels and Assignment

The *Population* form is relevant for each cohort when the user assigns SUMPOP to the *Results Weighting Factor* and selects *Create from Existing Site File* on the *Site Data* tab. After the *Populations Assigned* form is completed, the *Population* form is updated. The values shown are the number of people assigned to each spatial grid element for the given cohort category. The

Population form is an essential check for the analyst to ensure that the cohort distributions are correctly implemented. To change the *Population* values, a new site file must be specified on the *Site File* form or a different POP_DIST must be provided.

The cohort population for a grid element is calculated by considering the population assigned to that grid element and the fraction of the cohort specified for that population. For the cohort of interest, the population fraction associated with that cohort is multiplied by the total population of that grid element. If there is only one cohort in a grid element, the POP_DIST variable for that cohort would have a value of 1 for the population. For example, Population 5 in Figure 4-2 represents the non-evacuating cohort (Cohort 8) in the 15-100 mile region, where all of the population is assumed to be represented by the non-evacuating cohort. The corresponding value for POP_DIST is therefore set to 1 for Cohort 8 for Population 5 in Figure 4-2. The total population for each of the grid element can be viewed on the *EARLY/Model Basis/Population from Site File* form. The site file created by WinMACCS for use in the simulation, Sumpop_site.inp, is located in the project input folder and can be viewed with any text file editor.

Parameter Name: WTNAME

Parameter Description: Type of Weighting for Cohorts

Recommended Value: SUMPOP

Uncertainty Range: not applicable

References: [2], [40], [14]

Discussion: Use of SUMPOP allows the definition of geographically-specific cohorts and is the recommended weighting factor method when geographically distinct evacuating cohorts (e.g., institutional populations such as schools or medical care facilities) are defined.

4.3.1.2 Evacuation Routing

As discussed in [14], the analyses in NUREG-1150 [4], [5] modeled an evacuation of the area within 10 miles of the site. This value approximately corresponds to the size of the full EPZ, which was established as an area approximately 10 miles in radius based on the evaluation in NUREG-0396 [139]. The evacuees were assumed to travel for a distance of 10 miles beyond the evacuation zone before being removed from the calculation. These assumptions were revisited in SOARCA, which modeled the potential for evacuations beyond the ten-mile EPZ (e.g., a shadow evacuation cohort) and which, in [15], modeled evacuee movement out to a distance of 50 miles from the plant. Sensitivity analyses documented in [28] included evacuation of areas out to a distance of up to 20 miles. The radius of the evacuation and sheltering zone is defined by the MACCS variable NUMEVA, which is the index of the ring corresponding to the evacuation and sheltering zone. It may be different for different cohorts. However, the user should be aware that no cohort may have an evacuation and sheltering zone radius greater than that of the first cohort. The distance to which evacuees travel before they are removed from the calculation is defined by the MACCS variable LASMOV.

At the time of the analyses documented in NUREG-1150 [4], the only option for modeling evacuation in MACCS was to evacuate radially away from the plant. With the development of MACCS2, the capability to model evacuation routes was added and is now the preferred approach when evacuation routing information is available. This capability is invoked by setting the MACCS variable EVATYP to 'NETWORK'. The older radial model can still be invoked by setting the MACCS variable EVATYP to 'RADIAL'. With the development of WinMACCS, the ability to define the evacuation routes graphically using a map layer showing roadways was added [40]. An example of a network evacuation model is illustrated in Figure 4-4.

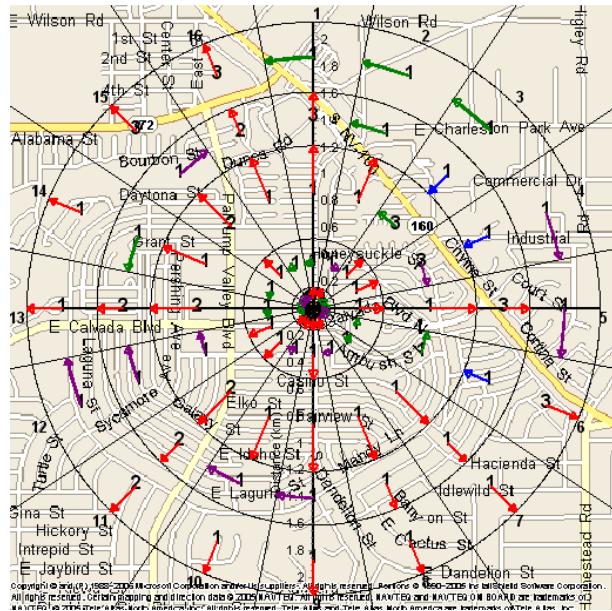


Figure 4-4 Illustration of Network Evacuation Directions

The evacuation area is mapped onto a grid with the desired number of compass sectors. 16 sectors are presented in Figure 4-4 for clarity, but the model may be developed for a 64-sector grid using the same approach. Each arrow represents the direction of travel through the grid element. A single direction may be selected for each grid section. The MACCS variable IDIREC, which is matrix with dimensions given by NUMCOR and LASMOV, is used to define the network evacuation direction. In the MACCS input file, a value of one indicates an outward evacuation to the next grid element, two indicates clockwise evacuation, three indicates inward evacuation, and four indicates counter clockwise evacuation. Previously, the values of IDIREC had to be inserted manually into the input file. IDIREC is currently implemented in WinMACCS via a user interface that allows the direction to be selected using the analysis grid overlaid upon the roadway network. The analyst should review the evacuation routing in the ETE to assist to determine the route evacuees are likely to follow. For areas beyond the EPZ or for areas where evacuation routes are not defined, the analyst should select the directions based on logical flow along roadways. Unless specific routing information is available, it is recommended that the evacuation direction be radially outward for grid elements beyond the evacuation zone. For a site-specific analysis that consider offsite impacts from events such as earthquakes, analysts may adjust the routing to account for bridges or roadways being unusable.

Parameter Name: NUMEVA

Parameter Description: Outer Boundary of Evacuation/Shelter Region

Recommended Value: Index of spatial ring corresponding to largest evacuation or sheltering radius; typically that corresponding to the full EPZ radius (10 miles) unless evacuation is modeled beyond the EPZ

Uncertainty Range: not applicable

References: [2], [40], [14]

Discussion: NUMEVA is typically assigned to represent a 10-mile evacuation zone corresponding to an evacuation of a full ten mile EPZ. However, it may be assigned to be either more or less than a ten mile radius. For example, it may be assigned to model an evacuation zone beyond the full EPZ to allow for shadow evacuation cohorts or for the potential for

evacuation orders beyond the EPZ. It may also be assigned to a value less than ten miles for small releases in which PAG doses are not expected to extend to the full ten mile EPZ and which would require sheltering or evacuation only to a 2 or 5 mile radius. The user should be aware that the evacuation radius defined by NUMEVA for cohorts after the first defined cohort may be less than that defined for the first cohort but cannot be greater than that defined for the first cohort. For that reason, the cohort with the largest evacuation zone radius should always be defined first. Alternatively, the user may define all evacuating cohorts with value of NUMEVA equal to the that of the largest evacuation zone, but then use the SUMPOP function to assign cohort populations for both the evacuating and non-evacuating cohorts to the desired location.

Parameter Name: LASMOV

Parameter Description: Last Ring in Movement Zone

Recommended Value: For evacuating cohorts, index corresponding to the 50 mile spatial ring. Non-evacuating cohorts are defined with a LASMOV=0.

Uncertainty Range: not applicable

References: [2], [40], [14]

Discussion: Consistent with [15], an evacuation movement zone of 50 miles is recommended for evacuating cohorts. A non-evacuating cohort is defined by assigning LASMOV=0. Since NUMEVA must be less than LASMOV, there is no evacuation region and the only protective action modeled for a non-evacuating cohort is the dose-dependent relocation model discussed in Section 4.3.3.

Parameter Name: EVATYP

Parameter Description: Evacuation Type

Recommended Value: NETWORK when site-specific evacuation route information is available

Uncertainty Range: not applicable

References: [2], [40]

Discussion: The use of a network evacuation model is considered to be a more realistic representation of evacuee movement and is currently the recommended approach when information is available to support the development of an evacuation network.

Parameter Name: IDIREC

Parameter Description: Direction in Network Evacuation Model

Recommended Value: Site-specific directions based on published evacuation routes

Uncertainty Range: not applicable

References: [2], [40]

Discussion: The MACCS variable IDIREC may be developed manually but use of the WinMACCS GUI greatly facilitates development of this matrix, as shown in Figure 4-4. The IDIREC variable is a matrix showing the direction of travel for the entire area defined by the radius given by LASMOV (i.e., a matrix with dimensions given by NUMCOR and LASMOV).

4.3.1.3 Modeling Keyhole Evacuations

NRC guidance [111] states that sites should implement a keyhole evacuation and expand to a full EPZ, when necessary, based on the accident characteristics. Reference [111] provides that wind persistence be considered, which may affect the boundary of the keyhole. Some site emergency

plans include evacuating 360 degrees around the plant, regardless of wind direction. Jones et al. [127] concluded that the evacuation methodology with most benefit comprised a radial area of 2 or 5 miles together with a central downwind sector and an adjacent buffer sector on each side. In this context, sector means a sixteenth of the compass, as illustrated in Figure 4-5.

The standard MACCS evacuation model, invoked by setting the MACCS variable EVAKEY to the value 'CIRCULAR', models a circular evacuation region. The capability to model a keyhole was added to MACCS after the original SOARCA project was completed and is therefore not reflected in [14]. The keyhole model allows the user to define the evacuation region with the radius of the inner, circular area, the number of sectors to evacuate beyond the circular area, and the outer radius of the evacuation area, which is usually the EPZ boundary. The location of the different zones is illustrated in Figure 4-5, with the red portion representing the circular portion of the keyhole, the yellow portion representing the central downwind sector, and the orange portions representing the adjacent buffer sections.

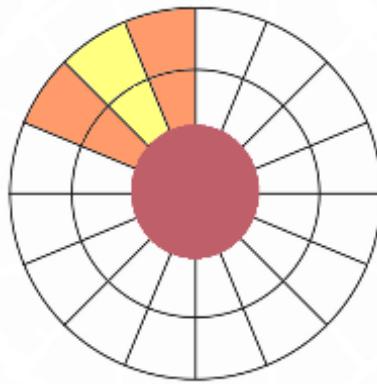


Figure 4-5 Illustration of a Keyhole Evacuation Including Buffer Zones

An analyst can use a keyhole evacuation model by setting the value of EVAKEY to 'KEYHOLE'. The motivation behind a keyhole evacuation is to move the population most at risk (close to the plant and downwind) out of the area as quickly as possible without the roadways becoming congested from population at lower risk. With keyhole evacuation, the evacuation area is a circular area surrounding the nuclear site and an odd number of sectors projecting out to a larger radius, as illustrated in Figure 4-6. The region is defined by the radius of the inner, circular area, the number of sectors to evacuate beyond the circular area, and the outer radius of the evacuation area. Initially, the keyhole is centered in the downwind direction, as shown by the yellow and purple portion of the keyhole in Figure 4-6. The keyhole is expanded as the wind direction changes in subsequent hours, as illustrated by the green/orange portion of the expanded keyhole.

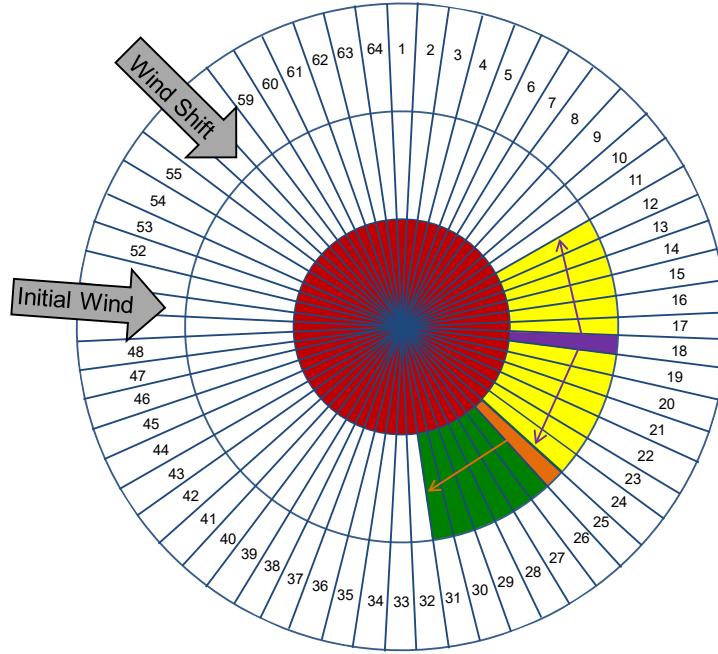


Figure 4-6 Illustration of a Keyhole Evacuation Model

In this example, a 2-mile circular area around the plant is evacuated along with the downwind sectors to at least 5 miles. The evacuation type (Circular Evacuation, Keyhole Evacuation, or None) can be assigned for each cohort.

With a 16-sector spatial grid, every sector is 22.5°; therefore, the blade of the keyhole in total is an angular area of 67.5° (central sector bordered on each side by a sector; 22.5° x 3). A total keyhole width of 67.5° is recommended for most analyses. The value of NSECTR corresponding to a 67.5° wide keyhole for various values of NUMCOR is outlined in Table 4-10.

Table 4-10 Recommended NSECTR values

NUMCOR	Degrees (°)/Sector	NSECTR
16	22.5	3
32	11.25	7
48	7.5	9
64	5.625	13

An analyst may modify this based on site-specific values, such as whether the meteorology at the site was well studied and understood. In this circumstance a smaller buffer area may be appropriate. The size of the emergency response zones at the site may also be considered in selecting the number of sectors to include in the keyhole model; for example, to realistically reflect the size of the areas that would be subject to evacuation orders.

The keyhole may be expanded in advance of an actual wind shift to account for weather forecasting. This parameter in WinMACCS is defined as KEYFORCST. The same forecast

interval is used for all evacuation cohorts that use keyhole evacuation. This parameter allows the keyhole to be expanded in advance of actual wind shifts to account for foreknowledge of weather. The user must specify the number of hours of weather forecasting to use in the model. When the number of hours is four, for example, the model considers the wind directions that will occur over the next four hours and expands the size of the keyhole accordingly. MACCS assumes a 100 percent forecast accuracy; therefore, when this feature is selected it is recommended that a forecast no greater than about 6 hours be used. Values greater than that might be unrealistic since typical transient weather patterns cannot be forecast with 100 percent accuracy. When no advance knowledge of weather is to be assumed in the model, the user enters 0. In Section 5.9.7 of [15], KEYFORCST was sampled from a uniform distribution with a lower bound of 1 hour and an upper bound of 6 hours.

The analyst should be aware that an important aspect of the keyhole evacuation model, as currently implemented in MACCS, is that evacuation routing is static and does not depend on the weather pattern that occurs during a weather sequence. When used in conjunction with the network evacuation model, this can potentially result in evacuees traveling through areas that were previously contaminated. If emergency planning precludes this from happening, it may be preferable to use the circular evacuation option even when keyhole evacuation would be implemented. The tradeoff is that circular evacuation can result in larger evacuation costs when economic losses are considered, although this is usually a small component of the overall losses; conversely, the keyhole evacuation model in MACCS can potentially result in larger population doses and estimated health effects when those consequences are considered, although this also is usually a small contributor to the population dose. The keyhole evacuation should only be considered for sites that would implement that strategy, but, depending on the application and the types of consequences to be evaluated, it may be preferable to choose circular evacuation in place of keyhole evacuation.

Parameter Name: EVAKEY

Parameter Description: Evacuation Model

Recommended Value: CIRCULAR. However, the KEYHOLE may be used if the keyhole evacuation would be used at the site.

Uncertainty Range: not applicable

References: [40]

Discussion: Potential biases in the results should be considered to justify which option should be used for a specific application.

Parameter Name: KEYDIS

Parameter Description: Radius of the Circular Portion of the Keyhole

Recommended Values: The recommended KEYDIS value is the index of SPAEND that aligns with the 2 or 5-mile radius.

Uncertainty Range: not applicable

References: [127]

Discussion: KEYDIS is the SPAEND index number corresponding to the radius of the circular portion of the keyhole. Setting KEYDIS to zero eliminates the circular portion of the keyhole. Setting KEYDIS to NUMEVA eliminates the key portion of the keyhole.

Parameter Name: NSECTR

Parameter Description: Number of Sectors in Keyhole Portion

Recommended Values: 3 or 13

Uncertainty Range: not applicable

References: [127]

Discussion: Set to 3 if a 16-sector grid is used or to 13 if a 64-sector grid is used.

Parameter Name: KEYFORCST

Parameter Description: Advance Time for Which Wind Shifts can be Reliably Forecast

Recommended Value: 2 to 4 hours

Uncertainty Range: 1 to 6 hours

References: [40], [15]

Discussion: Expands a keyhole in advance of an actual wind shift to account for weather forecasting. When no advance knowledge of weather is to be assumed in the model, the user enters 0.

4.3.1.4 Modeling Evacuation Delays and Speeds

The modeling of evacuation speed has progressed from the use of a single speed value for all evacuees in WASH-1400 without any delay to the ability to model unique delays and speed values for each cohort, for each evacuation phase, and within each grid cell. Recognizing that speeds may vary, WASH-1400 evaluated three discrete evacuation speeds of 0, 1.2, and 7.0 mph, with probabilities of 30, 40, and 30%, respectively [3], and based the evacuation speeds on the 1974 EPA evacuation study [140]. Since the early risk studies, such as WASH-1400, that included evacuation of the areas around NPPs, not only have models significantly advanced, but NRC regulations and guidance have been expanded in the areas of emergency response and preparedness. Emergency classification schemes required as part of the plant-specific emergency plan [135] may be used to determine when an emergency class associated with a protective action recommendation to shelter or evacuate would be issued. Site-specific ETEs are developed for each site and include speed values for selected roadways in accordance with [133].

The speed values for each cohort may be derived using information from the ETE. The speed values from the ETE cannot be directly input in the MACCS model because most commercial evacuation models used to generate the ETEs provide average speed values observed at the midpoint of roadway segments. Using the ETE speeds directly in MACCS would result in evacuating the cohorts too fast because the ETE values do not account for delays, such as those incurred at intersections (e.g., signal timing, headway discharge, slow down, turn movements). However, there is sufficient information in the ETE study to develop speeds for each of the cohorts used in the analysis. For the general public, the ETE provides mobilization and evacuation curves. Similar information is provided for special facilities, schools, transit-dependent residents, and other cohorts. Evacuation route distances are typically provided in the ETE documents. Evacuation routes are typically not directly radial away from the plant and therefore, the routes are usually longer than 10 miles.

Evacuation speed (ESPEED) values are assigned for the beginning, middle, and late phases of the evacuation representing the ESPEED1, ESPEED2, and ESPEED3 input parameters, respectively. Speeds may be assigned uniquely for the beginning, middle, and late phases and

for each cohort [14]. ESPEED1 and ESPEED2 are typically used to represent evacuation speeds within the EPZ. The early speed (ESPEED1) is applied during the DURBEG duration. The middle speed (ESPEED2) is applied during the DURMID portion of evacuation. Typically, ESPEED2 is established such that the cohorts have exited the EPZ at the end of this duration traveling at the specified speeds. ESPEED1 (early) values may be higher than ESPEED2 (middle) because there may be less congestion when evacuees first enter the roadway network. However, this is not necessarily the case for all cohorts, and the initial speeds can be very similar to ESPEED2 (middle) if continuous loading of multiple cohorts results in many vehicles entering the roadway network over the same timeframe. To check the values, DURBEG times ESPEED1 plus DURMID times ESPEED2 should equal the travel distance to the boundary of the EPZ. This distance is about 10 miles in a standard EPZ for a radial evacuation and normally a longer distance for the network evacuation model. ESPEED3 (late) typically represents speeds from the edge of the EPZ until evacuees are out of the analysis area (the distance corresponding to LASMOV). The value of ESPEED3 should normally reflect little congestion because evacuees are outside the EPZ where the traffic is less congested. The late speed (ESPEED3) is applied for the period after DURMID until the end of the early phase. After speeds are established for the roadways, adjustment factors at specific locations may be applied using the ESPGRD parameter to account for local congestion or to increase speeds in rural or free-flow areas.

Once the speeds are established, it is useful to review the cohort timelines with the assigned evacuation delays and speeds to check whether cohorts who are traveling on the same roadways are traveling at the same speed during the common durations. For a shadow cohort, which is evacuating from beyond the EPZ, the speeds may be different because this cohort travels on roadways that are not typically congested.

Parameter Name: OALARM

Parameter Description: Alarm Time

Recommended Value: The recommended value is 45 minutes after GE if only general public cohorts are included. This value may be set to 0 if the alarm time is added in to the DLTSHL variable.

Uncertainty Range: not available

References: [2], [40], [14], [135], [111]

Discussion: MACCS allows the user to choose a reference time for initiation of protective actions to be either the alarm time (specified by the input variable OALARM) or the arrival time of the first plume segment reaching the downwind location. Traditionally, OALARM has been chosen to be the time of a siren that notifies the public to check emergency messaging that is transmitted via local TV and radio stations. The timing of the siren may be based on declaration of an SAE or of a general emergency (GE), depending on site-specific emergency plan. For example, evacuation of schools is triggered based on SAE at some sites. The timing of the SAE or GE declaration and the protective action modeled should be consistent with the emergency procedures at the site [14], [135], [111]. It is important to note that no emergency response can take place prior to OALARM when ALARM is chosen as the reference point. In principle, OALARM can be chosen to be any reference point as early as accident initiation. MACCS 3.10 allows OALARM to be defined separately for each cohort. This allows the user the flexibility to base emergency response timing of some cohorts on declaration of SAE, some on declaration of GE, and others on additional reference points. Alternatively, this value may be set to 0 (accident initiation) if the alarm time is added in to the DLTSHL variable, as was done in SOARCA [14].

Parameter Name: DLTSHL

Parameter Description: Delay from Alarm Time to Shelter

Recommended Value: problem specific, varies by cohort. Derive based on site-specific ETE.

Uncertainty Range: problem specific, varies by cohort

References: [2], [133], site-specific ETE report when available

Discussion: The DLTSHL variable defines the period from the reference point (REFPNT) time to when individuals take shelter and is applied for each cohort for each distance ring [2]. Bixler et al. [14] describes DLTSHL as the duration it takes for the residents within the EPZ to receive the alert and notification and enter a sheltered location. The time for each cohort to shelter is based on when they receive notification of the accident. If DLTSHL is specified as 0 hours, sheltering occurs with no delay. This may be appropriate for special facilities or other unique cohorts who are in a shelter when the alert is broadcast. The delay times specified in [14] are with respect to accident initiation because some protective actions are implemented at SAE and others at GE. OALARM was chosen to be the time of accident initiation (i.e., 0 hours) and the warning delays were added to DLTSHL.

Parameter Name: DLTEVA

Parameter Description: Delay from Beginning of Shelter to Evacuation

Recommended Value: problem specific, varies by cohort. Derive based on site-specific ETE.

Uncertainty Range: problem specific, varies by cohort. May be developed based on information in the site-specific ETE.

References: [2], [133], site-specific ETE report when available

Discussion: The DLTEVA variable defines the duration of the sheltering period for each cohort for each distance ring [2]. When DLTEVA is specified as 0 hours, evacuation occurs with no delay (i.e., the duration of the sheltering period is zero). During the sheltering period, residents are preparing to evacuate. The time needed to prepare varies among individuals and cohorts and is represented as a distribution illustrated in a mobilization curve often in the site's ETE report. Delay to evacuation might be caused by individuals delay in response to the evacuation order, taking time to pack and secure the home, waiting for the return of commuters, waiting for public transportation, a need to shut down operations before leaving work, or any other practical reasons [135] [133]. ETE reports indicate that the delay is not uniform, with most of the evacuees experiencing a relatively short delay (e.g., 90 percent of the public begins to evacuate within about 60 percent of the response time) [141].

Parameter Name: DURBEG

Parameter Description: Duration of Beginning of Evacuation Phase

Recommended Value: problem specific, varies by cohort. Derive based on site-specific ETE.

Uncertainty Range: problem specific, varies by cohort. May be developed based on information in site-specific ETE.

References: [2], [133], site-specific ETE report if available

Discussion: The DURBEG variable is the duration assigned to the beginning phase of the evacuation when traffic congestion is at its lowest within the EPZ. An evacuation speed (ESPEED1) corresponds to this time period and may be assigned uniquely for each cohort [2]. This period begins when the sheltering period (DLTEVA) ends.

Parameter Name: DURMID

Parameter Description: Duration of Middle of Evacuation Phase

Recommended Value: problem specific, varies by cohort. Derive based on site-specific ETE.

Uncertainty Range: problem specific, varies by cohort. May be developed based on information in site-specific ETE.

References: [2], [133], site-specific ETE report if available

Discussion: The DURMID variable is the duration of the middle phase of the evacuation and may be assigned uniquely for each cohort. This period begins when the beginning phase (DURBEG) ends and typically represents the time duration in which there is a large concentration of evacuees on roadways and slower evacuation speeds are experienced. Like DURBEG, an evacuation speed (ESPEED2) corresponds to this period. Typically, but not necessarily, the value of DURBEG plus DURMID equals the time necessary for a cohort to exit the EPZ (generally 10-13 miles, depending on whether radial or network evacuation is used).

Parameter Name: ESPEED

Parameter Description: Evacuation Speed

Recommended Value: problem specific, varies by cohort. Derive based on site-specific ETE.

Uncertainty Range: problem specific, varies by cohort. May be developed based on information in site-specific ETE.

References: [2], [133], site-specific ETE report if available

Discussion: A recommended option is that ESPEED1 and ESPEED2 be based on the travel distance divided by the travel times from the site ETE and assigned such that the evacuees clear the 10-mile EPZ by the end of the time period defined by DURBEG + DURMID.

ESPEED3 should represent an increased traffic speed for travel beyond the EPZ. Typically, a value of 20 mph is used for ESPEED3. These values can be checked using the population movement output in MACCS. Roadway infrastructure type and demand are taken into consideration when developing ESPEEDS. For example, early evacuation speeds may be around 10 mph with congested speeds dropping to 1 to 5 mph, depending on the population density and road network at a specific site. While this is a recommended option and it is the one used in the SOARCA studies, there may be reasons to model the evacuation differently from this recommendation and the analyst should implement the best option for a specific site and for the application. For example, if the set of accidents to be evaluated allow all residents within the EPZ to evacuate before release begins, then a simplified evacuation model is adequate for that application.

Parameter Name: ESPGRD

Parameter Description: Speed Multiplier to Account for Grid-Level Variations in Road Network

Recommended Value: Derive based on site-specific ETE

Uncertainty Range: May be developed based on information in site-specific ETE

References: [2], [133], site-specific ETE report if available

Discussion: ESPGRD, which is a matrix with dimensions given by NUMCOR and LASMOV, defines the speed multiplier to account for location-specific speed variations in the evacuation region. A value of one causes the speed to be the same as the variable ESPEED. There is no recommended value because this parameter depends on site-specific conditions. To implement the grid multiplier, the road network is mapped onto the MACCS grid. The site-specific ETE document may be reviewed to identify congestion areas. ETE guidance [133] provides that the licensee includes the longest queue length for the 10 intersections with the highest traffic volume. ETE guidance also requires that color-coded graphics to identify the level of service for

roadways be included in the ETE studies, illustrating the extent and location of congestion over time [133]. ETE studies should also include the average speed for each major evacuation route that exits the EPZ. The analyst should review the ETE and determine whether it is appropriate to decrease or increase speeds using ESPGRD. Speed adjustment factors are typically applied to speed up vehicles in rural uncongested areas and to slow vehicles in more urban settings where the modeling indicates that speeds are lower than the average values used in the analyses.

Parameter Name: ESPMUL

Parameter Description: Speed Multiplier Employed During Precipitation

Recommended Value: for a generic site, 0.7; site-specific based on ETE

Uncertainty Range: not available

References: [2], [133], site-specific ETE report if available

Discussion: The evacuation speed multiplier (ESPMUL) is a factor that is applied to ESPEED during periods of precipitation. Precipitation is defined in the weather file and includes any type of precipitation. Adverse weather is typically defined as rain, ice, or snow that affects the response of the public during an emergency. Adverse weather is known to affect roadway capacity and operating speeds [142]. MACCS provides a means to address this through the ESPMUL. This parameter in MACCS is used to reduce travel speed when precipitation is occurring as indicated from the meteorological data file. The ESPMUL value should be based on the information in the site-specific ETE. ETE studies are developed for every site in accordance with [133]. Guidance is provided for speed and capacity reductions based on type of weather. The ETE study should describe the reductions and these can be used to develop a site-specific value of ESPMUL.

4.3.2 Potassium Iodide Administration

The purpose of the KI administration is to saturate the thyroid gland with stable iodine so that further uptake of radioiodine by the thyroid is diminished. If taken at the right time, KI can nearly eliminate doses to the thyroid gland from inhaled radioiodine. Some states have distributed KI tablets to people who live near commercial NPPs. For states in which a KI program is maintained, KI may be distributed, or residents may be directed to locations where the KI can be obtained. If the KI model is implemented, variables regarding the percentage of the population ingesting KI and its efficacy must be defined. Information in [136] may be used to support estimation of the percentage of population that be able to take KI in a timely manner and information in [143] may be used to estimate the efficacy of KI ingestion as a function of the time relative to exposure. It is suggested that if analysts wish to assess the impact of KI protective actions that they perform parameter sensitivity analyses to assess the impact of implementing KI administration for various population cohorts.

Parameter Name: KIMODL

Parameter Description: Model Flag for KI Ingestion

Recommended Value: NOKI unless site is in a state where a KI program is maintained and information is available to define parameters for the model.

Uncertainty Range: not applicable

References: [40]

Discussion: The KIMODL determines whether consequence calculations consider KI ingestion. It is recommended the KIMODL be used only for sites where an active KI program exists and for which information is available to define parameters for the model.

Parameter Name: POPFRAC

Parameter Description: Fraction of a Cohort that Ingests KI

Recommended Value: 0.5

Uncertainty Range: not available

References: [136]

Discussion: For sensitivity analyses to assess the impact of KI protective actions, a value of 50% may be used as baseline because this action requires residents to find their KI or to obtain KI during the emergency.

Parameter Name: EFFACY

Parameter Description: Thyroid Dose Reduction Factor for Inhalation due to KI Ingestion

Recommended Value: 0.7

Uncertainty Range: not available

References: [143]

Discussion: Factors that contribute to the effectiveness of KI include the timing of ingestion and the degree of pre-existing stable iodine saturation of the thyroid gland, which already inhibits absorption of inhaled radioiodine by the thyroid. For sensitivity analyses to assess the impact of KI protective actions, a value of 0.7, representing 70 percent efficacy, may be used as a baseline (see Table 2.1 of [143] for more information).

4.3.3 Early Phase Relocation

Relocation (which in MACCS is accomplished by limiting the exposure duration) is a protective measure that is expected to be implemented during the early phase in areas where residents would exceed a specified dose threshold. Relocation may be implemented in areas where contamination levels are higher than surrounding areas, resulting in areas that exceed the EPA PAG for evacuation even though they may be outside the EPZ. Depending on the release characteristics, terrain, weather, and other conditions, some areas with elevated dose rates may be categorized as hotspots [144]. Relocation was first introduced in the CRAC model to instantaneously remove the public from areas that exceeded specified dose limits [3] at a specified time after plume arrival. In WASH-1400, this was applied beyond the 25 mile evacuation zone assumed in that study:

If the ground contamination were sufficiently large to warrant relocation of people, it is assumed that such relocation will be accomplished within an average period of 7 days. If rain were to result in an unusually high ground contamination within a small area, the population within such an area is assumed to be evacuated within an average of 24 hours [3].

The early relocation from areas affected by rain beyond 25 miles has evolved into the current early phase hotspot and normal relocation models. These models are thus analogous to a targeted evacuation of hotspots beyond the sheltering and evacuation zone modeled in MACCS, prior to the relocation that is implemented at the beginning of the intermediate phase (i.e., after a period defined by ENDEMP). NUREG-1150 used a model in which a projected effective dose of

50 rem in 1 week triggered relocation of non-evacuees at 12 hours after plume arrival and a projected effective dose of 25 rem in 1 week triggered relocation at 24 hours after plume arrival [5], but the rationale for these choices was not provided. The relocation models in SOARCA were keyed to the EPA evacuation criteria of 1 to 5 rem¹² rather than the higher limits of 25 to 50 rem used in NUREG-1150. According to [14], “The relocation times used in SOARCA were 12 hours for hotspot and 24 hours for normal relocation for Peach Bottom and 24 hours for hotspot and 36 hours for normal relocation for Surry. The values for Surry are longer than Peach Bottom because the population density is greater and the area north and east of the plant is heavily urban. This would require additional resources to notify residents and support relocating them out of the affected area. Notifying and relocating the larger population would be expected to take a longer time.”

The use of the term relocation to describe the MACCS early phase protective actions outside the evacuation zone may be somewhat confusing. The EPA provides PAGs for relocation [145]; however, the EPA relocation PAGs are for implementation during the intermediate phase, and are for a different use than the hotspot and normal relocation that are implemented in the early phase in MACCS. The protective actions described as relocation in EPA guidance are implemented in MACCS by the criteria for intermediate phase relocation and long-term habitability described in Section 4.4. The MACCS early phase relocation model is consistent with an expanded evacuation of hotspot areas exceeding evacuation criteria beyond the initial evacuation zone and is therefore recommended to be based on the EPA early phase criteria for evacuation or sheltering, which is “a projected whole-body dose of 1 to 5 rem (10 to 50 mSv) total effective dose (TED) over four days” [145].

The determination of areas requiring relocation would likely be based on dose projections from state, utility, and Federal agency computer modeling coupled with field measurements. Onsite and offsite emergency plans provide that field teams are dispatched very early in an event to take field measurements and track plumes on the ground. Along with the results of dose assessments, this information is available to OROs to make informed decisions regarding the potential need to relocate residents. In consequence analyses, this protective measure can be simulated within MACCS as an expanded evacuation based on dose projections, which could occur relatively quickly, or as a post-deposition relocation based on field surveys, which could require more time to complete. In practice, the implementation of such an expanded evacuation may fall somewhat between these two limits due to conflicting priorities during a response. Determining the most appropriate values for these MACCS parameters requires a level of judgment involving site-specific information, accident scenario timing information, and knowledge of response activities.

4.3.3.1 Criteria for Early Phase Relocation

The MACCS model for determining the population subject to early phase relocation is defined by the variables DPPEMP, CRIORG, DOSHOT, and DOSNRM. These values are typically assigned to reflect the EPA PAG of an averted dose of 1 to 5 rem in four days as a criterion for recommending evacuation or sheltering.

Parameter Name: DPPEMP

Parameter Description: Dose Projection Period for Early Phase Relocation

Recommended Value: 4 days

¹² For Peach Bottom, the Pennsylvania intermediate phase relocation dose criterion of 500 mrem was used as the dose criterion for normal relocation.

Uncertainty Range: not applicable

References: [145]

Discussion: DPPEMP is the dose projection period for the early phase. This is a relatively new parameter in MACCS, which allows the duration of the early phase dose projection to be specified independently of the duration of the early phase and was added to MACCS in Version 3.10. Four days is appropriate because this is consistent with the EPA PAG related to dose projection. If a value is not defined for DPPEMP, MACCS automatically uses the duration of the early phase as the dose projection period. It should be noted that because relocation is based on the dose accrued from arrival of the first plume segment, a four-day dose projection period may be insufficient for accidents in the major release is preceded by a prolonged period of very low releases. In such cases, setting the dose projection period to the duration of the early phase and adjusting the relocation time to include the duration of the low-level releases prior to the major release may be warranted.

Parameter Name: CRIORG

Parameter Description: Critical Organ for EARLY Phase

Recommended Value: L-ICRP60ED

Uncertainty Range: not applicable

References: [145]

Discussion: CRIORG is the critical organ for relocation decisions during the early phase. People remain in the grid element when the projected TED to the critical organ is less than the values defined by either DOSHOT or DOSNRM, assuming an exposure period defined by DPPEMP. The EPA PAGs call for use of the TED, which is consistent with the L-ICRP60ED output in the recent dose coefficient files supplied with MACCS.

Parameter Name: DOSHOT

Parameter Description: Hot-Spot Relocation Dose Threshold

Recommended Value: 5 rem

Uncertainty Range: Triangular distribution with a mode of 5 rem, a lower bound of 1 rem, and an upper bound of 7.5 rem

References: [145], [15]

Discussion: The hotspot relocation dose (DOSHOT) establishes the threshold at which hotspot relocation is implemented. DOSHOT is typically established to represent the upper value of an aggregate 4-day early phase dose threshold at which the EPA PAG manual [145] recommends evacuation. A 4-day effective dose of 5 rem is recommended for DOSHOT based on the upper evacuation value in Table 1-1, “Planning Guidance and Protective Action Guides for Radiological Incidents,” in the EPA PAG manual [145]. Relocation parameters may be sampled to reflect uncertainty in post-evacuation activities. This approach was used in [15]. MACCS implements relocation using hotspot and normal relocation parameters to represent possible ORO actions, which would be determined based on dose projections using state, utility, and Federal agency computer models and field measurements. In practice, this protective measure could be implemented as a post-accident relocation or as an expanded evacuation, but the effect is essentially the same in either case. This value was sampled from a triangular distribution with a mode of 5 rem, a lower bound of 1 rem, and an upper bound of 7.5 rem in [15] based on the observation that “ORO decisions are influenced by many factors that could result in a higher or lower value.”

Parameter Name: DOSNRM

Parameter Description: Normal Relocation Dose Threshold

Recommended Value: 1 rem

Uncertainty Range: Triangular distribution with a mode of 1 rem, a lower bound of 0.5 rem, and an upper bound of 2 rem; perfectly rank correlated with DOSHOT because MACCS requires DOSNRM to be less than DOSHOT

References: [145], [15]

Discussion: The normal relocation dose (DOSNRM) establishes the threshold at which normal relocation is implemented. DOSNRM is typically established to represent the lower bound of an aggregate 4-day early phase dose threshold at which the EPA PAG manual [145] recommends evacuation. The EPA PAG manual explains that under normal conditions, evacuation should be implemented if residents are expected to receive 1 rem [145]. The 4-day effective dose of 1 rem is recommended based on the lower evacuation bound in Table 1-1, “Planning Guidance and Protective Action Guides for Radiological Incidents,” in the EPA PAG manual [145]. This value was sampled from a triangular distribution with a mode of 1 rem, a lower bound of 0.5 rem, and an upper bound of 2 rem in [15].

4.3.3.2 *Timing of Early Phase Relocation*

Early phase relocation is applied in MACCS throughout the entire analysis area beyond the sheltering and evacuation region defined by NUMEVA. Since NUMEVA can be different for each cohort, the area subject to relocation can also be different for each cohort. For example, a non-evacuating cohort effectively has NUMEVA defined to be zero (non-evacuating cohorts are defined by LASMOV = 0 in the MACCS input and NUMEVA is not specifically defined but is effectively equal to 0), so the entire cohort is subject to relocation. MACCS uses the TIMHOT and TIMNRM parameters to represent the time after plume arrival to relocate the population of areas exceeding hotspot and normal dose thresholds, respectively. These times should include the times required for emergency response personnel to identify affected areas, to notify residents to relocate, for the population to mobilize (e.g., gather family members, prepare home, and pack), and for the population to evacuate. Since relocation is modeled to occur instantaneously at TIMHOT and TIMNRM, at least a portion of the time required to evacuate should be included when these values are evaluated.

Areas beyond the EPZ are notified primarily through the emergency alert system (EAS) messaging and route alerting, both of which are identified in emergency plans. The notification and response of the public occur over a period of time, with some members of the public receiving the notification and leaving promptly and others taking more time [109]. Because MACCS relocates residents instantaneously (i.e., not accounting for travel time) after an interval of TIMHOT or TIMNRM following plume arrival, these parameters should reflect an average time to accomplish the necessary activities. The following rules are applied in the MACCS calculation [2]:

- Relocation is only applied throughout the analysis area to non-evacuees (i.e., the non-evacuating cohort within the evacuation area and all populations outside the evacuation area).
- All members of the population are either subject to evacuation or relocation; no member of the population is subject to both.

- Relocation occurs instantaneously at the time specified by TIMHOT or by TIMNRM after plume arrival.
- TIMHOT allowable range is $0.0 \leq \text{value} \leq \text{ENDEM}$ (after plume arrival).
- TIMNRM allowable range is $\text{TIMHOT} \leq \text{value} \leq \text{ENDEM}$ (after plume arrival).
- DOSHOT range is $0.0 \leq \text{value} \leq 1.E10$ (Sieverts).
- DOSNRM range is $0.0 \leq \text{value} \leq \text{DOSHOT}$.

Notice that the two relocation criteria can be collapsed into a single criterion by setting $\text{TIMHOT} = \text{TIMNRM}$ and $\text{DOSHOT} = \text{DOSNRM}$.

Parameter Name: TIMHOT

Parameter Description: Hot-Spot Relocation Time

Recommended Value: problem specific, typically less than or equal to 24 hours unless the transportation network is substantially damaged by an external initiating event (e.g., an earthquake)

Uncertainty Range: not available

References: not available

Discussion: TIMHOT defines the estimated time needed to relocate residents from areas that exceed the established dose threshold given by DOSHOT. At the user-specified time TIMHOT, residents are removed from the problem for the duration of the early phase. This time begins at plume arrival and should include all temporal elements that contribute to relocating the public. Some of the contributing activities include identifying the affected areas, developing messaging, implementing the EAS to notify the public, and a portion of the time required to evacuate. To simplify instructions to residents, OROs typically establish relocation boundaries based on geographic characteristics such as interstates, rivers, or major roadways [108]. Notification is often augmented by route alerting, Reverse 911®, or other communication methods [108]. Upon receipt of notification, residents begin to mobilize and then travel out of the affected area. Each of these activities can be influenced by factors such as, but not limited to, the size and population of the affected area, location of residents when the warning is received, available response resources, clarity of the notification, weather, or ORO resource capabilities. Since the timing is keyed to plume arrival, there is a period of exposure prior to relocation unless the user specifies the time to be zero.

Establishing a single value for a range of population densities, and other conditions that influence relocation is challenging. The time should consider the characteristics of the affected area including population density and the supporting roadway infrastructure. When constructing an uncertainty distribution, the lower bound is developed based on an optimal response where OROs relocate residents quickly after plume arrival. Notifications can be accomplished via EAS messaging, but route alerting is most likely necessary to notify the affected public. Traffic control is likely to be established to support a relocation effort. These efforts take a considerable amount of time and resources to implement and this time is often dependent on the infrastructure and planning between local and surrounding area OROs. Generalizing a process for this parameter is somewhat complicated because TIMHOT must be added to time of plume arrival, but plume arrival is not linked to other response timeline activities, such as declaration of a GE. Another issue that affects the implementation of these parameters is that often a source term begins with a small release and later, such as when containment fails, a

larger release occurs. Because MACCS implements relocation after plume arrival, the analyst should consider this when establishing the timings. To determine the size of the relocating population, the analyst could develop an initial MACCS model with a non-evacuating cohort subject to hotspot and normal relocation as the only cohort within the area of interest. The analyst could then examine the MACCS Type 14 output that provides a report of the size of the population that evacuates and relocates during each phase. This report can be generated at each spatial interval and provides an indication of the size of the relocated populations. Smaller projected populations support assignment of a shorter relocation time; whereas, larger populations support assignment of longer relocation times. For MACCS analyses that explicitly model evacuation beyond the ten-mile EPZ, the size of the population subject to the MACCS early relocation models can be small and confined to the non-evacuating fraction within the modeled evacuation zone, depending on the magnitude of the source term. For MACCS analyses that only model evacuation within the ten-mile EPZ, the size of the relocated population may be larger, and relatively longer relocation times may be appropriate. However, it should be noted that the values established for TIMHOT and TIMNRM apply to all individuals designated as non-evacuating, whether they are among the small fraction within the EPZ that is modeled as failing to evacuate or whether they are much farther from the plant and therefore beyond the modeled evacuation zone. Establishing a long delay to early phase relocation based purely on the potentially affected population size may overestimate the time needed to relocate individuals near the site who would be at the highest risk of elevated exposures. Using different values for TIMHOT and TIMNRM can partially alleviate this problem, but may not treat all members of the population adequately.

The discussion provided above should assist in selecting a TIMHOT value. There are situations in which OROs may be able to evacuate hotspots beyond the initial evacuation zone based on a proactive dose projection approach. In such cases, a time of zero hours may be reasonable if sufficient time would have been available to identify the affected areas and evacuate them prior to plume arrival at a particular location. The TIMHOT value should be determined based on the size of the affected area, population density, roadway capacity, and the time for emergency response personnel to evacuate hotspots beyond the initial evacuation zone, keeping in mind that the initial priority is to evacuate those within the EPZ.

Parameter Name: TIMNRM

Parameter Description: Normal Relocation Time

Recommended Value: problem specific, typically 6-24 hours after TIMHOT

Uncertainty Range: not available

References: not available

Discussion: TIMNRM defines the estimated time needed to relocate residents from areas that exceed an established dose threshold (DOSNRM). At a user-specified time, residents are removed from the problem for the duration of the early phase. The value of TIMNRM can account for the fact that the initial priority is on evacuating the public within the EPZ, for time needed to evaluate releases and project doses to the public, and for time needed for the public to receive notification and begin to relocate. Relocation is modeled as being instantaneous, so TIMNRM should also account for some portion of a realistic evacuation time. The same time elements described for TIMHOT are required. In addition, time may be needed to prioritize relocation of residents due to the hotspot criteria. Again, establishing a single value for a range of population densities, and other conditions that influence evacuation of areas exceeding PAG criteria beyond the initial evacuation zone is challenging. It is recommended that the TIMNRM be set to a time equal to TIMHOT plus the time to relocate the area that exceeds the normal

criteria. This additional time added to TIMHOT could be represented by the 90% 10-mile EPZ ETE. Therefore, the TIMNRM would follow an equation similar to the Equation (4-5):

$$\text{TIMNRM} = \text{TIMHOT} + (90\% \text{ ETE for the 10-mile EPZ}) \quad (4-5)$$

Evacuation of hotspots should be substantially complete under most circumstances prior to the start of the normal relocation. The TIMNRM value should be adjusted, as necessary, based on the size of the affected area, population density, roadway capacity, and the time for response personnel to implement relocation. Generally, normal relocation times of 6 to 24 hours after hotspot relocation are reasonable, although they could be longer following a major seismic event. OROs could implement evacuation of areas exceeding the lower end of the EPA PAG range concurrent with or shortly after evacuation of hotspots, but the affected population may be large and availability of resources to support the relocation need to be considered. If the analysis considers an uncertainty distribution for TIMNRM and TIMHOT, TIMNRM should be perfectly rank correlated with TIMHOT because MACCS requires TIMNRM be greater than (or equal to) TIMHOT. Furthermore, it is reasonable that delays for hotspot relocation would directly impact the timing of normal relocation.

4.3.4 Early Phase Costs

The evacuation and relocation costs describe the expected compensation for people who are subject to these protective actions. Evacuation only occurs during the early phase. It is triggered by an emergency declaration at a nuclear plant or facility (e.g., declaration of a GE). Relocation of individuals can occur during the emergency or intermediate phases. It can also occur during the long-term phase but is commonly referred to as interdiction in that case.

In the presentation of economic cost results, the costs associated with the early phase (i.e., for evacuation and early phase relocation) are reported separately from the costs associated with the intermediate phase (i.e., for relocation) and the long-term phase (i.e., decontamination, interdiction, condemnation, loss of use, and permanent relocation costs). EVACST defines the daily cost of compensation for evacuees and residents relocated during the early phase [2]. Costs are identified from the time of evacuation through the end of the early phase. After the early phase ends, continuing relocation costs are captured under the RELCST parameter for any resident who cannot return home because contamination exceeds the habitability criteria.

Cost per person is user supplied and can include the cost of temporary lodging, meals, and lost income [20]. Sprung et al. [5] escalated the per diem evacuation costs estimated in NUREG/CR-3673 [146] to 1986 for use in NUREG-1150. The NUREG/CR-3673 [146] per diem costs were based on the 1974 EPA study of evacuation risks [140]. The per-person-day cost of \$24 used in NUREG/CR-3673 did not include loss of personal or corporate income. Although several references say the parameter can include lost income [3] [146] [20] [2], lost income was not included in [5]. This may be because the DS RATE captures lost corporate income and addressing it in both parameters could be considered double counting. However, during this investigation, it was determined that lost personal income should be included with EVACST and RELCST. EVACST is the sum of the following:

- Lodging – Federal per diem rates
- Food – Federal per diem rates
- Transportation – based on average distance of 50 miles
- Lost income – based on wages lost during temporary displacement

In the EPA study, which was the basis for many previous cost studies, the costs were weighted based on an assumption that 20% of the public stays in mass care facilities. The majority of people who evacuate their homes do not use public shelter facilities for overnight stays [110] with generally less than 10% staying in shelters [108]. People most often stay with friends and relatives or in hotels. The lodging costs in this estimate assume Federal per diem rates for all evacuees.

Lodging costs vary based on the location of the site being analyzed. It is recommended the analyst use Federal per diem rates to establish these values. As an example to demonstrate how this could be applied, average 2018 Federal lodging per diem rates of \$180 per night for Philadelphia, Pennsylvania [147] were used to establish a parameter value for this report. Per diem values for a large urban area were selected rather than the often-lower statewide value because of the availability of hotel lodging in urban or suburban areas relative to more rural areas. Sufficient lodging capacity may not be available at the lower statewide rates in some cases. The analyst should update the value based on the specific location of the plant being analyzed. It is assumed one household would use one hotel room; therefore, to convert lodging to be on a per person basis, the lodging rate is divided by 2.58 people per household [148] for a lodging cost of \$70 per person-day. The 2018 Philadelphia federal per diem rate for meals and incidental expenses was \$64 per person-day [147].

Transportation costs are incurred for residents evacuating in personal vehicles as well as public and private transportation to evacuate transit-dependent residents and special needs facilities. With regard to schoolchildren, it is assumed that transportation costs are covered with the evacuation of the family. Although it is possible that schoolchildren may need to be evacuated separately, school is in session only about 14% of the year (about 7 hours per day for 180 days per year). Therefore, in most scenarios, children evacuate with their parents. An analyst may still decide to model a school cohort since special facility/special needs cohorts can be a limiting factor in terms of mobilization resources and time in some evacuations. For evacuees who own their vehicle, a round trip average evacuation of 100 miles is assumed (50 miles outbound and 50 miles return). Using the 2018 Internal Revenue Service (IRS) standard mileage rate of 18 cents per mile for moving purposes [149], this equates to \$18 per household. When divided by 2.58 persons per household [148], this equals about \$7 per person. Over a 7-day early phase, this is rounded to \$1.00 per person per day. The transportation cost for transit-dependent residents includes busing these residents out of the EPZ. Information from [150] and [151] suggests that charter bus rentals can range from \$1000 to \$2000 per day. ETE studies typically identify a mixture of school and charter buses with a capacity of 50 people, which considers that evacuees are carrying some amount of possessions. With 50 passengers per bus, the cost is approximately \$30 per person. Assuming two days of use (outbound and return) over a 7-day early phase, this translates to approximately \$8.60 per person per day. However, this cost is only applied to transit-dependent residents but must be allocated across the entire population. Assuming that transit-dependent residents comprise 5% of the evacuating population, a weighted average value for the total public and private transportation cost is therefore estimated to contribute approximately \$1.40 per person-day.

To account for lost income, an average wage can be derived from the Social Security Administration (SSA) Average Wage Index (AWI) obtained from [152] coupled with information on the fraction of the population that is employed from [153]. In 2018, the average wage was \$50000 from the AWI and the fraction of the population that was employed was 60%. This equates to an average wage of \$83/person/calendar day. Average wage is more appropriate than average income, because income includes such items as unemployment insurance, disability payments, child support received, and other types of income, not job related, that may be expected to

continue. As an alternative to lost income based on the SSA AWI and the employment-population ratio, per-capita labor compensation may be derived from information on the share of gross domestic product (GDP) that comes from labor coupled with the per-capita GDP. For 2018, with a per-capita GDP of \$63,000 [154] and an average 2016 labor share of 58% (from Figure 1 of [155]), this works out to a per capita labor compensation of \$101 per person per calendar day. The average of these two values is \$92 per person per day expressed in 2018 dollars.

Parameter Name: EVACST

Parameter Description: Emergency Phase Cost of Evacuation/Relocation

Recommended Value: Varies based on location (see above): \$230/person-day based on 2018 Federal per diem rates in Philadelphia and the 2018 national average wage index is a reasonable generic value if site-specific information are not available. This value is based on 2018 data and should either be rederived or adjusted using the CPI index (as discussed in Section 4.1.1) for the year to be evaluated.

Uncertainty Range: not available

References: [2], [147], [148], [152], [153], [154], [155]

Discussion: The total per person-day cost for EVACST is the sum of the above lodging per person-day, meals and incidental expenses per person-day, public and private transportation cost per person-day, and average wage per person-day. In the example given above, this is \$70 + \$64 + \$1.40 + \$92 which equals (after rounding) \$230 per person per day.

4.4 Intermediate and Long-Term Protective Actions and Exposures

The interdiction period in MACCS is the time during the intermediate and long-term phases when the public is not allowed to return to their homes or businesses. This period begins at the end of the early phase and continues until land is restored to the dose criteria defined by DSCRLT and TMPACT. The intermediate phase can have a duration of up to one year following the end of the early phase in MACCS 3.10. The only protective action modeled in this phase is relocation. When the exposure over the intermediate phase dose-projection period, DPP_INTERPHAS, leads to doses exceeding the intermediate phase dose criteria, DSCRTI, then the population is assumed to be relocated to uncontaminated areas for the entire intermediate phase. When the exposure over the long-term phase dose-projection period, TMPACT, leads to doses exceeding the long-term habitability criterion, DSCRLT, MACCS begins decontamination immediately following the intermediate phase. In practice, decontamination of some areas could begin earlier, while other areas may begin later. The significance of the time at which decontamination begins is that the habitability criterion is applied at that time to determine whether land needs to be decontaminated. When decontamination is needed, land becomes available to use after decontamination plus an additional interdiction period, if needed. Loss of use of property is calculated over the entire period of the emergency, intermediate, and long-term phases during which the land cannot be used. Thus, the duration of the intermediate phase can influence the amount of property that is decontaminated and the overall cost of the accident. Costs related to loss of use depend on the time it takes to restore land to habitability. The minimum period of loss of use for land, that requires decontamination, is the sum of the durations of the early and intermediate phase plus the time required for decontamination. Since loss of use is often the most important of the economic losses, the time at which decontamination is complete is more important to the predicted economic consequences than when decontamination begins (i.e., the end of the intermediate phase).

The MACCS model for assessing the cost of interdiction is based on the model originally developed in WASH-1400 [3]. The MACCS2 User's Guide [2] states that "The maximum duration of temporary farmland interdiction that can be selected by the code is 8 years, while the corresponding maximum duration for interdiction of population is 30 years. If the maximum-duration interdiction of either land use is insufficient to satisfy the respective criteria for use, then that land use is assumed to be permanently interdicted, or condemned." The farm interdiction criteria are based on "acceptable levels of foodstuffs contamination" [2]. Many decontamination processes reduce groundshine and resuspension doses by washing surface contamination into the ground. Since these processes may not move contamination out of the root zone, the WASH-1400 based economic cost model of MACCS assumed that farmland decontamination reduces direct exposure doses to farmers without reducing uptake of radioactivity by root systems [3]. This approach remains in the current model; thus, decontamination of farmland does not reduce the ingestion doses produced by consumption of crops that are contaminated by root uptake.

4.4.1 Intermediate and Long-Term Phase Durations

The EPA defines the intermediate phase to be a time when releases are brought under control but have not necessarily stopped, and the late phase is defined to be the period when recovery actions are carried out to reduce radiation levels in the environment [145]. The intermediate phase may last from weeks to months, and the late phase may extend from months to years. EPA explains that the intermediate phase may overlap with the early phase and late phase, whereas in MACCS the phases are discrete and cannot overlap. Releases in MACCS must be complete by the end of the early phase. In MACCS, the intermediate phase begins immediately after the early phase. The user can define the duration of the intermediate phase to be zero (i.e., no intermediate phase) or up to one year. The only response considered during the intermediate phase is relocation for those areas where doses exceed the intermediate-phase relocation criterion. Note that this criterion is different than either the hotspot or normal relocation criterion during the early phase and that the number of people affected could either be larger or smaller. Analysts may decide to not include an intermediate phase because it is feasible that the site would begin remedial actions, such as decontamination of land and property, as soon as possible following the release. Decontamination, followed by continued interdiction if necessary, is modeled in MACCS in the long-term recovery phase following the intermediate phase period¹³. In general, the decontamination activities for Fukushima took longer than one year to begin, but some activities began sooner.

Parameter Name: DUR_INTPHAS

Parameter Description: Duration of the Intermediate Phase

Recommended Value: 0 or 1 year

Uncertainty Range: not available

References: [2], [145]

Discussion: DUR_INTPHAS is the duration of the intermediate phase and represents the time period that immediately follows the early phase. During the intermediate phase, it is anticipated that better information concerning dose rates would become available, and the decision process for long-term recovery actions would be started [145], [20]. A maximum of 1 year is the limit set in MACCS 3.10 for this parameter. The effect of the duration of the intermediate phase on decision making related to decontamination in the MACCS model is described above. The

¹³ The length of the decontamination period itself, during which land and property is assumed to be interdicted while decontamination is in progress, is defined by the variable TIMDEC and is discussed under the decontamination plan description in Section 4.4.4.

user should keep in mind that the time needed to complete decontamination following the accident usually has a stronger effect on results than the time when decontamination starts (i.e., after the intermediate phase). However, it should be noted that the use of a one year intermediate phase allows weathering and radioactive decay to reduce doses and may thereby reduce the area subject to decontamination in the long-term phase. For accidents with very small releases resulting in very limited contamination, no intermediate phase may be needed. An intermediate phase should be included for cases with a relatively large atmospheric release. For these larger releases, a one year intermediate phase duration is recommended. The number of people subject to intermediate phase relocation may be examined using the MACCS Type 14 output and can inform the selection of the intermediate phase duration. As discussed below, a one year intermediate phase also allows the analyst to use the second-year EPA PAG criterion of 500 mrem when specifying the long-term phase dose criterion rather than having to choose a dose limit between the first year and second year criteria of 2 rem and 0.5 rem.

Parameter Name: EXPTIM

Parameter Description: Maximum Exposure Time

Recommended Value: 50 years

Uncertainty Range: not available

References: [14], [156]

Discussion: EXPTIM is the long-term exposure period. It begins when people return to their property, that is, when dose levels fall below the habitability criterion specified by DSCRLT and TMPACT. For example, when the code estimates that 5 years of decontamination and interdiction are needed at a specific location to satisfy the habitability criterion and EXPTIM is 50 years, doses to the resident population are calculated for an exposure period that starts at the beginning of year 6 and ends at the end of year 55 of the long-term phase. This value is discussed in [2], which states that "It is suggested that 30 years is a reasonable value since that is the value used by the EPA in its Superfund guidance" [157]. More recently, as discussed in [14], "NUREG-1150 and Sample Problem A used the maximum value of exposure period allowed by MACCS, 10^{10} seconds, which is approximately 317 years. More recent analyses have used exposure periods chosen to be the same as the commitment period. In SOARCA, 1.58×10^9 seconds (50 years) was chosen." Fifty (50) years has been traditionally assumed as the long-term exposure period reflecting International Commission on Radiological Protection (ICRP) methods of internal dose evaluation as having a 50-year commitment period for adults. The 50-year commitment period is a rounded value considered by the ICRP to be the working-life expectancy of a young person entering the workforce [156]. Another approach for determining the long-term exposure period is to consider that the exposed population consists of individuals with a median age of 37 years [158] and an approximate average life expectancy of 77.9 years [125]. The accrual of doses from food and water ingestion is not affected by the user-specified value of EXPTIM. This accrual is not strictly associated with the population from which the contaminated food and water originate. The ingestion of contaminated food and water is estimated as a societal dose to an unspecified population. However, the ingestion dose is accounted for in the grid element from which the food and water originated in the output. Food and water ingestion doses are thus assessed based on the LASTACUM parameter specified in the MACCS food model or the COMIDA2 food model. As described in Chapter 2 of [31], LASTACUM defines the duration of the ingestion dose exposure period. It should be noted that land that cannot be returned to production after 8 years is condemned. If the LASTACUM input variable is assigned a value less than 9, MACCS condemns farmland when the COMIDA2 model is used. The allowable range for LASTACUM is from 1 to 50 years.

4.4.2 Dose Criteria for Relocation, Interdiction, and Decontamination

The protective action parameters DSCRTI and DPP_INTERPHAS in MACCS define the dose-projection period and maximum dose that people are allowed to receive during the intermediate phase, and the parameters DSCRLT and TMPACT in MACCS define the dose-projection period and maximum dose that people are allowed to receive during the long-term phase [2]. The maximum allowable doses determine the need for relocation, decontamination, interdiction, and condemnation. It should be noted that required decontamination after a severe accident is uncertain because no long-term cleanup goal or level currently exists. As described in the EPA PAG manual [145], “Radiation protection considerations must be addressed in concert with health, environmental, economic, social, psychological, cultural, ethical, political and other considerations.” Because the MACCS dose criteria are used for decisions on cleanup and reoccupation, the current state-of-practice is to model decontamination to the level of meeting habitability criteria as defined by the intermediate-phase PAGs.

The EPA PAG for the intermediate phase is an unshielded 2-rem projected dose for the first year with 0.5 rem/year in subsequent years [145]. However, MACCS only allows a single habitability criterion defined by the variable DSCRLT for the long-term phase. To account for this in previous analyses, such as NUREG-1150 [4] and SOARCA [13] [14], the habitability criteria was chosen to be 4 rem in 5 years; however, an intermediate phase was not used in those analyses. In this update, consistent with [15], an approach for specifying the habitability criterion DSCRLT was developed to be consistent with the approach for specifying DSCRTI. To precisely define the DSCRTI and DSCRLT values, the duration of the intermediate phase, decontamination periods, and dose thresholds for the intermediate and long-term phases need to be considered. Scaling the values to represent an intermediate-phase duration between 0 and 1 year is complicated. The use of an intermediate phase duration that aligns with the intermediate phase dose projection periods allows the user to directly specify the PAG criteria and eliminates the need to interpolate the dose criteria across a period that spans the guidance for the first and second years.

No intermediate phase in a MACCS calculation corresponds to releases that are sufficiently small such that the intermediate phase, if it is needed at all, would be short. In this case, using the first year intermediate phase PAG level of 2 rem in the year of the accident to establish the habitability criteria is considered reasonable. For analyses where a duration of one year for the intermediate phase is chosen, the recommended habitability criteria is the second year EPA PAG level of 0.5 rem per year. For states that specify values different than the EPA PAGs, the dose level should be chosen to be the value specified by the state.

Parameter Name: DSCRTI

Parameter Description: Intermediate-Phase Dose Criterion

Recommended Value: 2 rem if DUR_INTPHAS greater than zero

Uncertainty Range: not applicable

References: [145]

Discussion: DSCRTI defines the intermediate phase dose criteria, which is the maximum allowable direct exposure committed dose to the long-term critical organ (CRTOCR) over the dose projection period defined by DPP_INTPHAS. If DSCRTI is exceeded at some location at the beginning of the intermediate phase, the population is relocated for the entire intermediate phase [2]. The direct exposure pathways considered in this evaluation are groundshine and resuspension inhalation. The EPA provides a PAG for relocation of the public in the intermediate phase of 2 rem for the first year and 0.5 rem per year in subsequent years

[145]. However, only one value for DSCRTI may be defined in MACCS. For analyses where no intermediate phase is recommended, the long-term phase is entered immediately. For analyses using 1 year for the intermediate phase, the criterion is should be chosen to be 2 rem, which is consistent with the EPA intermediate-phase PAG for the first year.

Parameter Name: DPP_INTERPHAS

Parameter Description: Dose Projection Period for Intermediate Phase Relocation

Recommended Value: 1 year

Uncertainty Range: not applicable

References: [145]

Discussion: DPP_INTERPHAS is a CHRONC parameter that defines the dose projection period for the intermediate phase. This period has recently been added to MACCS in Version 3.10 to improve accounting of doses during the intermediate phase. This parameter should be defined as 1 year. This allows the dose to be aligned with the EPA PAG for relocation in the first year [145].

Parameter Name: CROTCR

Parameter Description: Critical Organ for CHRONC Phase

Recommended Value: L-ICRP60ED

Uncertainty Range: not applicable

References: [145]

Discussion: The long-term critical organ (CROTCR) is used by MACCS for decision making regarding both the intermediate and long-term phases. The EPA recommends that decision making for the intermediate phase be based on projected whole body (effective) dose, which is represented in MACCS by L-ICRP60ED.

Parameter Name: DSCRLT

Parameter Description: Long-Term Phase Dose Criterion

Recommended Value: 0.5 rem if a one year intermediate phase is modeled, 2 rem if no intermediate phase is modeled

Uncertainty Range: not applicable

References: [145]

Discussion: DSCRLT is the long-term phase dose limit. In conjunction with the dose projection period, TMPACT, and the critical organ, CROTCR, this parameter defines the habitability criteria. Protective actions, including decontamination and additional interdiction following decontamination are evaluated to determine whether exposures can be reduced to satisfy the habitability criterion. If interdiction following decontamination is required, individuals are returned to their homes at a time when it is estimated that they receive a dose of DSCRLT to the critical organ over an exposure period of this duration [2].

Parameter Name: TMPACT

Parameter Description: Long-Term Phase Dose Projection Period

Recommended Value: 1 year

Uncertainty Range: not applicable

References: [145]

Discussion: TMPACT is the long-term dose projection period corresponding to the long-term dose limit, DSCR LT. When land is contaminated above the habitability criteria, protective actions such as decontamination or decontamination followed by additional interdiction are evaluated to determine whether the dose to an individual can be reduced so that it does not exceed the habitability criterion [2]. This period is evaluated at the beginning of the long-term phase. It is recommended that TMPACT be 1 year. This duration is appropriate when no intermediate phase is used and also when the intermediate phase is defined to be 1 year. The dose criterion associated with TMPACT depends on the duration of the intermediate phase.

4.4.3 Costs of Intermediate and Long-Term Phase Relocation/Interdiction

MACCS employs a cost-based evaluation of economic impacts [20] to calculate the following losses associated with a nuclear reactor accident:

- Daily costs incurred during temporary evacuation and relocation
- One-time relocation costs resulting from temporary or permanent interdiction
- Decontamination costs for property that can be returned to use
- Lost return on investment from properties that are temporarily interdicted
- Depreciation of temporarily interdicted property
- The value of property that is permanently interdicted (i.e., condemned)
- Economic losses of milk and crops destroyed or not grown.

In the early development of MACCS, a cost-based methodology was selected instead of input-output GDP based methodologies because, as described in NUREG/CR-3673 [146], data was not easily available at the time to support a GDP based approach. The authors of NUREG/CR-3673 explained the non-equilibrium nature of a disruption caused by a nuclear reactor accident did not lend itself to an input-output approach [146]. Similar data issues were also acknowledged with GDP methods in “Methodologies for Assessing the Economic Consequences of Nuclear Reactor Accidents” [159], where a group of international experts compared the economic models from MACCS, Model for Economic Consequence Assessment (MECA), Cost of Consequences Off-site (COCO-1), Assessment of Risks of Accidents and Normal Operation (ARANO), and COSYMA. The Organization for Economic Co-operation and Development (OECD) study recommended that input-output methods be used to show the relationships between local, regional, and national economies, but identified that data availability difficulties could be encountered with these methods [159]. Access to large amounts of economic data has since been resolved, making the original objections to the input-output approach obsolete. The implementation of a cost-based approach remains valid and reasonable, but it is now feasible to consider the input-output GDP based methodologies.

Parameter Name: RELCST

Parameter Description: Intermediate Phase Relocation Cost

Recommended Value: Varies based on location (see below): \$162/person-day based on 2018 Federal per diem rates in Philadelphia and the 2018 national average wage index is a reasonable generic value if site-specific information are not available. This value is based on 2018 data and should either be rederived or adjusted using the CPI index (as discussed in Section 4.1.1) for the year to be evaluated.

Uncertainty Range: not available

References: [2], [147], [148], [152], [153], [154], [155]

Discussion: RELCST defines the daily cost of compensation for all individuals removed from their homes over the duration of the intermediate phase [2]. This applies to the population that is projected to exceed a committed dose of DSCRTI over the intermediate-phase dose-projection period. Loss of personal income has not typically been included, but as described above with EVACST, lost personal income is considered appropriate for EVACST and for RELCST. It should be recognized that in developing the daily lost income derived here, the period of unemployment and resulting lost income is only applied over the duration of the early and intermediate phases. However, the analyst could choose to estimate a larger lost income to account for the duration of unemployment derived from unemployment statistics that could potentially extend beyond the period of either phase duration. RELCST has typically been the same as EVACST [146] [20] [5]). In review of the RELCST parameter for this study, the duration of relocation was considered. An adjustment to transportation cost is warranted because, once the initial relocation has occurred, use of the personal vehicles is not much different than normal use. Therefore, transportation costs are not recommended to be included in RELCST. Similarly, as relocated residents find long-term housing, they would incur similar costs for meals as they would at home. Thus, the per diem costs of food and incidentals are not recommended to be included in RELCST. For estimating lodging costs, a weighted lodging cost was historically estimated based on the percentage of the public who would use shelters [140]. However, weighting the values is not entirely appropriate for an extended stay. If relocation does occur, it is for the duration of the intermediate phase. A small percentage of residents may go to shelters initially, but the number of evacuees staying in shelters would be expected to decrease as the relocation period increases. For families that rent, they would no longer need to pay rent for their original lodging and would only pay rent for their new lodging. Thus, there is no increased financial burden to the family; however, the apartment owners may have continuing loan payments. Homeowners would likely be responsible to pay their mortgage loans until some disposition is achieved, even though their home is not available. For these reasons, the lodging expenses based on Federal per diem as included in the development of EVACST should be included in the RELCST parameter. Lodging costs vary based on the location of the site being analyzed. The same approach to estimating per-capita daily lodging costs used to derive EVACST, as described in Section 4.3.4, is recommended for RELCST. For the example given above, this amounts to \$70 per person per day in 2018 dollars. With regard to lost income, it is recommended this be retained for estimating the RELCST parameter. The same approach for estimating per-capita daily lost income used to derive EVACST, as described in Section 4.3.4, is recommended for RELCST. This amounts to \$92 per person per day in 2018 dollars. Therefore, the total recommended value for RELCST is the sum of locality-based lodging and lost wages (\$70 + \$92), resulting in a total relocation cost of \$162 per person-day based on estimates in 2018 for Philadelphia, Pennsylvania.

Parameter Name: POPCST

Parameter Description: Per Capita Cost of Long-Term Relocation

Recommended Value: \$7,750/person (based on 2014 data and should be escalated for the year of the analysis using the CPI index discussed in Section 4.1.1)

Uncertainty Range: not available

References: [160]

Discussion: POPCST is defined as the per capita one-time (i.e., not dependent upon the duration of interdiction) cost for temporary or permanent relocation of population and businesses in a region interdicted during the long-term phase [5]. This cost is assessed when decontamination, decontamination followed by interdiction, or condemnation is required. The value is intended to account for personal and corporate income losses for a transitional period, as well as moving expenses. Burke et al. [146] did not include costs of moving belongings to

new areas, explaining such costs should be small, since all tangible property in the interdicted area is assumed to be replaced. Although household contents are captured in the condemnation costs, moving costs should be captured in POPCST. Lost income is more appropriately captured with RELCST and is not included in POPCST. POPCST attempts to capture relocation costs in a single value for a large set of potential conditions. If decontamination alone is able to restore the land to acceptable dose levels, then the period of relocation is naturally shorter than if more protective measures are necessary. Relocation under these conditions may be short when the decontamination period is brief. When decontamination periods are longer, or when decontamination followed by an interdiction period is required, the relocation period is longer. Finally, if condemnation is required, the relocation is permanent. Each of these conditions could have different cost characteristics, making a single value of POPCST difficult to estimate. However, when relocation is required, expenses can be quite large for a typical household. The 2015 U.S. Transfer Volume and Cost Survey [160] provides the national average cost of relocation components for 2013 and 2014. Considering only the applicable components of the relocation costs (i.e., purchase closing costs, home-finding trips and travel and lodging at the time of the move, and a miscellaneous expense allowance) and eliminating components such as federal tax liabilities, loss-on-sale assistance, bonus pay for the employee to move, cost of shipping of goods, etc) shown in Figure 9 of that report, 2014 relocation costs of about \$20,000 appears appropriate for a household. With 2.58 people per household [148], this corresponds to \$7,750 per person in 2014 dollars. This value should be should be escalated for the year of the analysis using the CPI index discussed in Section 4.1.1.

Parameter Name: DSRATE

Parameter Description: Societal Discount Rate for Property

Recommended Value: 0.07

Uncertainty Range: A range of 3% to 10% may be considered.

References: [161], [162]

Discussion: DSRATE is the societal discount rate for property and it is used as the expected rate of return on property [20]. This parameter is intended to represent the rate of return on land, buildings, equipment, etc. Sprung et al. [5] recommended a value of 0.12 based on a number of measures of rates of return, including conventional mortgage rates and a ranges of estimated returns on equity. WASH-1400 also used the mortgage rate in its evaluation of DSRATE.

The discussions of discount rates in OMB Circular A-94 [161] and OMB Circular A-4 [162] are instructive for estimating an expected rate of return for a variety of assets. OMB Circular A-94 recommends a base case discount rate of 7%, stating that "This rate approximates the marginal pretax rate of return on an average investment in the private sector in recent years" [161]. As described in OMB Circular A-4, "The 7 percent rate is an estimate of the average before-tax rate of return to private capital in the U.S. economy. It is a broad measure that reflects the returns to real estate and small business capital as well as corporate capital [162]". Uses of higher or lower values, based on whether business investment or private consumption may be affected, may be considered. For example, if the disruption were largely to affect private investment in the corporate sector, "the opportunity cost may lie outside the range of 3 to 7 percent. For example, the average real rate of return on corporate capital in the United States was approximately 10 percent in the 1990s, returning to the same level observed in the 1950s and 1960s." ([162]). Because the values used in MACCS should reflect rates of return to variety of types of land and capital, the base case 7 percent rate from OMB Circular A-94 is considered a reasonable base case value for DSRATE.

Parameter Name: DPRATE

Parameter Description: Property Depreciation Rate

Recommended Value: 0.2

Uncertainty Range: not available

References: [3], [163]

Discussion: DPRATE is defined as the depreciation rate that applies to untended or abandoned property during a period of interdiction [1]. This depreciation rate is intended to account for the loss of value of buildings and other structures resulting from a lack of habitation and maintenance. In MACCS, the value of buildings and other structures is modeled to depreciate exponentially with a user-defined rate. No available data with respect to depreciation rates for untended property following a period of interdiction were identified in [5]. As such, the existing value of 0.20 (or 20%) is taken from Appendix VI of Reactor Safety Study [3], which was assumed to reflect the cost of property maintenance. WASH-1400 explains that the depreciation rate is the “only parameter in the equation (for the present value of property following a period of interdiction) whose value could be seriously in error,” but the value was judged to be appropriate because of lack of maintenance during interdiction. When property is maintained, depreciation is usually judged to be in the range of 3 to 5%. Current straight-line depreciation allows up to a 27.5-year life [163] for rental property. This corresponds to a straight-line rate of 3.63% per year for tended rental property. Interdicted property would not be tended and would be expected to depreciate at an accelerated rate. Most business and investment properties placed in service after 1986 are depreciated using the Modified Accelerated Cost Recovery System [163]. Additionally, the IRS allows a 50% special depreciation allowance, on top of the normal depreciation rate, for qualified disaster assistance property placed in service in federally declared disaster areas [163]. IRS corporate depreciation claimed on Form 4562 was also reviewed. An important feature of IRS Form 4562 is the variety of the depreciation schedules used. The schedules start with a 3-year basis for depreciation and extend to 50 years. This suggests that there is a significant amount of productive capital and equipment that depreciates quickly, even under normal conditions. There is also a concept of “consumption of fixed capital”, which represents depreciation and includes capital used up during production. According to [164], consumption of fixed capital in the U.S. was equal to 14% of gross national income in 2012.

Based on this review, it appears that the 20% depreciation rate remains reasonable. The recommended depreciation rate is the 20% per year used in previous analyses.

Parameter Name: VALWNF

Parameter Description: Weighted Average Value of Nonfarm Wealth

Recommended Value: Derive using VNFRM values from site file developed using SecPop and escalate the data to the year of interest using an appropriate inflator as discussed in Section 4.1.1.

Uncertainty Range: not available

References: [58]

Discussion: VALWNF is defined as the per-capita value of the non-farm wealth in the region [2]. Non-farmland wealth includes all residential, commercial, and public land, improvements, equipment, and possessions [20], not associated with farming, that would be unusable if the region was temporarily or permanently interdicted. The value of the non-farm wealth flows into MACCS in two ways. The site data input file contains a value of total per capita non-farm property value (VNFRM) for each economic region. VNFRM is calculated by SecPop from

county-level economic data and is included in the site file as a separate value for each grid element based on the economic region assigned in the site file. In contrast, the CHRONC input file requires a single value for VALWNF for the entire analysis area. The CHRONC input value, VALWNF, is used in the decision process to determine whether it is economical to decontaminate land or whether it should be condemned. VNFRM and VALWNF have similar meanings but are used differently in a calculation depending on whether there is a site file or not. Although calculations are not typically performed without a site file, MACCS can perform calculations with uniform population density, economic values, and land fraction over the entire grid. In this case, VALWNF defines the uniform value of wealth associated with real property. VNFRM is used when MACCS estimates the cost associated with loss of use of property during interdiction and losses when land is condemned when a site file is used in a calculation. The current state-of-practice is to define VALWNF by population-weighting the VNFRM values from a site file developed using SecPop for the region of interest. The user should additionally scale the values of VNFRM from SecPop to the year of interest using the CPI, which may be done uniformly for all economic values using the economic multiplier in SecPop or manually for each economic region in the site file [58]. Current versions of SecPop are based on 2012 economic data, but newer databases may become available and the user should verify the year upon which the SecPop data are based and escalate the data accordingly. A procedure for deriving VALWNF is described in Appendix E of [15]. It involves running SecPop with the same population multiplier that was used to develop the site file coupled with the appropriate economic multiplier but with a single radius over the region of interest (e.g., at 50 miles) and assigning a uniform economic region. The resulting single value for nonfarm wealth in the uniform economic region represents a population-weighted value for the non-farm wealth in the region.

Parameter Name: FRNFIM

Parameter Description: Nonfarm Wealth Improvements Fraction

Recommended Value: Assign a value consistent with SecPop county file used in the analysis. A value of 0.72 is consistent with the 2012 SecPop county file.

Uncertainty Range: not available

References: [58]

Discussion: FRNFIM defines the fraction of non-farmland wealth in the region due to improvements. This value only applies to areas that are interdicted. The parameter includes residential, commercial, industrial, and public real and personal property including any nonrecoverable household and commercial items. Table 5-1 of [5] identifies a range for FRNFIM of 0.7 to 0.9. A value of 0.8 [5] was used for Surry in the NUREG-1150 analyses. A related parameter in SecPop is the average fraction of home value due to land value in the U.S. This value was reviewed and updated to 0.28 in Appendix D of [58] as part of the development of the SecPop 2012 county file. With the fraction of total property value due to land value being 0.28, the value for the fraction representing the improvements is 0.72 (1 - 0.28). The analyst should refer to the latest SecPop manual to ensure that the value used in the analysis is consistent with the value used by SecPop to generate the site file.

Parameter Name: VALWF

Parameter Description: Weighted Average Value of Farm Wealth

Recommended Value: Obtain from SecPop and escalate to the year of interest if necessary

Uncertainty Range: not available

References: [58]

Discussion: VALWF defines the value of farmland wealth (property) in the region and includes publicly and privately-owned grazing lands, farmland, farm buildings, and farm machinery [5] [2]. The value of farmland wealth flows into MACCS in two ways. The site data input file contains the total value of farm property (VFRM) for each economic region or county. VFRM is determined by SecPop from county-level economic data and is included in the site file as a separate value for each economic region defined in SecPop. VFRM is used when MACCS estimates the cost associated with loss of use of properties during interdiction and losses when land is condemned. The CHRONC input value, VALWF, is used in the decision process to determine whether it is economical to decontaminate farmland or whether it should be condemned. The current state-of-practice is to define VALWF by developing an area-weighted average of the VFRM values from a site file developed using SecPop for the region of interest. The user should additionally scale the value to the year of interest using the CPI. SecPop Version 4 [58] uses 2012 economic values and these values should be escalated to the year of interest. The latest SecPop databases should be used and the user should verify the year upon which the SecPop data are based and escalate the data to the year of interest accordingly. A procedure for deriving VALWF is described in Appendix E of [15]. It involves running SecPop with the same population multiplier that was used to develop the site file coupled with the appropriate economic multiplier but with a single radius over the region of interest (e.g., at 50 miles) and assigning a uniform economic region. The resulting single value for farm wealth in the uniform economic region represents a weighted average value for the farm wealth in the region.

Parameter Name: FRFIM

Parameter Description: Farm Wealth Improvements Fraction

Recommended Value: 0.18

Uncertainty Range: not available

References: [165]

Discussion: FRFIM defines the fraction of farm property wealth in the region due to improvements. The value includes farm buildings, nonrecoverable machinery, and any infrastructure such as silos or irrigation systems that are devoted exclusively to the support of farming. According to the U.S. Department of Agriculture (USDA) [165], the farmland value represented 82% of the U.S. farm assets in 2012. Therefore, the value due to improvements is about 18%, so 0.18 is the value recommended for this parameter.

4.4.4 Decontamination

Decontamination implemented in MACCS during the long-term period is intended to reduce dose to acceptable levels [2]. During the decontamination period, the population from contaminated areas is assumed to be relocated to uncontaminated areas. MACCS uses dose-reduction factors, also referred to as decontamination factors (DFs), as linear scaling factors by which the doses are reduced [2]. These DFs are referred to as dose-reduction factors to indicate that the primary purpose is to reduce dose rather than to remove the source of contamination. Technically, dose-reduction factors allow for reducing doses without removing contamination, such as in-place stabilization of radionuclides, but in practice many non-farmland decontamination methods correspond to removal of contamination. Three DF values can be used in the code, although typically only two have been used [3] [5] [14]. Each DF represents an alternative strategy that would reduce the projected long-term groundshine and resuspension dose.

Because decontamination begins at different times at different locations, it is necessary to assign a representative time for when decontamination begins. As described in the EPA PAG manual

[145], the recovery phase overlaps with the intermediate phase. Limited areas may therefore complete decontamination before the intermediate phase ends in all affected areas. Because MACCS requires that all decontamination be completed during the long-term phase and uses a single point in time to define the end of decontamination for each DF, the user must determine a single representative time when decontamination is complete, perhaps using a mean or median value.

As summarized in Appendices A and B, SNL staff investigated responses to radiological releases and decontamination for several activities and found that decontamination activities can start relatively quickly for smaller releases and within weeks or months following a relatively large radiological event. A summary of cleanup costs for multiple smaller accidents can be found in NUREG/CR-4825 [166]. With regards to the Fukushima response, initial decontamination activities began relatively soon for some areas. The first documented decontamination efforts after the March 11, 2011, Fukushima accident began with removal of contaminated soils from schools in May 2011, about 10 weeks after the accident [167]. However, most of the larger scale activities began later. Section 1.4.1 of [167] states that whole-area decontamination projects in the Special Decontamination Area began in July 2012, approximately 16 months after the accident.

In MACCS, the objective of decontamination is to reduce the projected dose below an appropriate dose level to achieve the cleanup criteria. MACCS does not distinguish between a cleanup level and habitability level. As such, the current long-term dose criterion (DSCRLT) serves as the criterion for both. An area is restored to habitability in the long-term phase after the dose for the length of the dose-projection period (TMPACT) to the critical organ (CRTOCR) no longer exceeds DSCRLT. If the maximum decontamination level is insufficient to restore an area to habitability assuming decontamination alone, a period of additional temporary interdiction following the maximum decontamination level is considered to allow dose reduction through radioactive decay and weathering. If non-farm property does not meet the habitability criterion following decontamination and 30 years of additional temporary interdiction, or if the cost of restoring the habitability of the property exceeds the cost of condemning it, the property is condemned and permanently withdrawn from use [2]. The decision process for implementation of mitigative actions for non-farmland land is described as follows:

- (1). If the projected dose to the public is less than the habitability dose level immediately following the intermediate phase, no decontamination, relocation, or other mitigative actions are required.
- (2). If decontamination using the lowest DF (e.g., DF = 2) can reduce doses below the habitability level, the DF is applied, and residents return to the property after the time required to decontaminate at that level (TIMDEC for DF = 2).
- (3). If decontamination using the next DF (e.g., DF = 4) can reduce dose below the habitability level, the DF is applied and residents return to the property after the time required to decontaminate at that level (TIMDEC for DF = 4).
- (4). If decontamination using the highest DF (e.g., DF = 8) can reduce dose below the habitability level, the DF is applied and residents return to the property after the time required to decontaminate at that level (TIMDEC for DF = 8).
- (5). If decontamination using the highest DF plus additional interdiction for a period up to 30 years results in a projected dose less than the habitability level, the highest DF is

applied, and residents return to the property after the time required to decontaminate at that level, plus the additional interdiction time.

- (6). If the property cannot be made habitable within 30 years or if the cost of reclaiming the property exceeds the cost of condemning it, the property is condemned. This 30-year maximum duration is programmed in MACCS and cannot be changed by the user.

Decontamination workers engaged in the cleanup receive groundshine dose for both farmland and non-farmland property [20].

Parameter Name: LVLDEC

Parameter Description: Number of Decontamination Levels

Recommended Value: 3

Uncertainty Range: not applicable

References: not available

Discussion: LVLDEC is the number of decontamination levels that can be used. MACCS allows three levels, each of which is intended to represent a decontamination strategy. Typically, two DFs have been applied in MACCS analyses [3] [5] [14]. However, using two DFs may provide an unintended level of conservatism, because for any area where a low DF (e.g., DF = 2) is not sufficient, the model jumps to a much higher DF (e.g., DF = 8) which costs much more to implement, when only a small increase may have been necessary. Including an intermediate decontamination factor, such as a DF = 4, costs less to implement and represents a more realistic approach. The Site Restoration Study [168] describes a similar approach for 3 DFs described for light, moderate, and heavy contamination. It is recommended that a value of 3 be used for LVLDEC.

Parameter Name: DSRFCT

Parameter Description: Decontamination Factors

Recommended Values: 2, 4, 8

Uncertainty Range: not available

References: Appendix B, [169], [170], [171]

Discussion: DSRFCT defines the dose reduction effectiveness for each decontamination level [2]. The effectiveness of the dose reduction technique used to achieve a DF can be influenced by the type of contamination, timing of the decontamination activities, weather following deposition, the substrate being cleaned, and other factors. In Sample Problem A, contamination reduction levels of 66.7% for a DF = 3 and 93.3% for a DF = 15 were applied and in WASH-1400 a DF = 2 and DF = 20 were applied [3]. Each of these levels has an associated cost to implement with a higher cost corresponding to the higher level of decontamination. In MACCS, if a lower level of decontamination is selected if it is sufficient to restore habitability, and the cost to perform the decontamination is tallied. If it is not sufficient to restore habitability, the next higher level of decontamination is considered, etc. Current technologies can achieve high decontamination values [169]. Achieving a high DF often requires removal of surface materials (e.g., roofing or siding) or a two-phase approach with an initial gross decontamination followed by a final decontamination. In surveying the decontamination literature, a range of DF values for each decontamination activity and technology is possible. Increasingly aggressive decontamination techniques can be employed with increasing efficacy and cost to achieve higher DFs. Based on [169], DFs of 1 to 4 can be achieved using mechanical methods such as sweeping and washing; DFs of 5 to 10 can be

achieved by additional more aggressive methods such as high pressure washing, sand blasting and selective replacement. The following DFs are recommended as reasonable DFs in those ranges, as shown in Table 4-11:

Table 4-11 Recommended Decontamination Levels

Decontamination Level (DF)	Percentage of the Initial Dose Remaining After Decontamination	Total Dose Reduction Percentage
2	50%	50%
4	25%	75%
8	12.5%	87.5%

These values were selected based on direct experience with decontamination activities and review of published results of Fukushima and Chernobyl cleanup efforts [170] [171]. Appendix B lists the surfaces that were considered in formulating the cost estimates for the various decontamination activities that would occur at the three recommended decontamination levels.

Parameter Name: TIMDEC

Parameter Description: Decontamination Times

Recommended Values: 365 days, 365 days, and 365 days

Uncertainty Range: not available

References: [2]

Discussion: TIMDEC defines the time required for completion of each level of decontamination beginning at the start of the long-term phase (TMIPND) and continuing for the specified TIMDEC duration [2]. The TIMDEC values must be monotonically increasing with the DF values. The duration of decontamination activities may be influenced in part by the extent and location of the contamination, clean up criteria, types of substrates contaminated, stakeholders, and the availability of resources. Such diverse influences necessitate some assumptions to establish a single duration for each DF. Limited data exist on duration of large scale radiological decontamination, although ongoing activities in response to the Fukushima accident are applicable and provide the most relevant information (see Appendix B). Information from the Fukushima cleanup continue to become available as those decontamination efforts continue. Decontamination around Fukushima has taken longer than the maximum duration allowed under MACCS 3.10. Information in [167] suggests that the completion of decontamination projects in the Special Decontamination Area (SDA) occurred over a period ranging from 2–6 years after the accident. Large scale DOE site remediation activities also provide insight, but these efforts are not typically cost or schedule driven. The dispersion characteristics of a plume are such that the largest areas of contamination likely require the lowest level DF (because they have less ground contamination) as illustrated by the green area of the plume in Figure 4-7. Figure 4-7 is an illustrative example of deposition isopleths for a single plume segment and should not be interpreted to represent a realistic accident situation. Actual contamination fields would be much more complex. Because lightly contaminated areas are expected to represent the largest area, decontamination may take longer than areas with higher levels of contamination, as represented by the yellow, orange, and red areas in Figure 4-7.

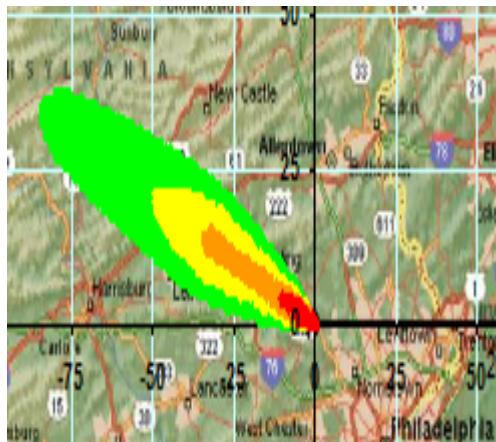


Figure 4-7 Simple Illustration of Deposition Isopleths Showing a Range of Contamination Areas and Levels

To account for the larger areas requiring a low DF, the MACCS limit that lower DFs be equal or less in duration than higher DFs, and because the maximum value allowed in MACCS 3.10 for TIMDEC is one year, it is recommended that the decontamination time for all levels be one year for large releases. Similar to the process described for establishing an intermediate phase duration, the number of people subject to long-term phase protective actions may be examined using the MACCS Type 14 output to inform selection of the decontamination period.

Parameter Name: CDNFRM

Parameter Description: Non-farmland Decontamination Cost

Recommended Values: \$78,000, \$180,000, and \$270,000 per person (in 2012 dollars) represent reasonable U.S.-average generic values.

Uncertainty Range: not available

References: Table B-23 of Appendix B

Discussion: CDNFRM defines the non-farmland decontamination costs for each level of decontamination. The MACCS2 User's Guide [2] and earlier documents [3] [146] discuss the approach to developing a cost value, but do not specify the cost elements of the decontamination process, such as characterization or disposal, that were included.

Decontamination costs were originally developed in WASH-1400 based on cleanup of streets, buildings, and homes where characteristics typical of urban and rural lots were used in the analysis [3]. The costs were identified in WASH-1400; however, the details for converting these to costs per person were not provided. Similarly, in Table 4.4 of NUREG/CR-3673 [146], the non-farmland decontamination costs per person are listed, but the source that is referenced to explain the per capita allocation was unpublished. Therefore, an approach to decontamination is provided in Appendices A and B. This approach includes costs from characterization, decontamination, and waste management, which includes transportation and final disposal of wastes arising from decontamination. An approach is also provided to evaluate costs for a range of land-use intensities and to average those for urban, rural, and continental U.S. areas. Reasonable U.S.-average generic values of CDNFRM for DF = 2, DF = 4, and DF = 8 are \$78,000, \$184,000, and \$269,000 per person, respectively, are based on the approach described in Appendix B and summarized in Table B-23. It should be noted that the cost values for dose-reduction factors of 4 and 8 in Table B-23 exceed \$100,000, which is the upper limit for the value of CDNFRM in MACCS version 3.10. At this time, the recommendation for users of MACCS version 3.10 is simply to replace values that exceed the limit by \$100,000.

Parameter Name: CDFRM

Parameter Description: Farmland Decontamination Cost

Recommended Values: \$3,700, \$38,000, and \$38,000 per hectare (in 2012 dollars) represent reasonable U.S.-average generic values.

Uncertainty Range: not available

References: Table B-24 of Appendix B

Discussion: CDFRM defines the farmland costs for each level of decontamination. A unit cost per hectare (ha) is required for each DF, and the values must increase monotonically. The MACCS2 User's Guide [2] and earlier documents [3], [146] discuss the approach to develop the costs, but there is limited information regarding specific cost element details. Therefore, an approach to farmland decontamination is provided in Appendices A and B. Recommended values of CDFRM for DF = 2, DF = 4, and DF = 8 are \$3,700, \$38,000, and \$38,000 per ha, respectively, based on the approach in Appendix B and shown in Table B-24. It should be noted that Appendix B only examined methods that did not remove contamination from the farmland because MACCS does not account for any effect of decontamination on the food pathway. MACCS only accounts for the effects of decontamination on reducing groundshine and resuspension doses to farmers working on farmland. The lowest level of decontamination is assumed to be performed by reversal tillage, which is relatively inexpensive. To achieve more than a DF of 2, interchanging of the topsoil with the subsoil, which would reduce external doses and doses from inhalation of resuspended aerosols, is assumed. Decontamination methods for farmland that require soil removal, storage, transportation, and disposal are expected to be so expensive that farmland would be condemned in the MACCS economic model based on cost effectiveness considerations. Even with no soil removal, the estimated costs to decontaminate farmland at Levels 2 (DF4) and 3 (DF8) are significantly larger than the value of most farmland in the U.S.

Parameter Name: DLBCST

Parameter Description: Hourly Labor Cost for Decontamination Worker

Recommended Value: \$76,000/year in 2012 dollars; escalate to project base year or reevaluate based on most recent BLS handbook data

Uncertainty Range: not available

References: [172]

Discussion: DLBCST represents the labor cost of a decontamination worker in dollars per person-year [2]. The parameter is used to estimate worker doses but does not affect economic losses. In May 2012, the median annual wage for hazardous-material workers was \$37,590 according to the U.S. Bureau of Labor Statistics Occupational Outlook Handbook [172]. This annual wage corresponds to approximately \$76,000 assuming a factor of two to cover overhead and all other indirect labor costs. Decommissioning and decontamination workers and radiation protection technicians are included in this category. Work activities of removal and treatment of radioactive materials generated by nuclear facilities and power plants are also included in this category. Work activities also include measuring, recording, and reporting radiation levels, operating high-pressure cleaning equipment for decontamination, and packaging radioactive materials for removal or storage. A 2012 base value of \$76,000 per year is recommended, escalated to the year of the analysis. The occupational handbook is published approximately every two years and provides ready access to current wage data. Analysts should check for the most current data appropriate for the site-specific analysis.

Parameter Name: FRNFDL

Parameter Description: Non-Farmland Decontamination Labor Cost Fraction

Recommended Values: 0.35; 0.35; 0.35

Uncertainty Range: not available

References: Appendix A

Discussion: FRNFDL defines the fraction of the non-farmland decontamination cost that is due to labor for each level of decontamination. A value is required for each decontamination level. This parameter was introduced in NUREG/CR-3673 [146] as RL_f , where values of 0.7, 0.5, and 0.5 were identified for DF = 3, 15, and 20, respectively [146]. As described below with FRFDL, there would be a different number of work crews implementing the decontamination, but the authors believe the fraction of cost due to labor is relatively independent of DF. It is recommended that a single value of 0.35 be used for all DFs.

Parameter Name: TFWKNF

Parameter Description: Fraction of Non-Farmland Decontamination Worker Time in Contaminated Zone

Recommended Value: 0.15; 0.15; 0.15

Uncertainty Range: not available

References: see discussion under TFWKF

Discussion: TFWKNF defines the fraction of the decontamination period (TIMDEC) that a non-farmland decontamination worker spends in the contaminated area for each DF value used in the analysis. The function of this parameter, together with DLBCST, is to estimate the collective dose to decontamination workers. The only difference from TFWKF described below is that this parameter applies to non-farmland. Decontamination of structures typically includes smaller equipment, often hand held, and the workers are operating in closer proximity to the contaminated substrate. For exterior areas such as landscape, roadways, and other paved areas, larger equipment would normally be used. However, the shielding from the equipment is not factored into the TFWKF parameter, although if desired, this can be implemented in MACCS by adjusting this parameter or the shielding parameters. The recommended value is 0.15.

Parameter Name: FRFDL

Parameter Description: Farmland Decontamination Labor Cost Fraction

Recommended Values: 0.35; 0.35; 0.35

Uncertainty Range: not available

References: Appendix A

Discussion: FRFDL defines the fraction of farmland decontamination cost that is due to labor for each level of decontamination [2]. This parameter is used with DLBCST to estimate the dose to the decontamination worker. A value must be supplied for each decontamination level. This parameter was introduced in NUREG/CR-3673 [146] as FL_f where values of 0.3, 0.35, and 0.35 were identified for decontamination factors of DF = 3, DF = 15, and DF = 20, respectively [146]. The study explains that the remaining decontamination costs are based on building materials and cleanup equipment. Based on decontamination experience and information from decontamination contractors¹⁴, a value of about 0.35 is estimated for similar work efforts. There

¹⁴ SNL staff consulted with Environmental Dimensions Inc. staff with direct and current experience in DOE and commercial decontamination projects.

can be a difference in the number of work crews implementing decontamination for different types of areas, but the fraction is relatively independent of the DF. It is recommended that a single value of 0.35 be used for all DFs.

Parameter Name: TFWKF

Parameter Description: Fraction of Farmland Decontamination Worker Time in Contaminated Zone

Recommended Value: 0.15, 0.15, 0.15

Uncertainty Range: not available

References: see discussion

Discussion: TFWKF defines the fraction of the decontamination period (TIMDEC) that a farmland decontamination worker spends in the contaminated area and a value is required for each DF level used in the analysis [2]. This parameter is used with DLBCST to estimate the dose to a decontamination worker. MACCS implements TFWKF by multiplying this value by the decontamination period, which estimate the time spent inside the contaminated area. Thus, the value of this parameter should account for the fact that many of the individuals involved in a large scale cleanup never enter the decontamination area. For simplicity, potentially minor doses from activities outside the contaminated area, such as waste handling or processing, is not included.

Based on decontamination experience and information from decontamination contractors¹⁵, it is estimated that 35% of the decontamination effort is for decontamination workers. The remaining labor occurs outside of contaminated zones, supporting activities such as management, procurement, safety, equipment maintenance, waste packaging, drivers, and radiological monitoring. For the actual decontamination workers, Burke et al. [146] estimated 55 hours per week (about 33% of a week) for decontamination labor. To estimate only the time decontamination workers are in the contaminated area, time spent donning and doffing personal protective equipment (PPE), screening out of the buffer zones, attending daily safety briefings, staging equipment, lunch, breaks, and supporting other activities outside the contaminated area must also be considered. Many of these activities, except those related to PPE, are typical of standard large scale construction activities. As an assumption, for a 10-hour workday, workers are only in the contaminated area receiving a planned dose for about 6 hours. Assuming a 6-day work week, this equates to 36 hours. Assuming two shifts, this equates to 72 hours of a 168-hour week (which is 43% of the time), during which workers are present in the contaminated area. Only 35% of the workforce are decontamination workers, therefore, $35\% \times 43\% = 15\%$ of the time. The makeup of the crews does not necessarily differ based on the level of contamination; therefore, the fraction of the decontamination period that a farmland decontamination worker spends in the contaminated area is estimated to be the same for each DF level used in an analysis. The recommended value is 0.15.

4.4.5 Modeling Agricultural Countermeasures and Food Ingestion

The MACCS parameter, FDPATH, is found on the Food tab under the Project Properties Form. The value for FDPATH can be “NEW,” “OLD,” or “OFF.” These correspond to the three food

¹⁵ SNL staff consulted with Environmental Dimensions Inc. staff with direct and current experience in DOE and commercial decontamination projects.

chain options. The FDPATH notation “NEW” corresponds to the selection of the COMIDA2¹⁶ Food Model [31] [173] [174]. The notation “OLD” corresponds to the original MACCS food model, which was developed for MACCS [1] [20]). Finally, when FDPATH is set to “OFF”, it indicates that the option “No Food Model” was selected by the analyst. Typically, the COMIDA2 model is used when food chain modeling is desired.

Agricultural countermeasures define the maximum allowable food ingestion doses from milk and nonmilk crops during the year of the accident and the combination of milk and nonmilk crops in subsequent years. The parameters DOSEMILK, DOSEOTH and DOSELONG define the farmland interdiction criteria. These parameters are loosely equivalent to the MACCS food chain model parameters PSCMILK, PSCOTH, and GCMAXR [2]. DOSEMILK and DOSEOTH define the maximum allowable food ingestion dose from milk and other food crops, respectively, during the first year of the accident. Costs are tallied when annual individual doses from dairy and other crops exceed DOSEMILK and DOSEOTH, respectively. The economic cost of milk and other crop losses during the first year is modeled as the economic costs assessed for the loss of sales. For subsequent years, up to eight, MACCS compares the doses from consumption of milk and other agricultural food products to the value of DOSELONG. Depending on the result, farmland is either interdicted or allowed to be in production for a given year. Once the food ingestion criterion is satisfied, food and dairy production continue for the rest of the MACCS calculation.

Loss of use of farmland is tallied as a loss that starts at the beginning of the early phase and continues for as long as the farmland is interdicted, up to eight years. If the projected individual dose from the second year of agricultural production exceeds the dose criteria, the projected doses are examined to determine if production can be resumed by the beginning of the ninth year after the accident. If the projected doses at the beginning of the ninth year exceed DOSELONG, no further tests are performed and the farmland is considered to be condemned. When farmland is condemned, the associated cost is the total value of the farmland taken from the site file [2]. The basis for the eight-year farmland interdiction period was not documented.

The milk and crop disposal cost calculations are described in the MACCS2 User’s Guide [2]. If the disposal in the year of the accident is triggered because the dose level of DOSEMILK is exceeded, milk disposal costs are assessed as 0.25 of annual milk sales for that year. The technical basis for factor of 0.25 is based on the assumption that cows would be taken off pasture and fed uncontaminated feed, allowing dairy production to resume after one-quarter of a year [2]. To maintain consistency with the MACCS food chain model, the factor of 0.25 for milk disposal costs has also been implemented for the COMIDA2 food chain model used in MACCS [2]. The values for food chain parameters currently provided in Sample Problem A are given in Table 4-12 and are based on adult consumption rates and dose coefficients [2].

Table 4-12 Values of DOSEMILK, DOSEOTH and DOSELONG in Sample Problem A

Organ	DOSEMILK (Sv)	DOSEOTH (Sv)	DOSELONG (Sv)
Effective	0.025	0.025	0.005
Thyroid	0.075	0.075	0.015

Source: [2]

¹⁶ Development of a COMIDA file using the COMIDA2 model requires definition of many parameters [31]. However, a comprehensive evaluation of the parameters used by the currently recommended COMIDA2 food chain preprocessor model was not performed in this report.

All the values presented above are annual committed effective dose equivalents. These values are large by comparison to the 1998 FDA food pathway PAGs (0.005 Sv Effective and 0.05 Sv for any organ or tissue) [175] and the CAC Guidelines (0.001 Sv Effective) [176]. There is also the limitation that MACCS presently only supports two organs for dose limitation, thyroid and effective, while the FDA PAGs are more general and include constraints on doses to all tissues and organs. Therefore, it is recommended to follow the FDA PAGs as appropriate for the analysis and site-specific agriculture conditions present. That is, the maximum allowable food ingestion dose from milk production and other food crops should be weighted by the site-specific fraction of farmland that is used to produce milk and nonmilk crops since the PAG is not specific to the type of food, only that food interdiction occurs when the projected whole-body dose exceeds 0.5 rem per year, or 5 rem per year to any individual organ or tissue. In the case of the MACCS parameters, the organ dose PAG limit would be applied to the thyroid organ. The analyst is cautioned to consider the appropriate parameter values for DOSEMILK and DOSEOTH such that reaching the maximum of either value does not result in exceeding the FDA PAG. For example, a choice where DOSEMILK = 0.5 rem and DOSEOTH = 0.5 rem, could result in a combined dose contribution of 1 rem in the first year when combining the two food types. In this instance, the FDA PAG requiring food pathway interdiction above 0.5 rem per year would be exceeded. Therefore, it is conservatively recommended to apportion the total FDA PAG between the two agricultural sources. Because DOSELONG more closely mimics the FDA PAGs, as it accounts for dose limits on both milk and nonmilk crops beyond one year, it enforces the 0.5 rem per year effective whole-body dose limit and 5 rem per year individual organ or tissue dose limit directly. Again, the FDA PAG individual organ or tissue limit is applied to the thyroid organ in the case of the MACCS model.

Parameter Name: FDPATH

Parameter Description: COMIDA2 vs. MACCS Food Model Switch

Recommended Value: NEW

Uncertainty Range: not applicable

References: [20], [2], [31]

Discussion: If ingestion doses are needed, the use of the COMIDA2 model is recommended because of its improved capability to account for seasonality effects relative to the original MACCS food model and its ability to account for the decay and ingrowth of radioactivity.

Parameter Name: DOSEMILK

Parameter Description: Maximum Allowable Food Ingestion Dose from Milk Crops During the Year of the Accident

Recommended Value: Effective: 0.25 rem; Thyroid: 2.5 rem

Uncertainty Range: not available

References: [175]

Discussion: The recommended value is based on the full FDA PAG [175], assumed to be equally apportioned between the milk and other crop pathways.

Parameter Name: DOSEOTHER

Parameter Description: Maximum Allowable Food Ingestion Dose from Non-Milk Crops During the Year of the Accident

Recommended Value: Effective: 0.25 rem; Thyroid: 2.5 rem (the full FDA PAG is equally apportioned between the milk and other crop pathways)

Uncertainty Range: not available

References: [175]

Discussion: The recommended value is based on the full FDA PAG [175], assumed to be equally apportioned between the milk and other crop pathways.

Parameter Name: DOSELONG

Parameter Description: Maximum Allowable Long-Term Annual Food Ingestion Dose from Milk and Non-Milk Crops

Recommended Value: Effective: 0.5 rem; Thyroid: 5 rem

Uncertainty Range: not available

References: [175]

Discussion: The recommended value is based on the full FDA PAG [175]. Alternatively, analysts might consider a methodology to develop agriculture countermeasure and food ingestion limits (DOSEMILK, DOSEOTH, and DOSELONG) based on the Codex General Standard for Contaminants and Toxins in Food and Feed [176]. This standard contains guideline levels for radionuclide contaminated foods following a nuclear or radiological emergency which are more restrictive for the effective dose limit (1 mSv versus 5 mSv for the FDA/EPA PAG [175]).

4.4.6 Modeling Water Ingestion

When radioactive material is deposited from the atmosphere onto land or water, a fraction makes its way into the drinking water consumed by humans [177]. MACCS models this process via two separate paths: (1) deposition of material directly onto freshwater bodies and (2) deposition of material onto land that is subsequently washed into the surface water. WINGF is an uptake factor that defines the fraction of the contamination in surface water that is ultimately consumed by humans.

Radioactive material deposited on a spatial element in MACCS is initially apportioned between water and land according to the fractions of the region covered by land and by water. For coastal sites, with fresh water and ocean water, it is recommended that the user create a site data file with more than one watershed. A site data file can include up to four watersheds, one or more of which can be defined to have zero consumption as drinking water (e.g., ocean water). By default, SecPop creates site files with a single watershed [58] so a site file needs to be modified manually by the user to include multiple watersheds if needed. MACCS only allows a single watershed when no site file is used.

Of the activity that is initially deposited on land, some fraction makes its way by wash off into the freshwater supply over a relatively short time period after deposition. MACCS conservatively treats this wash off to occur at the time of deposition. This fraction is specified by the value of WSHFRI. The remainder of the material deposited on land is assumed to be washed off to the freshwater supply at a constant fractional rate. The rate at which this subsequent wash off occurs is specified by the value of the rate constant WSHRTA. The model uses the values for WSHFRI and WSHRTA and evaluates the integral of the wash off fraction in a way that accounts for radioactive decay of the material deposited onto land surfaces [177]. The evaluation of this integral produces a numerical value representing the fraction of activity falling on land that is eventually transferred to surface water bodies that supply drinking water.

WINGF is the ratio of the total amount of a radionuclide consumed via the drinking water pathway (i.e., by the entire population of the region surrounding the facility) to the amount entering potable surface water bodies. Ideally, a value for WINGF should be derived from a model for radionuclide transport through the surface-water system of the surrounding region. The models used to develop values of WINGF can vary in complexity from very simple to very complex (e.g., three-dimensional fluid transport with temporal and spatial variability).

The user also specifies which radionuclides are to be included with the water ingestion pathway. For the purpose of calculating water ingestion doses, there is no provision for modeling the buildup of any radioactive decay products that result from decay before the water is consumed.

Historically, generic values rather than site-specific values for the water ingestion parameters have been used in consequence analyses. This is reasonable because water ingestion typically contributes only about 1% of the long-term population dose for reactor accident calculations. Historical values that have been used with MACCS are shown in Table 4-12.

Table 4-13 Watershed Transport Factor Parameters

NAMWPI	WSHFRI	WSHRTA	WINGF*
Sr-89	0.01	0.004	5.E-6
Sr-90	0.01	0.004	5.E-6
Cs-134	0.005	0.001	5.E-6
Cs-137	0.005	0.001	5.E-6

*WINGF is read from the site file when a site file is used.

As discussed in Section 2.8 of [5], the watershed transport factor parameters are primarily based on λ_a = WSHFRI and λ_b = WSHRTA from [177].

Parameter Name: NUMWPI

Parameter Description: Number of Water Ingestion Radionuclides

Recommended Value: 4

Uncertainty Range: not applicable

References: [5], [177]

Discussion: NUMWPI defines the number of water ingestion radionuclides. If the MACCS food chain model is used, the drinking water radionuclides must be a subset of the food ingestion radionuclides (defined by NFIISO and NAMIPPI in the MACCS Users Guide).

Parameter Name: NAMWPI

Parameter Description: Names of Water Ingestion Radionuclides

Recommended Value: Sr-89, Sr-90, Cs-134, and Cs-137

Uncertainty Range: not applicable

References: [5], [177]

Discussion: NAMWPI defines the names of the radionuclides used in the drinking water pathway. Typically, four radionuclides (Sr-89, Sr-90, Cs-134, and Cs-137) are treated in the water ingestion model. Most of the other radionuclides that are included in consequence analysis have half-lives that are too short to be important for water ingestion since MACCS does not treat the ingestion pathway during the emergency and intermediate phases.

Parameter Name: WSHFRI

Parameter Description: Washout Fraction

Recommended Value: 0.01 for Sr-89 and Sr-90 and 0.005 for Cs-134 and Cs-137 (dimensionless)

Uncertainty Range: 0.0002 to 0.02 for Sr-89 and Sr-90 and 0.001 to 0.01 for Cs-134 and Cs-137 (dimensionless)

References: [5], [177]

Discussion: WSHFRI is the fraction of material deposited on land that is washed off into the watershed drainage system quickly following the deposition of that radionuclide. The value of WSHFRI is generally the same for the isotopes of an element. The technical basis for the numerical values for WSHFRI is provided in [5] and [177].

Parameter Name: WSHRTA

Parameter Description: Annual Washout Rate

Recommended Value: 0.004 yr⁻¹ for Sr-89 and Sr-90 and 0.001 yr⁻¹ for Cs-134 and Cs-137

Uncertainty Range: 0.0008 to 0.008 yr⁻¹ for Sr-89 and Sr-90 and 0.0002 to 0.002 yr⁻¹ for Cs-134 and Cs-137

References: [5], [177]

Discussion: WSHRTA defines the fractional wash off rate for the specified radionuclide. This is the rate at which material deposited on land is washed off into the watershed drainage system following the initial deposition. The technical basis for the numerical values for WSHRTA is provided in [5] and [177].

Parameter Name: WINGF

Parameter Description: Water Ingestion Fraction

Recommended Value: 5.00E-06 (based on the upper limit for rivers for Sr-89, Sr-90, Cs-134 and Cs-137)

Uncertainty Range: 1.0E-06 to 1.0E-05 for Sr-89, Sr-90, Cs-134 and Cs-137

References: [5], [177]

Discussion: The water ingestion factor (WINGF) specifies the fraction of the activity in surface water that is eventually consumed by humans. Once activity is transferred to a water body, there is no adjustment to account for radioactive decay. The technical basis for the numerical values for WINGF is provided in [5] and [177]. Although the water ingestion factor is discussed in this section, it is not defined within the WinMACCS GUI if a site file is used. If a site file is defined, the value of WINGF may be modified by manually editing the site file. The site file also allows provision for multiple watersheds, each of which may have a different value of WINGF. For example, the site file may be edited to set WINGF values consistent with a large river for areas where rivers are the most likely water supply, to values for lakes where large lakes may be the most likely water supply, and to a very low (or zero) value to reflect deposition onto non-potable water sources such as saltwater (e.g., oceans or bays). An example of a SecPop-generated site data file for the water ingestion pathway is provided below in Figure 4-8.

Each grid element must be associated with one of the watershed indices included in the "WATERSHED DEFINITION" data block (columns 1 to 4 following the radionuclide name). The watershed definition data block begins with a 22-character separator beginning in column 2 containing the character string WATERSHED INDEX. The next line contains two-digit integers associating a watershed type for each of the grid elements in the first compass sector. Values

for all grid elements must be provided and each compass sector starts a new line. A watershed index of "1" means that the ingestion factors for watershed 1 is used for that grid element. That is, the ingestion factors for all listed radionuclides are applied in that grid element. For instance, in Figure 4-8, because all grid elements are defined as watershed 1, 5.00E-06 Becquerels ingested per Becquerel in the water is used for Sr-89, Sr-90, Cs-134, and Cs-137. In this example, if watershed 2 had been used, all the radionuclides would have a 0.0 ingestion factor (column 2 following the radionuclide name), indicating non-potable water, such as saltwater, is located in that grid element. The number of lines in this watershed index data block is the number of compass sectors, with a new line for each sector, ordered in a clockwise fashion starting from north.

Figure 4-8 Site File Watershed Information

5 DOSIMETRY AND HEALTH EFFECTS

Dosimetry and health effects are implemented in MACCS using a dose coefficient approach coupled to a set of dose-response models for early and late health effects. For external exposures, a dose coefficient is a factor that relates the quantity of a radionuclide in an environmental media outside of the body, such as soil or air, to the radiation dose received. For internal exposures, a dose coefficient is a factor that relates the quantity of a radionuclide that is ingested or inhaled to the radiation dose received. The dose coefficients for all exposure pathways and exposure types (acute and lifetime) are provided in the MACCS dose coefficient (DCF) file, a variety of which are supplied along with the code. The dose-response models in MACCS were originally based on the models developed in the NUREG/CR-4214 series of reports [178] as updated in [179], [180], [181], and [182]. For several parameters, these models have been supplemented or superseded by information from [25] and [26] as implemented in [27]. Most recently, the SOARCA project used FGR-13 [39] recommendations for cancer risk assessment [183].

Like most MACCS models, the parameters for the dosimetry and health effects models may be modified by the user according to the needs of the analysis. However, the dosimetry and health effects models in MACCS are based on average characteristics of the U.S. population and are therefore typically considered to be generic, non-site-specific parameters that are appropriate for most analyses.

5.1 Dose Coefficient File

The dose coefficient file contains data on dose coefficients for each radionuclide and organ for each of the following exposure types:

- cloudshine dose rate factor [Sv/(Bq-s/m³)],
- groundshine dose rate factor [Sv/(Bq-s/m²)],
- acute, short-term inhalation doses (Sv/Bq) used for calculation of early, deterministic health effects,
- lifetime, 50-year committed inhalation doses (Sv/Bq) used for calculation of effective doses and late, stochastic health effects from inhalation, and
- lifetime, 50-year committed ingestion doses (Sv/Bq) used for calculation of effective doses and late, stochastic health effects from food and water ingestion.

The DCF file also contains dose coefficient columns for an 8-hour and 7-day cumulative groundshine dose for backward compatibility with the original version of MACCS [1]. These fields are no longer used in MACCS 3.10 and a value of -1 is inserted in current MACCS DCF files.

Acute inhalation dose coefficients are supplied only for the organs used for calculating deterministic health effects from acute exposures. Because the effectiveness of the doses delivered over a longer period for inducing acute effects is lower compared with the effectiveness of doses delivered over a shorter period, the inhalation of radioactive materials leads to protracted exposures that must be weighted to account for dose protraction effects. Weighting of the integrated doses computed from the instantaneous dose rates yield a MACCS dosimetric quantity referred to as the “effective acute dose.” The effective acute dose, D_e , is the dose, which

if delivered entirely in one day, would induce the same acute health effects as a protracted dose delivered over many days.

MACCS has been distributed with several dose coefficient files since it was developed. Files that are currently distributed can be grouped into three types: DOSFAC, FGRDCF, and FGR13DCF type DCF files.

The original DOSDATA.INP file was generated using the DOSFAC code based on information in [184], and was later updated using the DOSFAC2 code [185] to generate the *dosdata20organs.inp* DCF file that is supplied with WinMACCS 3.10. The DOSFAC2 code allows a user to adjust several of the input parameters used to derive the dose coefficients, such as relative biological effectiveness (RBE) values, aerosol particle sizes, inhalation clearance class, and weighting fractions used to account for dose protraction impacts for acute health effects. DOSFAC and DOSFAC2 DCF files contain dose coefficients for the 60 radionuclides identified as important to dose for commercial reactor accidents [38] and up to 20 organs (if the DOSFAC2 code is used). The internal exposure dose coefficients for these files are based on ICRP-30 [186] dosimetric information as provided in the database DOSD87, and the external dose coefficients (for DOSFAC2 files such as *dosdata20organs.inp*) are based on DOE-EH-0070 [187]. The user should be aware that the DCF values in these files include contributions from short-lived decay progeny. To avoid double-counting of the dose from these isotopes, the nuclide list comprising the core inventory (defined by NUCNAM) should be adjusted to eliminate these decay progeny when using these DCF files¹⁷. It may also be noted that DOSFAC2 DCF files provide values for both an effective dose equivalent consistent with the tissue weighting factors of ICRP-26, as well as an effective dose consistent with the tissue weighting factors of ICRP-60.

As described in [31], MACCS can also accept FGRDCF dose coefficient files based on Federal Guidance Report 11 (FGR-11) [188] and Federal Guidance Report 12 (FGR-12) [189]. However, because of the limitations in the data provided in FGR-11, FGRDCF files do not contain dose coefficients needed to compute effective acute doses for inhalation. FGRDCF DCF files are therefore not recommended for use in commercial reactor applications where early health effects may be of interest. However, FGRDCF DCF files (such as the *DOSD825.inp* DCF file that is supplied with WinMACCS 3.10) may be used when dose coefficients based on FGR-11 and FGR-12 are required and when estimation of acute health effects, or of latent health effects based on the full set of equivalent organ doses described in [180], is not needed. If used, the user should be aware that the DCF values in FGRDCF files also include contributions from short-lived decay progeny, and the nuclide list comprising the core inventory should be adjusted to eliminate decay progeny implicitly included in the dose coefficients when using these DCF files.

With the introduction of WinMACCS, a dose coefficient file (*FGR13DCF.INP*) based on the information in the compact disc supplement to FGR-13 [190] was developed¹⁸. This file is recommended for most consequence analysis applications because it is the most up-to-date dose coefficient file set available for use with MACCS and contains all of the data needed to

¹⁷ These short-lived decay progeny should then be added to the list of pseudostable nuclides (NAMSTB).

¹⁸ This file was subsequently updated for the SOARCA project to produce the *FGR13GyEquivDCF.INP* file in order to implement recommendations for cancer modeling provided by Eckerman [184]. This file is not distributed with MACCS 3.10. However, a DCF file consistent with the recommendations of Eckerman [184] is available for later versions of MACCS.

estimate both acute and latent health effects¹⁹. The FGR13DCF.INP DCF file contains equivalent dose coefficients based on FGR-12 and FGR-13 for 825 radionuclides, 26 organs plus the committed effective dose, and five exposure pathways (groundshine, cloudshine, acute inhalation, chronic inhalation, and ingestion). The external dose coefficients in FGR13DCF.INP are consistent with those provided FGR-12 Tables III.1 (Dose Coefficients for Air Submersion) and III.3 (Dose Coefficients for Exposure to Contaminated Ground Surface) [189]. The internal dose coefficients in FGR13DCF.INP reflect integrated or cumulative absorbed doses following an instantaneous intake and are calculated from the instantaneous absorbed dose rate versus time data contained in the data files *fgr13inh.drt* and *fgr13ing.drt* [190]. The dose rate data for adult members of the public were numerically integrated and then weighted by the RBE appropriate for the radionuclide, exposure pathway, and type of health effect. The inhalation and ingestion dose coefficients are based on models for an adult member of the public provided in FGR-13. For chronic inhalation exposures and for ingestion exposures (for which only chronic exposures are considered credible), the dose rates were integrated over 50 years to compute the committed doses. Acute inhalation dose coefficients are supplied only for the organs used for calculating deterministic health effects from acute exposures. These doses differ from the chronic inhalation doses in the selection of RBE values (which depend on the biological effect) and the weighting of the time-dependent dose rates to account for the effect of dose protraction on health effects.

In addition to the equivalent organ dose coefficients, the effective dose is also used in MACCS calculations. The ICRP60ED quantity contains effective radiation dose coefficients for inhalation, ingestion, and external radiation based on the ICRP-60 [191] system of tissue weighting factors. It is typically assigned by the user as the quantity used internally by MACCS for simulating protective action decisions and is also typically used as the measure to compute the collective population dose. It is used in the threshold dose response models to determine whether an annual or lifetime dose has been exceeded. Although it can be used to compute total cancer occurrences and fatalities using an appropriate cancer mortality and morbidity risk coefficient from ICRP-60, this is not the recommended approach. The recommended approach is to use organ-specific equivalent doses together with organ-specific risk factors to compute cancer health effects. DOSFAC-type data files also include an effective dose equivalent quantity ("EDEWBODY") based on the tissue weighting factors recommended in ICRP-26 [192].

Although the file contains dose coefficients for 26 organs and the effective dose, MACCS 3.10 has a hardwired set of target organs defined by the ORGNAM variable²⁰. The assignment of a MACCS target organ to a DCF organ is determined by the type of DCF file that is selected in the WinMACCS GUI. The MACCS target organs for acute and lifetime exposures are shown in Table 5-1 and Table 5-2. MACCS 3.10 can accept only nine organs for use in estimating cancer risk when an FGR13DCF file is selected. To define a health effect model, the corresponding dosimetric quantity must be available for use in MACCS. This is done by setting the ORGFLG variable to "TRUE" for the MACCS target organ.

¹⁹ However, the user should be aware that some applications may require doses to be computed using dose coefficients consistent with earlier systems of dosimetry. For example, the dose criteria specified in 10 CFR 20 and 10 CFR 50 are based on the methodologies documented in [193] and [187]. An example of the difference is that the FGR13 DCF files do not contain values for the effective dose equivalent obtained using the tissue weighting factors of ICRP-26 [193]; instead, they contain values for an effective dose obtained using the tissue weighting factors of ICRP-60 [192].

²⁰ The hardwired organ list has been removed in later versions of MACCS.

Table 5-1 FGR13DCF MACCS Target Organs for Acute Exposures

MACCS Target Organ	FGR13DCF Organ Name
A-SKIN	not applicable ²¹
A-RED MARR	RED MARR
A-LUNGS	LUNGS
A-STOMACH	STOMACH
A-LOWER LI	LOWER LI

Table 5-2 FGR13DCF MACCS Target Organs for Lifetime Exposures

MACCS Target Organ	FGR13DCF Organ Name
L-ICRP60ED	ICRP60ED
L-RED MARR	RED MARR
L-BONE SUR	BONE SUR
L-BREAST	BREAST
L-LUNGS	LUNGS
L-THYROID	THYROID
L-LOWER LI	LOWER LI
L-BLAD WALL	BLAD WAL
L-LIVER	LIVER

Parameter Name: DCF_FILE001²²

Parameter Description: Dose Coefficient File

Recommended Value: FGR13DCF.INP

Uncertainty Range: not applicable

References: [189], [39], [190], [40]

Discussion: The FGR13DCF.INP file is recommended because it is based on the most current system of dosimetry, as documented in FGR-13 [39] [190]. A modified version of this file (FGR13GyEquivDCF.INP), developed to be compatible with the cancer model used in SOARCA and described in Section 5.3.2, can also be used when cancer model coefficients are based on the recommendations of [183]. An FGRDCF file, such as DOSD825.inp, may be used (after adjustment of NUCNAM and NAMSTB) to eliminate decay progeny that are implicitly included in the DCF file for applications requiring dose coefficients based on FGR-11 and

²¹ Note that the A-SKIN dosimetric quantity used by MACCS for estimating erythema and transepidermal injury from skin exposure is not read from the DCF file but is computed internally by MACCS.

²² Note that while the DCF file — unlike the site file and meteorological file — is specified via a MACCS input parameter, it cannot be redefined using the cyclic file set definition and should be specified directly in WinMACCS.

FGR-12 and for which estimation of acute health effects (or of latent health effects based on the full set of equivalent organ doses described in [180]) is not needed.

Parameter Name: ORGFLG

Parameter Description: Doses to be Calculated for Specified Organ

Recommended Value: “TRUE” for all FGR13DCF organs

Uncertainty Range: not applicable

References: [2], [40]

Discussion: Either the full set of MACCS target organs or at least the set used to estimate health effects should be included in a MACCS calculation. Effective dose is usually used to define protective actions, so at least one value for effective dose should be included. Also, thyroid is often used for some protective actions, such as ingestion doses, so this organ should also be included. The specific MACCS target organs to be used in dose-response modeling is assigned as part of the health effects model inputs discussed below.

5.2 Models for Early and Continuing Health Effects

Since the time of WASH-1400, three fatal early effects (hematopoietic, pulmonary, and gastrointestinal syndromes) have typically been included in the calculation of early health effects. The likelihood of death from any of these three effects is considered in a combined fashion. In addition, a variety of non-fatal early health effects can be analyzed in MACCS.

The technical bases for the early health effects dose-response models in MACCS are described in Chapter 2 of NUREG/CR-4214, Part II, Revision 1 [179] and are summarized in [182]. Models have been developed in [182] for a wide variety of early fatal and non-fatal effects (cf. Table 2.1 of [182]), and additional technical bases for early health effect models are included in [25]. A summary of the early and continuing health effects for which models have been developed is included in Table 5-3.

Table 5-3 Summary of Early and Continuing Health Effect Models for Accident Consequence Analysis

Effect	Models Developed in NUREG/CR-4214 [182]		Primary Source for Model Parameters
	Mortality	Morbidity	
Hematopoietic Syndrome	X		[27], based on expert elicitation data from [25] [182]
Pulmonary Syndrome	X		
Gastrointestinal Syndrome	X		
Pneumonitis		X	
Prodromal Vomiting		X	
Prodromal Diarrhea		X	
Thyroiditis		X	
Hypothyroidism		X	
Skin Erythema		X	
Transepidermal Injury		X	
*Cataracts		X	
*Microcephaly		X	
*Severe Mental Retardation		X	
*Death of Embryo/Fetus	X		

*Parameters developed for NUREG-1150 are documented in Appendix A of [5] but were not used in that study; note that those parameters treated fetal death distinct from the pooled assessment for early fatalities.

Source: adapted from [182] Table 2.1

The early health effect risk models implemented in MACCS are based on the models developed in [178] and are described in Section 6.1 of [20] and in Sections 6.7 and 6.8 of [2]. These models have sigmoidal dependences on dose to a target organ for individual risk to an exposed individual. These models have the following form:

$$r = 1 - e^{-\left(\ln(2) \cdot \left(\frac{D}{D_{50}}\right)^\beta\right)}, \quad D > D_{\text{Threshold}} \quad (5-1)$$

$$0, \quad D < D_{\text{Threshold}} \quad (5-2)$$

where

- r = individual risk of health effect
- D = equivalent dose delivered to the target organ
- $D_{\text{Threshold}}$ = equivalent dose below which the effect is not expected to occur
- D_{50} = equivalent dose that would induce the effect (impaired functioning of the target organ or fatality if the impairment is too large) in half the exposed population
- β = shape parameter that determines the steepness of the sigmoidal dose response curve

5.2.1 Early Fatalities Arising from Acute Exposures

As discussed in Chapter 2 of [179], early fatality models suitable for use in MACCS have been developed for hematopoietic, pulmonary, and gastrointestinal syndromes. Lethal doses to the central nervous system are accompanied by lethal doses to the red bone marrow, lungs, or stomach, such that the total lethality is adequately represented by those three organs. Likewise, lethal doses from radiation skin burns is not considered a significant risk contributor for NPP accidents, as the doses required to cause skin burns are accompanied by lethal doses to the red bone marrow (cf. Section 2.1.2.4 of [182]). However, information is provided in [25] for estimating fatalities arising from skin burns from acute beta skin doses.

The individual risk of an early (sometimes referred to as prompt, acute, or deterministic) fatality is modeled using a two-parameter Weibull function, which [2] refers to as a hazard function, H . The hazard function can be used to sum the cumulative risk from multiple types of fatal effects as shown below. The exponential term represents the probability of surviving all of the potential causes of radiation related prompt fatalities.

$$r = 1 - \exp \left[- \sum_i H_i \right] \quad (5-3)$$

$$H_i = \ln(2) \cdot \left(\frac{D_i}{D_{50,i}} \right)^{\beta_i}, \quad D_i > D_{\text{Threshold}} \quad (5-4)$$

$$0, \quad D_i < D_{\text{Threshold}} \quad (5-5)$$

where

r	=	Individual risk of prompt fatality
D_i	=	Equivalent dose (Gy-eq) delivered to the target organ
H_i	=	Hazard function for fatal effect i
$D_{\text{Threshold},i}$	=	Equivalent dose (Gy-eq) below which the effect is not expected to occur
$D_{50,i}$	=	Equivalent dose (Gy-eq) that would induce the effect (impaired functioning of the target organ or fatality if the impairment is too large) in half the exposed population
β_i	=	Shape parameter that determines the steepness of the sigmoidal dose response curve

The target organs for these effects are summarized in Table 2.1 of [182]. The target organ selected for these effects must be based on the organs defined in the DCF file. For a FGR-13 DCF file, the target organ for hematopoietic syndrome is the red bone marrow; the target organ for pulmonary syndrome is the lungs; and the target organ for gastrointestinal syndrome is the stomach. Because early health effects depend on dose rate effects, the effect of dose protraction is sufficiently important for early effects that an “effective acute dose” is used to account for dose protraction, and thus the acute dose commitment coefficients from the DCF file should be used to estimate early health effects.

Parameters representing fatal acute health effects are derived from expert elicitation data documented in NUREG/CR-6545 [25]. Uncertainty distributions suitable for use in MACCS are

developed in [27] for all three of the fatal deterministic effects (hematopoietic, gastrointestinal, and pulmonary syndromes) recommended by [179] and [182]. For early health effect risks that are caused by external exposures (cloudshine and short-term groundshine exposures), the D_{50} value is chosen to be appropriate for intense exposures delivered over a 24-hour period to be consistent with the assumption that the dose is delivered during the first day of the early phase. For internal exposures due to inhalation of radioactive materials, dose protraction is addressed and the dose coefficient for acute inhalation is adjusted to provide an effective acute dose comparable to a one-day dose.

The values recommended for use in MACCS by [27] are shown in Table 5-4. These values are based on a median value derived from a composite of expert judgment estimates. For the hematopoietic and gastrointestinal syndromes, the recommended values are based on an effective dose rate of 100 Gy/hr of low linear energy transfer (LET) radiation. For pulmonary syndrome, the values are based on a lung dose rate of 1 Gy/hr of beta radiation to a person under the age of 40. For all three effects, supportive medical treatment is assumed following exposure. The 5th to 95th percentile range is provided in parentheses below the central (median value) estimate value.

Table 5-4 Early Fatality Health Effect Dose-Response Parameters

Health Effect	MACCS Target Organ (ORGNAME)	$D_{\text{Threshold, Gy-Eq (EFFTHR)}}$	$D_{50, \text{Gy-Eq (EFFACA)}}$	Shape Factor (EFFACB)
Hematopoietic Syndrome	A-RED MARR	2.3 (1.1–5.3)	5.6 (3.3–10)	6.1 (2.8–14)
Pulmonary Syndrome	A-LUNGS	14 (8.6–24)	24 (17–45)	9.6 (4.4–19)
Gastrointestinal Syndrome	A-STOMACH	6.5 (3.8–9.5)	12 (7.9–19)	9.3 (3.4–18)

Source: [27], based on expert elicitation data from [25]

Parameter Name: NUMEFA

Parameter Description: Number of Early Fatality Effects

Recommended Value: 3

Uncertainty Range: not applicable

References: [179]

Discussion: Although MACCS has the capability to model up to five fatal effects using the cumulative risk model described above, parameters suitable for use in the MACCS early fatality models have been developed for hematopoietic, pulmonary, and gastrointestinal syndromes for the reasons discussed on p. II-8 of [179].

Parameter Name: ORGNAM

Parameter Description: MACCS Target Organ for Early Fatalities

Recommended Value: Table 5-4

Uncertainty Range: not applicable

References: Chapter 2 of [179]

Discussion: The MACCS organ names used for early fatality effects are given in Table 5-3.

Parameter Name: EFFTHR

Parameter Description: Threshold Dose to Target Organ

Recommended Value: Table 5-4

Uncertainty Range: Values in parentheses in Table 5-4 (5th–95th Percentile)

References: Chapter 2 of [179], [25], Section 6 in [27]

Discussion: The recommended values for threshold dose parameters are the central tendency point estimates summarized in Table 5-4. Upper and lower values for the uncertainty range can be used for sensitivity analyses.

Parameter Name: EFFACA

Parameter Description: LD₅₀ for Early Fatality

Recommended Value: Table 5-4

Uncertainty Range: Values in parentheses in Table 5-4 (5th–95th Percentile)

References: Chapter 2 of [179], [25], Section 6 in [27]

Discussion: The recommended values for LD₅₀ parameters are the central tendency point estimates summarized in Table 5-4. Upper and lower values for the uncertainty range can be used for sensitivity analyses.

Parameter Name: EFFACB

Parameter Description: Shape Factor for Early Fatality

Recommended Value: Table 5-4

Uncertainty Range: Values in parentheses in Table 5-4 (5th–95th Percentile)

References: Chapter 2 of [179], [25], Section 6 in [27]

Discussion: The recommended values for early fatality shape parameters are the central tendency point estimates summarized in Table 5-4. Upper and lower values for the uncertainty range can be used for sensitivity analyses.

5.2.2 Early Injuries Arising from Acute Exposure

The MACCS early injury risk model provides an estimate of the risk of manifesting a single acute radiation injury. This is in contrast with the MACCS early fatality model, which provides a combined risk estimate for fatality from any of several competing causes of early fatality.

Models for up to 11 early health effects have been developed in [182]. However, when using a DCF file based on FGR-13, effective acute dose coefficients are not available for the eye (needed to evaluate the incidence of cataracts) or for the embryo/fetus (needed to evaluate the incidence of microcephaly, severe mental retardation, or fetal death endpoints). The remaining seven non-fatal early health effects (pneumonitis, prodromal vomiting, prodromal diarrhea, skin erythema, transepidermal injury, thyroiditis, and hypothyroidism) have typically been included in MACCS calculations since the publication of NUREG-1150 [4].

Parameters representing early health effects are derived from expert elicitation data documented in NUREG/CR-6545 [25] or from the data in Sample Problem A based on the NUREG/CR-4214 series of reports [182] [179]. Uncertainty distributions suitable for use in MACCS are developed in [27] based on [25] for pneumonitis, which represents a deterministic injury to the lung. In addition to the central tendency values that are used as the basis for the parameter estimates in this report, upper and lower bounds for early morbidity dose response models are provided in

Table 2.5 of [182]. For the early health effect risks that are caused by external exposures (cloudshine and short-term groundshine exposures), the D_{50} value is chosen to be appropriate for intense exposures delivered over a 24-hour period to be consistent with the assumption that the dose is delivered during the first day of the early phase. For internal exposures due to inhalation of radioactive materials, dose protraction is addressed and the dose coefficient for acute inhalation is adjusted to provide an effective acute dose comparable to that of a one-day dose. The values used in MACCS are shown in Table 5-5.

Table 5-5 Deterministic Health Effect Dose-Response Parameters

Health Effect EINAME	MACCS Target Organ (ORGNAME)	$D_{\text{Threshold, Gy-Eq}}$ (EITHRE)	D_{50} , Gy-Eq (EIFACA)	Shape Factor (EIFACB)	Source
Pneumonitis	A-LUNGS	9.2 (4.4–17)	17 (8.9–31)	7.3 (4.0–22)	[27] (based on expert elicitation data from [25]) Sample Problem A [1] (based on data summarized in Table 2.5 of [182] and in [179])
Prodromal Vomiting	A-STOMACH	0.5 (n/a)	2 (1.5–2.5)	3 (n/a)	
Prodromal Diarrhea	A-STOMACH	1 (n/a)	3 (2.5–4)	2.5 (n/a)	
Skin Erythema	A-SKIN	3	6	5	
Transepidermal Injury	A-SKIN	10	20	5	
Thyroiditis* ^{**}	A-THYROID	40	240	2	
Hypothyroidism**	A-THYROID	2	60	1.3	

* Note that Table 2.5 of [182] states that there is no evidence suggesting that radiation thyroiditis can be induced by brief external exposures; thyroiditis is associated with protracted exposures.

** The values for hypothyroidism are based on those provided in Table 1.9 of [178].

Parameter Name: NUMEIN

Parameter Description: Number of Early Injury Effects

Recommended Value: 7

Uncertainty Range: not applicable

References: [179], [182], [1]

Discussion: The NUMEIN variable defines the number of early injury effects to be modeled and is defined to be consistent with the number of entries for EINAME and ORGNAM, which typically include seven entries. For analyses not requiring the computation of early injuries, the user should uncheck Early Injury Effects on the Early Effects tab of the Project Properties form, which will disable the computation of early injuries.

Parameter Name: EINAME

Parameter Description: Early Injury Effect Names

Recommended Value: Table 5-5

Uncertainty Range: not applicable

References: [179], [182], [1]

Discussion: The names of the early injuries for which MACCS dose response models are available are provided in Table 5-5.

Parameter Name: ORGNAM

Parameter Description: MACCS Target Organ for Early Injuries

Recommended Value: Table 5-5

Uncertainty Range: not applicable

References: [179], [182], [1]

Discussion: The MACCS target organ names corresponding to each of the early injuries for which dose response models are available are provided in Table 5-5.

Parameter Name: EISUSC

Parameter Description: Susceptible Population Fraction

Recommended Value: 1 for the early injuries listed in Table 5-5

Uncertainty Range: not applicable

References: not available

Discussion: The EISUSC parameter defines the fraction of the population that is susceptible to a given early injury. For example, early health effects arising from *in-utero* exposures are only relevant to pregnant women. For the early injuries listed in Table 5-5, this value should be set to 100% (i.e., the entire exposed population is susceptible to the health effect).

Parameter Name: EITHRE

Parameter Description: Early Injury Dose Threshold

Recommended Value: Table 5-5

Uncertainty Range: Values in parentheses in Table 5-5

References: Table 2.5 of [182], [179]

Discussion: The recommended values for early injury thresholds are the central tendency point estimates summarized in Table 5-5. Upper and lower values for the uncertainty range, where available, can be used for sensitivity analyses.

Parameter Name: EIFACA

Parameter Description: D₅₀ For Early Injuries

Recommended Value: Table 5-5

Uncertainty Range: Values in parentheses in Table 5-5

References: [182], [25], Section 6 in [27]

Discussion: The recommended values for early injury D₅₀ values are the central tendency point estimates summarized in Table 5-5. Upper and lower values for the uncertainty range, where available, can be used for sensitivity analyses.

Parameter Name: EIFACB

Parameter Description: Shape Factor for Early Injuries

Recommended Value: Table 5-5

Uncertainty Range: Values in parentheses in Table 5-5

References: [182], [25], Section 6 in [27]

Discussion: The recommended values for early injury shape parameter values are the central tendency point estimates summarized in Table 5-5. Upper and lower values for the uncertainty range, where available, can be used for sensitivity analyses.

5.3 Models for Latent Health Effects

The original version of MACCS [1] implemented a linear quadratic model for cancer risk assessment, consistent with the recommendations of the BEIR III Committee [193] and NRC-sponsored work [178]. MACCS 1.5.11.1 introduced a linear model with a DDREF to be consistent with the recommendations of BEIR V [194] and ICRP-60 [191] as reflected in LMF-132 [180]. The MACCS models for cancer risk are discussed in Section 6.2 of [20] and in Section 6.9 of [2].

At low doses below 0.1 Sv (10 rem), the shape of the dose response curve is uncertain because data concerning cancer risks lack statistical power for doses that are this small (i.e., numbers of fatalities are indistinguishable from the background) and because extrapolation of data from larger exposures is questionable. This uncertainty is reflected in the Health Physics Society's position [195] that cancer risks should not be estimated for such low doses by extrapolation of risk from data on larger doses. A useful summary of the state of knowledge on radiation and health effect risks and discussion of the limitations of quantitative inferences that may be drawn regarding radiation risks is contained in Annex X of [196]. That report, in keeping with several other recent consensus documents, cautions against estimating the total number of cancer cases based on exposures of large populations to low doses. Noting the uncertainties in the risks of individual exposures in the low dose range, Annex X states that:

Predictions of cancer fatalities using collective dose where individual exposures are in the low dose and very low dose range are based on an unsubstantiated premise and both UNSCEAR [X-6] and ICRP [X-7] have advised against this practice. This advice remains valid even if the process used for risk estimation does not formally calculate collective dose, but simply applies a risk coefficient to large numbers of people exposed to low doses [196].

To allow a user to address these cautionary discussions, MACCS includes models to evaluate the effect of thresholds in the dose response model on the total number of cancer occurrences and fatalities.

MACCS has a variety of models to evaluate stochastic health effects. In each risk model, MACCS can account for early fatalities, if any, as a competing cause of death when calculating the cases of latent cancers in the surviving population. In practice, MACCS accomplishes this by adjusting the population size subject to latent cancers. The models for stochastic health effects include the following options:

- linear quadratic model
- linear model with a dose and dose-rate effectiveness factor
- piecewise-linear model
- annual dose threshold model

The first two of these are non-threshold dose-response models. They assume that any radiation exposure carries some risk of latent cancer. They are based exclusively on lifetime doses and do

not account for annualized doses from internal pathways. These models evaluate cancer risk based on equivalent committed doses to specific organs. The standard MACCS dose coefficient files are compatible with the non-threshold models.

The second two computational models, the piecewise-linear and annual dose threshold models, allow the user to examine risks arising from non-linear dose-response functions or doses above user-definable thresholds. These models depend on the doses received during annual periods rather than total lifetime doses and require the use of dose coefficient files that provide dose coefficients for each of the years following an accident. These annual dose coefficient files are available for the FGR13DCF and the DOSFAC files, but not the FGRDCF file.

The recommended cancer model for most applications is the linear model with a dose and dose-rate effectiveness factor. In 1990, the BEIR V Committee adapted a linear latent-cancer-risk model and estimated a dose and dose-rate effectiveness factor of 2. This factor was based on the conclusion that a dose from low-LET radiation received over a short period of time is more effective at causing cancer than the same dose received over an extended period. ICRP-60 [191] expanded upon the BEIR V recommendation and proposed a formal dose and dose rate effectiveness factor (abbreviated DDREF in the ICRP publication and corresponding to DDREFA in MACCS) as well as criteria for applying it. The recommendation of ICRP-60 was that DDREF should be 1 for doses of low-LET radiation when the dose rate was less than a threshold (DDTHRE) of 0.1 Gray per hour and when the total dose was less than 0.2 Gray. Above these limits, DDREF should have a value of 2 for low-LET radiation [191]. In the BEIR V and ICRP-60 models, cancer risk factors are expressed in the low dose range (below 0.2 Gy) and DDREF multiplies these cancer risk factors in the high dose range (above 0.2 Gy). MACCS uses the opposite approach. Cancer risk factors are expressed in the high dose range and they are divided by DDREFA in the low dose range. This two approaches are completely equivalent, but the difference can cause confusion when communicating with the Health Physics community.

The LMF-132 [180] report concerning cancer risk assessment models adopted the ICRP recommendation. The MACCS computational model, described in Section 6.9.2 of [2], partially implements the recommendations of ICRP-60 and LMF-132. As implemented in MACCS, there is no test for whether dose rates exceed 0.1 Gray per hour. Furthermore, MACCS does not separately tally high- and low-LET radiation doses. However, MACCS does apply the DDREFA when the total dose is less than 0.2 Gray and in the long-term phase when dose rates are likely to be less than 0.1 Gy/hr due to protective actions. A linear model with a dose and dose rate effectiveness factor is implemented in MACCS, as indicated below, showing the individual risk of latent fatality:

$$r_i = \alpha_i \cdot D_i \quad \text{Early Phase, } D_i > \text{DDTHRE} \quad (5-6)$$

$$r_i = (\alpha_i / \text{DDREFA}_i) \cdot D_i \quad \text{Early Phase, } D_i < \text{DDTHRE} \quad (5-7)$$

$$r_i = (\alpha_i / \text{DDREFA}_i) \cdot D_i \quad \text{Late Phase} \quad (5-8)$$

Where

r_i individual risk of an occurrence or a fatality from a latent cancer of type i

D_i	Equivalent dose (Sv) to target organ i associated with cancer type i , computed using dose coefficients from the dose coefficient file, as discussed in Section 5.1
α_i	Risk factor for an occurrence or a fatality from cancer type i at high dose rate
$DDREFA_i$	Dose and dose-rate effectiveness factor for cancer type i
$DDTHRE$	Dose threshold for application of the dose and dose-rate effectiveness factor

The linear model is implemented by assigning the linear quadratic parameters as follows: the threshold (ACTHRE) is equal to 0, the linear factor (DOSEFA) is equal to 1, and the quadratic factor (DOSEFB) is equal to 0. The dose and dose-rate effectiveness factor appears in the denominator and reduces the health impact of low doses. MACCS applies the DDREFA to all dose calculations in the CHRONC module because it is assumed that protective actions always limit dose rates to be less than 0.1 Gy per hour after the end of the emergency phase. For the early phase, where dose rates could be greater than 0.1 Gy per hour, the user defines the lifetime dose commitment (MACCS input parameter DDTHRE) below which the DDREFA is applied to cancer risk calculations. Because of the way DDREFA is implemented in MACCS, the cancer induction risk factors (CIRISK and CFRISK) must be specified for the high dose range, i.e., for doses above the value of DDTHRE. The user is cautioned when taking values from compilations of risk factors, such as Table S-3 of ICRP-60 [191], which are often provided for the low dose range.

WinMACCS 3.10 is currently limited to a hardwired set of organs available for cancer risk assessment. Because the nine target organs available in MACCS do not include the full set of target organs in compilations such as FGR-13, the MACCS residual group must be adjusted to account for all cancers not otherwise addressed. Work is underway to allow the MACCS code to use the complete set of organs available in the DCF files, which will allow the cancer risk coefficients to be entered directly from tabulations available in the literature. Until then, there are currently two recommended approaches for modeling cancer risks in MACCS. The user may use the FGR13DCF.INP file in conjunction with cancer fatality risk factors from NUREG/CR-7161 [27], based on the expert elicitations documented in NUREG/CR-6555 [26]. Alternately, if the FGR13GyEquivDCF.inp file is available, it may be used in conjunction with the cancer risk values used in SOARCA based on [183]. As discussed in those reports, the cancer risk model is based on the BEIR V report [194].

5.3.1 NUREG/CR-6555 Cancer Risk Model

The cancer mortality parameters distributed with the MACCS 3.10 sample problem “Point Estimates LNT.mxd,” shown in Table 5-6, are based on the median value estimates provided in Chapter 5 of [27]. These values are in turn based on the expert elicitations documented in NUREG/CR-6555 [26]. The source of the DDREFA values is not provided, but it may be that the values were also derived from the elicitations documented in [26] and are consistent with the values provided for CFRISK. The value for skin cancer from [27] is not included as there is no MACCS target organ for lifetime exposure to the skin and no risk factor provided in BEIR V. The values for CIRISK in the sample problem are unchanged from the MACCS2 Sample Problem A CIRISK values, for which the source is unclear.

Table 5-6 Latent Cancer Mortality Dose-Response Parameters

Cancer Type	MACCS Target Organ (ORGNAME)	Dose Threshold, Sv (DDTHRE)	Dose and Dose Rate Reduction Factor (DDREFA)	$\alpha_{FATALITY}$, Fatalities/Sv (CFRISK)*
LEUKEMIA	L-RED MARR	0.2	2.27	9.50E-03
BONE	L-BONE SUR	0.2	1.92	4.20E-04
BREAST	L-BREAST	0.2	1.80	9.20E-03
LUNG	L-LUNGS	0.2	2.76	2.60E-02
THYROID	L-THYROID	0.2	1.85	6.30E-04
COLON	L-LOWER LI	0.2	2.11	1.00E-02
LIVER	L-LIVER	0.2	1.69	8.60E-04
PANCREAS	L-ICRP60ED	0.2	1.71	2.10E-03
STOMACH	L-LOWER LI	0.2	1.66	3.20E-03
OTHER	L-ICRP60ED	0.2	2.12	2.70E-02

*Note that the risk coefficients CFRISK are provided for high doses/dose rates because of how risks are computed within MACCS. For comparison with the more common low dose/dose rate risk coefficients, these values should be divided by the DDREFA values.

Source: based on [27] and [26]

Because no cancer incidence risk factors are provided, and the source of the cancer incidence risk factors in the sample problem is unclear, it is not recommended to compute cancer incidence when using the NUREG/CR-6555 [26], [27] cancer model.

5.3.2 SOARCA Cancer Risk Model

An alternative cancer model developed for the SOARCA project can also be implemented if the user has access to the FGR13GyEquivDCF.INP file, which was not distributed with the MACCS 3.10. This file is a modification of the FGR13DCF.INP file distributed with MACCS 3.10, in which the DCF values for the pancreas, a representative soft tissue, replace the entries for the bladder wall and the RBE values for high-LET radiation for lifetime exposures from inhalation and ingestion are set to 1 for red bone marrow and to 10 for breast tissue. These changes to the DCF file are necessary to use the SOARCA cancer model and are based on recommendations from Eckerman [183], as discussed in the following paragraph.

Eckerman [183] recommended to use risk factors in SOARCA from FGR-13, which are based on the BEIR V report. Values for the dose and dose-rate effectiveness factors (DDREFAs) and risk coefficients for an age and gender-averaged U.S. population are from Table 3 of [183]. Reference [183] includes both best estimate values and estimates for the uncertainty in both the mortality risk coefficient and the DDREFA. The dose and dose-rate effectiveness factor for all cancers except for the breast is 2.0 and for the breast it is 1.0, as recommended in the BEIR V report. The DDREFA for breast cancer reflects the linearity of the dose response observed in several study populations and an apparent invariance in risk with dose fractionation [197]. The list of cancer sites in the MACCS model does not include all of the cancer sites evaluated in FGR-13. The MACCS residual group therefore includes, in addition to the residual group of FGR-13, cancers of

the esophagus, stomach, skin, ovaries, bladder, and kidney. It is assumed that the mortality risk coefficients for the cancer sites are independent and not correlated. The values for use with the MACCS linear latent-cancer-risk model are given in Table 5-7.

Table 5-7 Latent Cancer Dose-Response Parameters

Cancer Type	MACCS Target Organ (ORGNAM)	Dose Threshold, Sv (DDTHRE)	Dose and Dose Rate Reduction Factor (DDREFA)	$\alpha_{FATALITY}$, Fatalities/Sv (CFRISK)**	$\alpha_{INCIDENCE}$, Incidence/Sv (CIRISK)**
LEUKEMIA	L-RED MARR	0.2	2	1.11E-02	1.13E-02
BONE	L-BONE SUR	0.2	2	1.90E-04	2.71E-04
BREAST	L-BREAST	0.2	1	5.06E-03	1.01E-02
LUNG	L-LUNGS	0.2	2	1.98E-02	2.08E-02
THYROID	L-THYROID	0.2	2	6.48E-04	6.48E-03
LIVER	L-LIVER	0.2	2	3.00E-03	3.16E-03
COLON	L-LOWER LI	0.2	2	2.08E-02	3.78E-02
RESIDUAL	L-BLAD WAL**	0.2	2	4.93E-02	1.69E-01

*The cancer model in this table should only be used with the Gray-equivalent DCF file FGR13GyEquivDCF.inp. The organ named bladder wall in that file, and therefore the MACCS target organ L-BLAD WALL, actually contain dose coefficients for the pancreas. The pancreas was selected by Eckerman [183] as a representative soft tissue for representing the dose to residual organs not included in the MACCS list of cancer sites.

**Note that the risk coefficients CFRISK and CIRISK are provided for high doses/dose rates because of how risks are computed within MACCS. For comparison with the more common low dose/dose rate risk coefficients, these values should be divided by the DDREFA values.

Source: Based on SOARCA [183] [14]

Parameter Name: DOSMOD

Parameter Description: Dose-Response Model Flag

Recommended Value: LNT

Uncertainty Range: not applicable

References: not applicable

Discussion: The base case model recommended for most applications is the linear no-threshold model, which is selected by setting the parameter DOSMOD to LNT, assigning ACTHRE a value of zero, DOSEFA a value of 1, and DOSEFB a value of zero for each cancer type. To examine the uncertainties arising from cancer risk estimation at low doses, a dose threshold model may be constructed by setting the value of DOSMOD to AT (“Annual Threshold”) and specifying an annual and lifetime dose threshold for cancer risk estimation.

Parameter Name: ACTHRE

Parameter Description: Linear Dose-Response Threshold

Recommended Value: 0

Uncertainty Range: not applicable

References: [194]

Discussion: ACTHRE is a parameter that is used in the linear quadratic model to define the low dose range. To implement the recommended linear model, ACTHRE should be set to zero.

Parameter Name: ACSUSC

Parameter Description: Population Susceptible to Cancer

Recommended Value: 1

Uncertainty Range: not applicable

References: not available

Discussion: The ACSUSC parameter defines the fraction of the population that is susceptible to a given latent cancer. This value should be set to 100% (i.e., the entire exposed population is susceptible to the health effect) for the cancers listed in Table 5-6 or Table 5-7.

Parameter Name: DOSEFA

Parameter Description: Cancer Dose-Response Linear Factors

Recommended Value: 1

Uncertainty Range: not applicable

References: [194]

Discussion: DOSEFA is a parameter that is used in the linear quadratic model to define the linear term of the linear quadratic model. To implement the recommended linear model, DOSEFA should be set to one for all cancer types.

Parameter Name: DOSEFB

Parameter Description: Cancer Dose-Response Quadratic Factors

Recommended Value: 0

Uncertainty Range: not applicable

References: [194]

Discussion: DOSEFB is a parameter that is used in the linear quadratic model to define the quadratic term of the linear quadratic model. To implement the recommended linear model, DOSEFB should be set to zero for all cancer types.

Parameter Name: NUMACA

Parameter Description: Number of Latent Cancer Health Effects

Recommended Value: 10

References: [26], [27]

Discussion: The number of cancers included in the cancer risk model is based on the cancer risk model selected. To be able to estimate total cancers, all cancers in the model should be included. For the NUREG/CR-6555 [26], [27] cancer model provided in Table 5-6, the number of cancers included in the cancer risk model is 10. If using the SOARCA cancer model given in Table 5-7 coupled with the FGR13GyEquivDCF.INP file DCF file, the number of cancers included in the cancer risk model is eight.

Parameter Name: ACNAME

Parameter Description: Latent Cancer Effect

Recommended Value: Table 5-6

Uncertainty Range: not applicable

References: [26], [27]

Discussion: The type of cancer and the corresponding MACCS target organ (ORGNAME) is listed in Table 5-6. If using the SOARCA cancer model described in Section 5.3.2 coupled with the FGR13GyEquivDCF.INP file DCF file, the type of cancer and the corresponding MACCS target organ (ORGNAME) is listed in Table 5-7.

Parameter Name: ORGNAM

Parameter Description: MACCS Target Organ for Latent Cancer

Recommended Value: Table 5-6

Uncertainty Range: not applicable

References: [26], [27]

Discussion: The type of cancer and the corresponding MACCS target organ (ORGNAME) is listed in Table 5-6. If using the SOARCA cancer model described in Section 5.3.2 coupled with the FGR13GyEquivDCF.INP file DCF file, the type of cancer and the corresponding MACCS target organ (ORGNAME) is listed in Table 5-7.

Parameter Name: DDTHRE

Parameter Description: Threshold for Applying Dose-Dependent Reduction Factor

Recommended Value: 0.2 Sv

Uncertainty Range: not applicable

References: [194], [191]

Discussion: The low dose region is defined as less than 0.2 Sv (<20 rem) for cancer models consistent with the recommendations in BEIR V [194] and ICRP-60 [191].

Parameter Name: CFRISK

Parameter Description: Lifetime Cancer Fatality Risk Factors

Recommended Value: Table 5-6

Uncertainty Range: Uncertainty ranges may be developed using the information in [27] or, if using the SOARCA cancer model, using the information in [183].

References: [26], [27]

Discussion: The cancer fatality risk factors are provided in Table 5-6 when using the NUREG/CR-6555 [26], [27] cancer model. The cancer fatality risk factors from the SOARCA model are provided in Table 5-7 if the Gray-equivalent DCF file FGR13GyEquivDCF.inp DCF file is available.

Parameter Name: CIRISK

Parameter Description: Lifetime Cancer Injury Risk Factors

Recommended Value: 0

Uncertainty Range: not available

References: not applicable

Discussion: Cancer incidence risk factors are unavailable when using the NUREG/CR-6555 [26], [27] cancer model. The SOARCA cancer incidence model summarized in Table 5-7 may be used if the Gray-equivalent DCF file FGR13GyEquivDCF.inp DCF file is available.

Parameter Name: DDREFA

Parameter Description: Dose-Dependent Reduction Factor

Recommended Value: Table 5-6

Uncertainty Range: not available if CFRISK values are based on [27].

References: [26], [27]

Discussion: The recommended values for DDREFA provided in Table 5-6 are chosen to be consistent with the values in [27] consistent with the information provided in [26]. The DDREFA values from the SOARCA model are provided in Table 5-7 and can be used if the Gray-equivalent DCF file FGR13GyEquivDCF.inp DCF file is available to the user.

6 QUANTIFICATION

MACCS can calculate a variety of different consequence measures to portray the impact of an accident on the surrounding region. The user has control over the results that are produced. By choosing appropriate values in the user input files, the user can ensure that the code does not perform unnecessary calculations. This affords a great deal of flexibility but it also requires that the user anticipate the results of interest. If any are omitted, it is necessary to correct the user input and rerun the calculation.

The outputs requested by the analyst depend on the purpose of the analysis. Individual early fatality risk and individual latent fatality risk are used to support comparison of results to NRC's quantitative health objectives [198]. These two metrics, supplemented with collective dose and economic impacts, are also used in the NRC regulatory analysis process described in NUREG/BR-0058 [17] and NUREG/BR-0184 [18]. National Environmental Policy Act analyses, as described in Section 7.2 of NUREG-1555 [199], include additional metrics. For example, environmental analyses typically include (on a frequency-weighted basis) collective dose, total early and latent fatalities, individual risk of early and latent fatality, offsite property damage, and land contamination areas. Analyses supporting evaluation of emergency planning, such as NUREG-0396 [139] and NUREG/CR-1131 [200], have also included measures of individual dose. Such measures may be computed as effective doses (for comparison with EPA protective action guidance) or acute doses to selected organs (for evaluating the risk of early health effects). PRA studies have examined a wide variety of output measures. For example, WASH-1400 reported risk of early fatalities, early illness, latent cancer fatalities, thyroid nodules, genetic effects, and property damage, and also produced probability distributions for early fatalities, early illness, latent cancer fatalities, thyroid nodules, genetic effects, property damage, decontamination area, and relocation area²³ for one reactor year and for a fleet of 100 reactors. NUREG-1150 [4] reported offsite consequences in terms of early and latent fatalities (on both a collective and individual basis) and collective population doses (both within 50 miles and throughout the entire modeling domain, which used a 1,000-mile radius).

In addition to the outputs required for the analysis, the analyst may choose to include additional outputs to assist in the interpretation of the reported consequence analysis results. For example, the extent of land contamination is useful for interpretation of collective measures (e.g., collective dose or health effects, total economic impacts, etc.). Contaminated land areas can be calculated several ways in MACCS, the simplest of which is to report land areas that exceed activity levels per unit area for one or more of the radionuclides. The analyses documented in Enclosure 5 of SECY-12-0157 [201] used the values of 1, 5, 15, and 40 Ci/km² (37, 185, 555, and 1480 kBq/m²) of Cs-137. These activity levels, reported in [202], were used to identify different contamination "zones" in the former Soviet Union following the accident at the Chernobyl Power Station. Areas subject to different types of protective actions (i.e., decontamination, interdiction, or condemnation, or areas subject to agricultural restrictions) can be produced and may provide useful insights. The size of the population impacted by different protective actions may also prove useful in evaluating model outputs or selecting input parameters in an iterative fashion. For

²³ Note that relocation is used in WASH-1400 in a somewhat different sense than is used in the current MACCS code. According to WASH-1400, "The major contributor to the overall cost would be from those areas where reasonable decontamination procedures could not reduce levels of radioactivity to acceptable levels of dose. In this study an acceptable dose level was chosen to be 25 rem in 30 years for urban areas and 10 rem in 30 years for areas where the population density is low." This explanation seems to be more consistent with the term "condemned" used in the current MACCS code.

example, the number of people subject to protective actions in the early, intermediate, and recovery phases may be useful for estimating the time needed to implement protective actions.

6.1 Output Control

Complete information on the specification of output control statements is discussed in the MACCS user manuals. The discussion here is intended to provide some information on how to translate some of the more commonly requested output measures into an output control statement. Output control statements (either generated by WinMACCS or specified in a text file) require the definition of regions of interest in terms of the ring number rather than the distance. The regions of interest must therefore be defined in the SPAEND variable. It is also useful to note that the MACCS output file contains results for each cohort (for those items defined as outputs of EARLY) as well as an overall average across all cohorts. Inspection of cohort specific results may yield insights into the contribution of each cohort to the overall risk that is computed.

Estimates of early or latent fatality risks to individuals may be generated using either the average individual risk (MACCS Type 4) or the population-weighted risk (MACCS Type 8) outputs. Neither of these individual risk measures includes the societal pathways of (1) ingestion of contaminated food and water originating from that region or (2) doses to decontamination workers working in the area. The average individual risk is obtained by taking the sum of the risk values in all sectors at a given distance and dividing it by the number of sectors. This measure does not account for the population distribution or the likelihood of the wind blowing toward different sectors, but does take into account any protective measures defined for one or all cohorts. It does not require any population to be defined in the interval and may therefore be useful for evaluating individual health effect risks where there is no resident population within the region of interest. An example of an output control statement to generate the average individual risk of an early fatality is provided below. For example, if the fifth ring represents the distance of one mile from the site boundary, the following statement generates the average individual risk to a hypothetical individual located one mile from the site boundary:

TYPE4OUT003 5 'ERL FAT/TOTAL' NONE

By contrast, the population-weighted health effect risk (MACCS Type 8) is obtained by calculating the cases of a health effect in a certain region and then dividing by the total population in the region. This value therefore requires that a resident population be defined within the region. This value therefore allows consideration of the lower likelihood of exposure in sparsely populated areas (or in sectors toward which the wind is less likely to blow) and can also provide an approach for averaging the risk over an entire region (such as the area within one mile of the site boundary or within 10 miles of the plant). An example of an output control statement to generate population-weighted individual risks is given below. For example, if the 5th ring corresponds to one mile from the site boundary and the 12th ring corresponds to 10 miles from the point of release, the following statements generate the population-weighted individual risk of an early fatality within one mile of the site boundary and the population-weighted individual cancer fatality risk to an individual within 10 miles of the point of release.

TYPE8OUT001 'ERL FAT/TOTAL' 1 5 NONE

TYPE8OUT002 'CAN FAT/TOTAL' 1 12 NONE

Collective measures that are often computed include both population dose and economic costs. Population dose results that include both the EARLY and CHRONC results may be generated

using MACCS Type 5 output. The user must supply the name of the target organ (the most commonly used target organ is the committed effective dose, e.g., L-ICRP60ED) as well as the inner and outer spatial intervals of the region of interest. If both EARLY and CHRONC are being run, the population dose from all pathways is included in the calculation. In addition to the direct pathways included in the individual risk calculations, the CHRONC pathways include both (1) food and water ingestion doses resulting from material deposited in the region and (2) doses to decontamination workers working in the region. An example of an output control statement to obtain population doses is given below. For example, if the 50-mile radius corresponds to ring 19, the following statement generates the collective effective dose over the interval from 0-50 miles.

```
TYPE5OUT001      L-ICRP60ED  1      19      NONE
```

The total economic costs can be generated by using MACCS Type 10 output. All of the economic cost measures are reported in dollars. Each request for economic results produces a block of 13 economic results: The first line is the total economic costs, which is the sum of population and farm dependent costs. The components of this cost are as follows:

- **TOTAL POPULATION DEPENDENT COSTS:** the sum of population dependent decontamination, interdiction, and condemnation costs as well as early phase and intermediate phase costs:
 - **EMERGENCY PHASE COSTS:** total per diem costs to compensate people for being away from home due to evacuation and relocation during the early phase.
 - **INTERMEDIATE PHASE COSTS:** total per diem costs to compensate people for being away from home due to relocation for the duration of the intermediate phase if DSCRTI is exceeded.
 - **POPULATION DEPENDENT DECONTAMINATION COST:** non-farmland property (i.e., property associated with residential population) decontamination cost.
 - **POPULATION DEPENDENT INTERDICTION COST:** depreciation, deterioration, and lost return on investment of non-farmland property during the period it cannot be used (starting with the early phase and ending after the interdiction period ends) plus the cost of population removal (see POPCST).
 - **POPULATION DEPENDENT CONDEMNATION COST:** compensation paid for permanent loss of non-farmland property plus the cost of permanent relocation of the population removal.
- **TOTAL FARM DEPENDENT COSTS:** the sum of farm dependent decontamination, interdiction, and condemnation costs as well as milk and crop disposal costs:
 - **MILK DISPOSAL COST:** Cost associated with the loss of milk sales from interdiction in the year of the accident. Only three months of lost milk sales are computed, as the code assumes that animals will be placed on stored feed to allow resumption of milk production. The additional cost to dispose of the contaminated milk is not included in this output.
 - **CROP DISPOSAL COST:** Cost associated with loss of crop sales from interdiction in the year of the accident. The additional cost to dispose of the contaminated crops is not included in this output.
 - **FARM DEPENDENT DECONTAMINATION COST:** farm property decontamination cost.

- FARM DEPENDENT INTERDICTION COST: depreciation, deterioration, and lost return on investment of farm property during the period it cannot be used during both decontamination and interdiction.
- FARM DEPENDENT CONDEMNATION COST: compensation paid for permanent loss of farm property because it could not be returned to production within eight years of the accident.

An example of an output control statement to obtain economic results from CHRONC is given below. For example, if the 50-mile radius corresponds to ring 19, the following statement generates economic results (total and cost categories) over the interval from 0-50 miles.

```
TYP10OUT001      1      19      NONE .TRUE.
```

The variation of individual dose with distance from the point of release may be of interest. For cases where network evacuation is used with the wind shift option, the MACCS Type A output reports individual doses at each distance over a range of distances in a manner analogous to the Type 6 centerline dose results. Only direct exposure pathways (i.e., no exposure pathways such as food or water ingestion) are included with this result. There is no dependence on population data, i.e., the dose is reported for phantom individuals assumed to be present at all locations. However, the phantom individuals evacuate or relocate according to the cohort description. As a result, these doses may be different for each cohort. The overall weighted sum of results represents the combination of doses calculated by EARLY and CHRONC, but caution should be taken when interpreting the overall results obtained by combining the emergency response cohorts because peak doses for the various cohorts may occur in different sectors. The user should also be aware that the value is an average dose over the width of the fine grid, rather than the peak centerline dose reported in the Type 6 output. Nonetheless, these values can be used to evaluate how doses vary as a function of distance from the point of release. An example of an output control statement to examine committed effective dose and acute dose to red bone marrow is provided below:

```
TYPEAOUT001      L-ICRP60ED  1      21      NONE
TYPEAOUT002      'A-RED MARR'  1      21      NONE
```

The size of the affected population, provided by the MACCS Type 14 output, may be of interest for establishing or checking model choices such as the modeled size of the evacuation zone, the time needed for early phase relocation (TIMHOT/TIMNRM), the duration of the intermediate phase (DUR_INTPHAS), or the duration of the cleanup phase (TIMDEC). The Type 14 output produces the following outputs:

- The number of evacuees that would not have been impacted by the plume if they had not evacuated
- Number of evacuees that would have been impacted by the plume if they had not evacuated
- Number of relocatees during the emergency phase associated with normal relocation
- Number of relocatees during the emergency phase associated with hotspot relocation

- Number of relocatees during intermediate phase
- Number of relocatees during the long-term phase associated with the first level of decontamination
- Number of relocatees during the long-term phase associated with the second level of decontamination
- Number of relocatees during the long-term phase associated with the third level of decontamination
- Number of relocatees during the long-term phase associated with decontamination plus additional interdiction
- Number of relocatees during the long-term phase whose property is condemned

An example of an output control statement to examine the affected population at a variety of radial intervals is given below. Assuming SPAEND is consistent with the example given in Table 3-1, these statements will provide the outputs above at intervals of 10, 15, 20, 25, 50, and 100 miles:

TYP14OUT001	1	12	NONE
TYP14OUT002	1	14	NONE
TYP14OUT003	1	15	NONE
TYP14OUT004	1	16	NONE
TYP14OUT005	1	19	NONE
TYP14OUT006	1	21	NONE

For example, a user may inspect the size of the early phase relocated population to determine whether the time needed for hotspot and normal relocation is consistent with the size of the population. For scenarios resulting in large early phase relocated populations, the user may consider either an explicit modeling of evacuation at longer distances (by increasing NUMEVA or by defining additional cohorts using SUMPOP) or use of longer relocation times. Conversely, if early phase relocation criteria are based on early phase PAG limits, very small early phase relocated populations may suggest that the actual evacuation zone could be smaller than that modeled. Likewise, inspection of the size of the intermediate phase relocated population over the modeled domain (e.g., 50 or 100 miles) and the size of populations subject to decontamination may inform the duration of the intermediate and cleanup phases, with larger affected population sizes supporting longer phase durations (and vice-versa).

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APPENDIX A

UPDATE OF MACCS COST PARAMETERS RELATED TO PROTECTIVE MEASURES AND DECONTAMINATION

As a part of the initial development of this document, literature reviews and original research were carried out by Sandia National Laboratories (SNL) to update MACCS parameters related to protective measures and decontamination. That work was the foundation for the comprehensive update provided in this report. The results of much of that effort have been integrated into the main text. However, to develop a consistent level of technical detail across the entire document, some of the background information developed by SNL staff was not included in the main text. For some parameters, the approach was updated further during the development of this document. Appendix A provides documentation of the work that was done to update those cost parameters that is not otherwise included or updated in the main text. Because much of the focus of that work was on developing an updated technical basis for modeling decontamination, that work is separately documented in Appendix B. This appendix includes the discussion of the literature review and processes followed to update all the parameters examined in that earlier work.

The last major review and update of MACCS cost parameters was conducted in support of NUREG-1150 [1], [2]. Since that time, there have been advancements in technologies, economies of scale, and lessons learned that have occurred through large scale decontamination and demolition of many U.S. Department of Energy (DOE) sites. The ongoing decontamination activities at Fukushima are providing insights into the use of decontamination techniques and cost at a large scale. As additional information related to large scale decontamination becomes available from the Fukushima activities, analysts should consider such information in developing site-specific analyses.

A total of 32 input parameters related to decontamination and protective measures were reviewed. While tracing the origins of the parameters, it was found that many parameters were developed decades ago and have been escalated over time, but not updated. The basis for some of the parameters was not fully traceable. The basis for parameter ranges could often not be identified and some ranges appeared overly restrictive given the current estimates for these parameters. For some parameters, it was difficult to establish a single value given the potential variability in offsite contamination and the land types that may be involved (e.g., farmland or non-farmland). Where practical, a process was described that analysts may implement to update or develop site-specific parameters.

The decontamination approach used to support the cost estimate development describes techniques that are commercially available and identifies costs for implementation. Development of the parameter values was based on direct experience with decontamination of DOE radiological facilities, research of existing commercial capabilities, and review of DOE studies [3], [4], [5], [6]. Information was obtained from DOE staff, experienced decontamination professionals, and through the acquired services of an experienced decontamination contractor who supported the development of selected cost parameters. The SNL team also met with NRC decommissioning staff to discuss decontamination and decommissioning activities. Insights and cost data were also obtained from information related to the decontamination around Fukushima. As additional Fukushima data related to large scale radiological decontamination becomes available, analysts should consider the new data as they develop MACCS model inputs.

A.1 Objective

The primary objective of the project was to update MACCS protective measures parameter values with a transparent approach to facilitate consistent application in the accounting of offsite impacts for regulatory applications. The update will facilitate consistent application among the MACCS user community. To support this objective, a decontamination approach was developed to identify contributing costs from decontamination, waste storage, waste sampling and characterization, transportation, and disposal.

A.2 Scope and Limitations

The scope of the project included performing a comprehensive review of MACCS parameters to identify protective measures parameters that influence cost. The scope included updating the identified parameters based on current knowledge. In order to understand the original bases, research was conducted of historical documentation, equations, and algorithms used to calculate costs. In addition to updating the existing cost basis, the scope included a review and update of decisions regarding timeframes for implementation of protective measures and decontamination, and describing processes for updating parameters.

To achieve the specified objectives within a reasonable level of effort, project limitations were necessary. The scope of this project did not include implementation of code modifications or the consideration for costs that have typically not been included in MACCS analyses. For example, the scope did not include onsite costs or overarching costs of Federal, state, and local public sectors such as deployment of the National Guard, loss of tax revenue, or surveillance. This project does not attempt to address economic costs of health effects, litigation costs, or indirect costs [7]. Costs related to psychological effects, long-term social and political impacts, and similar costs described in “Methodologies for Assessing the Economic Consequences of Nuclear Reactor Accidents” [8] are also not included.

A.3 Background

The cost parameter values currently in MACCS were largely developed in the 1970s and 1980s to support early versions of consequence codes. As part of the Reactor Safety Study [9], the CRAC code was developed to calculate health and economic consequences of accidental releases of radioactive material into the atmosphere [10]. MACCS was based on the CRAC and CRAC2 code [11] and with the publication of [12], MACCS superseded CRAC and CRAC2. During the transition to MACCS, most of the original parameter values were maintained with some values escalated at the time using the consumer price index (CPI).

Many parameter values were updated in support of the NUREG-1150 severe accident analysis [1]. This update is documented in [2] and included farm and non-farmland parameters, protective measures parameters, and the depreciation rate and societal discount rate. Sprung et al. [2] provided a technical basis for most of the values and was the last major update to the parameters.

A.4 Approach

In the event of a nuclear power plant (NPP) accident, protective measures would be implemented to ensure the health and safety of the public. These include planned actions, such as sheltering and evacuation in the early phase of the accident, followed by relocation, interdiction of land, and decontamination in the later phases of the event. The approach herein was focused on using

current and defensible data in the update of the protective measures parameters. The following activities were included:

- Literature review
- Review of protective measures decontamination activities
- Selection of parameters for review
- Update of the parameters

A.5 Literature Review

Research into the technical basis of MACCS cost parameters included review of historical documentation that describes the development and intent of the parameters. A comprehensive literature review was performed to identify the original technical basis for each cost parameter. The original basis was not found for all parameters. The review also provided a current understanding of recent and ongoing experience in radiological decontamination.

The 1975 Reactor Safety Study [9] included the first application of the CRAC code and included parameters with technical bases that can be traced to pre-1970 studies. In 1982, NUREG/CR 2723 [7] was published presenting techniques for estimating the financial consequences of potential NPP accidents. Offsite cost estimates in NUREG/CR-2723 were based on CRAC2. Discussion of a decontamination timeline, which establishes durations for some parameters, is first presented in NUREG/CR-3673 [13]. Some cost and decontamination details discussed in NUREG/CR-3673 were taken from an unpublished SNL draft document identified as OS84, "An Assessment of Decontamination Costs and Effectiveness for Accident Radiological Releases," by R.M. Ostmeyer and G.E. Runkle.

The most recent comprehensive update to cost parameters is [2], which was performed in support of NUREG-1150 [1]. For select parameters, the values in [2] were escalated from the original values of earlier documents based on the CPI. The State-of-the-Art Reactor Consequence Analyses (SOARCA) project [14] is a recent comprehensive study that incorporates improvements and advancements in severe accident understanding; but cost was not a focus of SOARCA and cost parameters were only used to support decision making that affects evaluation of health effects consequences. However, some emergency response parameters were updated in SOARCA. The following key historical documents, listed chronologically, were reviewed to trace the origins and understand the intended application of parameters:

- EPA-520/6-74-002, "Evacuation Risks – An Evaluation," 1974
- NUREG-75/014, "Reactor Safety Study" Appendix VI, 1975
- NUREG/CR-2723, "Estimates of the Financial Consequences of Nuclear Power Reactor Accidents," 1982
- NUREG/CR-2300, "PRA Procedures Guide," Volume 2, 1982
- NUREG/CR-2552, "CRAC2 Model Description," 1984
- NUREG/CR-3673, "Economic Risks of Nuclear Power Reactor Accidents," 1984
- NUREG/CR-3413, "Off-Site Consequences of Radiological Accidents: Methods, Costs and Schedules for Decontamination," 1985

- NUREG/CR-4551, Vol. 2, Part 7, "Evaluation of Severe Accident Risks: Quantification of Major Input Parameters," 1990
- NUREG-1150, "Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants," 1990
- NUREG/CR-4691, Volume 2, "MELCOR Accident Consequence Code System (MACCS)," 1990
- SAND96-0957, "Site Restoration: Estimation of Attributable Costs from Plutonium-Dispersal Accidents," 1996
- NUREG/CR-6613, "Code Manual for MACCS2," Volume 1, 1998
- NUREG-1935, "State-of-the-Art Reactor Consequence Analyses (SOARCA) Report," 2012

EPA-520/6-74-002, "Evacuation Risks – An Evaluation," 1974 [15]

EPA-520/6-74-002 summarizes evacuation experience in the U.S. for the period of 1959 to 1973. The U.S. Environmental Protection Agency (EPA) report provides data on 64 evacuations, which were caused mostly by transportation accidents, floods, and hurricanes. The evacuations were carried out predominantly by private vehicles, which are the primary mode of transportation in the event of an NPP accident. The study estimated the costs for evacuees and emergency response personnel in dollars per person-day. The evacuation related costs included food, housing, transportation, and loss of income.

EPA estimated the cost of food, housing and transportation for evacuees as \$11 per person-day, assuming 80% of the public used commercial resources, such as hotels, and 20% used mass care shelter facilities. The number of emergency response personnel needed to evacuate and secure an affected area was estimated as 2% of the number of evacuees. The study estimated the cost of emergency responders at \$35 per person-day assuming these were largely National Guard resources.

NUREG-75/014, "Reactor Safety Study" Appendix VI, 1975 [9]

The Reactor Safety Study, also called WASH-1400, presented the first comprehensive NPP PRA. As part of the study, the CRAC code was developed to estimate health and economic consequences of accidental releases of radioactive material to the atmosphere [10]. WASH-1400 describes the development of the CRAC economic model, provides detail regarding the parameters used in the model, and provides a basis for the values used. The model was intended to estimate the direct costs of measures used to mitigate the effects of a reactor accident. The costs included managing the evacuation, temporary accommodation for the evacuees, the value of goods that might be condemned, the decrease in value of interdicted property, and the cost of decontaminating property. For evacuation and relocation, WASH-1400 used the cost values from the 1974 EPA study [15] escalated to the current year. Table VI, 12-9 "Input Parameters for the Model," of WASH-1400 lists some of these values, including evacuation cost of \$13.50/person day, explaining that costs had increased about 15% since the 1974 EPA evacuation study.

The costs of decontaminating developed property were estimated assuming two alternative methods would be used, depending on the degree of decontamination required to meet the radiation exposure standards. If a DF of 2 would suffice (50% reduction in contamination), the method would consist of replacing lawns and cleaning roofs and paving. If a DF of 20 were

required (95% reduction in contamination), lawns, paving, and roofing would be replaced. A maximum DF of 20, averaged over large areas, was considered practical. The study states that costs for decontamination of developed property include costs for preparation of a disposal site; however, no detail regarding disposal is provided and the unit cost values do not appear to be sufficient to address any large scale disposal.

The study describes estimates for single family dwellings and apartment developments that were based on typical sizes. For a single family dwelling, the study estimates the decontamination cost of a structure occupying 2,000 square feet to be in the range of \$320 to \$370 per person for a decontamination factor of 2 and in the range \$560 to \$1,630 per person for a DF of 20. The study explains that if three floors of apartments are assumed, the decontamination cost becomes about \$30 per person for a DF of 2, and in the range \$140 to \$420 per person to achieve a DF of 20. For a six-floor structure, these per person costs would be halved. For commercial, industrial, and public property, the study explains that by assuming commercial and industrial land is 50 percent occupied by structures and 50 percent paved for streets, parking lots and driveways, the cost of decontamination of these areas would be about \$21 per person for DF=2 and in the range \$140 to \$490 for DF=20. By assuming parks are mainly lawn with surrounding streets, the per person cost would be in the range \$26 to \$33 for DF=2 and \$31 to \$46 for DF=20. The study explains that public areas include a variety of buildings, such as schools, government buildings, and sewage plants, and in general, the land use in these areas is less intensive than in commercial and industrial areas. On the assumption that public land is 30 percent occupied by structures and the remainder is paved for streets and parking lots, the decontamination cost was estimated to be about \$2,200 per acre for DF=2 and in the range \$11,000 to \$35,000 per acre for DF=20. This would equate to a range of \$27,000 to \$86,500 per hectare in 1975 dollars. The per person cost was about \$40 for DF=2 and in the range \$200 to \$640 for DF=20. No detail was provided to support these estimates. The details in developing cost per person were not provided in the document.

WASH-1400 also considered interdiction and relocation, explaining that if land were to be interdicted, the occupants and owners would bear two kinds of costs, including the loss of productive use of the land and its improvements (structures and other fixtures) and the cost of relocation. Relocation costs included loss of income and moving costs for households, businesses, and the public sector. This loss of income would only be applicable during the period of resettlement. WASH-1400 assumed that this period lasts 90 days, allowing the person time to resettle and to find a job, based on unemployment data at the time. The household loss was thus estimated at \$1,100 per person. Corporate income loss was estimated at \$940 per person. Moving costs for residents were estimated at \$400 per person to include moving 10,000 pounds of family belongings. Moving costs for businesses were estimated at \$420 per person and costs for moving public sector facilities (e.g., government buildings) were estimated at \$50 per person. The total relocation cost was estimated as a sum of the above, equal to about \$2,900 per person.

NUREG-2300, "PRA Procedures Guide," Volume 2, 1982 [16]

The PRA Procedures Guide describes methods for estimating costs of protective measures and decontamination, generally referring to WASH-1400. It is the user's responsibility to collect and process data related to emergency response information and criteria for interdiction and decontamination. The guide discusses the possible modes of decontamination, including physical removal of the radionuclides, stabilization of the radionuclides in place, and management of the environment. The procedure used in a given case would depend on many factors, including (1) the type of surface contaminated, (2) the external environment to which the surface is

exposed, (3) the possible hazards to people, (4) the costs, (5) the degree of decontamination that is required, and (6) the consequences of the decontamination operation.

The PRA Procedures Guide discusses a large body of experimental data related to decontamination of structures, pavements, and land with most of the data generated from planning for reclamation in the event of a nuclear war. The guide clarifies that due to differences in the sizes of contaminant particles and in decontamination criteria, some of these experimental data are not directly applicable to reactor accidents. A maximum DF of 20 was considered practical on the basis of the review carried out for the Reactor Safety Study. The PRA Procedures Guide discusses evacuation costs available from the 1974 EPA study. The guide describes the WASH-1400 approach for use in developing relocation and decontamination costs and provides examples of inputs for use in the consequence model.

NUREG/CR-2723, “Estimates of the Financial Consequences of Nuclear Power Reactor Accidents,” 1982 [7]

This report developed preliminary techniques for estimating the financial consequences of potential nuclear power reactor accidents. The report includes a limited discussion on the parameters and then presents the cost results in Appendix A of that document. The offsite cost estimates were based on CRAC2 calculations. Calculations were performed for 91 sites, many of which had more than one reactor. All persons within the EPZ were assumed to evacuate to 15 miles, at which point they receive no further exposure. The evacuation speed was 10 mph after a delay of 1, 3 or 5 hours (with weights on the delay times of 30%, 40%, and 30%, respectively). The report includes a discussion of the discounting approach used in the calculation. The report explains that several classes of costs are not included, such as indirect costs, socio-economic costs, and health care costs. The report describes the uncertainties associated with these types of analyses.

NUREG/CR-2552, “CRAC2 Model Description,” 1984 [11]

The release of CRAC2 provided an improved model for evacuation that considered a delay time followed by evacuation away from the reactor in a radial direction at a constant speed. All persons within the designated evacuation area were assumed to move as a group at the same speed after an assumed delay. Different shielding factors were available for evacuees.

Evacuation costs were based on WASH-1400 and escalated to current dollars. The costs of evacuation were computed by multiplying the total number of individuals evacuated by an average cost per evacuee. The CRAC2 model description states that cost per evacuee included evacuation supervision costs, transportation costs, and food and lodging costs. The cost for disposal of farm products was described as a calculation of the farm production multiplied by the season, which was 0 if outside the growing season and 1 if within the growing season. The crop was therefore either fully disposed or no disposal costs were assumed. However, only the value of the crop was included in the equation provided. No variable representing disposal costs was described. This omission of disposal cost appears to have continued through to the current MACCS model.

NUREG/CR-3673, “Economic Risks of Nuclear Power Reactor Accidents,” 1984 [13]

NUREG/CR-3673 included newly developed offsite economic consequence models to estimate the costs of protective measures for the public and public health impacts. The cost of evacuation and relocation, agricultural product crop disposal, land and property interdiction were included in

the economic models. Details regarding crop disposal were not provided. The offsite economic consequences included costs associated with countermeasures taken to reduce population dose, offsite property damage or losses (e.g., costs associated with countermeasures to reduce population dose), cost of radiation induced health effects, and health care costs incurred by the population living at offsite locations. The new economic model was based on staged implementation of offsite protective measures from evacuation through completion of the decontamination program identified as 120 days. Discussion of a decontamination timeline which establishes durations for some parameters was presented; however, many of the costs and decontamination details discussed in NUREG/CR-3673 were taken from an unpublished draft document identified as OS84, "An Assessment of Decontamination Costs and Effectiveness for Accident Radiological Releases." Similarly, in Table 4.4 of NUREG/CR-3673, the non-farmland decontamination costs per person are listed, but the source that is referenced to explain the per person allocation was unpublished.

NUREG/CR-3673 describes evacuation costs per person to include housing, food, transportation, and cost of evacuation personnel to supervise the process. The evacuation cost values were obtained from the 1974 EPA study of evacuation risks and were escalated to 1982 dollars. The calculation in NUREG/CR-3673 includes \$24.60 per person-day for commercial care facilities and \$11.90 per person-day for mass care facilities, applying 80% to the former and 20% to the latter following the EPA approach [15]. This totaled \$22.06 per person-day. NUREG/CR-3673 adds \$1.64 per person-day to represent cost for emergency workers at a rate of 2% of the total number of evacuees at \$58 per person-day. The total is \$23.70 which is rounded to \$24 per person-day. However, the number of evacuees is never discussed in the document, making it unclear how the cost of emergency workers was calculated. It is also not clear why the duration of evacuation personnel costs was selected the same as evacuee costs. Once the area is cleared, most of these workers are no longer involved.

NUREG/CR-3673 describes lost income plus lost corporate profit and interest estimated to be \$26 per person-day in 1982 dollars. This cost component was modeled by accounting for lost personal income (not including interest, dividends, and transfer payments) and corporate income and profits during an evacuation period. The national average personal income plus corporate profits and interest was estimated to be \$26 per person-day (1982 dollars) based on Department of Commerce values at the time. But this additional \$26 per person-day does not appear to have been added into the parameter; which may be appropriate since lost income may be double counted under other parameters. Costs of moving belongings to new areas were described as small and were not included, since all tangible property in the interdicted area is assumed to be replaced. The cost of permanent relocation was estimated at \$4,000 per person in the interdiction areas and was entirely from temporary income losses.

NUREG/CR-3413, "Off-Site Consequences of Radiological Accidents: Methods, Costs and Schedules for Decontamination," 1985 [17]

NUREG/CR-3413 was undertaken to provide NRC with improved technical information and enhanced analytical capabilities for site restoration following a major radiological accident at an NPP. Objectives of the study included, in part, collecting information related to decontamination, developing cost functions for decontamination procedures, and developing a computer program called DECON compatible with CRAC2 to produce information related to decontamination activities. NUREG/CR-3413 was listed in the bibliography of the Site Restoration Study [3], but was not identified as a reference in any other MACCS related documents investigated with this study.

The approach included development of generic costs based on decontamination operations (e.g., vacuum, spray, or mow) and surface types (e.g., agriculture fields, vacant land, wooded areas, and exterior walls). The approach distinguished percent contamination on various surfaces including 10% for exterior vertical walls, 5% for interior vertical walls, and 50% for interior floors. The calculation assumes decontamination is conducted within the scheduled year. In nearly all cases, the decontamination costs constituted only a small fraction of the total property losses.

NUREG/CR-4691, "MELCOR Accident Consequence Code System (MACCS)," 1990 [12]

With the publication of NUREG/CR-4691, the MACCS code was released for use superseding CRAC and CRAC2. This document describes the algorithms and provides details related to the technical bases but does not provide numerical values for parameters. Costs resulting from emergency response actions and from long-term protective actions are modeled in MACCS. Protective action costs are dependent on the site of the accident, the actions taken during and after the accident, and the accident itself. Economic and demographic data associated with the accident site are supplied in the site data file which is developed with SecPop. The economic models in MACCS were intended to estimate the direct offsite costs resulting from a reactor accident. NUREG/CR-4691 described the following costs treated in MACCS:

- food and lodging costs for short-term relocation of people who are evacuated or relocated during the emergency phase of the accident,
- decontamination costs for property that can be returned to use if decontaminated,
- economic losses incurred while farm and non-farm property are temporarily interdicted for a period of time during decontamination and possibly additional time following decontamination to allow for radioactive decay to reduce doses to acceptable levels,
- relocation cost from hotspot and normal relocation,
- POPCST for non-farmland population temporary or permanent relocation,
- economic losses resulting from milk and crop disposal, and
- economic losses due to permanent interdiction of property.

The total cost of early protective actions is the sum of the evacuation and relocation costs. The estimation of early protective action costs in the MACCS economic model is dependent on the number of individuals involved in the emergency actions being taken, the period during which people are provided with temporary lodging, and daily cost of the protective actions per individual. The farm interdiction period was introduced as eight years, but the basis for this duration was not documented. The 8-year time period is programmed into the MACCS code and is not an input parameter. The parameter name TMIPND was introduced for the intermediate time period as typically being one month. The name of the parameter was later changed to DUR_INTPHAS in NUREG/CR-6613. Although crop disposal is mentioned, there are no details provided regarding cost of disposal.

NUREG/CR-4551, “Evaluation of Severe Accident Risks: Quantification of Major Input Parameters,” 1990 [2]

NUREG/CR-4551 provides the technical basis and recommended values for a set of farm and non-farmland economic parameters developed for the five sites evaluated in NUREG-1150. The document describes RELCST, EVACST, POPCST, VALWF, VALWNF, DPRATE, and DSRATE in reasonable detail to understand the basis.

Relocation costs (RELCST) included food, housing, and transportation and were estimated based on NUREG/CR-3673, which was based on the 1974 EPA study [15]. NUREG/CR-3673 study values were escalated to \$27 per person-day. A separate and brief calculation was performed in NUREG/CR-4551 that confirmed this value was reasonable. The same \$27 per person-day was also recommended for evacuation cost (EVACST). The document did not address cost of evacuation support from emergency responders and did not address lost income or replacement of personal property, which were described in earlier studies (WASH 1400 and NUREG/CR-3673). It appears lost personal and corporate income were not included in the evaluation of this parameter, and this practice was carried forward.

For POPCST, which is a one-time per capita cost for temporary or permanent relocation of population and businesses interdicted during the long-term phase, a recommended value of \$5,000 per person was based on NUREG/CR-3673, which only included temporary loss of income.

NUREG/CR-4551 estimated the value of non-farmland wealth (VALWNF) and provided recommendations on the fraction of farm wealth (VALWF) in the region from improvements such as buildings, equipment, and infrastructure, using data from the U.S. Department of Commerce. NUREG/CR-4551 recommends 20% for a depreciation rate (DPRATE) of untended property explaining no data was available for this choice but that depreciation should be greater than tended property, which ranges from 3% to 5% per year. These values appear to be carried forward from WASH-1400. The recommended discount rate (DSRATE) is 12%, which was based on national rates of return of selected investments at the time of the study.

NUREG-1150, “Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants,” 1990 [1]

NUREG-1150 included PRAs for five commercial NPPs, and MACCS was used for the consequence analyses. The dose mitigation effects from emergency response actions included evacuation, sheltering, and relocation of people. Interdiction of crops, decontamination, temporary interdiction, and condemnation of land and buildings were also considered. Most of the parameters were developed in NUREG/CR-4551.

For the base case analyses, it was assumed that 99.5 percent of the population within the plume exposure pathway EPZ evacuated. Hotspot and normal relocation was implemented at 12 and 24 hours, respectively. Normal and hotspot relocation values of 25 and 50 rem, respectively, were used in the analysis. Appendix A to NUREG-1150 states that relocation assumptions outside the 10-mile EPZ were based on the 1989 draft of the EPA “Manual of Protective Action Guides and Protective Actions for Nuclear Incidents.” The 1989 draft document was not available for review; however, the 1975 Protective Action Guide (PAG) Manual [18] and the 1992 PAG Manual [19] identify 1 and 5 rem as the evacuation thresholds.

NUREG/CR-6613, "Code Manual for MACCS2, Users Guide" Volume 1, 1998 [10]

This document was published as an updated version of MACCS, named MACCS2. It is primarily a user's guide but includes some model description information. Protective measures and decontamination parameters are described, and the allowable range for each parameter is provided.

EVACST is described as including food, housing, transportation, and lost income. However, the value provided is the \$27 per person-day from NUREG/CR-4551, which was found not to include lost income. RELCST is described as including food, housing, transportation, lost income, and replacement of lost personal property. The value provided was the same \$27 per person-day found in NUREG/CR-4551.

Decontamination parameters and the application of dose criteria are described. Up to three levels of decontamination can be defined. If the maximum decontamination level is insufficient to restore an area to immediate habitability, an additional period of temporary interdiction following the maximum decontamination level is considered to allow for dose reduction through radioactive decay and weathering. If the property cannot be made habitable within 30 years for non-farmland and within eight years for farmland, or if the cost of reclaiming the property exceeds the cost of condemning it, the property is condemned and permanently withdrawn from use. EPA Superfund guidance is referenced as the basis for 30 years. The 30-year time period is currently hard wired in the MACCS code. No basis was provided for the farmland duration of eight years.

Farm dependent decontamination cost is a function of the area of the grid element devoted to agriculture. Population dependent decontamination cost is a function of the population residing in the grid element. During the decontamination period, the population from areas that are being decontaminated is assumed to be relocated to uncontaminated areas, and the associated cost from loss of use is calculated during this period of temporary interdiction.

Many decontamination processes (e.g., plowing or fire-hosing) reduce groundshine and resuspension doses by washing surface contamination down into the ground. NUREG/CR-6613 explains that since these processes may not move contamination out of the root zone, the WASH-1400-based economic cost model assumed that farmland decontamination reduces direct exposure doses to farmers without reducing uptake of radioactivity by root systems. Thus, decontamination of farmland does not reduce the ingestion doses produced by consumption of crops that are contaminated by root uptake.

The intermediate phase can have a duration from 0 to 1 year. If the intermediate phase dose criteria is satisfied, the resident population is assumed to be present and subject to radiation exposure from groundshine and resuspension for the entire intermediate phase. If the intermediate phase exposure leads to doses in excess of the established criteria (DSCRTI), then the population is assumed to be relocated to uncontaminated areas for the entire intermediate phase, with a corresponding economic cost defined by the user through the input variable RELCST.

The long-term phase immediately follows the intermediate phase. Mitigative action models for the long-term exposure phase implemented in MACCS2 differ slightly from the previous models implemented in MACCS. The model decisions on mitigative action in the long-term phase are based on two sets of independent actions: (1) decisions relating to whether land at a specific location and time is suitable for human habitation, "habitability," and (2) decisions relating to whether land at a specific location and time is suitable for agricultural production, "farmability."

SAND96-0957, “Site Restoration Study,” 1996 [3]

The Site Restoration Study presents a detailed evaluation of the cost of cleanup of a nuclear weapons facility accident and describes the methodology applied in the estimation. The study estimated the costs of compensation for damaged property and lost income, site characterization, decontamination, demolition, transportation, waste disposal, and ecological restoration. To support development of the estimates, assumptions were provided regarding land use for typical residential areas, commercial sites, industrial areas, vacant land, and streets. The study methodology was applied to mixed-use urban areas, midwestern farmland, western rangeland, and forested land. For the mixed-use urban areas, the cost estimates do not include downtown business and commercial districts, heavy industrial areas, or high-rise apartment buildings.

The study discusses advancements in technologies, economies of scale, and lessons learned that have occurred through large scale decontamination and demolition of many DOE sites. The Site Restoration Study provides cost estimates of decontamination strategies that would yield DFs of 2 to 5, 5 to 10, and greater than 10 for urban areas under normal and expedited decontamination schedules. The study concludes that compensation for acquired property, decontamination, and waste disposal are major components of costs. It states these components of cost are uncertain to possibly a large degree and as a result of these uncertainties, “it is not possible to identify the major cost component with any confidence.” The study is quite detailed, but also explains there were many types of costs that were difficult to quantify and thus omitted from the analysis.

NUREG-1935, “State-of-the-Art Reactor Consequence Analyses (SOARCA) Report,” 2012 [14]

The NRC initiated the SOARCA project to develop best estimates of accident progression and offsite radiological health consequences for potential severe reactor accidents for two pilot plants. The SOARCA project evaluated plant improvements and changes not reflected in earlier NRC publications such as WASH-1400, [9], NUREG/CR-2239, [20], and NUREG-1150 [1]. SOARCA included system improvements, improvements in training and emergency procedures, offsite emergency response, and security-related improvements, as well as plant changes such as power uprates and higher core burnup. The SOARCA project did not include any research related to the update of cost parameters. Cost values in SOARCA were only used to support the habitability decisions in the model. The cost parameters associated with decontamination were escalated to account for inflation using the CPI-U. Two levels of decontamination were represented by dose-reduction factors (also referred to as DFs) of 3 and 15, which are the same as those applied in NUREG-1150. SOARCA did include updates to emergency response parameters.

A.6 Review of Decontamination Activities

In addition to the literature review, multiple meetings were held with experienced decontamination professionals. The services of Environmental Dimensions Inc. (EDI) were acquired to support the development of some cost parameters. EDI has current experience in radiological site characterization, remediation, decontamination, decommissioning, waste transportation, and disposal. In addition, meetings with DOE and NRC staff were held to discuss decontamination and decommissioning experience. In meetings with the DOE, decontamination activities at Rocky Flats, Fernald, and other sites were discussed. Detailed unit pricing for the DOE decontamination techniques was not available for these projects and it was explained that prices varied. As techniques were improved, costs typically went down [6].

Large scale decontamination of urban areas has been implemented around Chernobyl, Goiana, and Fukushima ([21], [22], [23], [24]). In addition, substantial radiological cleanup of residential and industrial sites was completed during the 1990s and later is documented in [6]. These efforts provide insights into approaches that could be implemented in a large scale cleanup. One example is the decontamination of 40 residential properties during the 1995 to 1997 Austin Avenue Radiation remedial action in Pennsylvania [6]. For most of these properties, the EPA gave the building owner the choice of having the government rebuild the structure, offsite relocation, or building repair. These and other decontamination activities were researched to support development of the updated parameters.

A.7 Identification and Summary of Recommended Cost Parameters

The scope of the project included performing a comprehensive review of protective measures parameters applied in MACCS. This included identifying where specific costs related to protective measures are captured in the model. Parameters that influence the timeframes for implementing protective measures and decontamination were also reviewed, because the timeframe can affect cost. NRC published a MACCS best practices document [25] which addresses most MACCS parameters and provided a technical basis for many of the protective measures parameters. The best practices document provided a starting point for identifying candidate parameters; however, the document does not address cost parameters. Additional candidate parameters were identified through review of the comprehensive parameter table provided in Appendix D of the MACCS Users Guide [10]. The 32 parameters in Table A-1 were selected and reviewed for this project.

Table A-1 MACCS Parameters Selected for Review

Parameter	Module	Description	Origin ²⁴
DOSHOT	EARLY	Hotspot relocation dose	NUREG/CR-4691, Vol. 2
DOSNRM	EARLY	Normal relocation dose	NUREG/CR-4691, Vol. 2
DPPEMP	EARLY	Dose Projection Period for Early Phase	New Parameter
TIMHOT	EARLY	Estimated time to relocate residents from areas that exceed DOSHOT	NUREG/CR-4691, Vol. 2
TIMNRM	EARLY	Estimated time to relocate residents from areas that exceed DOSNRM	NUREG/CR-4691, Vol. 2
CDFRM	CHRONC	Farmland Decontamination Cost	WASH-1400 ²⁵
CDNFRM	CHRONC	Non-farmland Decontamination Cost	WASH-1400
DLBCST	CHRONC	Decontamination Worker Labor Cost	NUREG/CR-3673
DOSEMILK	CHRONC	Maximum allowable food ingestion dose from milk crops	WASH-1400
DOSEOTHER	CHRONC	Maximum allowable food ingestion dose from nonmilk crops	WASH-1400
DOSELONG	CHRONC	Maximum allowable long-term annual dose to an individual from ingestion of the combination of milk and nonmilk crops.	WASH-1400
DPRATE	CHRONC	Property Depreciation Rate	WASH-1400

²⁴ Identifies the document where the first use of the current terminology for the parameter was found.

²⁵ WASH-1400 Table VI 12-2 references 1974 cost reports.

Table A-1 MACCS Parameters Selected for Review (cont.)

DPP_INTERPHAS	CHRONC	Dose Projection Period for Intermediate Phase	New Parameter
DSCRLT	CHRONC	Long-term Phase Dose Criteria	WASH-1400
DSCRTI	CHRONC	Intermediate Phase Dose Criteria	WASH-1400
DSRATE	CHRONC	Societal Discount Rate for Property	WASH-1400
DSRFCT	CHRONC	Decontamination Factors	WASH-1400
DUR_INTPHAS	CHRONC	Duration of Intermediate Phase Period	NUREG/CR-3673 ²⁶
EVACST	CHRONC	Early Phase Cost of Evacuation	WASH-1400 ²⁷
FRFDL	CHRONC	Fraction of Farm Decontamination Cost for Labor	NUREG/CR-3673 Table 4.3 ²⁸
FRFIM	CHRONC	Farm Wealth Improvements Fraction	WASH-1400
FRNFIM	CHRONC	Non-farmland Wealth Improvements Fraction	WASH-1400
FRNFDL	CHRONC	Fraction of Non-Farmland Decontamination Cost for Labor	NUREG/CR-3673 Table 4.4 ²⁹
LVLDEC	CHRONC	Number of decontamination strategies	WASH-1400
POPCST	CHRONC	Per Person Cost of Long-term Relocation	WASH-1400
RELCST	CHRONC	Relocation Cost per Person-Day	WASH-1400 ³⁰
TFWKF	CHRONC	Farm Decontamination Workers Work Fraction	NUREG/CR-3673 Table 4.3 ²⁸
TFWKNF	CHRONC	Non-farmland Decontamination Workers Work Fraction	NUREG/CR-3673 Table 4.3 ²⁸
TIMDEC	CHRONC	Decontamination Times	NUREG/CR-3673
TMPACT	CHRONC	Time Action Period Ends	NUREG/CR-4691, Vol. 2
VALWF	CHRONC	Value of Farm Wealth	WASH-1400 ³¹
VALWNF	CHRONC	Value of Non-farmland Wealth	WASH-1400 ³²

Developing a defensible technical basis for the updated cost parameters included investigation of implementation of protective measures and decontamination activities. The technical basis for most of the cost parameters has been incorporated into the appropriate sections of Chapter 4. A decontamination approach was developed (see Appendix B) to identify decontamination and related costs and attribute these to specific MACCS parameters.

²⁶ The equation for application of intermediate phase relocation is first described in NUREG/CR-3673 [13], but the parameter name first appears as TMIPND in NUREG/CR-4691.

²⁷ WASH-1400 references the 1974 EPA evacuation study for this cost data.

²⁸ Table 4.3, "Decontamination Cost and Effectiveness Values for Farm Areas," is referenced to Os84, which was a document by R.M. Ostmeyer that was never published and is not available. Thus, the origin is not traceable.

²⁹ Table 4.4, "Decontamination Cost and Effectiveness Values for Non-Farm Areas," is referenced to Os84, which was a document by R.M. Ostmeyer that was never published and is not available. Thus, the origin is not traceable.

³⁰ Average income was based on 1972 data, escalated to 1975. Duration of benefits was based on average unemployment from 1960 to 1972. Lost income for corporations was based on 1974 data.

³¹ Described as value of farm property. Agricultural land use data escalated from 1969 to 1975.

³² References 1971 National Bureau of Economic Research data.

A.8 Summary

A total of 32 input parameters related to decontamination and protective measures were updated by SNL staff. Updated values for each parameter were recommended. Where practical, a process was described that analysts may implement to update or to develop site-specific parameters.

A.9 References

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APPENDIX B

GENERAL DECONTAMINATION APPROACH

B.1 Introduction

This appendix provides a method for deriving the decontamination cost parameters CDNFRM and CDFRM for use in MACCS. Decontamination costs in MACCS are calculated separately for farmland and non-farmland. Total decontamination costs for farmland are estimated by multiplying the hectares of farmland considered contaminated³³ (i.e., the farmland area of grid elements where doses exceed the habitability criteria but could be made habitable by decontamination followed by interdiction) by a derived cost per hectare represented by the MACCS parameter CDFRM. Non-farmland includes any land that is not farmland or water, namely urban, rural, and undeveloped lands that make up a large portion of the U.S. Total decontamination costs for non-farmland are estimated by multiplying the population of grid elements where doses exceed the habitability criteria (but could be made habitable by decontamination followed by interdiction) by a derived cost per person represented by the MACCS parameter CDNFRM.

It is the responsibility of the user to derive the MACCS input parameters CDFRM and CDNFRM for use in the code. In this appendix, models are developed to estimate the costs of both farmland (CDFRM) and non-farmland (CDNFRM) decontamination needed to achieve a number of different of dose reduction factors (DF). In the model developed in this appendix, each DF level is based on a process or set of processes to achieve that level. The model is developed using a “bottom-up” approach that combines land use data and population data from U.S. databases with unit cost and dose-reduction effectiveness information obtained from Fukushima-related research and experience. This methodology is illustrated using data applicable to the conterminous United States (CONUS), resulting in a set of generic U.S. average results. It should be emphasized that although the values developed here are considered reasonable generic U.S. average values, this methodology could be modified with justification to fit specific applications. The explanation of the methodology, coupled with the assumptions and the references for the underlying data sources, are provided in order to allow examination of the approach and resulting values to facilitate evaluation and/or modification for site-specific application.

B.2 Background

As discussed in Appendix A, decontamination costs were first estimated as part of WASH-1400. Two dose reduction levels (a DF of 2 and a DF of 20) were assumed and some decontamination methods were identified. For example, replacing lawns and cleaning roofs and paving were assumed to achieve a DF of 2 and replacement of lawns, paving, and roofing were assumed to achieve a DF of 20. Estimates of the per-capita decontamination costs of different types of land uses (e.g., single family dwellings, apartments, commercial and industrial property, parks, streets, etc.) were provided. However, neither the details of the calculation to support these estimates nor the approach used weight these per-capita costs associated with specific types of land uses to yield an overall per-capita costs were provided.

With the development of MACCS, a value for decontamination costs was provided in the sample problems used for MACCS [1], [2]. As stated in [1], “The parameter values found on these data

³³ MACCS also applies a test to determine whether the farmland can be made farmable (i.e., if the ingestion dose criteria defined by DOSEOTH) can be met by a period of interdiction in its decision logic for determining whether to decontaminate or condemn farmland.

cards are for the most part identical to the values used in the MACCS calculations for the second draft of NUREG-1150.” However, although the technical bases for MACCS parameter values developed for NUREG-1150 are documented in [3], the discussion in [3] does not provide any additional information on the derivation of these decontamination cost parameters. The values reported in [3] are based on [4], which discusses the approach to developing decontamination cost value, but does not provide details of the derivation of the unit cost values. For example, in Table 4.4 of NUREG/CR-3673 [4], the per-capita non-farmland decontamination costs are listed but rely on an unpublished SNL draft document.

There are limited sources available for estimating non-farm decontamination costs in a form suitable for direct use in MACCS, which requires a weighted average per-capita or per-hectare decontamination cost. Two studies ([6], [7]), neither of which provide decontamination costs on per-capita basis, were identified in Appendix A. Tawil et al. [6] developed a computer program called DECON compatible with CRAC2 to produce information related to decontamination activities. Chanin and Murfin [7] describes a methodology for estimating cleanup costs for mixed-use urban areas, midwestern farmland, western rangeland, and forested land. The study provided cost estimates of decontamination strategies that would yield DFs of 2 to 5, 5 to 10, and greater than 10 for urban areas under either normal or expedited decontamination schedules. Both studies provide a detailed database for their decontamination methods and both include consideration of the transportation and disposal of wastes arising from decontamination; however, only [7] includes an estimate of the ultimate disposal costs in its calculations. Lemay [8] estimated per-capita decontamination costs for areas in and around New York City using a variety of data sources, including [7], [9], [10], [11], and [12]. The analysis in [8] showed that there could be a wide range in estimated per-capita decontamination costs.

For this analysis, most unit costs for decontamination activities in this appendix are based on the results of the decontamination pilot projects carried out after the Fukushima accident, as documented in [13]. This report provides datasheets for a wide array of decontamination techniques, and includes information on the unit cost (cost per surface area decontaminated), unit waste generation rates, and the range of dose reduction factors achieved. These values are considered to be appropriate because they are based on recent actual experience obtained from wide-area decontamination of the types of materials released in a severe light-water reactor accident. This information is coupled with information representing typical U.S. patterns of land use and U.S.-specific sources of information on waste transportation and disposal costs.

B.3 Methods

The methodology is presented in the following sections by providing the governing equations for both non-farm and farmland decontamination in Section B.3.1. This is followed in Section B.3.2 by a summary of the specific decontamination methods assumed and their characteristics, and a justification for why the selected combination of decontamination methods would achieve the expected overall wide-area dose reduction factor. The actual values used to parameterize the model, together with their data sources, are provided in Section B.3.3 for farmland and Section B.3.4 for non-farmland. The resulting final set of weighted average decontamination costs are provided in Section B.4

B.3.1 Cost Categories and Equations

There are three basic cost categories that are used to account for the overall cost of decontamination. These are

- the cost to perform the decontamination processes on the property itself,
- the cost to sample and characterize the waste that is generated by the decontamination processes, and
- the cost to manage the waste.

The governing equation is provided in Equation (B-1):

$$CD_{Tot} = CD_{Decon} + CD_{Char} + CD_{Waste} \quad (B-1)$$

Here, CD_{Tot} is the total cost to perform the decontamination of the contaminated property, CD_{Decon} is the cost to perform the decontamination processes on the property, CD_{Char} is the cost to characterize the waste generated by the decontamination processes, and CD_{Waste} is the cost to manage the waste, i.e., store, transport, and dispose of the waste. The appropriate units in Equation (B-1) for farmland are \$/ha; for non-farmland they are \$/person. The equivalent MACCS input parameters for CD_{Tot} are CDFRM for farmland and CDNFRM for non-farmland.

There are typically multiple processes needed to perform the decontamination of the contaminated property, especially for non-farmland, and the total costs for farmland and non-farmland are expressed by the following equations:

$$CDFRM_{DECON,n} = \sum_i F_{Farm}^{DECON} \cdot (SURF_{i,Farm} \cdot COST_{i,n}) \quad (B-2)$$

$$\begin{aligned} CDNFRM_{DECON,n} \\ = \left(\frac{AREA_{TOTAL}}{POP_{TOTAL}} \right) \cdot \sum_l \sum_i f_l \cdot F_l^{DECON} \cdot (SURF_{i,l} \cdot COST_{i,n}) \end{aligned} \quad (B-3)$$

The parameters in Equations (B-2) and (B-3) are defined as follows:

f_l	Average fraction of area dedicated to land use l (dimensionless)
F_l^{DECON}	Fraction of area dedicated to land use l that is decontaminated (dimensionless)
$SURF_{i,l}$	Average decontamination surface area i per land area dedicated to land use l (square yards per acre)
$COST_{i,n}$	Average unit cost to decontaminate surface area i to achieve an overall decontamination level n (\$ per square yard)
$AREA_{TOTAL}$	Total area (acres)
POP_{TOTAL}	Total population (people)

In Equation (B-2), the only land use is farming. Results from the equation are in \$/acre but are converted to \$/ha to define the values for CDFRM.

In Equation (B-3), the land uses, l , included in the model are listed below:

- (1). High-density urban
- (2). Medium-density urban
- (3). Low-density urban
- (4). Low-density rural
- (5). Road
- (6). Forest (used to characterize the costs for a range of land uses, as described below)

For generality, a summation over multiple surface types is included in Equation (B-2); however, in Section B.4, the only surface considered is the farmland itself. The types of non-farmland surfaces, i , included in Equation (B-3) are listed below:

- (1). Asphalt
- (2). Concrete
- (3). Roof area
- (4). Roof gutters
- (5). Wall area (exterior)
- (6). Wall area (interior), including ceiling area
- (7). Floor area
- (8). Landscape trees
- (9). Landscape shrubs
- (10). Landscape lawn
- (11). Roads
- (12). Other

Values for the parameters in Equations (B-1) through (B-3) are developed for farmland in Section B.4 and for non-farmland in Section B.5. The data sources for are identified in those sections. The specific values for these depend upon the decontamination methods assumed, which are discussed in Section B.3. Overall decontamination costs are divided into three main cost categories: decontamination of the property; waste management (storage, transportation, and disposal); and waste sampling and characterization.

B.3.2 Decontamination Methods

A range of decontamination factors were selected for evaluation. DFs of 2 and 4 are ones that were achieved at Fukushima (a DF of 2 over larger areas and a DF of 4 on some properties) and are thought to be realistically achievable in the U.S. and in other countries. However, it should be noted that some more aggressive decontamination measures required to achieve high DFs were not taken at Fukushima, e.g., multistage and deeper soil removal for farmland and residential land, and replacing siding and shingles, cleaning and replacing interior surfaces, etc., for residential land. Thus, a DF of 8 may be achievable in practice if these more aggressive measures are taken. Even higher DFs should be achievable if whole buildings are demolished and the debris removed, but these methods are likely to be too expensive to be practical and may not be desired by the public.

The DF achievable for each surface by each process is uncertain, and each process therefore is therefore characterized by a range of DFs. In nearly all cases, the range reflects uncertainties created by multiple variables, many of which are out of the control of the decontamination workers. Some of these factors include whether deposition was by dry or wet processes, how

quickly the decontamination was performed following the accident, the nature of the soil or surface onto which the contaminant deposited, the nature of the contaminant, and the care involved in applying the decontamination processes. It is likely that many of these factors would lead to suboptimal results in practice, so DFs somewhere in the middle of the range are used in this development.

The methods assumed for achieving decontamination levels 1, 2, and 3 (associated with DFs of 2, 4, and 8, respectively) for farmland and for non-farmland are displayed in Tables B-1, B-2, and B-3, respectively. The methods in these tables are chosen as a relatively economical approach to achieve the required DFs; however, no effort has been made at this time to comprehensively assess which combination of methods result in achieving the highest dose reductions at the lowest costs. The costs associated with applying these methods are developed in the following sections. Most of the methods relate to data found in [13], which includes information on decontamination effectiveness, unit costs, and quantity of waste generated. The methods associated with interior surfaces are identified as assumptions because [13] did not provide methods for cleanup of interior surfaces. Most of the references in Tables B-1 to B-3 (the ones ending in -N, where N is an integer) are obtained from Appendix A of [13]. That report provides datasheets for a large number of decontamination methods.

A key assumption in MACCS is that decontamination (more accurately, reduction of doses) of farmland only affects doses to individuals working on the farmland; it does not affect contamination levels in crops produced on the land. If reducing contamination of foodstuffs were part of the motivation for farmland decontamination, it might not be appropriate to consider what [13] refers to as Reversal Tillage (Agricultural land-1) or Interchanging Topsoil with Subsoil (Agricultural land-2) as decontamination methods (more accurately, dose reduction methods). These methods are based on mixing or exchanging surface and subsoil layers and do not remove contamination; they simply bury the contamination below the surface so that the overlying soil provides shielding. However, since MACCS does not account for reduction of doses to foodstuffs resulting from decontamination, consideration of these methods for farmland decontamination is considered appropriate because they are consistent with the MACCS conceptual models. Following this line of reasoning, Reversal Tillage and Interchanging Topsoil with Subsoil are included in all three decontamination levels in Tables B-1 to B-3. A reasonable method with supporting cost data was not found to achieve an intermediate dose reduction for farmland, so the same method is used for both DF=4 and DF = 8.

The decontamination effectiveness values in Appendix A of [13] generally have a range, which conveys that the effectiveness of a decontamination method has variability. In this appendix, the ranges of DFs are converted into dose reduction percentages and are shown in Tables B-1 to B-3 in the columns labeled “low” and “high.” These tables also indicate the mean over the range assuming a uniform distribution. The mean values are used to estimate the overall dose reduction from decontamination of multiple surfaces that contribute to human doses.

Table B-1 Decontamination Methods Assumed for Level 1 (DF = 2)

Decontamination Surface	Dose Reduction			Reference or Assumption
	low	high	mean	
Asphalt	0%	67%	34%	Public infrastructure-1b ¹ , -3 ¹
Concrete	23%	70%	47%	Residential-14 ¹
Roof area			50%	Residential-1a ¹
Roof gutters	30%	90%	60%	Residential-2 ¹
Wall area - exterior	20%	70%	45%	Residential-15 ¹
Wall area - interior			50%	Wash ²
Floor area			50%	Scrub floors and shampoo carpets ²
Landscape - trees	23%	80%	52%	Forest-2 ¹
Landscape - shrubs	23%	80%	52%	Forest-2 ¹
Landscape - lawn			53%	Residential-8 ¹ , 3.5 cm, 67% of surface ²
Rural roads - asphalt		67%	67%	Public infrastructure-1b ¹ , -3 ¹
Forest area				No action
Farm area	20%	70%	45%	Agricultural land-1 ¹

¹ Source: Appendix A of [13]

² Source: Assumption/No data located

Table B-2 Decontamination Methods Assumed for Level 2 (DF = 4)

Decontamination Surface	Dose Reduction			Reference or Assumption
	low	high	mean	
Asphalt			95%	Public Infrastructure-1b ¹ , -8 ¹ , seal coat ²
Concrete			80%	Residential-12 ¹
Roof area	70%	80%	75%	Residential-1a 50% of surface ¹ Remove and replace 50% of surface ²
Roof gutters	30%	90%	60%	Residential-2 ¹
Wall area - exterior	60%	85%	73%	Residential-15 ¹ 50% of surface Remove and replace 50% of surface ²
Wall area - interior			75%	Wash 50% ² , Replace 50% ²
Floor area	70%	75%	73%	Scrub floors and shampoo carpets, 50% ² Replace 50% ²
Landscape - trees	23%	80%	52%	Forest-2 ¹
Landscape - shrubs	23%	80%	52%	Forest-2 ¹
Landscape - lawn			80%	Residential-8 ¹ , 3.5 cm
Rural roads - asphalt	95%	95%	95%	Public Infrastructure-1b ¹ , -8 ¹ , seal coat ²
Forest area	42%	61%	52%	Forest-3 ¹ , -2 ¹ with moderate soil removal
Farm area	83%	92%	88%	Agricultural land-6 ¹ , -2 ¹

¹ Source: Appendix A of [13]

² Source: Assumption/No data located

Table B-3 Decontamination Methods Assumed for Level 3 (DF = 8)

Decontamination Surface	Dose Reduction			Reference or Assumption
	low	high	mean	
Asphalt	95%	95%	95%	Public Infrastructure-1b ¹ , -8 ¹ , seal coat ²
Concrete			80%	Residential-12 ¹
Roof area	90%	100%	95%	Remove and replace 100% ²
Roof gutters	30%	90%	60%	Residential-2 ¹
Wall area - exterior	90%	100%	95%	Remove and replace ²
Wall area - interior	90%	100%	95%	Remove and replace ²
Floor area	90%	100%	95%	Remove and replace ²
Landscape - trees	42%	80%	61%	Forest-2 ¹ with increased topsoil removal
Landscape - shrubs	42%	80%	61%	Forest-2 ¹ with increased topsoil removal
Landscape - lawn	85%	100%	93%	Residential-8 ¹ , 3.5 cm; Residential-5 ¹ , 3.5 cm
Rural roads - asphalt	95%	95%	95%	Public Infrastructure-1b ¹ , -8 ¹ , seal coat ²
Forest area	42%	61%	52%	Forest-3 ¹ , -2 ¹ with moderate soil removal
Farm area	83%	92%	88%	Agricultural land-6 ¹ , -2 ¹

¹ Source: Appendix A of [13]

² Source: Assumption/No data located

Table B-4 provides a basis for the values of the DFs shown in the above tables (i.e., DFs of 2, 4, and 8). In this table, the mean values for dose reduction percentage shown in Tables B-1 through B-3 for each surface type are multiplied by the percentage contribution to dose for that surface type, as taken from Appendix B of [14]. The totals at the bottom of the table are the weighted average dose reduction percentages for each combination of methods, calculated separately for dry and wet deposition³⁴. The values in the row labeled “Total” indicate that the combination of techniques approximately produce overall DFs of 2, 4, and 8 for the three levels of decontamination, i.e., DFs of 2, 4, and 8 reduce overall doses by $1 - 1/DF$, or 50%, 75%, and 88%, respectively.

The contribution of doses from temporary occupancy of, or proximity to, rural roads, forested areas or farmland is not included in Appendix B of [14] and is therefore not included in Table B-4. It may be noted that although the recommended decontamination methods for forested land consistently produce a dose reduction that is less than the overall DF for the other surface types, this is consistent with Fukushima experience and is justified by the expectation that relatively little of the overall dose to an individual is from exposures to forested areas. DFs in the context of the MACCS code are intended to account for long-term averages for an individual, accounting for fractions of time spent at home, commuting, working, and doing other indoor and outdoor activities.

³⁴ Wet deposition refers to deposition during a period of precipitation; dry deposition is the only contributor to deposition when precipitation does not occur.

Table B-4 Decontamination Effectiveness

Decontamination Surface	Approximate Dose Contribution by Surface and Type of Deposition ¹		DF2		DF4		DF8	
	dry	wet	dry	wet	dry	wet	dry	wet
Asphalt	4%	7.5%	1.4%	2.5%	4.0%	7.1%	4.0%	7.1%
Concrete	4%	7.5%	1.9%	3.5%	3.3%	6.0%	3.3%	6.0%
Roof area	11%	9%	5.7%	4.5%	8.6%	6.8%	10.9%	8.6%
Roof gutters ²	-	-	-	-	-	-	-	-
Wall area - exterior	9%	1%	4.2%	0.5%	6.8%	0.7%	8.9%	1.0%
Wall area - interior	8%	0%	4.2%	0.0%	6.3%	0.0%	7.9%	0.0%
Floor area	8%	0%	4.2%	0.0%	6.0%	0.0%	7.9%	0.0%
Landscape - trees	10%	0.5%	5.4%	0.3%	5.4%	0.3%	6.4%	0.3%
Landscape - shrubs	10%	0.5%	5.4%	0.3%	5.4%	0.3%	6.4%	0.3%
Landscape - lawn	32%	74%	18%	40%	27%	59%	31%	69%
Total	96%	100%	50%	51%	72%	80%	86%	92%

¹ Values are inferred from Appendix B of [14]. When the relative contribution between two surface types is unknown (e.g., interior walls and floors), each surface is assumed to contribute an equal amount.

² Information on the contribution to dose from roof gutters was not available in Appendix B of [14].

Table B-5 summarizes, for the methods used in Tables B-1 through B-3, the methods and values from Appendix A of [13] in a convenient tabular form. All values in the Table B-5 are on a per-area basis except rain gutters, which are provided on a per-length basis. One of the decontamination methods identified in the table is strimming, which is the removal of vegetative cover using a string trimmer. Other methods in the table are self-explanatory.

Table B-5 Summary of Decontamination Methods and Parameters

Reference	Type of Surface	Method	Unit Cost* (\$/yd ² unless otherwise noted)	Dose-Reduction Factor	Solid Waste Volume (Liters/m ² unless otherwise noted) and Type
Residential-1a	Residential Houses: tile roof, iron roof	Surface brushing and washing (iron roof)	9.11	1.1–1.5	almost none (sludge & solids)
Residential-2	Residential Houses: gutter	Removal of debris and wiping	3.35 \$/linear foot	1.4–10	1 m ³ per house on average (litter, soil)
Residential-5	Residential Land: garden	Thin-layer topsoil stripping	4.93	1.1–10	20–40 (thickness of stripping 2–3 cm) (vegetation, soil)
Residential-8	Residential Land: turf	Turf stripping	12.54	5	20 – 50 (stripping 2–5 cm) (turf)
Residential-12	Concrete/asphalt surfaces: hard-packed floors, scaracement, flat roofs, stairs, terraced areas, car parks, pavements	Ultra-high-pressure water jet	9.62	5	~3 (Concrete & asphalt)
Residential-14	Concrete surfaces: concrete walls, scaracement	Brushing followed by high pressure water-jet washing	8.03	1.3–3.3	almost none (sludge)
Residential-15	Concrete surfaces: hard floors, scaracement, roof, stairs, balcony	High-pressure washing	8.03	1.3–3.3	almost none (sludge)
Public Infrastructure-1b	Asphalt roads	Road Sweeper (On-board road sweeper)	0.17	1–2	1–1.5 (soil, road dust, vegetation)
Public Infrastructure-3	Asphalt roads	Water-jet vehicle	1.25	1–3	few (sludge)
Public Infrastructure-8	Asphalt roads	Asphalt removal by surface stripping machine	3.26	22	~8 (stripping ~5 mm) (Asphalt)
Forest-2	Forested flat ground	Humus and thin-layer topsoil removal (stripping)	7.44	1.3–5	20–90 (litter, humus, soil)
Forest-3	Forested flat ground	Strimming	1.34	-	5–10 (grasses, shrubs, litter)
Agricultural land-1	Paddy fields, vegetable fields	Reversal tillage	0.28	1.4–2.5	-
Agricultural land-2	Paddy fields, vegetable fields	Interchanging topsoil with subsoil	2.59	~3	-
Agricultural land-6	Paddy fields, vegetable fields	Mowing	0.59	-	9–12 (vegetation)
Agricultural land-7	Paddy fields, vegetable fields, fruit farm	Strimming	0.84	-	9–12 (crops)

*Assumed conversion of 100 Yen per dollar

Source: adapted from Appendix A of [13]

The processes associated with interior surfaces in Tables B-1 through B-3 are defined by assumption because [13] does not provide processes for cleanup of interior surfaces. The costs provided in Tables B-12 to B-14 for some of these processes (e.g., wash, scrub floors and shampoo carpets, remove & replace) are assumed based on a review of costs from [15]. Cost values from [15] were escalated by a factor of roughly two to account for the increased difficulty of performing work in a contaminated environment.

Some of the decontamination processes for farmland in Appendix A of [13] involve stripping a layer of topsoil followed by permanent disposal. Such methods have both advantages and disadvantages. The primary advantage is that most of the contamination is removed from the site and farming can be reestablished more quickly. The chief disadvantage is that soil disposal is extremely expensive, potentially resulting in costs in the multiple hundreds of thousands of dollars per hectare. Another disadvantage is that the top layer of soil is generally the most fertile, and this layer is removed from the farmland. Finally, as stated above, MACCS does not fully accommodate this type of decontamination in that it does not account for the effect of decontamination on dose levels of future crop and dairy production. Removal and disposal of soil was initially considered as a potential method for farmland decontamination, but was discarded for the above reasons. Instead, to achieve the higher dose-reduction factors for farmland, it was assumed that the land would be mowed (Agricultural land-6) and then the topsoil would be interchanged with the subsoil (Agricultural land-2). The unit cost estimates from [13] were used for this method together with the assumption that the any debris from mowing would be emplaced with the topsoil in order to minimize waste generation. However, the dose reduction percentages for the Agricultural Land-2 in Tables B-2 and B-3 are based on information from Public Health England (PHE) [16] [17] for a method similar to Agricultural Land-2 that is called skim and burial plowing; it essentially inverts the top approximately 5-cm layer of soil with a 45-cm layer of subsoil. References [16] and [17] indicate a significantly larger DF than the JAEA report for similar methods, indicating significant uncertainty in the outcome of decontamination methods. The PHE reports add the caveat that the dose-reduction factors can be achieved if the method is "optimized according to the contaminant distribution in the soil." This caveat corresponds to the fact that the contaminant may be spread over a thinner or thicker layer of soil and that it is important to take this into account when the inversion is performed. For this analysis, we assume that the dose reduction percentages from the PHE reports can be achieved in practice.

B.3.3 Farmland Decontamination Costs

As mentioned above, it is assumed that the cost of farmland decontamination includes reversal tillage (plowing to move most of the surface contamination well below the surface) and interchanging topsoil and subsoil by mechanically removing the top layer, excavating the sublayer then replacing the surface layer below and the sublayer on top. This latter method is similar to reversal tillage, but significantly reduces the mixing of soil layers during the decontamination process. In principle, soil stripping should diminish the contamination level of agricultural products following the decontamination; however, MACCS only accounts for the effects of decontamination through the pathways of groundshine and inhalation of resuspended aerosols. MACCS does not account for any effect of decontamination on the food pathway. The decontamination methods for farmland that required waste storage and disposal were examined, but these resulted in costs of multiple hundreds of thousands of dollars per hectare and would have been so expensive that farmland would have been condemned in the MACCS economic model based on cost-effectiveness considerations. The MACCS algorithm for remediation is designed to choose the most cost effective option based on user inputs. Given the relatively low value of farmland, this means that any method requiring significant quantities of material to be disposed offsite would never be implemented assuming that the user follows the guidance in this report.

The approach described here assumes that farmland consists primarily of crops and pasture that are amenable to soil layer inversion. Orchards would be more difficult to decontaminate, but are not explicitly considered here because in many regions they comprise a small fraction of farmland and because the increased cost associated with decontamination would likely not prove cost-beneficial within the MACCS framework.

Farmland decontamination costs are simpler to assess than non-farmland costs because the primary cost is from cleaning up land. Here, we assume that other costs, e.g., decontaminating barns, sheds, silos, and farm machinery, are insignificant compared with decontaminating the land. It should be noted that this may lead to an underestimation of the farmland decontamination costs, but the underestimation is not expected to be significant compared with uncertainties in the overall costs.

Overall decontamination costs are divided into three main cost categories as shown in Table B-6, which are decontamination of the property; waste management (storage, transportation, and disposal); and waste sampling and characterization. For all three decontamination levels, there are no costs for storage, transportation, and disposal because all of the contaminated soil and debris remains on site.

Table B-6 Farmland Decontamination Costs

Level	Decontamination		Waste Generation		Waste Management		Soil Characterization	CDFRM
	\$/yd ²	\$/ha	yd ³ /yd ²	yd ³ /ha	\$/yd ²	\$/ha		
Level 1 (DF 2)	\$0.28	\$3,349	0	0	\$0	\$0	\$330	\$3,679
Level 2 (DF 4)	\$3.18	\$38,032	0	0	\$0	\$0	\$330	\$38,362
Level 3 (DF 8)	\$3.18	\$38,032	0	0	\$0	\$0	\$330	\$38,362

The values in Table B-6 are calculated as follows:

- Decontamination cost per square yard is the sum of the unit costs from [13], where the sum is taken over the decontamination methods listed in Tables B-1 to B-3 for Farm Area.
- Decontamination cost per hectare (ha) is the product of the value in the previous column with the area conversion factor (11,960 yd²/ha).
- The number of cubic yards of waste generated per square yard is from the values summed over the decontamination methods listed in Tables B-1, B-2, and B-3 for Farm Area. The yd³/ha uses the area conversion factor provided above to calculate the value per hectare. For the case of farmland, these values are all zero because waste is assumed to remain on site.
- The Waste Management costs are assumed to be zero because methods selected (deep plowing or soil inversion) are assumed to result in negligible or no waste generation for all three decontamination levels.

- Waste Characterization cost is a small fraction of the value of CDfrm, \$330/ha. This value assumes that there is a cost of \$750 to acquire and \$900 to analyze each sample and that one sample is taken for every 5 hectares.
- CDfrm is the sum (cf. Equation B-1) of the Decontamination, Waste Management, and Waste Characterization costs on a per-hectare basis.

Even with no offsite disposal, the estimated costs to decontaminate farmland at Levels 2 (DF=4) and 3 (DF=8) are significantly larger than the value of most farmland in the U.S. Normally, MACCS condemns farmland when the decontamination costs at the required level exceed the value of the property itself; however, the average value of farmland (VALWF) is a user input. In a standard cost/benefit analysis, a representative value for farmland property is used to define VALWF based on the assumption that the least expensive method of dose reduction would be selected. In that case, the MACCS economic model would condemn rather than decontaminate farmland using the values of CDfrm for Levels 2 and 3 derived in this appendix.

Waste management costs are discussed below for completeness, even though they are not used. This is intended to facilitate evaluation of other decontamination methods that require waste disposal. As mentioned above, any methods that require any significant soil disposal are prohibitively expensive and would result in MACCS condemning farmland that requires such methods. The costs for waste management are broken into costs for temporary storage, transportation to the final disposal site, and disposal of the waste at the final site. The total waste management cost for farmland-derived waste is estimated to be \$784/yd³, based on the discussion below.

The cost for temporary storage is based on Table 3 from [18] and is estimated to be \$216.24/yd³ based on temporary storage cost of 20,000 yen per container, each of which is assumed to hold 0.9 m³ of waste and cost 8,000 yen per container³⁵.

The cost for transportation of farmland waste from temporary storage to final disposal assumes an average waste transportation distance of 1,000 miles. The cost estimate is based on 1994 estimates of shipping using flatbed trucks with a fixed cost of \$880 per truckload and mileage of \$4.00 per mile [19]. After escalating from 1994 to 2012 dollars, this equates to \$7,564 per truckload. The assumed truck capacity is 18.5 yd³ per truckload for farmland, based on a waste volume fraction of 82% soil and 18% debris (Table 1 of [20]), a soil density of 2,500 lbs/yd³, a debris density of 600 lbs/yd³ (mostly vegetation), and an effective payload capacity of 20 tons for highway travel. Combined, this results in a waste transportation cost of \$408.18/yd³ for farmland.

The estimated unit cost for disposal is estimated to be \$159/yd³. If an accident comparable to the Fukushima accident were to occur in the U.S., it is likely that existing facilities would be overwhelmed and that new facilities would need to be created. However, we assume that the cost for disposal at new facilities would be comparable to existing facilities. Review of historical disposal contract information found rates beginning as low \$145/yd³ (circa 2005) for U.S. Army Corps of Engineers contracts and increasing considerably depending on waste type. This compares to a planning cost of about \$14.5/ft³ (\$392/yd³) for disposal of radioactive waste from DOE sites at the Nevada Test Site [21]. The Nevada Test Site is not approved for receipt of waste from an NPP accident and does not have rail access; but, the disposal cost is important to

³⁵ Note that for this calculation, a currency conversion rate of 110 Yen per dollar was assumed. Use of the 100 Yen per dollar currency conversion rate used elsewhere in this appendix would result in temporary storage costs of \$240/yd³.

inform this disposal discussion. This study assumes unit costs for disposal are \$250/yd³ for soil and \$630/yd³ for debris at a low-level waste (LLW) facility. Furthermore, we assume that the disposal cost would be reduced by half because a significant portion of the waste may be able to go to local hazardous waste landfills rather than LLW disposal facilities. Waste segregation or volume reduction may also reduce the volume of waste requiring transportation and disposal, but these would also incur costs that are not included here. Putting these values and assumptions together produces a net cost of \$159.20/yd³ for disposal. Summing the three waste management costs, \$216.24/yd³ + \$408.18/yd³ + \$159.20/yd³, gives a total cost of \$784/yd³ rounded to the nearest dollar.

B.3.4 Non-Farmland Decontamination Costs

Unlike farmland, a significant portion of the cost to decontaminate non-farmland is to decontaminate structures and other improvements to the land. This appendix establishes a methodology for estimating a U.S.-wide average decontamination cost based on representative mixtures of houses and land areas on a per-capita basis. In addition, this section can be used to estimate decontamination costs based on site or regional characteristics if the user so chooses and has the information needed to estimate site-specific values.

The first step in solving Equation B-3 for non-farm property is to estimate the amount of the different types of surfaces, i , per acre for each of the land uses, l . This corresponds to estimation of the term $SURF_{i,l}$ in Equation B-3. Typical properties for three housing models were developed and evaluated. Each housing model includes an area of land and assumed specifications for the house or apartment building built on the land. To represent the range of single unit housing, two prototypic housing units were created to represent low-intensity and medium-intensity housing. In general, low-intensity housing represents single family dwellings on one or more acres; medium-intensity housing represents single family dwellings on less than one acre; and high-intensity housing represents urban multi-unit apartments and condominiums. The dimensions of these structures and land parcels are based on reasonable assumptions.

On average for the entire U.S., an occupied unit contains 2.58 individuals [22]. Accounting for unoccupied units, the number of individuals per unit drops to 2.38 for urban areas and 2.12 for rural areas. The assumption that 2.38 individuals per unit for all three housing intensities in urban areas and 2.12 for rural areas means that all housing units are assumed to be occupied and would require decontamination. For rural areas, the low-intensity housing on average is representative for the entire population.

Low-intensity housing surface areas, for both urban and rural land uses, are based on the assumption of a prototypical single-level, 2,000-ft² house on 2.68 acres. The dimensions of the house are taken to be 40 by 50 feet with 10 foot high exterior walls and a pitched roof. The interior wall surface area accounts for 3 bedrooms, 2 baths, 1 kitchen, 1 living room, and 1 hall. The interior wall surface area is estimated to be 2.8 times the exterior wall surface area plus the ceiling area (same as floor area). The roof is estimated to be about 15% larger than the floor area to account for pitch and overhang. The landscape (excluding the areas occupied by the house, concrete, and asphalt) is assumed to be 2/3 lawn, 1/6 trees, and 1/6 shrubs/bushes/plants. A half-width of asphalt road surface is included with the house, with assumptions of 5 yards by 220 yards of road surface per unit. A concrete driveway associated with the unit is assumed to be 120 yd². The estimated decontamination surface areas for the prototype low-intensity unit are shown in Table B-7. A U.S.-average of 2.38 individuals are assumed to dwell in low-intensity urban units and a U.S.-average of 2.12 individuals are assumed to dwell in low-intensity rural units.

Medium-intensity housing surface areas are based on the assumption of four prototypical single-level, 2,000-ft² houses on one acre (one unit per quarter-acre). The house is assumed to have the same dimensions as the low-intensity unit. A half-width of asphalt road surface is included with each house, with assumptions that the half-width of the road surface is 5 yards and the length is based on a square, quarter-acre lot. A concrete sidewalk is assumed to run parallel to the road and to be 2 yards wide. Finally, a concrete driveway of 6 by 8 yards connects the house with the road. The remaining land is assumed to be 2/3 grass, 1/6 trees, and 1/6 shrubs, bushes, and plants. The decontamination surface areas for the prototype medium-intensity unit are shown in Table B-7. A U.S.-average of 2.38 individuals are assumed to dwell in each of the four units.

High-intensity housing surface areas are based on the assumption of two prototypical two-story, 10-unit structures on one acre, with each unit consisting of 1,000 ft² of floor space. The dimensions of a single unit are taken to be 28 feet wide by 36 ft deep, making the overall width of the building 140 feet. Exterior walls are 20 feet high, 10 feet for each story. Each unit is comprised of 6 rooms, which are 2 bedrooms, 2 baths, 1 kitchen, and 1 living room. The ratio of the interior wall to exterior wall surface area is estimated to be about 8.8. The total interior wall area also includes the ceiling area, which is the same as the floor area. The roof is assumed to be flat, so the roof area is the same as the total floor area of a single story. Asphalt roads are included as part of the property and include a full width of road along the width of the one acre property and a half-width of road along the depth of the property. In addition, there is a 5 yard deep parking area along the width of the property. The width and the depth of the one acre property are assumed to be the same, i.e., the property is a square. Concrete sidewalks are assumed to be along the edge of all roads plus two 3-yard-long sidewalks leading to each of the 10-unit buildings. Sidewalks are 2 yards wide. Of the remainder of the one acre area, 2/3 is assumed to be lawn, 1/6 trees, and 1/6 shrubs, bushes, and plants. The decontamination surface areas for the prototype high-intensity units are shown in Table B-7. A U.S.-average of 2.38 individuals are assumed to dwell in each of the 20 units.

The resulting estimates, shown in Table B-7, represent the term $SURF_{i,l}$ (average decontamination surface area i per land area dedicated to land use l) in Equation (B-3). These values are used to evaluate the contributions from a set of decontamination activities to the overall decontamination cost.

Table B-7 Areas Associated with Each Housing Intensity

Decontamination Surface Area (yd ² /acre decontaminated)	Low Intensity	Medium Intensity	High Intensity
Asphalt	205	696	1,316
Concrete	45	470	383
Roof area	96	1,026	1,111
Roof gutters (linear feet/acre)	37	400	560
Wall area – exterior	94	1,005	1,562
Wall area – interior	292	3,129	15,967
Floor area	83	889	2,222
Landscape – trees	752	464	338
Landscape – shrubs	752	464	338
Landscape – lawn	3010	1,857	1,353

Note: based on prototypes on a square yard per acre basis (roof gutters are linear ft/acre)

The next step in the process involves estimation of the fraction of land subject to decontamination, corresponding to the terms f_l (Average fraction of land dedicated to land use l) and F_l^{DECON} in Equation B-3. Lots associated with single family dwellings come in a wide range of sizes, as indicated in Table B-8, which reproduces values from [23] for the United States. Urban units in Table B-8 reflect a summation of urbanized areas and urban clusters.

Table B-8 Rural and Urban Lot Sizes for Single Unit Structures in the U.S.

Property Size	Urban Units	Rural Units
<1/8 acre	14,634,000	1,589,000
1/8 - 1/4 acre	22,879,000	2,129,000
1/4 - 1/2 acre	14,677,000	2,164,000
1/2 - 1 acre	7,448,000	2,751,000
1 - 5 acres	8,810,000	11,783,000
5 - 10 acres	481,000	2,635,000
10+ acres	629,000	3,548,000
Total	69,558,000	26,599,000

Source: [23]

Data from the [24] provides a fractional split between the populations residing in single unit versus multi-unit housing: in urban areas it is 0.69 to 0.31; in rural areas it is 0.96 to 0.04; and overall in the U.S. it is 0.79 to 0.21. Estimated urban populations by housing intensity are shown in Table B-9. The total population is from the 2010 Census. Data on residential lot sizes (Table B-8) and the number of housing units in structures (both from [23]) were used to inform the estimated urban population distribution that corresponds to the lot sizes of the three urban land use intensities.

Table B-9 Estimated Population by Urban Housing Intensity

Urban Housing Intensity	Population
Total	249,253,306
High	41,235,465
Medium	185,382,058
Low	22,635,783

Source: based on data from [23] and [25]

The urban population distribution (shown in Table B-9) and the corresponding model lot sizes discussed above were multiplied to obtain approximate urban housing areas, as shown in Table B-10.

Table B-10 Estimated Areas and Fractions by Housing Intensity Category

Land Use	Population	Assumed Population Density (people/acre)	Estimated Housing Area (acres)	Adjusted Area (acres)	Adjusted Population Density (people /acre)	Fraction of CONUS Area (f_l)
Urban High Intensity	41,235,465	47.60	866,291	1,312,639	31.41	0.069%
Urban Medium Intensity	185,382,058	9.52	19,472,905	29,506,117	6.28	1.6%
Urban Low Intensity	22,635,783	0.89	25,489,033	38,621,991	0.59	2.0%
Urban Total	249,253,306	5.44	45,828,229	69,440,747	3.59	3.7%
Rural Low Intensity	59,492,267	0.79	75,207,205	106,000,000	0.56	5.6%
Total	308,745,573	2.55	121,035,435	175,440,747	1.76	9.3%

The resulting total urban housing area (45.8 million acres) is less than 2/3 of the total urban area (69.4 million acres) as reported by [26]. This is reasonable since urban areas also include industrial, institutional, commercial, and public administrative land; parks; and other built-up areas. Consistent with the discussion in Section 4.3 of [27], we assume that the entire urban area would require decontamination if it were contaminated by an accident. To account for the difference in areas, the column labeled Adjusted Urban Area in Table B-10 apportions the additional urban area uniformly by estimated housing area over each of the urban housing intensity categories so that the Urban Total under Adjusted Area matches the 69.4 million acres of urban area reported in [26]. This assumes that the cost to decontaminate entire urban areas is the same as to decontaminate the residential portion of the urban areas on a per area basis. The sixth column of Table B-10 adjusts the urban population density for each of the urban housing intensities using the Adjusted Urban Area.

Table B-10 also shows the estimated housing area for the rural population. It should be noted that the values for Rural Low-Intensity were derived based on estimates of the total rural population (59,492,267), an assumed rural lot size of 2.68 acres as discussed above, and an assumed household size of 2.12 individuals per household as discussed above. The resulting value of 75 million acres, corresponding to 4% of the total CONUS area, is lower than the 106 million acres of rural residential land reported in [26]. The rural residential area was therefore adjusted to match the total rural residential area for purposes of deriving a value for f_l (Average fraction of land dedicated to land use l) for use in Equation (B-3). The last column of the table provides the fraction of the entire CONUS area (1,891 million acres according to Table 4 of [26]) occupied by each land usage type. The final column of Table B-10 represents the value of for f_l (average fraction of land dedicated to land use l) for use in Equation B-3.

In addition to residential areas, rural areas include areas comprised of roads and especially of open areas such as parks, forests, and wildlife refuges. A portion of each of these areas may require decontamination as well to reduce exposure from the temporary occupancy of these

areas, such as during transit along roadways. Data from Table 4 of [26] shows that in 2012 a total of 1,430 million acres in the 48 states comprising CONUS was classified as forest-use land, special and miscellaneous use land, grassland, and pasture and range. These land uses comprised 76% of the total CONUS land area and include rural residential land (106 million acres according to [26]) and rural transportation (26.9 million acres according to Table 10 of [26]). Because both rural residential and rural transportation land uses are treated explicitly in this appendix, the total amount of “Other” (forest-use land, special and miscellaneous use land, grassland, and pasture and range) is adjusted by subtraction of these land uses to yield 1,297 million acres, or 69% of the CONUS land area.

The next step is to derive a value of F_l^{DECON} (Fraction of area dedicated to land use l that is decontaminated) in Equation B-3. Table B-11 shows the assumptions that are used for the fractions of land that are assumed to be decontaminated for each land-use category considered in this appendix. For urban land use categories, it is assumed that 100% of areas characterized as urban land use would be decontaminated. For rural residential areas, it is assumed that only 2.68 acres per rural residential household would be subject to decontamination. This corresponds to a value of 71% for F_l^{DECON} for areas characterized as rural residential (75 million estimated rural residential acres subject to decontamination divided by 106 million total rural residential acres). While the entire area of rural roads is assumed to be decontaminated, the choice of fraction decontaminated for the category “Other” is based on the assumption that only a 20 yard strip along both sides of roads would be decontaminated to reduce exposures to people in automobiles and trucks traveling along these roads. The category “Other” is treated as forest to estimate decontamination costs³⁶. The choice of a 20 yard decontamination zone along both sides of public roads and highways is consistent with the practices at Fukushima. The fraction of surface area dedicated to rural roads in the CONUS is approximately 1.4%, but a significant portion of these roadways are included as part of the rural housing units, as described above; the remaining area fraction requiring decontamination is estimated to be 1.2% of the CONUS area.

Table B-11 CONUS-Averaged Land Use Fraction and Decontamination Fraction by Land Use Category

Land Use	High-Intensity Urban	Medium-Intensity Urban	Low-Intensity Urban	Rural Residential	Rural Roads ¹	Other (Treated as Forest)
Estimated Land-Use Fraction (f_l)	0.069%	1.6%	2.0%	5.6%	1.2%	69%
Fraction Decontaminated (F_l^{DECON})	100%	100%	100%	71%	100%	4.5% ²
CONUS-averaged fraction decontaminated	0.069%	1.6%	2.0%	4.0%	1.2%	3.1%

¹ Accounts for paved roads not already included in the rural residential areas

² “Other” land uses are only assumed to require decontamination when DF=4 or greater is required.

³⁶ This 20 meter buffer area is not considered to be subject to decontamination for DF 2 decontamination strategies, but is assumed to be subject to decontamination for DF 4 and DF 8 decontamination strategies.

Accounting for all types of surfaces, about 79% of the CONUS area falls into one of the land usage types shown in Table B-11; the remaining land is dedicated to cropland, which is considered in the preceding section of this appendix. Of the set of land usage categories discussed in this section, the authors estimate that about 15% on average would be decontaminated. This corresponds to an average of about 12% of the entire CONUS-averaged area.

The final step in the process involves estimation of the term $COST_{i,n}$ (Average unit cost to decontaminate surface area i to achieve an overall decontamination level n) in Equation (B-3). Tables B-12 to B-14 provide the assumed method (consistent with Tables B-1 to B-3), unit costs, unit waste generated, and any additional assumptions for Level 1, 2, and 3 decontamination, respectively. Most of the references in Tables B-12 to B-14 (the ones ending in -N, where N is an integer) are obtained from Appendix A of [13]. Because the information in Appendix A of [13] does not include methods for decontamination of interiors, some of the items in Tables B-12 to B-14, e.g., "Wash, Scrub floors and Shampoo carpets", "Remove & replace", are based on a review of costs from [15]. Those values were used with an assumed escalation factor of roughly 2 for operations that are performed during decontamination to account for the increased difficulty of performing work in a contaminated environment. The "Costs" and "Waste Generated" quantities are consistent with the values in [13] subject to the assumptions listed when a range of values is provided. In developing these costs, it may be noted that when housing units are decontaminated, some or all of the contents may need to be decontaminated or disposed of. These costs are not included. Likewise, costs that arise from handling and disposal of liquid wastes generated when performing decontamination processes like washing roofing, siding, and interior surfaces are also not included. A preliminary estimate indicates that these costs are relatively small compared with the costs that are included.

Table B-12 Assumed Methods, Costs, and Waste Generated for Level 1 Decontamination (DF = 2)

Model Area	Method	Cost (\$/yd ²)	Waste Generated (yd ³ /yd ²)	Assumption	Reference
Asphalt	Road sweeper (on-board road sweeper) followed by water-jet vehicle	\$1.42	0.0014		Public infrastructure-1b ¹ Public infrastructure-3 ¹
Concrete	Brushing followed by high pressure water washing	\$8.03	0		Residential-14 ¹
Roof area	Surface brushing and washing	\$9.11	0		Residential-1a ¹
Roof gutters	Removal of debris and wiping	\$3.35	0.0131		Residential-2 ¹
Wall area - exterior	High-pressure washing	\$8.03	0		Residential-15 ¹
Wall area - interior	Wash	\$10.00	0		See Note 2
Floor area	Scrub floors and shampoo carpets	\$10.00	0		See Note 2
Landscape - trees	Humus and thin-layer topsoil removal (stripping)	\$7.44	0.0601	Waste generation assumed to be 55 liters/m ²	Forest-2 ¹
Landscape - shrubs	Humus and thin-layer topsoil removal (stripping)	\$7.44	0.0601	Waste generation assumed to be 55 liters/m ²	Forest-2 ¹
Landscape - lawn	Turf stripping, 67% of surface	\$8.40	0.0257	3.5 cm layer removed	Residential-8 ¹
Rural roads - asphalt	Road Sweeper (On-board road sweeper) followed by water-jet vehicle	\$1.42	0.0014		Public infrastructure-1b ¹ Public infrastructure-3 ¹
Forest area	No Action	0	0	No forest area decontamination	

B-10

¹ Source: Appendix A of [13]

² Source: Assumption/No data located

Table B-13 Assumed Methods, Costs, and Waste Generated for Level 2 Decontamination (DF = 4)

Model Area	Method	Cost (\$/yd ²)	Waste Generated (yd ³ /yd ²)	Assumption	Reference
Asphalt	Road sweeping, asphalt removal by surface stripping machine, followed by seal coating	\$6.08	0.0101		Public Infrastructure-1b ¹ Public Infrastructure-8 ¹ Apply seal coat ²
Concrete	Ultra-high-pressure water jet	\$9.62	0.0033		Residential-12 ¹
Roof area	Surface brushing and washing and replace 50% of roof	\$21.56	0.0302		50% Residential-1a 50% Remove & Replace ²
Roof gutters	Removal of debris and wiping	\$3.35	0.0131		Residential-2 ¹
Wall area - exterior	High-pressure washing and replace 50% siding	\$24.01	0.0513		50% Residential-15 50% Remove & Replace ²
Wall area - interior	Wash 50% and replace 50% wall surface	\$20.00	0.0174	Drywall thickness is 5/8 inch	See Note 2
Floor area	Scrub floors and shampoo carpets 50% Replace 50% carpets	\$30.00	0.0581		See Note 2
Landscape - trees	Humus and thin-layer topsoil removal (stripping)	\$7.44	0.0601	Waste generation assumed to be 55 liters/m ²	Forest-2 ¹
Landscape - shrubs	Humus and thin-layer topsoil removal (stripping)	\$7.44	0.0601	Waste generation assumed to be 55 liters/m ²	Forest-2 ¹
Landscape - lawn	Turf stripping	\$12.54	0.0383	3.5 cm layer	Residential-8 ¹
Rural roads - asphalt	Road sweeper (On-board road sweeper), asphalt removal by surface stripping machine, apply seal coat	\$6.08	0.0101		Public Infrastructure-1b ¹ Public Infrastructure-8 ¹ Apply seal coat ²
Forest area	Strimming, followed by humus and thin-layer topsoil removal (stripping)	\$8.78	0.0683	Waste: 7.5 liters/m ² for strimming, 55 liters/m ² humus and soil removal	Forest-3 ¹ Forest-2 ¹

B-20

¹ Source: Appendix A of [13]

² Source: Assumption/No data located

Table B-14 Assumed Methods, Costs, and Waste Generated for Level 3 Decontamination (DF = 8)

Model Area	Method	Cost (\$/yd ²)	Waste Generated (yd ³ /yd ²)	Assumption	Reference
Asphalt	Asphalt removal by surface stripping machine	\$6.08	0.0101		Public Infrastructure-1b ¹ Public Infrastructure-8 ¹ Apply seal coat
Concrete	Ultra-high-pressure water jet	\$9.62	0.0033		Residential-12 ¹
Roof area	Remove and replace	\$34.00	0.0603		100% Remove & Replace ²
Roof gutters	Removal of debris and wiping	\$3.35	0.0131		Residential-2 ¹
Wall area - exterior	Replace 100% siding	\$40.00	0.1027		100% Remove & Replace ²
Wall area - interior	Replace 100% wall surface	\$30.00	0.0347	Drywall thickness is 5/8 in	100% Remove & Replace ²
Floor area	Scrub Floors Replace 100% carpets	\$50.00	0.1161		100% Remove & Replace ²
Landscape - trees	Humus and thin-layer topsoil removal (stripping)	\$7.44	0.0820	Waste generation assumed to be 75 liters/m ² in order to increase dose reduction	Forest-2 ¹
Landscape - shrubs	Humus and thin-layer topsoil removal (stripping)	\$7.44	0.0820	Waste generation assumed to be 75 liters/m ² in order to increase dose reduction	Forest-2 ¹
Landscape - lawn	Turf stripping Thin-layer topsoil stripping, sod replacement	\$20.12	0.0766	3.5 cm layer 3.5 cm layer	Residential-8 ¹ Residential-5 ¹
Rural roads - asphalt	Road sweeper (On-board road sweeper), asphalt removal by surface stripping machine, apply seal coat	\$6.08	0.0101		Public Infrastructure-1b ¹ Public Infrastructure-8 ¹ Apply seal coat ²
Forest area	Strimming, followed by humus and thin-layer topsoil removal (stripping)	\$8.78	0.0683	Waste: 7.5 liters/m ² for strimming, 55 liters/m ² humus and soil removal	Forest-3 ¹ Forest-2 ¹

B-21

¹ Source: Appendix A of [13]

² Source: Assumption/No data located

Total costs for each land use type and decontamination level are generated by combining the unit costs and waste generated in Table B-12 through B-14, the surface areas in Table B-8, and the waste management costs discussed in Section B.4, using Equations (B-1) and (B-3) from this appendix. The results are provided in Tables B-15 through B-23. These tables present the resulting costs for local decontamination, waste management, waste characterization, and the total cost to perform decontamination. Most of the cost categories are presented in \$/acre; however, the total cost is also presented as \$/person, which is the unit required for CDNFRM. The tables below contain values for decontaminating high-intensity housing (Table B-15), medium-intensity housing (Table B-16), low-intensity urban housing (Table B-17), an average over the three housing intensities for urban areas (Table B-18), low-intensity rural housing (Table B-19), additional rural roads not included with the housing areas (Table B-20), other land areas (Table B-21), an average for rural housing that includes Rural Roads and Other land-usages (Table B-22), and an OCONUS average (Table B-23). The meaning of the entries in these tables is discussed in more detail below. The purpose for the level of detail in the tables is so the values can be reweighted by the user to create region- or site-specific values of CDNFRM if the data are available to support such estimates.

In Tables B-15 to B-17 and B-19 to B-21, the quantities on a per-area basis assume that all urban areas are decontaminated, that 71% of the area classified as rural residential is decontaminated (that is, the same 2.68 acres/household that was assumed for low-intensity urban areas), but that only a fraction (4.5%) of the land-use category Other is decontaminated. The costs for decontamination for level n and for land-use category l , expressed in the first column of these tables, are calculated using a simplified version of Equation (B-3) as follows:

$$Decontamination\ Cost_{l,n} = \sum_i F_l^{DECON} \cdot (SURF_{i,l} \cdot COST_{i,n}) \quad (B-4)$$

$$Decontamination\ Cost_{ave,n} = \left(\sum_l f_l \cdot Decontamination\ Cost_{l,n} \right) / \left(\sum_l f_l \right) \quad (B-5)$$

Here, l is summed over the appropriate subset of land-use categories to obtain the average of interest.

Waste generation quantities are created using Equations (B-6) and (B-7), which are analogous to Equations (B-4) and (B-5). The values of $WASTE_{i,n}$ are taken from Tables B-12 to B-14.

$$Waste\ Generation_{l,n} = \sum_i F_l^{DECON} \cdot (SURF_{i,l} \cdot WASTE_{i,n}) \quad (B-6)$$

$$Waste\ Generation_{ave,n} = \left(\sum_l f_l \cdot Waste\ Generation_{l,n} \right) / \left(\sum_l f_l \right) \quad (B-7)$$

The cost for Waste Management in the third column of Tables B-15 to B-23 is simply the quantity of Waste Generation, in column two, times the unit cost for waste management.

As discussed in Section B.4, the cost for management of wastes derived from non-farmland decontamination is comprised of three components: storage, transportation, and disposal. The

unit costs for temporary storage is taken to be the same for non-farmland as for farmland, \$216/yd³. The unit cost for transportation is estimated to be lower than for farmland because a larger fraction of the waste is estimated to be debris (0.61) and a smaller fraction to be soil (0.39) (Table 1 of [20]). Using the same assumptions as discussed in Section B.4, the unit cost for transportation is estimated to be \$254/yd³. In contrast, the unit cost for disposal is estimated to be higher for non-farmland because a larger fraction of the waste is estimated to be debris. As discussed in Section B.4, the unit disposal costs are assumed to be \$250/yd³ for soil and \$630/yd³ for debris. Furthermore, we assume that the disposal cost would be reduced by half because a significant portion of the waste may be able to go to local hazardous waste landfills rather than LLW disposal facilities. Thus, the estimated disposal cost for non-farmland waste is \$241/yd³ and the total unit waste management cost is \$711/ yd³.

The costs for waste characterization are based on the following assumptions:

- One sample is collected per household (per housing unit).
- The cost to collect a sample is \$750 and the cost to analyze it is \$900.
- The total sample cost is divided by the number of persons per household to get an average per person sampling cost of \$693 for urban residential properties and \$778 for rural residential properties. The number is adjusted on a per acre basis to account for adjusted population density.
- On a per acre basis, the cost of waste characterization for Roads and Other land-use categories is assumed to be the same as for rural housing, but Other is adjusted lower to account for the small fraction that would be decontaminated (4.5%).

The values on a per area basis are shown under the Waste Characterization column of Tables B-15 to B-23. This cost category contributes a relatively small fraction to the Total Cost to Decontaminate in the final column of the tables.

B.4 Results

The total cost to decontaminate is reported in Tables B-15 to B-23 on a per-acre and a per-capita basis. The costs per acre are the summation of the three cost categories listed in the tables: Decontamination, Waste Management, and Waste Characterization. The cost per person is the cost per area divided by the relevant adjusted population density from Table B-10. Because the two land-use categories of Roads and Other are associated with the rural population, the per person values for Tables B-20 and B-21 are based on the rural populations; to calculate the per person costs, the per-acre values are multiplied by the land area that is assumed to be decontaminated for the land use category then divided by the rural population to create a cost per rural person. The per person values in Table B-22 are the sum of the corresponding entries in Tables B-19 to B-21. Finally, the values in Table B-23 are an average over the CONUS area. These values are calculated similarly to those in Table B-22; the per area values are multiplied by the relevant area fraction, which is the fraction of the CONUS area in the six land-use categories in Table B-10, summed, then divided by the CONUS population, which is taken from the 2010 census to be almost 309 million people. The CONUS-averaged results can also be computed directly from Equation (B-3).

Table B-15 Decontamination Costs for Urban, High-Intensity Housing

Level	Decontamination	Waste Generation	Waste Management	Waste Characterization	Total Cost to Decontaminate	
	\$/LU acre	yd ³ /LU acre	\$/LU acre	\$/LU acre	\$/LU acre	\$/person
Level 1 (DF 2)	\$230,000	84	\$60,000	\$22,000	\$310,000	\$9,900
Level 2 (DF 4)	\$480,000	630	\$450,000	\$22,000	\$960,000	\$30,000
Level 3 (DF 8)	\$740,000	1200	\$870,000	\$22,000	\$1,600,000	\$52,000

Table B-16 Decontamination Costs for Urban, Medium-Intensity Housing

Level	Decontamination	Waste Generation	Waste Management	Waste Characterization	Total Cost to Decontaminate	
	\$/LU acre	yd ³ /LU acre	\$/LU acre	\$/LU acre	\$/LU acre	\$/person
Level 1 (DF 2)	\$86,000	110	\$78,000	\$4,400	\$170,000	\$27,000
Level 2 (DF 4)	\$180,000	330	\$230,000	\$4,400	\$410,000	\$66,000
Level 3 (DF 8)	\$270,000	610	\$430,000	\$4,400	\$700,000	\$110,000

Table B-17 Decontamination Costs for Urban, Low-Intensity Housing

Level	Decontamination	Waste Generation	Waste Management	Waste Characterization	Total Cost to Decontaminate	
	\$/LU acre	yd ³ /LU acre	\$/LU acre	\$/LU acre	\$/LU acre	\$/person
Level 1 (DF 2)	\$43,000	170	\$120,000	\$400	\$160,000	\$280,000
Level 2 (DF 4)	\$63,000	230	\$160,000	\$400	\$220,000	\$380,000
Level 3 (DF 8)	\$93,000	390	\$280,000	\$400	\$370,000	\$640,000

Table B-18 Decontamination Costs for a Land-Intensity Averaged Urban Area

Level	Decontamination	Waste Generation	Waste Management	Waste Characterization	Total Cost to Decontaminate	
	\$/acre	yd ³ /acre	\$/acre	\$/acre	\$/acre	\$/person
Level 1 (DF 2)	\$65,000	140	\$100,000	\$2,500	\$170,000	\$47,000
Level 2 (DF 4)	\$120,000	280	\$200,000	\$2,500	\$320,000	\$89,000
Level 3 (DF 8)	\$180,000	500	\$360,000	\$2,500	\$540,000	\$150,000

Table B-19 Decontamination Costs for Rural, Low-Intensity Housing

Level	Decontamination	Waste Generation	Waste Management	Waste Characterization	Total Cost to Decontaminate	
	\$/LU acre	yd ³ /LU acre	\$/LU acre	\$/LU acre	\$/LU acre	\$/person
Level 1 (DF 2)	\$30,000	120	\$85,000	\$400	\$120,000	\$210,000
Level 2 (DF 4)	\$45,000	160	\$110,000	\$400	\$160,000	\$280,000
Level 3 (DF 8)	\$66,000	280	\$200,000	\$400	\$260,000	\$470,000

Table B-20 Decontamination Costs for Rural Roads not Included with Rural Housing

Level	Decontamination	Waste Generation	Waste Management	Waste Characterization	Total Cost to Decontaminate	
	\$/LU acre	yd ³ /LU acre	\$/LU acre	\$/LU acre	\$/LU acre	\$/person
Level 1 (DF 2)	\$6,900	7	\$4,700	\$440	\$12,000	\$4,400
Level 2 (DF 4)	\$29,000	49	\$35,000	\$440	\$65,000	\$24,000
Level 3 (DF 8)	\$29,000	49	\$35,000	\$440	\$65,000	\$24,000

Table B-21 Decontamination Costs for Other Category (rural forest areas)

Level	Decontamination	Waste Generation	Waste Management	Waste Characterization	Total Cost to Decontaminate	
	\$/LU acre	yd ³ /LU acre	\$/LU acre	\$/LU acre	\$/LU acre	\$/person
Level 1 (DF 2)	\$0	0	\$0	\$20	\$20	\$430
Level 2 (DF 4)	\$1,900	15	\$11,000	\$20	\$13,000	\$270,000
Level 3 (DF 8)	\$1,900	15	\$11,000	\$20	\$13,000	\$270,000

Table B-22 Decontamination Costs for Rural Population Including All Non-Urban Land Usages

Level	Decontamination	Waste Generation	Waste Management	Waste Characterization	Total Cost to Decontaminate	
	\$/acre	yd ³ /acre	\$/acre	\$/acre	\$/acre	\$/person
Level 1 (DF 2)	\$2,400	9	\$6,400	\$57	\$8,800	\$210,000
Level 2 (DF 4)	\$5,500	26	\$19,000	\$57	\$24,000	\$580,000
Level 3 (DF 8)	\$7,100	35	\$25,000	\$57	\$32,000	\$770,000

Table B-23 Non-Farm Decontamination Costs Averaged Over All Land Usages within the CONUS

Level	Decontamination	Waste Generation	Waste Management	Waste Characterization	Total Cost to Decontaminate	
	\$/acre	yd ³ /acre	\$/acre	\$/acre	\$/acre	\$/person
Level 1 (DF 2)	\$5,200	15	\$11,000	\$170	\$16,000	\$78,000
Level 2 (DF 4)	\$11,000	38	\$27,000	\$170	\$38,000	\$180,000
Level 3 (DF 8)	\$15,000	57	\$40,000	\$170	\$56,000	\$270,000

For a typical MACCS calculation, the CONUS-averaged values for decontamination, on a per-person basis, are considered reasonable generic values to use for CDNFRM if site-specific information is not available. These are about \$78 K, \$180 K, and \$270 K per person for Levels 1 (DF = 2), 2 (DF = 4), and 3 (DF = 8), respectively. Some users may be able to evaluate specific urban and rural populations for a region of interest, in which case the urban and rural values in Tables B-18 and B-22 could be used to evaluate a site-specific set of decontamination costs. If the user were to be able to identify populations or areas relevant to each of the land uses, Tables B-15 to B-17 and B-19 to B-21 could be used to provide an even more site-specific set of decontamination costs.

For comparison, it may be noted that a range of alternate per-capita non-farm decontamination costs were provided in Table 11 of [8]. Values reported therein, derived for an urbanized region, ranged from \$19,000 to \$272,000 (in 2005 USD) per person for light decontamination (DF=3) and from \$90,000 to \$898,000 in 2005 USD) per person for heavy decontamination (DF=15). Although these results are not directly comparable to the results derived in Table B-23, it does suggest that the results in Table B-23 are within the range of values that could be derived using a variety of alternate approaches at a specific location.

It should be noted that some of the cost values in B-23 exceed \$100,000 per person, which is the upper limit for the value of CDNFRM in MACCS version 3.10. At this time, the recommendation is simply to replace values that exceed the limit by \$100,000 when using this version of MACCS.

For farmland, the unit costs for decontamination are summarized in Table B-24 below based on Table B-6. These values are considered reasonable generic values to use for CDFRM if site-specific information is not available.

Table B-24 Farmland Decontamination Costs

Level	Decontamination	Waste Generation	Waste Management	Waste Characterization	Total Cost to Decontaminate	
	\$/acre	yd ³ /acre	\$/acre	\$/acre	\$/acre	\$/ha
Level 1 (DF 2)	\$1,400	0	\$0	\$130	\$1,500	\$3,700
Level 2 (DF 4)	\$15,000	0	\$0	\$130	\$15,000	\$38,000
Level 3 (DF 8)	\$15,000	0	\$0	\$130	\$15,000	\$38,000

As previously noted, even with no costs for waste generation and offsite disposal, the estimated costs to decontaminate farmland at Levels 2 (DF=4) and 3 (DF=8) are significantly larger than the value of most farmland in the U.S. For most analyses, this would result in MACCS projecting that the farmland be condemned rather than decontaminated. Methods involving soil removal and disposal, which would lead to higher unit decontamination costs than estimated here, would be even more likely to result in a MACCS projection of condemnation rather than decontamination.

B.5 Conclusions

It should be noted that decontamination and waste management costs derived in this appendix are uncertain. While this appendix derives what are considered to be reasonable values for the MACCS parameters related to decontamination, a relatively wide range of values could have been derived. Sources of uncertainty include uncertainties in the underlying data (e.g., estimation of decontamination effectiveness, estimations of unit costs and waste generation rates). Uncertainties also arise as a result of assumptions made in developing the models, (e.g., estimation of the dimensions of structures and other improvements requiring decontamination, identification of appropriate currency conversion rates for unit costs, selection of methods for selected decontamination levels, assumptions regarding which areas would be decontaminated). The impact of these uncertainties could be explored using sensitivity analyses that varied these assumptions or values for these parameters. In addition, many of the decision processes that determine how decontamination would be performed if an accident were to occur are subject to considerable decision-making variations. Decision making regarding decontamination methods would include factors other than achieving the maximum dose reduction at the minimum cost. Consideration of other factors may result in very high overall decontamination costs, in some cases exceeding the value of the property being decontaminated. However, in MACCS, standard practice is to assign the values of VALWF and VALWNF to represent the regional average per-hectare farmland value and per-capita wealth values, respectively. If the total costs of decontamination and interdiction exceeds these values, MACCS assumes that it is more cost effective to simply condemn the land than to clean it up, and estimates economic losses by assuming total loss of the per-hectare farmland value and per-capita wealth value. Also, some of the non-farm cost values developed using the approaches in this appendix may exceed \$100,000 per person, which is the upper limit for the value of CDNFRM in MACCS version 3.10. Likewise, if the user rederives CDFRM values using methods that generate significant quantities of waste requiring storage, transportation, and disposal, the derived CDFRM values may significantly exceed \$100,000 per hectare. At this time, the recommendation for developing parameters for use in MACCS 3.10 is simply to replace values that exceed the limit by \$100,000 (per person or per hectare).

Uncertainties also arise as a result of the potential impact of processes that were not included in this model. For example, models were not developed to estimate potential costs arising from a number of project management and organizational processes along with personal property damages associated with long-term cleanup. However, the analyst should consider, under a separate analysis, if there are methods for estimating project management costs or economic/personal valuation data sources available that could be utilized to help minimize such uncertainties. These include:

- Mapping of contamination, monitoring of food and water contamination, monitoring of environmental transport and supplemental decontamination of hotspots, and efforts to ensure public safety (such as enforcement of restricted areas and tasks related to public reentry).

- The development of local decontamination implementation plans and decontamination worker guidelines; acquisition of decontamination workers and provision of decontamination and radiation safety training; contract management and associated planning, oversight, and verification of cleanup work; research and development of decontamination and waste management methods; and pilot projects to guide planning efforts.
- Community outreach and communication, such as the cost to obtain land owner permission to perform decontamination, to obtain community support for securing temporary storage sites, and more generally to educate the public about radiation and decontamination.
- Costs of decontaminating mildly contaminated areas from which populations were never evacuated or relocated.
- Costs for the decontamination or disposal of the contents of housing units subject to decontamination.
- Costs for demolition and disposal of contaminated structures in condemned areas.
- Secondary costs of interdiction such as potentially increased crime rates, loss of property tax collections, increased pest populations, increased fire and safety hazards, etc.

It is also noted that, in the development of this model, costs for short-term temporary storage were estimated but no costs were estimated for long-term interim storage prior to final disposal. A widespread contamination event could quickly overwhelm existing disposal capacities, thereby requiring the identification and development of more disposal site(s). If such sites cannot be developed in a timely manner, an interim storage facility may be necessary to bridge the gap between temporary storage and final disposal. Although cost estimates for such an interim storage facility are not included in this analysis, they could be added to the disposal costs estimated in this appendix provided sufficient information could be identified to develop such estimates.

Despite these uncertainties, the methodology and its application as described in this appendix is considered to represent a reasonably traceable and transparent basis to develop unit decontamination cost estimates suitable for use in MACCS. These values may be made more site-specific by using substituting site-specific regional values for urban vs rural population (available from census data) or regional land use values (available from, for example, [25]). In addition, alternate sources of unit cost or waste generation rates (e.g., [14] or similar) may be used to examine the effects of uncertainties in unit costs.

B.6 References

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APPENDIX C

MACCS INPUT PARAMETER TECHNICAL BASIS APPLICABILITY

In this document, a summary of technical bases has been provided for the majority of MACCS parameters that may be defined by a user. However, there is a range of applicability for these values or modeling choices. Some of these modeling choices are considered standard practice and should generally not be changed without very good reason, whereas other parameters may require varying degrees of independent development by a MACCS user. This appendix provides recommendations regarding how the technical bases provided in this document may be used. The parameters generally fall into three categories. Technical bases for parameters annotated with "Standard" generally represent modeling choices that should not be changed without very good reason. Only limited justification of the parameter choice is expected or needed for most analyses. Technical bases for parameters annotated with "Generic" represent modeling choices that are considered reasonable generic choices but could be changed by a user, depending on the analysis. These include, for example, most non-site-specific parameters. The technical bases provided in this document for such parameters are expected to be applicable for most U.S. locations, but if data are available the parameter may be made more site-specific. The user should verify applicability of these input parameters with little additional documentation on the technical basis expected or needed; usually review or consideration is sufficient to verify parameter applicability for most analyses. In contrast, the technical basis for parameters annotated with "User-Defined" should in almost all cases be evaluated by the user. These include, for example, site-specific parameters. Examples are provided for such parameters, but these values may not be applicable to many applications. The user should develop and document the parameter value chosen for a specific application with a reasonable and defensible technical basis. Recommendations in this appendix on the technical basis for MACCS input parameters as standard, generic, or user-defined and the commensurate expected documentation requirements are informed both by professional judgment as well as by the content in the "Standard for Radiological Accident Offsite Consequence Analysis (Level 3 PRA) to Support Nuclear Installation Applications" [1].

There are several notes in Table C-1. Note (1) indicates that some analyses may require site- or analysis-specific input. Note (2) indicates that a number of recognized sources may be of general applicability. Note (3) refers to cost values that should be escalated from the base year identified in this document to the year of interest by the analyst. Note (4) indicates that the parameter is not generically needed, but if used it should be site-specific with justification.

Table C-1 MACCS Parameter Application Guidance

MACCS Parameter Name	Standard	Generic	User-Defined	Notes and caveats
ACNAME	X			
ACTHRE	X			Should only be changed when updating to different guidance, e.g., BEIR VII.
APLFRC		X	X ¹	May depend upon source term characteristics
BNDMXH		X	X ¹	Should be based on regional or U.S. data, depending on size of grid.
BNDRAN		X	X ¹	Boundary rain only recommended for use beyond 500 mi.
BNDWND		X	X ¹	Should be based on regional or U.S. data, depending on size of grid.
BRGSMOD	X			
BRKPNT	X			
BRRATE		X		
BUILDH			X	
CDFRM		X ³	X ¹	
CDNFRM		X ³	X ¹	
CFRISK	X			Should only be changed when updating to different guidance, e.g., BEIR VII.
CIRISK	X			
CORINV			X	
CORSCA			X	
CRIORG	X			Protective actions are almost always based on effective dose.
CRTOCR	X			
CSFACT		X		Generic U.S. values can be used or site-specific values may be derived.
CWASH1		X		
CWASH2		X		
CYCOEF	X			
CYDIST	X			
CYSIGA		X ²		Use of SOARCA power-law coefficients facilitates uncertainty analysis
CYSIGB		X ²		
CZSIGA		X ²		
CZSIGB		X ²		
DCF_FILE001		X ²	X ¹	Some applications may require dose coefficients based on FGR-11 and FGR-12
DDTHRE	X			Should only be changed when updating to different guidance, e.g., BEIR VII.
DISPMD		X		Recommended option is LRTIME.

Table C-1 MACCS Parameter Application Guidance (continued)

MACCS Parameter Name	Standard	Generic	User-Defined	Notes and caveats
DISTANCE		X		
DLBCST		X ³	X ¹	
DLTEVA			X	
DLTSHL			X	
DOSEFA	X			
DOSEFB	X			
DOSELONG		X		
DOSEMILK		X		
DOSEOTHER		X		
DOSHOT		X	X ¹	Generic if based on EPA early phase PAG criteria.
DOSMOD	X			
DOSNRM		X	X ¹	Generic if based on EPA early phase PAG criteria.
DPP_INTERPHAS		X	X ¹	Generic for states that follow EPA intermediate phase relocation criteria.
DPPEMP		X	X ¹	Generic if based on EPA early phase PAG criteria.
DPRATE		X		
DRYDEP		X		
DSCRLT		X	X ¹	Generic for states that follow EPA intermediate phase relocation criteria
DSCRTI		X	X ¹	
DSRATE		X		May change over time.
DSRFCT		X	X ¹	
DUR_INTPHAS			X	Depends on site and accident sequence.
DURBEG			X	
DURMID			X	
EFFACA	X			
EFFACB	X			
EFFACY			X ⁴	No KI modeling is generally recommended, but if the user chooses to model KI ingestion, this parameter should be site-specific with justification.
EFFTHR	X			
EIFACA	X			
EIFACB	X			
EINAME	X			
EISUSC	X			

Table C-1 MACCS Parameter Application Guidance (continued)

MACCS Parameter Name	Standard	Generic	User-Defined	Notes and caveats
EITHRE	X			
ENDEMP		X	X ¹	Duration of early phase may need to be adjusted for delayed and/or prolonged source terms
ESPEED			X	
ESPGRD			X	
ESPMUL			X ¹	
EVACST			X	
EVAKEY		X	X ⁴	The keyhole evacuation model is not generically recommended for most analyses, but if used it should be site-specific with justification.
EVATYP			X	
EXPTIM		X		
FRFDL		X		May change over time.
FRFIM		X		May change over time.
FRNFDL		X		May change over time.
FRNFIM		X		May change over time.
GRPNAM		X ²		
GSHFAC		X		Generic U.S. values can be used or site-specific values may be derived.
GWCOEF		X ²		
IBDSTB		X	X ¹	Should be based on regional or U.S. data, depending on size of grid.
IDIREC			X	
IGROUP		X ²		
INDXBN		X	X ¹	Automatically generated based on rain bin sampling
INWGHT			X	
IPLUME		X		
IRSEED		X		
KEYDIS			X ⁴	Parameter not generically needed, but if used it must be site-specific with justification.
KEYFORCST			X ⁴	
KIMODL		X	X ⁴	Parameter should normally be set to NOKI, but if the user chooses to model KI ingestion, it must be site-specific with justification.
LATITU, LONGIT			X	
LBRRATE		X		

Table C-1 MACCS Parameter Application Guidance (continued)

MACCS Parameter Name	Standard	Generic	User-Defined	Notes and caveats
LIMSPA		X	X ¹	Generic but should correspond to 500 miles for most analyses, depending on size of grid.
LPROTIN		X		Generic U.S. values can be used or site-specific values may be derived.
LVLDEC		X		
MAXGRP		X ²		
MAXHGT		X		
MAXRIS			X	
METCOD		X		Generic based on the sampling scheme chosen by the analyst.
Meteorological File Name			X	
MNDFAC	X			
MNDIST	X			
MNDMOD		X		
NAMSTB		X		Generic list for LWRs
NAMWPI		X		
NGWTRM		X ²		
NPSGRP		X ²		
NRINTN		X		
NRNINT		X		
NRWTRM		X ²		
NSBINS		X		
NSECTR			X ⁴	Parameter not generically needed, but if used it must be site-specific with justification.
NSMPLS		X		Generic based on the sampling scheme chosen by the analyst.
NUCNAM		X		Generic for LWRs
NUMACA	X			All cancers in the model should be included
NUMCOR		X	X ¹	Generally based on resolution of available meteorological data
NUM_DIST		X		
NUMEFA	X			
NUMEIN	X			
NUMFIN	X			
NUMISO		X		List is generic for LWRs
NUMRAD			X	
NUMREL			X	

Table C-1 MACCS Parameter Application Guidance (continued)

MACCS Parameter Name	Standard	Generic	User-Defined	Notes and caveats
NUMSTB		X		List is generic for LWRs
NUMWPI		X		
OALARM			X	
ORGFLG	X			
ORGNAM	X			
OVERRID		X		
PDELAY			X	
PLHEAT			X	
PLHITE			X	
PLMDEN			X	
PLMFLA			X	
PLMMOD		X	X ¹	“Density and Flow” is generically recommended but “Power” is appropriate if information on plume density and flow rate is unavailable
PLUDUR			X	
POPCST		X ³		
POPFLG		X		Use of a site file is recommended unless analysis does not require consideration of population distribution.
POPFRAC			X ⁴	No KI modeling is recommended, but if the user chooses to model KI ingestion, this parameter must be site-specific with justification.
PROTIN		X		Generic U.S. values can be used or site-specific values may be derived.
PSDIST			X	
REFTIM		X		
RELCST			X	
RELFRC			X	
RESCON		X ²		
RESHAF		X ²		
RNDSTS		X		
RNRATE		X		
RWCOEF		X ²		
SCLADP	X			Values may be varied for uncertainty analysis
SCLCRW	X			
SCLEFP	X			

Table C-1 MACCS Parameter Application Guidance (continued)

MACCS Parameter Name	Standard	Generic	User-Defined	Notes and caveats
SIGMA_Y_nnn		X ²		Values based on Eimutis and Konicek approximation to Pasquill-Gifford curves are recommended for general use.
SIGMA_Z_nnn		X ²		
SIGYINIT			X	
SIGZINIT			X	
Site File Name			X	
SKPFAC		X		U.S. or site-specific values can be used.
SPAEND			X	
TFWKF		X		
TFWKNF		X		
TGWHLF		X ²		
TIMBAS	X		X ¹	For dispersion parameters based on Pasquill-Gifford curves, should be set to 10 min; site-specific dispersion data may be used if available
TIMDEC		X		
TIMHOT			X	
TIMNRM			X	
TMPACT		X	X ¹	Generic for states that follow EPA relocation criteria.
TRWHLF		X ²		
VALWF			X ³	
VALWNF			X ³	
VDEPOS		X	X ¹	
WETDEP		X		
WINGF		X		
WINSP1	X			
WINSP2	X			
WSHFRI		X		
WSHRTA		X		
XPFAC1	X			
XPFAC2	X			
YSCALE	X			
ZSCALE			X	

¹ Some analyses may require site- or analysis-specific input.

² A number of recognized sources may be of general applicability.

³ Cost values that should be escalated from the base year identified in this document to the year of interest by the analyst.

⁴ The parameter is not generically needed, but if used it should be site-specific with justification.

References

- [1] American Society of Mechanical Engineers & American Nuclear Society, "Standard for Radiological Accident Offsite Consequence Analysis (Level 3 PRA) to Support Nuclear Installation Applications (ASME/ANS RA-S-1.3-2017)," American Nuclear Society, La Grange Park, IL, 2017.

APPENDIX D

DISPERSION PARAMETERIZATIONS

Several approximations to represent the original Pasquill-Gifford (PG) dispersion curves [1], [2], [3] are available for use with MACCS. Dispersion parameters based on approximations provided in Tadmor and Gur [4], as corrected in [5], have commonly been used in MACCS. An alternate set of parameters is provided by Eimutis and Konicek [6]. These approximations are power law fits expressed by Equation (D-1):

$$\sigma_y = A_y \cdot x^{B_y} + C_y \quad (D-1a)$$

$$\sigma_z = A_z \cdot x^{B_z} + C_z \quad (D-1b)$$

where

- σ_y is the crosswind dispersion parameter (m),
- σ_z is the vertical dispersion parameter (m),
- x is downwind distance (m),
- A_y , B_y , and C_y are the crosswind dispersion power law coefficients, and
- A_z , B_z , and C_z are the vertical dispersion power law coefficients.

It should be noted that direct implementation of these relationships using the MACCS power law dispersion model is only possible when C_y and C_z are zero, because MACCS does not allow entry of a constant term. It should also be noted that these approximations are only valid over specified distance ranges. Implementation of these over the full set of distances, or where the constant term is used, requires use of the MACCS lookup table formulation.

The coefficients used in the Tadmor and Gur parameterization are provided in Table D-1. For use in Equations (D-1a) and (D-1b), C_y and C_z are both zero for all distances. Thus, this formulation can be implemented directly in MACCS, although only for a single distance range (0.5 to 5 km or 5 to 50 km).

Table D-1 Dispersion Coefficients for the Tadmor and Gur Formulation

Stability Class	Sigma-y, 0.5 to 50 km		Sigma-z, 0.5 to 5 km		Sigma-z, 5 to 50 km	
	Ay	By	Az	Bz	Az	Bz
A	0.3658	0.9031	2.5E-04	2.1250	*	*
B	0.2751	0.9031	1.9E-03	1.6021	*	*
C	0.2089	0.9031	0.20	0.8543	0.5742	0.7160
D	0.1474	0.9031	0.30	0.6532	0.9605	0.5409
E	0.1046	0.9031	0.40	0.6021	2.1250	0.3979
F	0.0722	0.9031	0.20	0.6020	2.1820	0.3310

* [4] note that "no graphical data is available in this range"

The coefficients used in the Eimutis and Konicek formulation are provided in Table D-2. For use in Equation (D-1a), $C_y = 0$ for all distance ranges, but $C_z \neq 0$ for some of the distance ranges. Thus, the Eimutis and Konicek model cannot be implemented as a power law function in MACCS; it must be implemented as lookup table.

Table D-2 Dispersion Coefficients for the Eimutis and Konicek Formulation

Stability Class	Sigma-y (m) All Distances		Sigma-z (m), Less than 100 meters			Sigma-z (m), 100 to 1,000 meters			Sigma-z (m), greater than 1,000 meters		
	Ay	By	Az	Bz	Cz	Az	Bz	Cz	Az	Bz	Cz
A	0.3658	0.9031	0.192	0.936	0.000	6.6E-04	1.941	9.27	2.4E-04	2.094	-9.6
B	0.2751	0.9031	0.156	0.922	0.000	0.0382	1.149	3.30	0.055	1.098	2.00
C	0.2089	0.9031	0.116	0.905	0.000	0.113	0.911	0.00	0.113	0.911	0.00
D	0.1471	0.9031	0.079	0.881	0.000	0.222	0.725	-1.70	1.26	0.516	-13.0
E	0.1046	0.9031	0.063	0.871	0.000	0.211	0.678	-1.30	6.73	0.305	-34.0
F	0.0722	0.9031	0.053	0.814	0.000	0.086	0.740	-0.35	18.05	0.180	-48.6

An additional dispersion formulation has been developed by Briggs [7], [3]. An analytical formulation for the Brigg dispersion parameters is presented in Table 4.5 of [8]. This formulation follows a different functional form than the power law used in the Tadmor-Gur and Eimutis and Konicek formulations and, thus, it cannot be implemented in MACCS as a power-law function. Table D-3 provides the Briggs open country dispersion parameterization as a function of PG stability class.

Table D-3 Briggs Open Country Dispersion Parameters (where x is in meters)

Stability Class	σ_y (m)	σ_z (m)
A	$0.22x(1 + 0.0001x)^{-\frac{1}{2}}$	$0.20x$
B	$0.16x(1 + 0.0001x)^{-\frac{1}{2}}$	$0.12x$
C	$0.11x(1 + 0.0001x)^{-\frac{1}{2}}$	$0.08x(1 + 0.0002x)^{-\frac{1}{2}}$
D	$0.08x(1 + 0.0001x)^{-\frac{1}{2}}$	$0.06x(1 + 0.0015x)^{-\frac{1}{2}}$
E	$0.06x(1 + 0.0001x)^{-\frac{1}{2}}$	$0.03x(1 + 0.0003x)^{-1}$
F	$0.04x(1 + 0.0001x)^{-\frac{1}{2}}$	$0.016x(1 + 0.0003x)^{-1}$

Lookup tables for use in MACCS can be developed based on these expressions. A lookup table implementing the Eimutis and Konicek formulation of the Pasquill-Gifford dispersion curves for use in MACCS is provided in Tables D-4 and D-5.

Table D-4 Eimutis and Konicek Crosswind Dispersion (σ_y (m)) Lookup Table

Distance (m)	Stability A	Stability B	Stability C	Stability D	Stability E	Stability F
1.0E+00	3.66E-01	2.75E-01	2.09E-01	1.47E-01	1.05E-01	7.22E-02
1.4E+00	4.96E-01	3.73E-01	2.83E-01	1.99E-01	1.42E-01	9.78E-02
2.0E+00	6.84E-01	5.14E-01	3.91E-01	2.75E-01	1.96E-01	1.35E-01
3.0E+00	9.87E-01	7.42E-01	5.63E-01	3.97E-01	2.82E-01	1.95E-01
4.0E+00	1.28E+00	9.62E-01	7.31E-01	5.14E-01	3.66E-01	2.52E-01
6.0E+00	1.84E+00	1.39E+00	1.05E+00	7.42E-01	5.28E-01	3.64E-01
8.0E+00	2.39E+00	1.80E+00	1.37E+00	9.62E-01	6.84E-01	4.72E-01
1.0E+01	2.93E+00	2.20E+00	1.67E+00	1.18E+00	8.37E-01	5.78E-01
1.4E+01	3.97E+00	2.98E+00	2.26E+00	1.59E+00	1.13E+00	7.83E-01
2.0E+01	5.47E+00	4.12E+00	3.13E+00	2.20E+00	1.56E+00	1.08E+00
3.0E+01	7.89E+00	5.94E+00	4.51E+00	3.17E+00	2.26E+00	1.56E+00
4.0E+01	1.02E+01	7.70E+00	5.84E+00	4.12E+00	2.93E+00	2.02E+00
6.0E+01	1.48E+01	1.11E+01	8.43E+00	5.94E+00	4.22E+00	2.91E+00
8.0E+01	1.91E+01	1.44E+01	1.09E+01	7.70E+00	5.47E+00	3.78E+00
1.0E+02	2.34E+01	1.76E+01	1.34E+01	9.41E+00	6.69E+00	4.62E+00
1.4E+02	3.17E+01	2.39E+01	1.81E+01	1.28E+01	9.07E+00	6.26E+00
2.0E+02	4.38E+01	3.29E+01	2.50E+01	1.76E+01	1.25E+01	8.64E+00
3.0E+02	6.31E+01	4.75E+01	3.61E+01	2.54E+01	1.81E+01	1.25E+01
4.0E+02	8.19E+01	6.16E+01	4.68E+01	3.29E+01	2.34E+01	1.62E+01
6.0E+02	1.18E+02	8.88E+01	6.74E+01	4.75E+01	3.38E+01	2.33E+01
8.0E+02	1.53E+02	1.15E+02	8.74E+01	6.16E+01	4.38E+01	3.02E+01
1.0E+03	1.87E+02	1.41E+02	1.07E+02	7.53E+01	5.36E+01	3.70E+01
1.4E+03	2.54E+02	1.91E+02	1.45E+02	1.02E+02	7.26E+01	5.01E+01
2.0E+03	3.50E+02	2.63E+02	2.00E+02	1.41E+02	1.00E+02	6.91E+01
3.0E+03	5.05E+02	3.80E+02	2.88E+02	2.03E+02	1.44E+02	9.97E+01
4.0E+03	6.55E+02	4.93E+02	3.74E+02	2.63E+02	1.87E+02	1.29E+02
6.0E+03	9.45E+02	7.10E+02	5.39E+02	3.80E+02	2.70E+02	1.86E+02
8.0E+03	1.22E+03	9.21E+02	7.00E+02	4.93E+02	3.50E+02	2.42E+02
1.0E+04	1.50E+03	1.13E+03	8.56E+02	6.03E+02	4.28E+02	2.96E+02
1.4E+04	2.03E+03	1.53E+03	1.16E+03	8.17E+02	5.81E+02	4.01E+02
2.0E+04	2.80E+03	2.11E+03	1.60E+03	1.13E+03	8.01E+02	5.53E+02
3.0E+04	4.04E+03	3.04E+03	2.31E+03	1.63E+03	1.16E+03	7.98E+02
4.0E+04	5.24E+03	3.94E+03	2.99E+03	2.11E+03	1.50E+03	1.03E+03
6.0E+04	7.56E+03	5.68E+03	4.32E+03	3.04E+03	2.16E+03	1.49E+03
8.0E+04	9.80E+03	7.37E+03	5.60E+03	3.94E+03	2.80E+03	1.93E+03
1.0E+05	1.20E+04	9.02E+03	6.85E+03	4.82E+03	3.43E+03	2.37E+03
1.4E+05	1.62E+04	1.22E+04	9.28E+03	6.53E+03	4.65E+03	3.21E+03
2.0E+05	2.24E+04	1.69E+04	1.28E+04	9.02E+03	6.41E+03	4.42E+03
3.0E+05	3.23E+04	2.43E+04	1.85E+04	1.30E+04	9.25E+03	6.38E+03
4.0E+05	4.19E+04	3.15E+04	2.39E+04	1.69E+04	1.20E+04	8.27E+03
6.0E+05	6.05E+04	4.55E+04	3.45E+04	2.43E+04	1.73E+04	1.19E+04
8.0E+05	7.84E+04	5.90E+04	4.48E+04	3.15E+04	2.24E+04	1.55E+04
1.0E+06	9.59E+04	7.21E+04	5.48E+04	3.86E+04	2.74E+04	1.89E+04
1.4E+06	1.30E+05	9.77E+04	7.42E+04	5.23E+04	3.72E+04	2.57E+04
2.0E+06	1.79E+05	1.35E+05	1.02E+05	7.21E+04	5.13E+04	3.54E+04
3.0E+06	2.59E+05	1.95E+05	1.48E+05	1.04E+05	7.40E+04	5.11E+04
4.0E+06	3.35E+05	2.52E+05	1.92E+05	1.35E+05	9.59E+04	6.62E+04
6.0E+06	4.84E+05	3.64E+05	2.76E+05	1.95E+05	1.38E+05	9.55E+04
8.0E+06	6.27E+05	4.72E+05	3.58E+05	2.52E+05	1.79E+05	1.24E+05
1.0E+07	7.67E+05	5.77E+05	4.38E+05	3.09E+05	2.19E+05	1.51E+05

Table D-5 Eimutis and Konicek Vertical Dispersion (σ_z (m)) Lookup Table

Distance (m)	Stability A	Stability B	Stability C	Stability D	Stability E	Stability F
1.0E+00	1.92E-01	1.56E-01	1.16E-01	7.90E-02	6.30E-02	5.30E-02
1.4E+00	2.63E-01	2.13E-01	1.57E-01	1.06E-01	8.45E-02	6.97E-02
2.0E+00	3.67E-01	2.96E-01	2.17E-01	1.45E-01	1.15E-01	9.32E-02
3.0E+00	5.37E-01	4.30E-01	3.14E-01	2.08E-01	1.64E-01	1.30E-01
4.0E+00	7.03E-01	5.60E-01	4.07E-01	2.68E-01	2.11E-01	1.64E-01
6.0E+00	1.03E+00	8.14E-01	5.87E-01	3.83E-01	3.00E-01	2.28E-01
8.0E+00	1.34E+00	1.06E+00	7.62E-01	4.93E-01	3.85E-01	2.88E-01
1.0E+01	1.66E+00	1.30E+00	9.32E-01	6.01E-01	4.68E-01	3.45E-01
1.4E+01	2.27E+00	1.78E+00	1.26E+00	8.08E-01	6.28E-01	4.54E-01
2.0E+01	3.17E+00	2.47E+00	1.75E+00	1.11E+00	8.56E-01	6.07E-01
3.0E+01	4.63E+00	3.59E+00	2.52E+00	1.58E+00	1.22E+00	8.45E-01
4.0E+01	6.06E+00	4.68E+00	3.27E+00	2.04E+00	1.57E+00	1.07E+00
6.0E+01	8.86E+00	6.80E+00	4.72E+00	2.91E+00	2.23E+00	1.48E+00
8.0E+01	1.16E+01	8.87E+00	6.12E+00	3.75E+00	2.86E+00	1.88E+00
1.0E+02	1.43E+01	1.09E+01	7.49E+00	4.57E+00	3.48E+00	2.25E+00
1.4E+02	1.89E+01	1.45E+01	1.02E+01	6.29E+00	4.72E+00	2.98E+00
2.0E+02	2.86E+01	2.01E+01	1.41E+01	8.64E+00	6.36E+00	3.99E+00
3.0E+02	5.17E+01	3.01E+01	2.04E+01	1.22E+01	8.79E+00	5.51E+00
4.0E+02	8.34E+01	4.06E+01	2.65E+01	1.54E+01	1.10E+01	6.89E+00
6.0E+02	1.72E+02	6.28E+01	3.84E+01	2.12E+01	1.48E+01	9.43E+00
8.0E+02	2.94E+02	8.60E+01	4.99E+01	2.66E+01	1.83E+01	1.17E+01
1.0E+03	4.48E+02	1.10E+02	6.11E+01	3.15E+01	2.15E+01	1.39E+01
1.4E+03	9.20E+02	1.59E+02	8.30E+01	3.99E+01	2.73E+01	1.79E+01
2.0E+03	1.95E+03	2.34E+02	1.15E+02	5.06E+01	3.44E+01	2.23E+01
3.0E+03	4.58E+03	3.64E+02	1.66E+02	6.54E+01	4.34E+01	2.77E+01
4.0E+03	8.36E+03	4.98E+02	2.16E+02	7.80E+01	5.05E+01	3.17E+01
6.0E+03	1.96E+04	7.76E+02	3.13E+02	9.92E+01	6.16E+01	3.78E+01
8.0E+03	3.57E+04	1.06E+03	4.06E+02	1.17E+02	7.03E+01	4.24E+01
1.0E+04	5.70E+04	1.36E+03	4.98E+02	1.33E+02	7.77E+01	4.61E+01
1.4E+04	1.15E+05	1.96E+03	6.76E+02	1.61E+02	8.98E+01	5.20E+01
2.0E+04	2.44E+05	2.91E+03	9.36E+02	1.96E+02	1.04E+02	5.87E+01
3.0E+04	5.69E+05	4.53E+03	1.35E+03	2.44E+02	1.22E+02	6.68E+01
4.0E+04	1.04E+06	6.22E+03	1.76E+03	2.86E+02	1.36E+02	7.30E+01
6.0E+04	2.43E+06	9.70E+03	2.55E+03	3.55E+02	1.59E+02	8.22E+01
8.0E+04	4.44E+06	1.33E+04	3.31E+03	4.14E+02	1.77E+02	8.91E+01
1.0E+05	7.08E+06	1.70E+04	4.06E+03	4.66E+02	1.91E+02	9.48E+01
1.4E+05	1.43E+07	2.46E+04	5.51E+03	5.57E+02	2.16E+02	1.04E+02
2.0E+05	3.02E+07	3.64E+04	7.63E+03	6.72E+02	2.45E+02	1.14E+02
3.0E+05	7.07E+07	5.68E+04	1.10E+04	8.31E+02	2.81E+02	1.26E+02
4.0E+05	1.29E+08	7.79E+04	1.43E+04	9.67E+02	3.10E+02	1.35E+02
6.0E+05	3.02E+08	1.22E+05	2.07E+04	1.19E+03	3.55E+02	1.49E+02
8.0E+05	5.51E+08	1.67E+05	2.70E+04	1.39E+03	3.91E+02	1.60E+02
1.0E+06	8.79E+08	2.13E+05	3.30E+04	1.56E+03	4.21E+02	1.68E+02
1.4E+06	1.78E+09	3.08E+05	4.49E+04	1.86E+03	4.70E+02	1.82E+02
2.0E+06	3.75E+09	4.56E+05	6.21E+04	2.23E+03	5.28E+02	1.97E+02
3.0E+06	8.78E+09	7.12E+05	8.99E+04	2.76E+03	6.02E+02	2.16E+02
4.0E+06	1.60E+10	9.76E+05	1.17E+05	3.20E+03	6.60E+02	2.30E+02
6.0E+06	3.75E+10	1.52E+06	1.69E+05	3.95E+03	7.52E+02	2.51E+02
8.0E+06	6.84E+10	2.09E+06	2.20E+05	4.58E+03	8.24E+02	2.67E+02
1.0E+07	1.09E+11	2.67E+06	2.69E+05	5.14E+03	8.84E+02	2.80E+02

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BIBLIOGRAPHIC DATA SHEET

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Technical Bases for Consequence Analyses Using MACCS (MELCOR
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11. ABSTRACT (200 words or less)

The use of MELCOR Accident Consequence Code System (MACCS) in regulatory applications requires that input parameters used in MACCS models have a defensible and transparent technical basis. The existing technical basis for MACCS parameters was identified and updates were developed based on current data and information. The transparent way these updates are documented provides a technical basis for updating MACCS parameters with consistent application among the MACCS user community.

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MACCS, MELCOR, severe accident, environmental consequence,
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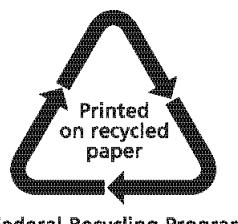
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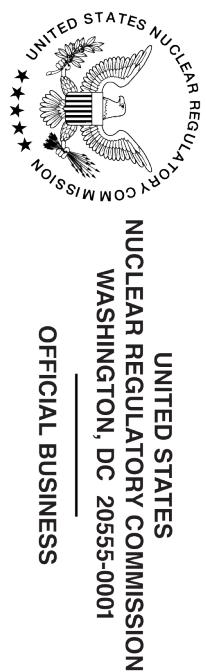
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