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MELCOR Accident Consequence Code System (MACCS)

Model Description

Prepared by H-N Jow, J. L. Sprung, J. A. Rollstin, L. T. Ritchie, D. I. Chanin,

Sandia National Laboratories

Prepared for
U.S. Nuclear Regulatory Commission

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Running MACCS 1.5.11.1

IMPORTANT: The new version must use the new dosdata.inp file as there are new organs listed in the dose conversion file.

The code is now run with a batch file, "RUNMAXPC.BAT" with the following syntax:

```
RUNMAXPC ATMOS-fname EARLY-fname CHRONC-fname MET-fname SIT-fname OUTPUT-fname
```

where ????-fname is the filename of the particular function <u>without any extension!</u>

For example: in 1.5.11, the files were listed in the ATMOS file (All of these file handling card images may be deleted, if not, they will just elicit warning messages.) If you used the "MAX.BAT" batch file, you would type "max problem" and the batch file would add the extension ".ATM" and find the file called "problem.atm".

In 1.5.11.1, the "RUNMAXPC" batch file adds the extension ".INP" to all file names, except the output file which gets an extension of ".OUT".

While not important to running the code, but of interest, whereas 1.5.11 looked at individual files (ATMOS, EARLY, etc.), 1.5.11.1 concatenates all of the files together first into a temporary file named TEMP23.INP. This means that more hard disk space is needed to run version 1.5.11.1 for the input files. (Also, one sample run that I made took 30% longer to run than using the old version.)

At the end of the MACCS run, the computer will beep several times to identify that the program is finished, not that there has been an early termination.

File Modifications MACCS 1.5.11 to 1.5.11.1

<u>EARLY File:</u> ADD the column in BOLD type at the right

```
*              ACNAME      ORGNAM     ACSUSC DOSEFA DOSEFB  CFRISK   CIRISK  DDREFA
*
LCANCERS001 'LEUKEMIA' 'RED MARR'   1.0    1.0    0.0   9.70E-3  9.70E-3  2.0
LCANCERS002 'BONE'     'BONE SUR'   1.0    1.0    0.0   9.00E-4  9.00E-4  2.0
LCANCERS003 'BREAST'   'BREAST'     1.0    1.0    0.0   5.40E-3  1.59E-2  1.0
LCANCERS004 'LUNG'     'LUNGS'      1.0    1.0    0.0   1.55E-2  1.73E-2  2.0
LCANCERS005 'THYROID'  'THYROIDH'   1.0    1.0    0.0   7.20E-4  7.20E-3  1.0
LCANCERS006 'GI'       'LOWER LI'   1.0    1.0    0.0   3.36E-2  5.75E-2  2.0
LCANCERS007 'OTHER'    'BLAD WAL'   1.0    1.0    0.0   2.76E-2  5.52E-2  2.0
```

ADD the following card images:

```
*
* THRESHOLD DOSE FOR APPLYING DDREFA
*
LCDDTHRE001  1.0
*
```

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Prepared by
H-N Jow, J. L. Sprung, J. A. Rollstin,* L. T.Ritchie,
D. I. Chanin,**

Sandia National Laboratories
Albuquerque, NM 87185

*GRAM, Inc. Albuquerque, NM
**Technadyne Engineering Consultants, Inc.
Albuquerque, NM

Prepared for
Division of Systems Research
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555
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ABSTRACT

This report describes the MACCS computer code. The purpose of this code is to simulate the impact of severe accidents at nuclear power plants on the surrounding environment. MACCS has been developed for the U.S. Nuclear Regulatory Commission to replace the previously used CRAC2 code, and it incorporates many improvements in modeling flexibility in comparison to CRAC2.

The principal phenomena considered in MACCS are atmospheric transport, mitigative actions based on dose projection, dose accumulation by a number of pathways including food and water ingestion, early and latent health effects, and economic costs.

The MACCS code can be used for a variety of applications. These include (1) probabilistic risk assessment (PRA) of nuclear power plants and other nuclear facilities, (2) sensitivity studies to gain a better understanding of the parameters important to PRA, and (3) cost-benefit analysis.

This report is composed of three volumes. Volume I, the User's Guide, describes the input data requirements of the MACCS code and provides directions for its use as illustrated by three sample problems. Volume II, the Model Description, describes the underlying models that are implemented in the code, and Volume III, the Programmer's Reference Manual, describes the code's structure and database management.

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FOREWORD

This report provides the documentation of the MACCS computer code, which performs probabilistic calculations of potential offsite consequences of the atmospheric releases of radioactive material in reactor accidents. Sandia National Laboratories (SNL) developed the code for the U.S. Nuclear Regulatory Commission (NRC). The report consists of three volumes -- Volume I being the User's Guide; Volume II, the Model Description; and Volume III, the Programmer's Reference Manual.

With the publication of this report, the MACCS code is released for use within the NRC and for the benefit of other interested users. The MACCS code supersedes the earlier NRC consequence codes, namely, CRAC and CRAC2. The code, its formatted data files, and two pre-processor programs, namely, DOSFAC and MAXGC, which generate certain types of data for the code, are available on magnetic tape from the National Energy Software Center, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439.

The MACCS code has evolved through several draft versions. The current version (i.e., Version 1.5), simply called MACCS, has been substantially improved and subjected to rigorous quality assurance and verification processes. Idaho National Engineering Laboratory (INEL) performed line-by-line checking of the individual code modules to (a) assess the internal and interfacing consistencies and (b) verify that the FORTRAN statements correctly represent the algorithms, statistical techniques, input data requirements, and output capabilities. INEL's efforts were to ensure that the intended models were implemented into a consistent and essentially error-free computer code as specified by state-of-the-art coding standards for large scientific computer programs. Mr. Ulf Tveten, Institute of Energy Technology, Kjeller, Norway, under a subcontract from SNL, performed a comprehensive review of the chronic exposure pathway modeling in MACCS and compared it with those in the latest versions of the consequence codes that are being used, or planned to be completed in the near future, in several member countries of the Organization for Economic Cooperation and Development (OECD). INEL, Mr. Tveten, and SNL were interactively involved in the processes of quality assurance, verification, review, identification of errors and implementation of their correction, and model updating. These processes were largely completed before the MACCS code was used for consequence analysis for the second draft of NUREG-1150. INEL's quality assurance and verification report will be published as NUREG/CR-5376. Mr. Tveten's chronic exposure pathway review report will be published as NUREG/CR-5377.

An NRC effort is under way for comparing MACCS with similar codes of earlier vintage using the benchmark problems of the International Consequence Code Comparison Study. This study was sponsored by the OECD, Nuclear Energy Agency (NEA), Committee on the Safety of Nuclear Installations (CSNI), and was completed in 1983. The staff findings will be published as NUREG-1364. Further, it is also planned that MACCS will participate in the forthcoming NEA/CSNI-sponsored consequence code comparison study scheduled to be completed in 1992. Several other new generation consequence codes from the OECD member countries will also participate in the study. The NRC staff will be assisted by Brookhaven National Laboratory in performing the required analysis using MACCS for the study.

Some of the major new features of MACCS are: (a) improved approximation of the Gaussian crosswind concentration profile, (b) improved health effect models, (c) improved weather sampling, (d) treatment of multiphase release with capability for treatment of change in the wind direction at the reactor between the release phases, (e) detailed chronic exposure pathway modeling, (f) inclusion of inhalation of resuspended radionuclides as an early exposure pathway, (g) provision for more complex emergency response and long-term protective measures, and (h) code flexibility, so that virtually all model parameters can now be provided by the user via input.

The item (h) above is a very useful feature of MACCS that will facilitate the analysis of consequence uncertainties due to uncertainties in the model parameters. However, the user now has to prepare much more data, involving multiple disciplines, for input. This introduces the potential for an inexperienced user to produce distorted results because of improper or inconsistent data.

MACCS continues to use a straight line Gaussian plume dispersion and transport model like its predecessors, CRAC and CRAC2. Although this model is very convenient for probabilistic calculations of consequences using a large number of weather samples, care should be exercised in the MACCS applications to any deterministic, or real-time, situations because of such limitations of the model.

Additional improvements in MACCS will be undertaken in the near future. These include incorporation of latent cancer effect models for high-LET radiation (discussed in the BEIR IV report) and any changes that may be dictated by the recently revised assessment of latent cancer risks of radiation (discussed in the BEIR V report). Research for improvements in these areas is under way. In the longer term, additional areas for improvement will be identified by comparing MACCS with other full-scope consequence codes, such as CONDOR (United Kingdom), UFOMOD (Federal Republic of Germany), and COSYMA (Commission of the European Communities).

The MACCS code represents a significant advancement in the development of severe accident analysis methods. Comments based on use of the code would be greatly appreciated and should be forwarded to the undersigned.

Brian W. Sheron

Brian W. Sheron, Director
Division of Systems Research
Office of Nuclear Regulatory Research

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1.0 INTRODUCTION

Sandia National Laboratories has developed a severe accident risk assessment code, MACCS, for the U.S. Nuclear Regulatory Commission. MACCS, the MELCOR Accident Consequence Code System, calculates the off-site consequences of an atmospheric release of radioactive nuclides.

1.1 Historical Background

The Reactor Safety Study [US75] presented the first comprehensive assessment of the consequences and risks to society from nuclear power plant accidents. As part of the Reactor Safety Study, the CRAC code was developed to calculate the health and economic consequences of accidental releases of radioactive material to the atmosphere [Wa77].

Consequence modeling has received widespread attention and application throughout the world since the Reactor Safety Study, and a significant number of consequence models have been developed [OE84]. CRAC2, released in 1982, incorporated significant improvements over CRAC in the areas of weather sequence sampling and emergency response modeling [Ri83, Ri84].

During the last ten years, as consequence models were used to evaluate severe accident risks, emergency response plans, criteria for reactor siting, safety goals, and the benefits of alternative design features, the need for improved, computationally efficient consequence models became clear. Modular architecture, enhanced site-specific modeling capabilities, more realistic models of actions that mitigate radiation exposures, user specification of all model parameters, and the capability to determine model sensitivities and to estimate the uncertainties associated with code predictions were widely recognized as desirable improvements.

The goal of the MACCS development effort was to produce a portable code with a modular architecture and data base that facilitated performance of many site-specific calculations, estimation of sensitivities and uncertainties, and incorporation of new or alternative models. To support portability, all MACCS coding was required to conform to ANSI standard FORTRAN 77. To facilitate the performance of uncertainty and sensitivity analyses, almost all model parameters are defined by values specified by the user.

1.2 Model Overview

MACCS models the offsite consequences of a severe reactor accident that releases a plume of radioactive materials to the atmosphere. Should such an accidental release occur, the radioactive gases and aerosols in the plume while dispersing in the atmosphere would be transported by the prevailing wind. The environment would be contaminated by radioactive materials deposited from the plume and the population would be exposed to radiation. Estimation of the range and probability of the health effects induced by the radiation exposures not avoided by protective measure actions and the economic costs and losses that would result from the contamination of the environment is the object of a MACCS calculation.

There are two fundamental aspects of the organization of MACCS which are basic to its understanding: the time scale after the accident is divided into various "phases," and the region surrounding the reactor is divided into a polar-coordinate grid.

The time scale after the accident is divided into three phases: emergency phase, intermediate phase, and long-term phase. Of the three time phases, the only one which must be defined by the user is the emergency phase, the other two are optional.

The emergency phase begins immediately after the accident and could last up to seven days following the accident. Within the code, this period is modeled by the EARLY module of MACCS. In this period, the exposure of population to both radioactive clouds and contaminated ground is modeled. Various protective measures can be specified for this phase, including evacuation, sheltering, and dose-dependent relocation.

The intermediate phase can be used to represent a period in which evaluations are performed and decisions are made regarding the type of protective measure actions which need to be taken. Within the code, this period is modeled by the CHRONC module of MACCS. In this period, the radioactive clouds are assumed to be gone and the only exposure pathways are those from the contaminated ground. The protective measure which can be taken during this period is temporary relocation.

The long-term phase represents all time subsequent to the intermediate phase. Within the code, this period is modeled by the CHRONC module of MACCS. As with the intermediate phase, the only exposure pathways considered here are those resulting from the contaminated ground. A variety of protective measures can be taken in the long-term phase in order to reduce doses to acceptable levels: decontamination, interdiction, and condemnation of property. The duration of the exposure period modeled by the long-term phase is essentially infinite.

The spatial grid used to represent the region is centered on the reactor itself. That is, the reactor is located at the point $(r=0, \theta=0)$. The user specifies the number of radial divisions as well as their endpoint distances. Up to 35 of these divisions may be defined extending out to a maximum distance of 9999 km. The angular divisions, θ, used to define the spatial grid correspond to the sixteen directions of the compass. All of the calculations of MACCS are stored on the basis of this polar-coordinate spatial grid.

Since the emergency phase calculations utilize dose-response models for early fatality and early injury which are highly non-linear, it is necessary for those calculations to be performed on a finer grid than the calculations of the intermediate and long-term phases. For this reason, the sixteen compass sectors are subdivided into 3, 5, or 7 user-specified subdivisions in the calculations of the emergency phase.

1.2.1 Input Data and Quantities Calculated by MACCS

MACCS calculations require the following input data [Ch89]:

The inventory at accident initiation (e.g., reactor scram) of those radioactive nuclides important for the calculation of ex-plant consequences (e.g., an end-of-cycle reactor core contains about 10^{18} Bq of I^{131}).

The atmospheric source term produced by the accident (number of plume segments released, sensible heat content, timing, duration, height of each plume segment of release, time when offsite officials are warned that an emergency response should be initiated, and for each important radionuclide, the fraction of that radionuclide's inventory released with each plume segment).

Meteorological data characteristic of the site region (usually one year of hourly windspeed, atmospheric stability, and rainfall recorded at the site or at a nearby National Weather Service station). Although one year of hourly readings contains 8760 weather sequences, MACCS calculations examine only a representative subset of these sequences (typically about 150 sequences). The representative subset is selected by sampling of the weather sequences after sorting them into weather bins defined by windspeed, atmospheric stability, and intensity and distance of the occurrence of rain.

The population distribution about the reactor site (distributions are constructed from census data on a polar coordinate grid having 16 angular sectors aligned with the 16 compass directions and a number of radial intervals that extend outward to 500 miles or more).

Emergency response assumptions for evacuation (delay time before evacuation, area evacuated, average evacuation speed, and travel distance), sheltering (area sheltered), and post-accident relocation (dose criteria and relocation time) are specified by the user. Long-term protective measures based on protective action guide (PAG), such as, decontamination, temporary relocation, contaminated crops and milk condemnation, and farmland production prohibition, are user specified for the long-term phase.

Land usage (habitable land fractions, farmland fractions), and economic data (worth of crops, land, and buildings) for the region about the reactor site are user specified.

Given the preceding input data, MACCS estimates the following:

- The downwind transport, dispersion, and deposition of the radioactive materials released to the atmosphere from the failed reactor containment.

- The short- and long-term radiation doses received by exposed populations via direct (cloudshine, plume inhalation, groundshine, and resuspension inhalation) and indirect (ingestion) pathways.

- The mitigation of those doses by protective actions (evacuation, sheltering, and post-accident relocation of people; disposal of milk, meat, and crops; and decontamination, temporary interdiction, or condemnation of land and buildings).

- The early fatalities and injuries expected to occur within one year of the accident (early health effects) and the delayed (latent) cancer fatalities and injuries expected to occur over the lifetime of the exposed individuals.

- The offsite costs of short-term emergency response actions (evacuation, sheltering, relocation), of crop and milk disposal, and of the decontamination, temporary interdiction, or condemnation of land and buildings.

1.2.2 Atmospheric Dispersion and Transport

MACCS allows a release of radioactive materials to the atmosphere to be divided into successive plume segments, which can have different compositions, release time, durations, release height, and energies (amounts of sensible heat). Plume segment lengths are determined by the product of the segment's release duration and the average windspeed during release. The initial vertical and horizontal dimensions of each plume segment are user specified. If release occurs into a building wake, then wake dimensions can be used to set the initial crosswind dimensions of the plume. If not, a point source can be specified.

A lift-off criterion (a critical windspeed that increases as plume buoyancy increases [Ha86]) determines whether buoyant plumes are subject to plume rise. When the windspeed at release equals or exceeds the critical windspeed, plume rise is prevented. When the windspeed at release is less than the critical windspeed, plume rise is allowed, and the height to which a buoyant plume rises is determined using equations recommended by Briggs [Br75, Ha82].

After release, windspeed determines the rates at which plume segments transport in the downwind direction, and wind direction at the time of release determines the direction of travel. As is done in many consequence codes [US83, CE86], MACCS neglects wind trajectories. The 16 compass sector population distributions are assumed to constitute a representative set of downwind exposed populations. The exposure probability of each of the 16 compass sector population distributions is assumed to be given by the frequency with which wind blows from the site into the sector (i.e., site compass sector wind rose frequencies).

During transport, dispersion of the plume in the vertical and horizontal (crosswind) directions is estimated by using an empirical straight line Gaussian plume model [Ka84]. Thus, dispersion rates depend on windspeed and on atmospheric stability. Although horizontal dispersion of plume segments is unconstrained, vertical dispersion is bounded by the ground and by the top of the mixing layer (as specified by annual or seasonal mixing layer heights [Ho72]), which are modeled as totally reflecting layers using mirror image sources [Ka84]. Since the number of reflections increases as travel times lengthen, eventually, the vertical distribution of each plume segment becomes uniform and is so modeled thereafter [Tu70].

1.2.3 Deposition, Weathering, Resuspension, and Decay

In MACCS, aerosols are removed from the plume by radioactive decay, by washout, which varies with rainfall rate [Br81], and by diffusion to, impaction on, and gravitational settling onto surfaces. The combined removal rate from diffusion, impaction, and settling is modeled using an empirical, dry deposition velocity [Se84]. Because dry deposition velocity varies with particle size, if the aerosol size distribution is divided into ranges, a dry deposition velocity must be specified for each range.

Water bodies (rivers, the Great Lakes, oceans) are contaminated by direct deposition of radioactive materials onto their surfaces by dry deposition and wet deposition (washout) and by washoff from land by uncontaminated rain of previously deposited contamination. Weathering, resuspension, washoff, and radioactive decay decrease surface concentrations of radioactive materials deposited on the ground. Weathering is modeled using Gale's equation [US75]. Resuspension is modeled using resuspension factors [Se84] that attempt to represent the average effect of resuspension by many processes at very different rates throughout large regions. Washoff is modeled as a first order removal process that is integrated over all time after the initial deposition [He85]. Decrease of radioactivity from radioactive decay treats only first generation daughter products.

1.2.4 Weather Data

Plume rise, dispersion, downwind transport, and deposition depend on prevailing weather conditions (windspeed, atmospheric stability, rain rate). In MACCS these may either be invariant or may vary hour by hour. If variable, they can be user specified or can be read from a weather file. When variable weather data is used to model a multiple segment release, one of the plume segments must be specified as risk dominant. Usually, the risk dominant segment will be the segment that produces the acute doses that dominate early fatalities (e.g., the blowdown puff of a three segment release comprised of a leak, a blowdown puff, and a core-concrete interactions tail). Once a risk dominant segment has been specified, MACCS automatically causes the leading edge of that segment to be released at the beginning of the first hour of weather data in the hourly sequence of variable weather data.

1.2.5 Dosimetry

The MACCS dosimetry model consists of three interacting processes: projection of individual exposures to radioactive contamination for each of the seven exposure pathways modeled over a given time period specified by the user, mitigation of these exposures by protective measure actions, and calculation of the actual exposures incurred after mitigation by protective measure actions. For each exposure pathway, MACCS models the radiological burden for the pathway as diminished by the actions taken to mitigate that pathway dose. The total dose to an organ is obtained by summing the doses delivered by each of the individual pathways.

1.2.5.1 Dose Mitigation

MACCS divides time after accident initiation into three phases: an emergency phase, an optional intermediate phase, and a long-term phase. During the emergency phase, which can last up to seven days, doses are reduced by evacuation, sheltering, and temporary relocation of people. During the intermediate phase, doses may be avoided by temporary relocation of people, and ground contamination would be surveyed to prepare for decontamination actions. During the long-term phase, doses are reduced by decontamination of property that is not habitable, by temporary interdiction of property that can not be restored to habitability by decontamination alone, by condemnation of property that can not be restored to habitability at a cost that does not exceed the worth of the property, by disposal of contaminated crops, and by banning farming of contaminated farmland.

In MACCS, people relocate only if their projected doses exceed a user-specified dose criterion (e.g., if projected seven day exposures will exceed 0.25 Sv, people are relocated one day after their exposures commenced). In contrast to temporary relocation, evacuation and sheltering automatically take place within some specified region without regard to projected exposures. After a delay period that follows warning, evacuation proceeds at an effective average speed in the downwind direction chosen to reflect the site condition. At some downwind distance outside the evacuation zone, evacuees are assumed to be directed out of the path of the plume so that further exposures are avoided. The MACCS sheltering model also assumes that there is a delay period between the time when warning is given and the time when shelter is taken. Once shelter is taken, people remain sheltered for a user-specified shelter duration, after which further exposures are avoided.

At the beginning of the long-term phase after the accident, MACCS projects the doses that people would receive if no recovery actions are taken, and compares these doses to the user-specified long-term PAG (e.g., the proposed EPA habitability criteria of no more than 0.02 Sv in the first year following the accident and no more than 0.005 Sv in any subsequent year, which MACCS implements by causing relocation to occur whenever projected 5-year doses exceed 0.04 Sv). If the long-term dose criterion is not met, MACCS attempts to meet the criterion, first by decontamination alone and, if that is insufficient, by decontamination followed by a period of temporary interdiction to allow nuclide removal by weathering and radioactive decay. However, these actions are taken only if they are cost-effective (i.e., the worth of the recovered property is greater than the sum of the following recovery costs: decontamination costs, earnings from investments that are lost by temporary interdiction of property, and the cost of any repairs necessitated by lack of maintenance of property during the temporary interdiction period).

During the long-term phase, dose is also avoided by controlling the consumption and production of contaminated foodstuffs. When the accident occurs during the growing season and thus contaminates crops and pasture by direct deposition to plant surfaces, disposal of crops and milk occurs if ground concentrations of food pathway nuclides exceed user-specified maximum allowable ground concentrations for those nuclides or the habitability PAG dose criterion is exceeded for the area where the foodstuffs are grown. Farming is prohibited in subsequent years until farmland is habitable (i.e., can be worked without violating habitability criteria), and then crops are grown only if ground concentrations of food pathway nuclides do not exceed user-specified maximum allowable ground concentrations. The maximum allowable ground concentrations specified in the MACCS sample input files were calculated by limiting the ingestion dose to a maximally exposed individual (see Appendix C). Because deep ploughing, the most likely decontamination method for farmland, is unlikely to remove significant amounts of radioactivity from the root zone, MACCS assumes that decontamination of farmland will reduce doses to farmers from groundshine and from inhalation of resuspended radioactive materials, but will not decrease uptake of radioactivity by root systems. Thus, decontamination of farmland does not affect food ingestion doses. Accordingly, root uptake of radioactivity can be decreased only by temporary interdiction of farmland to allow radioactivity to be removed by weathering and decay, a procedure MACCS allows only if the worth of the crops that will not be grown does not exceed the worth of the farmland, and only if the length of the interdiction period does not exceed eight years.

1.2.5.2 Exposure Pathways

MACCS models seven exposure pathways: exposure to the passing plume (cloudshine), exposure to materials deposited on the ground (groundshine), exposure to materials deposited on skin (skin deposition), inhalation of materials directly from the passing plume (cloud inhalation), inhalation of materials resuspended from the ground by natural and mechanical processes (resuspension inhalation), ingestion of contaminated foodstuffs (food ingestion), and ingestion of contaminated water (water ingestion). Ingestion doses do not contribute to the doses calculated for the emergency phase of the accident. Only groundshine and inhalation of resuspended materials produce doses during the optional intermediate phase of the accident. Long-term doses are caused by groundshine, inhalation of resuspended materials, and ingestion of contaminated foodstuffs and water. Ingestion of contaminated food or water produces doses to people who reside at unknown locations (i.e., societal doses) both on and off of the computational grid.

Cloudshine doses are calculated by applying a correction factor for finite cloud size to the dose that would be produced by a cloud of infinite extent [He84]. Skin dose is modeled assuming that skin is contaminated only by dry deposition, and skin dose is caused only by β particles.

Ingestion doses result from the consumption of contaminated water or contaminated foods. The drinking water pathway is modeled by assuming that a fixed fraction of all contaminated fresh water is consumed by man (the water cycle is neglected, that is, aquifers are not modeled and oceans are permanent sinks for radioactivity). Ingestion doses are also produced by consumption of contaminated milk, meat, or crops. Crops are divided into categories (the MACCS default input file uses seven crop categories: pasture, stored forage, grains, green leafy vegetables, legumes and seeds, roots and tubers, and other crops). Transfer of radioactivity through root systems or from plant surfaces to edible portions of plants, losses during harvesting, incorporation into meat and milk, and retention in meat, milk, or edible portions of plants during processing, shelf-storage, and cooking are all modeled using transfer factors.

1.2.5.3 Shielding Factors

MACCS assigns people to three groups: evacuees, people actively taking shelter, and people who continue normal activities indoors, outdoors, and riding in vehicles. Doses to evacuees are calculated using vehicle shielding factors. Shielding factors for people who actively take shelter are smaller (i.e., they are better shielded) than those for people who continue normal activities indoors because people who actively take shelter are assumed to close doors and windows, turn off air circulation systems, and move to interior rooms or basements. Shielding factors for people are calculated outside of the code and specified by the user.

1.2.6 Health Effects

Health effects are calculated from doses to specific organs [Ru85]. Doses to specific organs are calculated using dose conversion factors [Ko80]. Early injuries and fatalities (those that occur within one year of the accident) are estimated using nonlinear dose-response models. A recent expert review of radiation induced health effects [Ev89] recommended the use of Hazard (H_i) functions, when calculating early injuries or fatalities due to damage to organ i. Thus, the risk (r) that an individual will contract a given early health effect is given by

$$r = 1 - \exp\left\{- \sum_i H_i\right\} , \tag{1.1}$$

where

$$H_i = (\ln 2) \left[\frac{D_i}{D_{50,i}}\right]^{\beta} ,$$

and

$$H_i = 0, \quad \text{if } D_i \leq D_{th,i} .$$

Here, D_i is the dose received by the impaired organ, $D_{th,i}$ is the damage threshold (dose threshold values are poorly known and variable over any population cohort), $D_{50,i}$ is the dose that induces the specified health effect in half of the exposed population (LD_{50} value for deaths), and the exponent, β, is a parameter that determines the shape of the dose-response curve. Hazards (H_i) are summed (1) over time periods to model any health effect that has D_{50} values that vary significantly with exposure period and (2) over organs to model early fatalities in which fatality may be caused by the impaired functioning of several organs. With regard to early fatalities and injuries, the lessened effectiveness of dose delivered at low dose rates over long time periods (dose protraction) is modeled using "effective" acute dose conversion factors [Ru85].

As is recommended by several recent reviews [UN77, BE80, NC80, Ab89], MACCS calculates mortality and injury resulting from radiation-induced cancers using a linear-quadratic, zero-threshold, dose-response model. However, the quadratic portion of the model is usually not important, when long-term individual exposures are limited by some exposure criterion (e.g., 0.04 Sv during the first five years after the accident) as is done in most consequence calculations. Accordingly, MACCS cancer fatality predictions are usually linear with dose. The predictions are not always linear with source term magnitude because the dose is avoided by crop disposal and by decontamination, temporary interdiction, and condemnation of land and buildings.

1.2.7 Economic Effects

Economic consequences [Bu84] are estimated by summing the following costs: evacuation costs, temporary relocation costs (food, lodging, lost income), costs of decontaminating land and buildings, lost return-on-investments from properties that are temporarily interdicted to allow contamination to be decreased by decay of nuclides, the cost of repairing temporarily interdicted property, the value of crops destroyed or not grown because they were contaminated by direct deposition or would be contaminated by root uptake, and the value of farmland and of individual, public, and nonfarm commercial property that is condemned. Costs associated with damage to the reactor, the purchase of replacement power, medical care, life-shortening, and litigation are not calculated by MACCS.

1.3 MACCS Computational Framework and Analysis Strategy

The models in MACCS are implemented in three modules: ATMOS, EARLY, and CHRONC. Figure 1.1 depicts the progression of a MACCS consequence calculation for one source term, one weather sequence, and one exposed population distribution. The ATMOS module treats the atmospheric dispersion and transport of material and its deposition onto the ground. The EARLY module models direct exposure pathways, dosimetry, mitigative actions and health effects during the emergency phase. The CHRONC module models the direct and indirect exposure pathways, dosimetry, mitigative actions, and health effects during the period that follows the emergency phase: the intermediate and long-term phases. It also models the economic costs with the mitigative actions during the emergency, intermediate, and the long-term phases.

Severe accidents can lead to source terms of quite different magnitudes (e.g., negligible at TMI, substantial at Chernobyl), and the weather conditions at the time of the release can greatly alter consequence magnitudes (e.g., intense rain at the time of the release or plume transport out to sea would largely eliminate health effects, while rainout of the plume onto a nearby downwind city could greatly increase early health effects).

Because consequences vary with source term magnitude, weather, and population density, in order to develop statistical distributions of consequence measures (doses, health effects, costs) that depict the range and probability of consequences for the reactor being examined, consequence assessments must examine all possible combinations of representative sets of source terms, weather sequences, and exposed populations. Usually distributions that display the variation of consequences with weather and population density are first developed for each representative source term. Then, an integral depiction of consequences may be constructed by weighted summation of these source-term dependent distributions, with each distribution weighted by the estimated absolute probability of occurrence of its underlying source term.

Given a source term, a MACCS consequence calculation generates results for all possible combinations of a representative set of weather sequences j (usually about 150 sequences) and a representative set of exposed downwind population distributions k (usually 16), thereby producing about 2400 results for each consequence measure examined. Since the probability of occurrence of each weather sequence (P_{wj}) and the exposure probability of each population distribution (P_{pk}) are known, the variability with weather and population of the 2400 results may be displayed by plotting the probability that a consequence magnitude will be equaled or exceeded against consequence magnitude. The latter plot is called a Complementary Cumulative Distribution Function (CCDF) [US83].

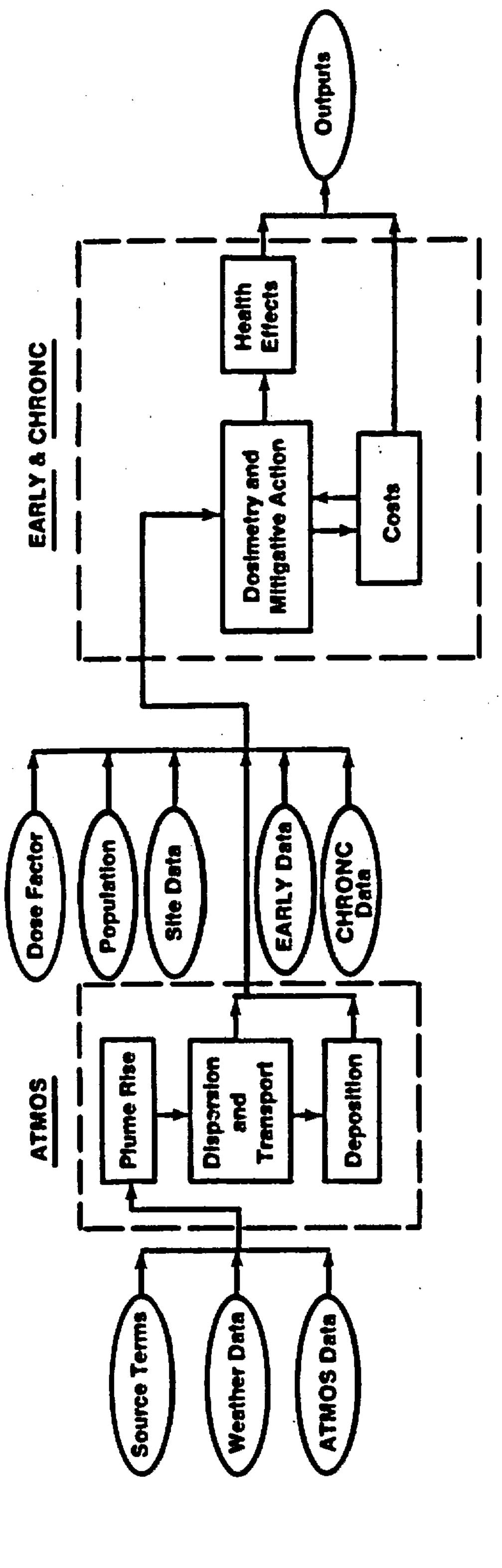


Figure 1.1 Progression of a MACCS Consequence Calculation

Figure 1.2 presents a CCDF of the number of early fatalities that resulted from each of the 2400 trials calculated by MACCS for a source term example. The calculation used regional meteorology and assumed evacuation of 95 percent of the population located within 10 miles of the reactor.

The following statistical results may be extracted from a CCDF: the probability that any consequences occur (y-intercept); the expected (mean) consequence magnitude, $E(X) = \sum_i P_i X_i$, where P_i is the probability ($P_i = P_{wj} P_{pk}$) and X_i the magnitude of each of the 2400 results; the consequence magnitudes that correspond to given quantile values (e.g., for any consequence the 90th quantile is the consequence magnitude that has a conditional probability of 0.1 of being equal or exceeded), and the largest consequence magnitude calculated for any weather trial (the consequence magnitude that corresponds to the tail of the CCDF). For the example shown in Figure 1.2, the probability of having any early fatalities = 0.2; early fatality 90th quantile = 2; and largest result calculated = 30.

1.4 Report Structure

The next five chapters of this report describe in detail the models used in MACCS to treat Atmospheric Transport (Chap.2), Dosimetry and Exposure Pathways (Chap. 3), Economic Costs (Chap. 4), Mitigative Actions and Dose Accumulation (Chap. 5), and Health Effects (Chap. 6). Parameters with hard-wired values are listed in Appendix A. The weather sequence categorization scheme used to sort the weather sequences used by MACCS is presented in Appendix B. Appendix C describes the calculation of maximum allowable ground concentrations for food pathway nuclides. Appendix D presents the dose conversion factor data provided with MACCS.

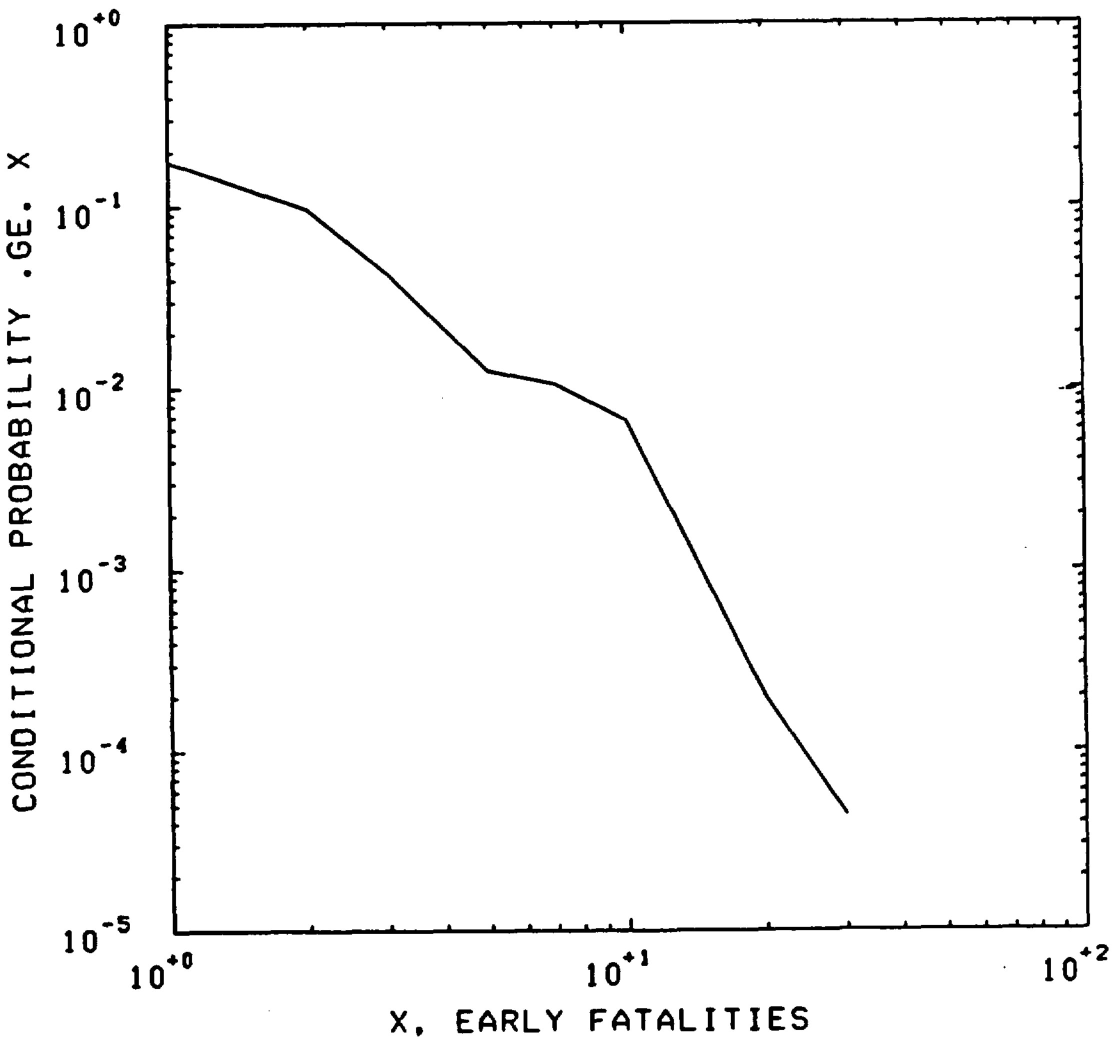


Figure 1.2 An Example of Conditional Early Fatality CCDF

2.0 ATMOSPHERIC DISPERSION AND TRANSPORT

2.1 Introduction

If a severe reactor accident were to proceed to containment failure, radioactive gases and aerosols would be released to the atmosphere. Thus, the first phase in the calculation of the ex-plant consequences of a hypothetical severe accident is calculation of the downwind transport, dispersion, and deposition of the radioactive materials released from the failed containment.

Downwind transport, dispersion, and deposition are treated in the ATMOS module of the MACCS code. In addition to the values of the parameters implemented in its phenomenological models, the ATMOS module also requires that the nature of the release and the dimensions of the computational grid be specified as input. Given these data, ATMOS models plume liftoff and plume rise, the capping of plume rise and of vertical plume expansion by inversion layers, downwind transport of the plume, horizontal and vertical dispersion of the plume, plume depletion by wet and dry deposition, and radioactive decay, and calculates the centerline air and ground concentrations that these processes produce on the computational grid.

Most of the models implemented in the ATMOS module use weather conditions as input data. Either constant or variable weather data can be used. Variable data is specified as a sequence of hourly values of wind speed, atmospheric stability class, and amount of precipitation, that begins at a time specified by the user or selected by the weather categorization and sampling algorithm embedded in the code. If variable data is used to model a release that is divided into plume segments, the user must designate one of the segments as risk dominant, whereupon ATMOS automatically causes the release of that segment to coincide with the start time of (first hour of data in) the variable sequence of weather conditions. The user must also select a representative weather point for each plume segment, which determines the weather conditions that will be used to calculate all transport processes except wet deposition.

The phenomenological models implemented in the ATMOS module of the MACCS code are described in the following sections of this chapter.

2.2 Release Specification

A large number of radionuclides are produced in the core of a nuclear reactor by fissioning of uranium, decay of fission products, and activation of structural materials. Inventories for over 300 radionuclides can be calculated for pressurized and boiling water reactors by the ORIGEN code [Be82]. Inspection of the abundances and half-lives of this large set of nuclides allows the set to be reduced until only those nuclides that are significant for assessment of the ex-plant consequences of a reactor accident are left [US75]. A set of 54 radionuclides is used to assess ex-plant consequences in the CRAC2 code [Ri84]. The default MACCS input files presently specify a set of 60 nuclides, although 150 nuclides can be treated.

For each nuclide defined in the MACCS ATMOS input file, the user must specify the nuclide's half-life, radioactive parent if produced by decay, physical properties (noble gas, or aerosol) and chemical character (chemical element class). All elements assigned to the same chemical class are assumed to have identical chemical properties.

To model long-duration releases, MACCS allows any plume to be divided into plume segments. The amount of material released in each plume segment is specified by a set of release fractions (typically estimated using codes that model core degradation, core-concrete interactions, and vapor and aerosol transport). One release fraction, referenced to the inventory of the reactor when the neutron chain reaction is terminated (scram inventory) must be specified for each chemical element class. In addition to the release fractions, MACCS also requires that the release time and duration, warming time before release, the release height, and the sensible heat content of each plume segment be specified.

2.3 Weather Data

The atmospheric transport models implemented in MACCS require hourly readings of windspeed, wind direction, atmospheric stability, and rainfall (precipitation) as input. For each weather sequence examined by ATMOS, 120 hours of weather data are required. In addition, four values of the mixing height (height of the capping inversion layer), one for each season of the year, must also be specified.

2.3.1 Weather Sequence Selection

In MACCS, there are five ways to specify the required 120 hours of weather data that constitute a weather sequence:

Constant Weather Conditions: one windspeed, one atmospheric stability class, one hourly amount of precipitation.

User-specified Weather Sequence: 120 hourly readings of windspeed, stability class, and precipitation amounts.

User-specified Start Time: the day and hour in a one-year-long weather file when the 120-hour-long weather sequence selected for use begins.

Stratified Random Sampling: the length of the time period (number of hours or days) from which one start time is to be selected by random sampling from a one-year-long weather file (e.g., randomly select one start time from each sequential period of 12 hours).

Structured Monte-Carlo Sampling: random selection of a user-specified number of weather sequences (start times) from the set of sequences assigned to user-specified weather categories by sorting a one-year-long weather file according to user specified criteria (a one-year-long file of hourly weather data contains 8760 hours of data and thus 8760 sequence start times).

2.3.2 Weather Sequence Categorization

The algorithm used by MACCS to categorize weather sequences (start times) is similar to the algorithm implemented in CRAC2 [Ri84]. The algorithm is described in detail in Appendix B. The algorithm sorts weather sequence start times (start day and hour) into weather categories in two ways:

> By Initial Conditions: stability class and windspeed during the start hour of the sequence (e.g., F-stability with a windspeed between 1 and 2 m/s).
>
> By Precipitation Characteristics: the downwind distance at which precipitation begins and the rate (mm/hr) of that precipitation (e.g., precipitation will commence after the plume segment has moved 3 km and before it has moved 6 km; the precipitation rate during the first hour in which precipitation occurs will lie between 1 and 2 mm/hr).

2.3.3 Boundary Weather

Because 120 hours of weather data may not be sufficient to transport a single segment release (or the last plume segment in a multiple segment release) off the computational grid, a constant set of weather conditions called "Boundary Weather" must be specified for use should a segment still be partly or wholly on the computational grid after the last hour of data in the 120-hour weather sequence has been used. The MACCS user may also specify that Boundary Weather will be used whenever a plume segment reaches a user-specified downwind distance (spatial element on the computational grid).

Boundary Weather is required by ATMOS in order to model (a) short releases that encounter persistent, low windspeed conditions and (b) long duration releases. Two examples illustrate the need for Boundary Weather. First, a one-hour release will require at least 125 hours of data to traverse a 500-mile computational grid if all of the hourly windspeed readings in the 120 hours of data lie below 4 mph. Second, even if average windspeed in the 120-hour sequence is as high as 5 mph, a release comprised of a blowdown puff and a lengthy (20 h) tail, generated by core-concrete interactions that do not commence until an overlying water layer boils away 10 hours after release of the puff, will also require more than 120 hours of weather data to ensure transport of the tail across the entire 500-mile computational grid.

Finally, the MACCS user can use Boundary Weather to ensure that all of the aerosols in a plume segment are deposited on the ground before the segment completely traverses the computational grid. This is done either by specifying Boundary Weather with a very low windspeed (the very slow transport rate allows dry deposition to deplete the plume segment of aerosols completely) or by specifying a high rain rate (whereupon all aerosols are removed by washout).

2.4 Risk Dominant Plume

When variable weather data is used to model a multiple segment release, one of the plume segments must be designated as the risk dominant segment. The characteristics of the categorization algorithm used to sort weather sequences will usually suggest how the risk dominant segment should be chosen. If, as is done in MACCS, weather sequences have been sorted according to their potential to cause early fatalities (e.g., sorted for stable atmospheric conditions upon release and for rainfall within 20 miles of the site), then the plume segment expected to make the largest contribution to the induction of early fatalities should be designated as the risk dominant segment. Once a risk dominant segment has been designated, MACCS automatically causes the leading edge of that segment to be released from the failed containment at the start time (beginning of the first hour) of each weather sequence used in the calculation. If the source term contains plume segments that are released earlier than the segment that has been designated as risk dominant (e.g., a leak that precedes a large blowdown puff), then hourly data that precede the start hour of the selected sequence are used to govern the transport of the earlier segments.

2.5 Initial Plume Dimensions

As is discussed below in Section 2.9, MACCS models plume dispersion during downwind transport using Gaussian plume models. Thus, the horizontal and vertical extent of plume segments is expressed in terms of the horizontal (σ_y) and vertical (σ_z) standard deviations of the normal concentration distributions that characterize a Gaussian plume. The Gaussian equations implemented in MACCS are derived assuming that turbulent velocities are negligible compared to the mean windspeed [Ka84]. Accordingly, MACCS assumes that the initial length of plume segments is unaffected by diffusion during downwind transport (i.e., plume segment lengths are constant once release from containment is completed). Thus, plume segment lengths, L (meter), are given by

$$L = \sum_i \left(\Delta t_i \bullet v_i\right) \tag{2.1}$$

where

$\sum_i \Delta t_i$ = the release duration of the plume segment and

Δt_i = a part of the release duration during which the windspeed was v_i.

When release occurs under turbulent conditions, mixing of the plume into the wake of the building from which the release occurs will determine the initial crosswind dimensions of the plume. For the purpose of initializing plume dimension, MACCS assumes the release point to be at the ground level and in the middle of the downwind face of the building.

If plume concentrations at the sides and roofline of the building from which the release occurs are assumed to be 10 percent of plume centerline concentrations (building edges are 2.15 sigma from the plume centerline), then initial values of the horizontal and vertical standard deviations of the Gaussian plume are given by

$$\sigma_y(t=0) = W_b/4.3$$
$$\sigma_z(t=0) = H_b/2.15 \tag{2.2}$$

where W_b and H_b are the width and height of the building wake and are specified by the user.

2.6 Representative Weather Point

There is a fundamental problem in treating the long-duration releases (plume segments with release durations of many hours) that are allowed in MACCS. Since the segment's characteristics must be uniform along its length, weather conditions seen by one point along that length must be used for all points along its length. In CRAC2, the weather conditions experienced by a plume's leading edge control plume transport (plume rise, downwind transport, dispersion, and deposition) at all points along its length. Thus, the length of the plume is essentially ignored, and transport processes are modeled as though all plume materials are concentrated at the head of the plume.

For short plume segments (segments with short release durations), this is a reasonable approximation. However, for segments with release durations of many hours, use of weather experienced by some interior point along the length of the segment would seem to better represent the average weather conditions seen by the entire length of the segment.

Accordingly, the MACCS user must select a representative weather point for each plume segment. The representative weather point is a fixed point along the length of the plume (usually the segment's leading edge or midpoint). Once selected, the weather conditions experienced by that point are applied to the entire length of the plume for purposes of calculating plume rise, transport, dispersion, and dry deposition (wet deposition is calculated using the rain rates experienced hour-by-hour by each portion of the plume, see Section 2.10). The representative weather point is specified as a fraction that can assume any value from zero to one, where values of 0.0, 0.5, and 1.0 correspond to selection of weather conditions experienced by the head, midpoint, and tail of the segment.

2.7 Downwind Transport

Because after it is fully released the length of a plume segment does not change during downwind transport (except when a transition from weather sequence data to Boundary Weather occurs), the arrival time of any reference point along the plume's length (e.g., head, midpoint, tail) at any downwind grid point (e.g., near boundary, midpoint, or far boundary of some spatial element) is determined by the following equation:

$$d = \sum_{i=1}^{n} v_i \Delta t_i$$

and (2.3)

$$\Delta t_d = \sum_{i=1}^{n} \Delta t_i$$

where

- d = downwind (radial) distance (m) of the grid point from the reactor (center of the polar coordinate computational grid),
- Δt_d = arrival time (s) of the reference point at the distance d,
- v_i = windspeed (m/s) during the time period Δt_i, and
- n = number of time periods.

The values of Δt_2 through Δt_{n-1} are all equal to one hour and Δt_1 and Δt_n may be parts of an hour. All times are measured from the time of exit from the failed containment of the plume segment's reference point. Thus, the time of arrival of any part of a plume segment at any downwind location is easily calculated. Finally, since the arrival time of the head (t_h) and the tail (t_t) of a plume segment at any downwind location (e.g., grid element midpoint) can be calculated, the time period (Δt_e) that a person situated at that location is exposed to the passing plume is given by

$$\Delta t_e = t_t - t_h \tag{2.4}$$

2.8 Plume Rise

Plume segments that are hot (contain appreciable sensible heat) and thus buoyant may rise to heights much greater than their initial release height. In MACCS, plume rise is calculated using equations recommended by Briggs [Br75, Ha82]. Plume rise is inhibited whenever the prevailing windspeed at the time of release exceeds a critical windspeed (liftoff criterion). Plume rise is also limited by the mixing height (height of any capping inversion layer).

2.8.1 Liftoff Criterion

When windspeeds are high, a buoyant plume segment that is released into a strong building wake will be unable to escape from the wake. In MACCS, escape of buoyant plume segments from building wakes is governed by a liftoff criterion (Equation (2.5) below) proposed by Briggs [Br73] and validated by experiments performed at the Warren Spring Laboratory in Great Britain [Ha86]. The criterion states that plume rise occurs only when the windspeed upon release of the segment is less than a critical windspeed (u_c) that is calculated using the following formula [Ha86]:

$$u_c = \left(\frac{9.09F}{L_p} \right)^{1/3} \tag{2.5}$$

where L_p is a plume scale length (m) (e.g., the height of the building) and F is the buoyancy flux (m^4/s^3) of the source (plume segment), which depends both on ambient atmospheric conditions and on the sensible heat release rate ($\dot{Q}$) of the plume segment (sensible heat content of the segment divided by its release duration). When the ambient conditions used to calculate F are those that define the International Civil Aviation Organization Standard Atmosphere [We72], $F = 8.79 \times 10^{-6} \dot{Q}$, where $\dot{Q}$ is expressed in Watts.

2.8.2 Plume Rise Equations

Plume rise, when atmospheric conditions are neutral or unstable (stability classes A-D), is treated using the "two thirds" law for bent over plumes of Briggs [Ha82]:

$$\Delta h = \frac{1.6\, F^{1/3}\, x^{2/3}}{\bar{u}} \tag{2.6}$$

where

Δh = the amount of plume rise (m),

$F = 8.79 \times 10^{-6} \dot{Q}$, the buoyancy flux ($m^4/s^3$) of plume segment,

$\dot{Q}$ = the rate of release of sensible heat (w),
x = downwind (radial) distance (m), and
$\bar{u}$ = mean wind speed (m/s).

Buoyant plume rise is terminated when any of the following conditions occur:

1. When, as is recommended by Briggs [Br75], Δh reaches a value of $300\ F/\bar{u}^3$.

2. When H = L, where H is the height of the plume centerline and L is the mixing height (height of the capping inversion layer).

3. When one hour has elapsed since release of the plume segment began.

When Equation (2.6) is used in MACCS, the weather conditions that characterize the hour during which release of the segment begins are used to calculate the entire rise of the segment even when the rise extends into the next hour (e.g., a buoyant plume segment released at 1:30 p.m., which rises under unstable conditions for a full hour, would have its entire rise calculated using 1:00 p.m. weather).

Plume rise, when atmospheric conditions are stable (stability classes E and F), is calculated using the Briggs equation for the final rise (Δh) of a bent-over buoyant plume [Ha82]:

$$\Delta h = 2.6 \left[\frac{F}{\bar{u}\ S}\right]^{1/3} \tag{2.7}$$

where

- Δh = the amount of plume rise (m),
- F = $8.79 \times 10^{-6}\ \dot{Q}$, the buoyancy flux ($m^4/s^3$) of plume segment,
- $\dot{Q}$ = the rate of release of sensible heat (w),
- $\bar{u}$ = mean wind speed (m/s), and
- S = stability parameter (s^{-2}) defined by the following equation [Ha82].

$$S = \frac{g}{T_a}\left[\frac{\partial T_a}{\partial z} + \frac{g}{c_p}\right] \tag{2.8}$$

where

- g = the acceleration due to gravity (m/s^2),
- T_a = the ambient temperature (°K),
- $\partial T_a/\partial z$ = the ambient temperature lapse rate (°K/m),
- c_p = the heat capacity of air (J/kg-°K), and
- g/c_p = the dry adiabatic lapse rate (0.98°K/100 m).

Regulatory Guide 1.23 [US72] specifies ranges for temperature lapse rates ($\partial T_a/\partial z$) for the six atmospheric stability classes A through F. The values of the stability parameter S used in MACCS were derived using midpoint values for these lapse rate ranges. The lapse rate ranges specified for Stability Classes E and F are -0.5°K/100 m to 1.5°K/100 m and 1.5°K/100 m to 4.0°K/100 m. Thus, Class E has a lapse rate range midpoint of 0.5°K/100 m and Class F a midpoint of 2.75°K/100 m. Substitution of these midpoint values and the International Civil Aviation Organization standard atmosphere [We72] value of 288.16°K (15°C) into Equation (2.8) yields values of 5.04×10^{-4} and 1.27×10^{-3} for the stability parameter S for Stability Classes E and F. These values differ slightly from those used in CRAC2 [Ri84].

Because near-surface windspeeds increase with altitude, Equations (2.6) and (2.7) both overestimate plume rise if surface windspeeds are used to calculate Δh. Since this could produce a significant underestimation of radiation exposures, for purposes of calculating plume rise, windspeeds aloft are estimated from surface windspeeds using the following equation [Ha82]:

$$u = u_o \left(\frac{z}{z_o}\right)^p \tag{2.9}$$

where

u_o = the surface windspeed (m/s) at the reference height z_o (usually 10 m),
u = the windspeed (m/s) at the height z, and
p = parameter (dimensionless) that varies with stability class and surface roughness as is shown in Table 2.1 [Ha82].

Presently, the values of p for rural surfaces are hard-wired into MACCS. The maximum value of z in Equation (2.9) is 200 m.

Table 2.1

Estimates of the Exponent p in Equation (2.9) for Six Stability Classes and Two Surface Roughnesses

Stability Class	A	B	C	D	E	F
Urban Surfaces	0.15	0.15	0.20	0.25	0.40	0.60
Rural Surfaces	0.07	0.07	0.10	0.15	0.35	0.55

In MACCS an average value of u for use in Equations (2.6) or (2.7) is calculated in three steps. First, the surface windspeed u_o and either Equations (2.6) or (2.7) are used to make a first-order estimate of the final centerline height (z) of the plume segment after plume rise has taken place ($z = h_o + \Delta h$, where h_o is the initial release height of the plume segment). Then the windspeed u at the height z is calculated using Equation (2.9). Finally, an average windspeed over this range is estimated by averaging u_o, the reference windspeed, and u, the windspeed at the first-order estimate of the final height of the plume centerline. This average value of u is then used in either Equations (2.6) or (2.7) to make a second-order estimate of the amount of plume rise, Δh.

2.8.3 Mixing Height

A single value for the mixing height (the top of the well-mixed surface layer of air, frequently the location of the lowest lying temperature inversion in the temperature structure of the surface layer) is used in MACCS to limit both buoyant plume rise and vertical dispersion (see Section 2.9) of plume segments. Although the value is allowed to vary season by season, it does not vary with stability class and is held constant during each weather trial (does not change even if the weather trial begins in one season and ends in another).

Because the mixing height is used in MACCS as an impenetrable cap, normally afternoon mixing heights [Ho72] should be used in MACCS calculations. If the concentrating effects of low lying inversion layers (e.g., radiation inversions) are examined, the user should remember that MACCS models neither penetration of inversion layers by buoyant plumes [Br84], nor the temporal variation of the height of the mixing layer (normally the depth of the well-mixed layer increases from several hundred meters at sunrise to several thousand meters by mid-afternoon [Ho72]).

2.9 Dispersion

During downwind transport, atmospheric turbulence will cause plume segments to expand in all directions with the rate of expansion increasing as atmospheric turbulence increases. Vertical expansion of the plume is increased by surface roughness and constrained by the ground and by the temperature structure of the atmosphere (location of inversion layers). Crosswind spreading of the plume along the y-direction is unconstrained. The effective crosswind dimensions of a plume segment are increased by lateral meander of the plume about its centerline trajectory. Because turbulent velocities are almost always very small compared to the mean wind speed that transports the bulk plume, expansion in the along-wind direction can be neglected after a plume segment's release duration [Tu70].

2.9.1 Gaussian Plume Equations

Because they are simple and computationally efficient, Gaussian plume models have often been used to model atmospheric dispersion in reactor accident risk assessments (see for example the PRA Procedures Guide [US83]). Gaussian plume models assume that the diffusion of gas molecules and aerosol particles in the plume during its downwind transport can be modeled as a random walk that generates a normal distribution for air concentration in all directions. Because windspeed and temperature vary significantly with height near the ground, vertical and horizontal plume distributions will differ significantly and must be separately calculated. Because the along-wind distribution does not appear in the Gaussian plume equations implemented in MACCS, only the vertical and crosswind distributions are actually calculated.

The size of a Gaussian plume in the vertical and crosswind directions is defined by the standard deviations (σ_y and σ_z) of the normal distributions of material concentrations in the vertical and crosswind directions. When not constrained by the ground or by inversion layers, the Gaussian plume equation has the following form [Tu70]:

$$\chi(x,y,z) = \frac{Q}{2\pi\,\bar{u}\,\sigma_y\,\sigma_z} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{z-h}{\sigma_z}\right)^2\right] \qquad (2.10)$$

where

$\chi(x,y,z)$ = the time-integrated air concentration ($Bq\text{-}s/m^3$) at the downwind location (x,y,z),

Q = the source strength (Bq),

$\bar{u}$ = the mean windspeed (m/s),

σ_y and σ_z = the standard deviations (m) of the normal crosswind and vertical concentration distributions of plume materials,

(x=0,y=0,z=h) = the source location, and

h = release height (m).

Once a plume has expanded sufficiently in the vertical direction so that further vertical expansion is now constrained by the ground and/or the capping inversion layer, Equation (2.10) can no longer be used. To treat restricted growth in the vertical direction, the ground and the inversion layer are treated as impenetrable totally reflecting boundaries. Mathematically, reflection is accomplished by the addition of mirror image sources above the inversion layer and below the plane of the ground. This produces the following equation, which is used in MACCS to calculate both the plume centerline air concentration, $\chi(x,y=0,z=H)$, and ground-level air concentration under the plume centerline, $\chi(x,y=0,z=0)$, from the time a plume segment is released until the vertical distribution of the segment becomes uniform between the ground and capping inversion layer (becomes well mixed in the vertical direction):

$$\chi(x,y=0,z) = \frac{Q}{2\pi\sigma_y\sigma_z\bar{u}} \left\{ \exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right] \right.$$

$$+ \sum_{n=1}^{5} \left\{ \exp\left[-\frac{1}{2}\left(\frac{z-H-2nL}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H-2nL}{\sigma_z}\right)^2\right] \right.$$

$$\left.\left. + \exp\left[-\frac{1}{2}\left(\frac{z-H+2nL}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H+2nL}{\sigma_z}\right)^2\right] \right\} \right\} \quad (2.11)$$

where

$\chi(x,y=0,z)$ = the time-integrated air concentration ($Bq\text{-}s/m^3$) at the downwind location ($x,y=0,z$), along the plume centerline, (note that $z = 0$ and $z = H$ correspond to ground level and plume centerline air concentrations, respectively)

Q = the source strength (Bq),

$\bar{u}$ = the mean windspeed (m/s),

σ_y and σ_z = the standard deviations (m) of the normal crosswind and vertical concentration distributions of plume materials,

$H = h + \Delta h$ = the height of the plume centerline (m),

h = the initial release height (m) of the plume before plume rise,

Δh = the amount of plume rise (m), and

L = the height (m) of the capping inversion layer (mixing height).

In MACCS, only five terms of the summation in Equation (2.11) are considered since subsequent terms are expected to be small [Tu70].

In the ATMOS module of MACCS, off-centerline concentrations are not calculated. The off-centerline concentrations required for dose calculations are calculated using the plume centerline air concentration or the ground-level air concentration under the plume centerline and the appropriate off-centerline correction factors. These off-centerline concentrations are calculated in the EARLY and CHRONC modules of MACCS (see Sections 3.1.1 and 3.2.1).

At each spatial interval along the plume's trajectory, MACCS tests for the occurrence of a uniform concentration distribution in the vertical direction (well-mixed plume between the ground and the capping inversion layer). Once a uniform vertical distribution is attained, the following simple Gaussian equation [Tu70] is used to calculate centerline air concentrations:

$$\chi(x,y=0,z) = \frac{Q}{\sqrt{2\pi}\,\bar{u}\,\sigma_y\,L} \tag{2.12}$$

where x, y, z, Q, $\bar{u}$, and σ_y have definitions unchanged from those given for Equation (2.11) and L is the mixing height (m).

A heuristic test is used to determine when the plume becomes well mixed between the ground and the inversion lid. Two conditions must be met to pass the test: (1) σ_z must be larger than H, the height of the plume centerline and (2) the ground level centerline air concentration calculated using the uniform mixing Equation (2.12) must exceed the ground level centerline air concentration calculated using the multiple reflection Equation (2.11). Once uniform mixing in the vertical direction is attained, the multiple reflection equation is no longer used. Thereafter, there is no need to calculate σ_z.

2.9.2 Dispersion Parameters

The rate at which materials disperse in the atmosphere depends strongly on atmospheric turbulence, which varies greatly with stability class. Therefore, the rate of expansion of a plume during downwind transport will also vary with stability class.

The growth of plume dimensions during downwind transport to short distances (1 km) has been experimentally determined [Ha59] over flat terrain covered by prairie grass (surface roughness length z_0 = 3 cm) for short plumes (10 min release durations) released during stable, neutral, and unstable atmospheric conditions. Pasquill [Pa61] used this data to develop curves that depict the increase of plume dimensions (σ_y and σ_z values) with downwind distance for each of the six Pasquill-Gifford Stability Classes A through F. Although measurements had only been made to 1 km, Pasquill extrapolated the curves to 100 km. These curves, as later modified by Gifford [Gi75 and Gi76], are presented in Figure 2.1.

Tadmor and Gur [Ta69] have constructed analytical fits to the Pasquill-Gifford (P-G) curves depicted in Figure 2.1. The fits have the following functional form:

$$\sigma_{yi} = a_i x^{b_i} \quad \text{and} \quad \sigma_{zi} = c_i x^{d_i} \qquad (2.13)$$

where i denotes the prevailing stability class (Pasquill-Gifford classes A through F correspond to i values 1 through 6) and the values in Table 2.2 for the constants a_i through d_i are supplied on the sample ATMOS input file.

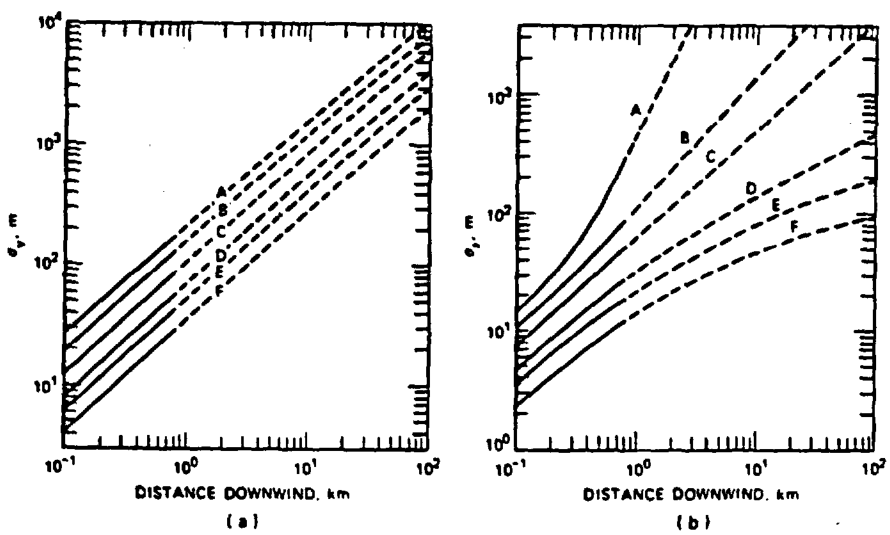


Figure 2.1 Dependence of σ_y and σ_z on distance for the six Pasquill-Gifford Stability Classes A through F (solid lines depict the range of the experimental data; dashed lines are extrapolations)

Table 2.2

Values for Constants for σ_y and σ_z Equations

Stability Class		Constant*			
P-G	i	a_i	b_i	c_i	d_i
A	1	0.3658	0.9031	0.00025	2.125
B	2	0.2751	0.9031	0.0019	1.6021
C	3	0.2089	0.9031	0.2	0.8543
D	4	0.1474	0.9031	0.3	0.6532
E	5	0.1046	0.9031	0.4	0.6021
F	6	0.0722	0.9031	0.2	0.6020

* The values of these constants reflect correction of typographical errors identified by Dobbins [Do79].

As used in MACCS, the values of the dispersion parameters, σ_y and σ_z in Equations (2.11) and (2.12) must change continuously although not necessarily smoothly. Since stability class changes discretely, whenever stability class changes, the source distance x in the dispersion parameter equation (Equation (2.13)) must be changed to some new value that causes dispersion parameter growth to be continuous. The new value of the source distance is called the "virtual source" distance. It will have a different value for σ_y and for σ_z. It is calculated as follows. Let i be the stability class before the change in atmospheric conditions, j the stability class after the change, x_{yi} and x_{zi} be the source distances under the old conditions (downwind distances of the plume when the stability class changes; if this is the first change in stability class, then $x_{yi} = x_{zi}$), and x_{yj} and x_{zj} be the source distances under the new conditions (i.e., the virtual source distances). To ensure continuity, σ_{yi} must equal σ_{yj}, and σ_{zi} must equal σ_{zj}. Thus,

$$
\begin{aligned}
a_i \left(x_{yi}\right)^{b_i} &= \sigma_{yi} = \sigma_{yj} = a_j \left(x_{yj}\right)^{b_j} \\
c_i \left(x_{zi}\right)^{d_i} &= \sigma_{zi} = \sigma_{zj} = c_j \left(x_{zj}\right)^{d_j}
\end{aligned}
\tag{2.14}
$$

which after solving for the new "virtual source" distances gives,

$$x_{yj} = \left[\frac{1}{a_j} a_i \left(x_{yi} \right)^{b_i} \right]^{1/b_j} = \left[\frac{\sigma_{yi}}{a_j} \right]^{1/b_j} \quad . \tag{2.15}$$

$$x_{zj} = \left[\frac{1}{c_j} c_i \left(x_{zi} \right)^{d_i} \right]^{1/d_j} = \left[\frac{\sigma_{zi}}{c_j} \right]^{1/d_j}$$

Figure 2.2 illustrates growth of σ_y over three time periods characterized by stability classes i, j, and k, during which σ_y first grows at a moderate rate, then slowly, and finally rapidly.

Finally, although new "virtual source" distances for σ_y and σ_z are calculated every time stability class changes, these distances are used only to calculate growth of σ_y and σ_z. Plume locations are always expressed relative to the release point that is the center point of the polar-coordinate computational grid.

For a given spatial element, the average values of σ_y and σ_z are used in calculating air and ground concentrations for the entire spatial element. The average values of σ_y and σ_z are the arithmetic means of the initial and final values of these two parameters as a plume segment traverses the spatial element.

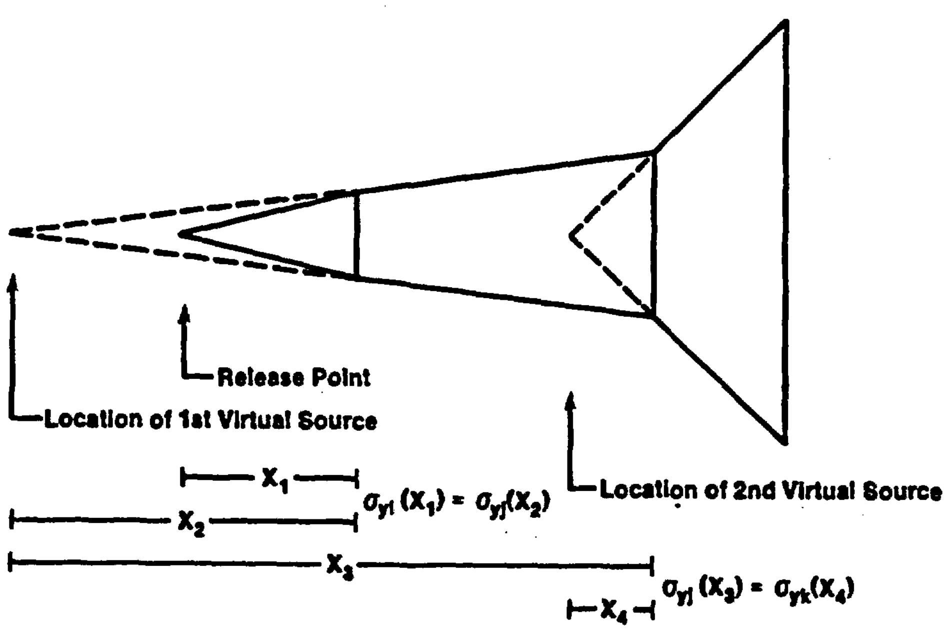


Figure 2.2 Growth of σ_y During Three Time Periods Characterized by Different Atmospheric Stabilities i, j, and k

2.9.3 Surface Roughness

The Pasquill-Gifford curves depicted in Figure 2.1 are appropriate for transport over flat terrain covered by prairie grass (surface roughness length $z_o = 3$ cm). But plume transport will usually be over areas characterized by surface roughness lengths greater than 3 cm. Table 2.3 presents some approximate surface roughness lengths for different surfaces based on the values in [Le69, Br84, Ra84].

Table 2.3

Approximate Surface Roughness Lengths (z_o) for Different Surfaces

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

Table 2.3 suggests that a roughness length greater than 3 cm, at least 10 cm and possibly 100 cm, is more likely typical of populated areas.

Surface roughness principally affects vertical dispersion and thus σ_z values. The following formula [AMS77] can be used to correct Pasquill-Gifford values of $\sigma_{z,P\text{-}G}$, which are appropriate for $z_0 = 3$ cm, for the effects of rougher surfaces:

$$\sigma_{z,new} = \sigma_{z,P\text{-}G} \left[\frac{z_{o,new}}{z_{o,P\text{-}G}}\right]^{0.2} \tag{2.16}$$

If $z_{o,new} = 10$ cm and $z_{o,P\text{-}G} = 3$ cm, then $\sigma_{z,new} = 1.27\ \sigma_{z,P\text{-}G}$. Since in MACCS both σ_y and σ_z can be scaled by changing the value of an input scale factor, surface roughness effects on σ_z can be corrected by changing the value of the σ_z scale factor. In fact, in the sample ATMOS input file, the value of the σ_z scale factor is set to 1.27 in order to scale Pasquill-Gifford values of σ_z up to values appropriate for surfaces characterized by 10 cm roughness lengths.

2.9.4 Plume Meander

Both theoretical and experimental studies [Mu86,Hi68,Dr84] indicate that as sampling (measurement) times (τ) increase, the maximum values of plume concentrations (χ_{max}) for continuous (stack) plumes measured at some fixed downwind location decrease, because plume meander in the horizontal and vertical directions increases the effective lateral and vertical dimensions of the plume. Specifically, $\chi_{max} \alpha \tau^{-p}$ where p = 0.5 for sampling times greater than 1 hour. Since $\chi_{max} \alpha (\sigma_y \sigma_z)^{-1}$, if σ_y and σ_z are of similar magnitude, then $\sigma_y \simeq \sigma_z \propto \tau^m$ where m = 0.25, which has been confirmed experimentally for σ_y [Mu86]. Now, since for puff releases, release duration may be equated to sampling time, the increase in effective plume dimensions (values of σ_y and σ_z) with release time (effects of plume meander) can be calculated using the following equation,

$$\sigma_y = \sigma_{ref} \left[\frac{\Delta t}{\Delta t_{ref}} \right]^m \qquad (2.17)$$

where σ_{ref} and Δt_{ref} are the sigma value and release duration (10 minutes for the experiments that support the Pasquill-Gifford curves) of the reference plume, Δt is the release duration of the long duration release, and as recommended by Gifford [Gi75] m equals 0.2 for release durations less than 1 hour and 0.25 for release durations greater than 1 hour.

In MACCS, Equation (2.17) is used to model the increase in σ_y caused by lateral meandering of the plume, which increases with increasing release duration. Vertical meander is neglected since it is expected to become unimportant shortly after release is completed (within 30 minutes)[Mu86]. As implemented in MACCS, the user must specify values of m for short and long duration releases and the release durations to which they apply. The values recommended by Gifford are specified in the sample input file for ATMOS provided with MACCS.

2.10 Plume Depletion

Radioactivity is removed from plume segments by decay and by deposition of radioactive materials onto the ground. Deposition onto the ground is caused by washout and by gravitational settling onto, impaction on, and diffusion to surfaces. The deposition caused by rain is called wet deposition. Deposition not caused by rain is called dry deposition. In MACCS, all of these processes are modeled as first-order rate processes.

2.10.1 Radioactive Decay

During downwind transport, radioactive decay of each nuclide in the MACCS inventory and build-up of radioactive daughters is evaluated using standard formulae [Ad73]. The treatment of decay chains is restricted to two-member decay chains (i.e., only simple parent-daughter chains). Decay of a parent to more than one daughter is not treated (i.e., parent nuclides can have only one daughter).

Simple first-order decay of a radioactive parent to a nonradioactive daughter, or to a daughter whose decay can be neglected, is calculated using the following equation:

$$\frac{D(t)}{D_o} = \frac{\lambda N(t)}{\lambda N_o} = e^{-\lambda t} \qquad (2.18)$$

where

$D(t)$ = the radioactivity (Bq) at time t,
D_o = the radioactivity (Bq) at time zero,
$N(t)$ = the number of radioactive atoms at time t,
N_o = the number of radioactive atoms at time zero,
$\lambda = (\ln 2)/t_{1/2}$ = the decay constant (s^{-1}), and
$t_{1/2}$ = the half-life(s) of the radioactive nuclide.

Decay of a radioactive parent to a radioactive daughter is calculated using the following equation:

$$D_2(t) = \frac{\lambda_2}{\lambda_2 - \lambda_1} D_{1,o}\left[e^{-\lambda_1 t} - e^{-\lambda_2 t}\right] + D_{2,o}\, e^{-\lambda_2 t} \qquad (2.19)$$

where

$D_2(t)$ = the radioactivity (Bq) of the daughter at time t,
$D_{1,o}$ and $D_{2,o}$ = the radioactivity (Bq) of the parent and daughter at time zero, and
λ_1 and λ_2 = the decay constants (s^{-1}) of the parent and daughter ($\lambda_1 \neq \lambda_2$).

In Equation (2.19), the second term represents decay of daughter atoms initially present at time zero.

2.10.2 Dry Deposition

Dry deposition is modeled using Chamberlain's source depletion method [Ch53,Ho74,Ka82] modified to allow treatment of a particle size distribution and of capping of vertical expansion by an inversion lid. The source depletion method calculates the rate at which materials are deposited onto the ground (the deposition flux) as the product of the ground level air concentration of the materials and the dry deposition velocity [Se84] of those materials. The method neglects the effects of deposition on the vertical distribution of the plume. Thus, dry deposition does not perturb the normal distribution of plume materials in the vertical direction. This is a reasonable assumption when vertical mixing is efficient (i.e., when neutral or unstable atmospheric conditions prevail). When stable conditions occur, the assumption introduces an artificial flux of material from upper regions of the plume to regions near the ground.

The ground level air concentration at a location (x,y,z=0) of a plume that is capped by an inversion lid at the height L is obtained from Equation (2.11) by multiplying it by the normal distribution function along the y-axis, exp $(-y^2/2\sigma_y^2)$, and setting z = 0, which yields

$$\chi(x,y,0) = \frac{Q}{\pi\sigma_y\sigma_z\bar{u}} \exp\left\{-\frac{y^2}{2\sigma_y^2}\right\} \left[\exp\left\{-\frac{H^2}{2\sigma_z^2}\right\} + \sum_{n=1}^{5}\left[\exp\left\{-\frac{(H+2nL)^2}{2\sigma_z^2}\right\} + \exp\left\{-\frac{(H-2nL)^2}{2\sigma_z^2}\right\}\right]\right]$$

$$= \frac{Q}{\pi\sigma_y\sigma_z\bar{u}} \exp\left\{-\frac{y^2}{2\sigma_y^2}\right\} [F] \tag{2.20}$$

where F is the sum of all of the exponential terms that contain σ_z (the terms in the larger set of brackets).

The flux of plume material to the ground, $\omega(x,y)$ is given by

$$\omega(x,y) = v_d\, \chi(x,y,0) \tag{2.21}$$

where v_d, the dry deposition velocity, embodies the combined effects of gravitational settling of materials onto, impaction on, and diffusion to the ground [Se84].

The rate of loss of plume materials (dQ/dx) by dry deposition to the ground into a differential length dx located at the downwind distance x is given by [Ho74]:

$$\frac{dQ}{dx} = -\int_{-\infty}^{\infty} \omega(x,y)dy \tag{2.22}$$

Substitution of Equations (2.20) and (2.21) into Equation (2.22) now gives,

$$\frac{dQ}{dx} = -F\sqrt{\frac{2}{\pi}}\,\frac{v_d Q}{\sigma_z\bar{u}} \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}\,\sigma_y}\left[\exp\left\{-\frac{y^2}{2\sigma_y^2}\right\}\right]dy = -F\sqrt{\frac{2}{\pi}}\,\frac{v_d Q}{\sigma_z\bar{u}} \tag{2.23}$$

since the value of the integral is one. During any single hour of weather data, the mean windspeed, $\bar{u}$, is constant. Thus $dx = \bar{u}\, dt$, which when substituted into Equation (2.23) gives,

$$\frac{dQ}{dt} = -F\sqrt{\frac{2}{\pi}}\ \frac{v_d Q}{\sigma_z} \tag{2.24}$$

Rearranging and integrating gives,

$$\frac{Q}{Q_o} = f_d = \exp\left\{-\ \frac{v_d \Delta t}{F'}\right\} \tag{2.25}$$

where

$$F' = \sqrt{\frac{\pi}{2}}\ \sigma_z\ \frac{1}{F}$$

and f_d is the fraction of material in the plume at the beginning of the time period (Δt) that is not removed by dry deposition during the time period. Since $dQ/dt = -v_d(A/V)Q$, where A is the deposition surface area (area onto which dry deposition is occurring) and V is the plume volume (volume from which deposition is occurring), $A/V = 1/\bar{z}$ where $\bar{z} = F'$ is the height of the column from which deposition is occurring, here an effective plume height. As noted in the Reactor Safety Study [US75],

$$\bar{z} = \frac{\int_0^\infty \chi(x,0,z)dz}{\chi(x,0,0)} = \text{effective height of plume} \tag{2.26}$$

Finally, once the plume has become well mixed below the inversion lid, $V = AL$, so $dQ/dt = -v_d(A/AL)Q = -v_dQ/L$, and thus $\bar{z} = L$.

In MACCS, the effect of particle size on dry deposition velocity is treated by dividing the particle size range of the materials subject to dry deposition (the radioactive aerosols) into i sections, specifying the fraction (f_i) of all aerosol materials in each section, assigning a dry deposition velocity (v_{di}) to each size section, and applying Equation (2.25) separately to each section. Thus,

$$f_{di} = \frac{Q_i}{Q_{oi}} = \exp\left\{-\ \frac{v_{di}\Delta t}{\bar{z}}\right\} \tag{2.27}$$

where Q_{oi} is the amount of aerosol in section i transported into the spatial element, Q_i is the amount transported out of the element, $f_{di} = Q_i/Q_{oi}$ is the fraction remaining after the plume segment traverses the spatial element, Δt is the time required for the segment to traverse the spatial element, and $\bar{z}$ is the effective height of the segment.

Finally, since $Q = \Sigma_i Q_i$, $Q_i = Q_{oi} f_{di}$, and $Q_{oi} = Q_o f_i$, the fraction (f_d) of all aerosol materials in all of the size sections i that remains after dry deposition has occurred from each section onto the entire spatial interval is given by

$$f_d = \frac{Q}{Q_o} = \frac{1}{Q_o} \sum_i Q_i = \frac{1}{Q_o} \sum_i Q_{oi} f_{di} = \frac{1}{Q_o} \sum_i Q_o f_i f_{di} = \sum_i f_i f_{di} \qquad (2.28)$$

When dry deposition is calculated in MACCS, Δt in Equation (2.27) is taken to be the time required for the representative weather point of the plume segment to cross the spatial element. Thus, Δt equals the time of arrival of the segment's representative weather point at the far side of the spatial element minus the time of its arrival at the near side of the element. Please see Section 2.11 for the treatment of dry deposition (Equation 2.28) in calculating the air and ground concentrations.

Because MACCS allows plume segments to have release durations as long as 10 hours, lengthy plume segments, which during transport lie over more than one spatial element, are common. Of course, when exiting a spatial element, even a short plume segment will lie over at least two spatial elements. Even when a plume segment lies above more than one spatial element, dry deposition from the segment is assumed to occur entirely onto the spatial element that the segment's representative weather point is above. Thus, dry deposition always occurs only onto the element that the representative weather point of the segment is traversing, no matter how many elements lie under the entire length of the segment.

After a segment has traversed a spatial element, the amounts of material in each size section are decreased by the amounts removed from the section by dry deposition during transport across the spatial element. Then, the fractions that specify the amounts of aerosol materials in the sections of the aerosol size distribution are recalculated and as a consistency check their sum is renormalized to one.

2.10.3 Wet Deposition

Wet deposition, that is, washout, is calculated using the model of Brenk and Vogt [Br81]:

$$\frac{dQ}{dt} = - \Lambda Q = -aI^b Q \qquad (2.29)$$

where

Λ = the washout coefficient (s^{-1}),
I = precipitation intensity (mm/hr), and
a and b = constants and dimensionless (in the ATMOS sample input file $a = 9.5 \times 10^{-5}$ and $b = 0.8$ [Jo86]).

Rearrangement and integration of Equation (2.29) gives

$$\frac{Q}{Q_o} = f_w = \exp\left\{-aI^b \Delta t\right\} \tag{2.30}$$

where

Q_o = the amount of radioactive material (Bq) transported into the spatial element,
Q = the amount of radioactive material (Bq) transported out of the element,
Δt = the time(s) that the plume segment takes to cross the spatial element, and
$f_w = Q/Q_o$ = the fraction of aerosol material in the segment at the beginning of the time period Δt that is not removed by wet deposition during the time period.

Unlike dry deposition, which is a continuous and relatively slow process, wet deposition is not continuous and often is quite rapid, at least when compared to dry deposition. Therefore, washout of all of the materials in a plume segment onto the spatial element that lies under the segment's representative weather point is not acceptable. Instead, washout should be apportioned over all of the spatial elements that lie under the segment.

For example, consider the release of a plume segment during a 10-hour period during which the average windspeed is 5 m/s. At the end of the release, the plume segment will have a length of 180 km and during the early stages of a MACCS calculation will extend over many spatial intervals. Suppose the windspeed now drops to 1 m/s and that a one-hour-long rainstorm begins just as the segment's representative weather point enters a 3.6 km long spatial element. Since the storm will end just as the representative weather point leaves the spatial element, if wet deposition occurs only onto the spatial element under the representative weather point, all materials washed out from the segment will be deposited onto only one spatial element even though the segment most likely covers several spatial elements on the standard MACCS computational grid. This would produce very high ground concentrations in the single spatial element onto which deposition would occur, concentrations possibly appropriate for areas lying under rain cells, but most likely not representative of the average ground concentrations over all areas (spatial elements) beneath the segment during the storm.

To apportion wet deposition over all of the spatial elements traversed wholly or partly by a plume segment during a rainstorm, on an hourly basis, the average value of the fraction of the segment's length that lies over each element that the segment traverses during the course of the storm (f_{av}) must be calculated. Let L_{SI} be the length of the portion of the plume segment that lies over one of the spatial intervals beneath the plume at time t. Figure 2.3 is a plot of L_{SI} vs t for a segment of total length L_S and an interval of radial length L_I (length in the downwind direction), where $L_S \neq L_I$. Because $L_S \neq L_I$, the plot has a trapezoidal shape with height $L_{max} = \text{Min}(L_S, L_I)$. Note that when $L_S = L_I$ the trapezoid is reduced to a triangle.

In Figure 2.3, t_1 is the time when the head of the plume segment enters the spatial element; t_6 is the time when the tail of the segment leaves the element. If $L_S < L_I$, t_2 is the time when the tail of the segment enters the element and t_4 the time when the head leaves the element; if $L_S > L_I$, t_2 is the time when the head of the segment leaves the element and t_4 is the time when the tail enters the element. The time points, t_3 and t_5, are indicated by vertical dashed lines, denote the beginning and end of a one-hour time period ($t_5 - t_3 = 1$ hr) during which weather data is constant. Since windspeed has only one value during any hour of weather data, the geometric shape bounded by the dashed lines will always be regular no matter where the hourly time points fall. Let the area of this regular shape be A. Then, since L_S and L_I and thus L_{max} are known, and all of the time points on the figure (points t_1 through t_6) are known

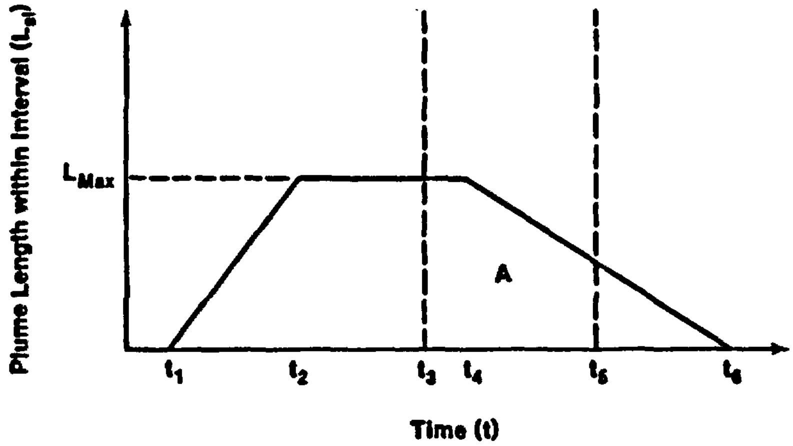


Figure 2.3 Temporal Dependence of the Portion of a Plume's Length That is Over a Spatial Interval

or are calculated by MACCS, A can be calculated. Thus, for any one-hour time period, L_{av}, the average value of L_{SI} during that time period, is given by $L_{av} = A/(t_5 - t_3) = A$, since $t_5 - t_3 = 1$ hr; and the hourly average value of the fraction of the segment's length that lies over each element that the segment traverses during the course of the rainstorm (f_{av}) is given by $f_{av} = L_{av}/L_S$. So f_{av} can be calculated hour-by-hour for each plume segment and every spatial element.

The quantity f_{av} now must be introduced into Equation (2.30). To see how this is done, let Δt be the time required to transport a plume segment across a given spatial element k. If that time is several hours long, then $\Delta t = \sum_j \Delta t_j$ where the first and last values of Δt_j can be fractional hours. Let $\{f_{av,j}\}$ be the set of hourly values of $f_{av,j}$ that cover the time period Δt during which the plume segment is transported across the spatial element; let Q_j and Q_{j+1} be the amounts of aerosol material in the entire plume (not just the portion over the spatial element) at the beginning and the end of time step j; and let I_j be the rain intensity during time step j. Because weather data is constant during any hour, I_j is single valued during any time step j. But during time step j, the rate of wet deposition from the entire plume is given by $\Lambda_j = a(I_j)^b$. Therefore, the rate of wet deposition onto the spatial element is given by $\Lambda_j f_{av,j}$. And thus f_{wj}, the fraction of aerosol material remaining in the plume after deposition during time step j only onto the spatial element, is given by

$$f_{wj} = \exp\left\{- \Lambda_j f_{av,j} \Delta t_j\right\} = \exp\left\{- a\left(I_j\right)^b f_{av,j} \Delta t_j \right\} \tag{2.31}$$

And f_w, the fraction of aerosol remaining in the plume after deposition only onto the spatial element during all of the time steps j required to transport the plume segment across the spatial element, is given by

$$f_w = \prod_j f_{wj} \tag{2.32}$$

2.11 Centerline Air and Ground Concentrations

As modeled in MACCS, dry and wet deposition are independent processes. For example, assume that during transport across a spatial element dry deposition alone would deplete a plume segment of one-tenth of the material in the segment, and wet deposition alone would remove one-half of the material in the segment. Then, if the two processes are independent and occur simultaneously, the fraction of the material in the segment upon entry into the element, that remains when the segment leaves the element, is 0.45 = (1.0 - 0.1)(1.0 - 0.5). Thus, the total amount of material (ΔQ_k) deposited onto the ground during transport of a plume segment across spatial element k is given by,

$$\Delta Q_k = Q_k\left(1 - f_d f_w\right) \tag{2.33}$$

where Q_k is the amount of airborne aerosol material that is transported into interval k by the plume segment, f_d and f_w are the fractions of material that would remain in the plume after transport across the spatial element if only dry deposition or wet deposition occurred, and f_d and f_w are calculated using Equations (2.28) and (2.32) above. Now let $GC_k(y=0)$ be the average ground concentration under the plume centerline along the length (L_k) of spatial interval k. Then

$$\Delta Q_k = L_k \; GC_k(y=0) \int_{-\infty}^{\infty} \exp\left\{ -\frac{y^2}{2\sigma_y^2} \right\} dy$$

$$= \sqrt{2\pi}\, \sigma_y \; L_k \; GC_k(y=0) \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}\, \sigma_y} \exp\left\{ -\frac{y^2}{2\sigma_y^2} \right\} dy$$

$$= \sqrt{2\pi}\, \sigma_y \; L_k \; GC_k(y=0) \tag{2.34}$$

since the value of the second integral is one. Accordingly,

$$GC_k(y=0) = \frac{\Delta Q_k}{\sqrt{2\pi}\, \sigma_y \; L_k} \tag{2.35}$$

Average values for σ_y, σ_z, plume height H, and average windspeed $\bar{u}$ for transport of a plume segment across spatial interval k are given by

$$\begin{aligned}
\sigma_{y,av} &= 0.5 \left(\sigma_{y,k} + \sigma_{y,k+1}\right) \\
\sigma_{z,av} &= 0.5 \left(\sigma_{z,k} + \sigma_{z,k+1}\right) \\
\bar{H} &= 0.5 \left(H_k + H_{k+1}\right) \\
\bar{u}_{av} &= L_k \Big/ \left(t_{k+1} - t_k\right)
\end{aligned} \tag{2.36}$$

where the subscripts k and k+1 signify that the value of the parameter pertains respectively to the near and far sides of the spatial interval (the values when the segment enters and leaves the element), and L_k is the length of the element. Accordingly, the average plume centerline air concentration, $AC_k(y=0,z=H)$, of the plume segment during transport across spatial element k is,

$$AC_k(y=0,z=H) = \left[\frac{\chi}{Q}\right]_{av} \left[Q_k - 0.5\, \Delta Q_k\right] \tag{2.37}$$

where $[\chi/Q]_{av}$ is calculated at the plume centerline using average values for σ_y, σ_z, and $\bar{u}$ as defined by Equation (2.36) substituted into either the multiple reflection (Equation (2.11)) or vertically well-mixed (Equation (2.12)) Gaussian plume equations defined previously. Finally, the amount of material still airborne in the plume segment after transport across the spatial element is $Q_{k+1} = Q_k - \Delta Q_k$.

2.12 <u>Results Calculated by ATMOS</u>

Consider a MACCS calculation that examines a release comprised of only one plume segment. For each weather trial examined during the calculation, ATMOS calculates values at the midpoint of each spatial element traversed by the segment for the following quantities: the arrival time of the leading edge (head) of the segment; the duration overhead of the segment (the arrival time at the spatial element's midpoint of the segment's tail minus that of the segment's head); average values of σ_y, σ_z, H, and $\bar{u}$ calculated using Equation (2.36); the ratio of the air concentration at ground level under the centerline to the centerline air concentration calculated using the average values of σ_y, σ_z, H, and $\bar{u}$; and the angular width of the segment. In addition, for each nuclide in the inventory specified for the calculation, ATMOS uses Equations (2.37) and (2.35) to calculate for each spatial element the average plume centerline air concentration and the average ground concentration under the centerline. If the release used in the calculation is comprised of several plume segments, then all of these quantities are calculated for each segment of the release.

3.0 DOSIMETRY AND EXPOSURE PATHWAYS

The calculation of radiation doses in MACCS is divided into two domains: early exposure during and shortly after plume passage (emergency phase) and long-term or chronic exposure (intermediate and long-term phases) after early exposure. Radiation doses are encountered by two different population cohorts: (1) individuals residing in the spatial elements surrounding the accident site (i.e., for the population-specified on the computational grid, or the direct cohort), and (2) individuals, who reside in unspecified locations (some on the computational grid and some off the grid), that consume food grown in, or drink water originating in, the spatial elements surrounding the accident site (the indirect cohort). In addition, MACCS also estimates radiation doses for the decontamination workers, as discussed in Section 5.3.

The two domains of exposure are discussed in separate sections. Section 3.1 discusses the calculation of doses for the emergency phase. The exposure pathways considered during the emergency phase include cloud-shine, groundshine, cloud inhalation and inhalation of resuspended radionuclides. Section 3.2 discusses the calculation of doses for the intermediate and long-term phases. The exposure pathways for the long-term phase include groundshine, inhalation of resuspended radionuclides, food ingestion, and water ingestion. In this chapter, the discussion of dosimetry for the long-term groundshine and resuspension inhalation also applies to the intermediate phase.

It should be noted that Chapter 3 describes only the dosimetry models for different exposure pathways. The dose accumulation depends on the duration of exposure and the mitigative actions. Chapter 5 discusses different mitigative actions modeled in MACCS during the emergency phase, the intermediate phase, and the long-term phase. For the long-term phase, the cost effectiveness of mitigative actions is also included in Chapter 5 (economic cost models are described in Chapter 4). Therefore, the dose models described in Chapter 3 are used as the starting points of the final dose calculations.

3.1 Early Exposure Pathways

The calculation of radiation doses from early exposure considers five pathways: (1) direct external exposure to radioactive material in the plume (cloudshine), (2) exposure from the inhalation of radionuclides from the plume (cloud inhalation), (3) exposure to radioactive material deposited on the ground (groundshine), (4) inhalation of resuspended material (resuspension inhalation), and (5) skin dose from material deposited on the skin. Two kinds of doses are calculated: (1) acute doses used for calculating early fatalities and injuries and (2) lifetime dose commitment used for calculating cancers resulting from the early exposure. The accumulation of radiation doses from early exposure is strongly dependent on the assumed emergency response, that is, evacuation, sheltering, or early relocation. Cloudshine and cloud inhalation exposures are limited to the time of cloud passage.

Groundshine and resuspension inhalation doses for early exposure are limited to the duration of the emergency phase.

In general, the dose equation for an early exposure pathway in MACCS in a given spatial element is the product of the following quantities: radionuclide concentration, dose conversion factor, duration of exposure, and shielding factor. The quantities used in the dose equations depend on the exposure pathway. For example, for the cloud inhalation exposure pathway, these quantities are the ground level air concentration at a spatial element, inhalation dose conversion factor, duration of exposure, breathing rate, and inhalation shielding factor.

The dose conversion factors of all exposure pathways are provided by the MACCS Dose Conversion Factors File [Ch89]. The duration of exposure depends on the exposure pathway and the emergency response at a spatial element and is calculated by MACCS. The shielding factor is a dimensionless quantity used to reduce the radiation dose as a result of shielding protection provided by a given protective action for a given exposure pathway (see Chapter 5). Shielding factors for the various exposure pathways (cloudshine, inhalation, groundshine, and skin dose) and for three different groups of people (evacuees, people doing normal activity, and people taking shelter) are specified by the user [Ch89].

The radionuclide concentrations calculated by the ATMOS module are along the plume centerline (see Section 2.12). In order to calculate the doses at a spatial element, we need to estimate the radionuclide concentration at the spatial element using those centerline radionuclide concentrations. In MACCS, this is done by using the off-centerline correction factors discussed in the next section.

3.1.1 Off-Centerline Correction Factors for Early Exposure Pathways

As discussed in Section 2.12, the ATMOS module calculates the air concentration at the plume centerline, the ground concentration under the plume centerline, and the ratio of ground level air concentration under the plume centerline to the air concentration at the plume centerline. This ratio is multiplied by the plume centerline air concentration to obtain the ground level air concentration under the plume centerline. These three concentrations, namely the plume centerline air concentration, the ground level air concentration under the plume centerline, and the ground concentration under the plume centerline, are used in the dose equations discussed in this Chapter.

In order to calculate the radiation doses at the off-centerline region of various spatial elements, these centerline concentrations are modified by the appropriate off-centerline correction factors depending on where the spatial elements are located. As discussed in Section 1.2, a spatial element is specified by its radial interval number and its compass direction sector number. The spatial element is also called the <u>coarse spatial element</u>.

For people in the process of evacuation, the top-hat function shown in Figure 3.1 is used to approximate the Gaussian crosswind distribution [Ri84]. The amplitude of the top hat is 0.836 of the Gaussian peak and the crosswind width of the top hat is $3\sigma_y$, where σ_y is the standard deviation (m) of the Gaussian crosswind distribution.

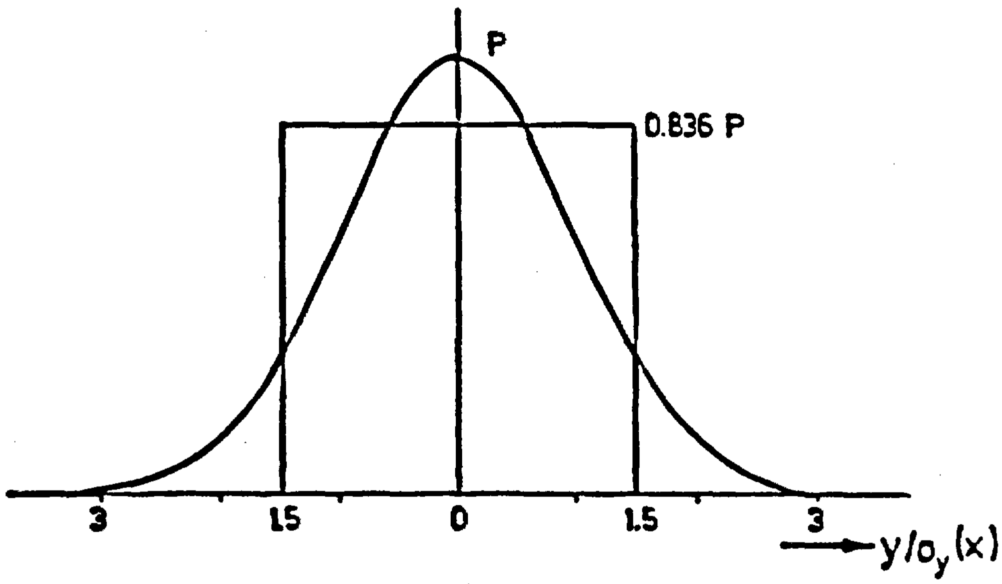


Figure 3.1 Top-Hat Approximation of the Gaussian Crosswind Distribution

For stationary people, in order to obtain a finer resolution in the dose calculations of the emergency phase, each one of the 16 compass sectors is further subdivided into a number of fine grid divisions. The number of fine grid divisions, m_o, is specified by the user (m_o = 3, 5, or 7). For a given spatial element, let r be its radial interval number and m be the fine grid division number from the plume centerline. Then a <u>fine spatial element</u> may be specified using the two parameters (r,m).

The off-centerline correction factor of a fine spatial element for the cloudshine pathway is calculated in a different manner than correction factor for the other exposure pathways of the emergency phase. For the cloudshine pathway, the off-centerline correction factor of a fine spatial element (r,m) is the finite cloud correction factor, C_{rm}, discussed later in Section 3.1.2. This finite cloud correction factor takes into account both the total distance to the plume centerline and the size of the plume.

For the cloud inhalation, groundshine, resuspension inhalation and skin exposure pathways of the emergency phase, a multistep histogram approximation of the Gaussian crosswind distribution is used for calculating the off-centerline correction factor. The boundaries of the multistep histogram are specified by the fine divisions. The outermost histogram step includes the point where the height of the Gaussian crosswind distribution falls to one-tenth of the Gaussian peak, i.e., the outermost step contains the point at which the crosswind distance is $2.15\sigma_y$ from the plume centerline. Figure 3.2 shows an example of a histogram approximation to the Gaussian crosswind distribution. In this figure, the number of fine grid divisions, m_o, is 3, the angle of each fine division is $\Delta\theta = 2\pi/(16*3)$, the outermost histogram step is 4, and the total number of histogram steps is 7. Let the outermost histogram step be M which is derived later in this section.

The off-centerline correction factor, J_{rm}, of a fine spatial element (r,m) for the exposure pathways other than the cloudshine dose is calculated as the ratio of the height of the crosswind histogram at (r,m) to the height of the Gaussian peak. This correction factor J_{rm} is used later in the dose equations in Sections 3.1.3, 3.1.4, 3.1.5, and 3.1.6. The method of deriving J_{rm} is discussed in the following paragraphs.

Let σ_{yr} be the standard deviation (meter) of the Gaussian crosswind distribution of a plume segment at a spatial element which has radial interval number r. Let $\Delta\theta$ be the angle of a fine spatial element, then $\Delta\theta = 2\pi/16m_o$. Let θ_m be the angle between the plume centerline and the outer edge of the m-th steps of the crosswind histogram, then $\theta_m = (m-1/2)\Delta\theta$. Furthermore, let R_r be the radial distance (meter) from the mid-point of the spatial element having radial interval number r to the release point, and W_{rm} be the perpendicular distance (meter) from the plume centerline to the outer edge of the m-th step of the crosswind histogram at the midpoint of a fine spatial element(r,m). The perpendicular distance, W_{rm}, can also be expressed as $d\sigma_m$ (dimensionless) in units of standard deviations, σ_{yr}. Then J_{rm} may be calculated using the following equation:

$$J_{rm} = \frac{\int_{d_{\sigma_m}}^{d_{\sigma_{m+1}}} \exp(-\frac{x^2}{2})\, dx}{d_{\sigma_{m+1}} - d_{\sigma_m}} \tag{3.1}$$

where

$$d_{\sigma_m} = \frac{W_{rm}}{\sigma_{yr}} \text{ and}$$

$$W_{rm} = R_r \bullet \tan\theta_m$$

In order to conveniently solve Equation (3.1), the following integral is solved numerically in steps of 0.01 from $d_\sigma = 0.01$ to $d_\sigma = 3$ and the results are stored in a look-up table in MACCS. This look-up table is then used for solving the integration shown in Equation (3.1) by linear interpolation.

$$A = \int_{o}^{d_\sigma} \exp\left(-\frac{x^2}{2}\right) dx \qquad (3.2)$$

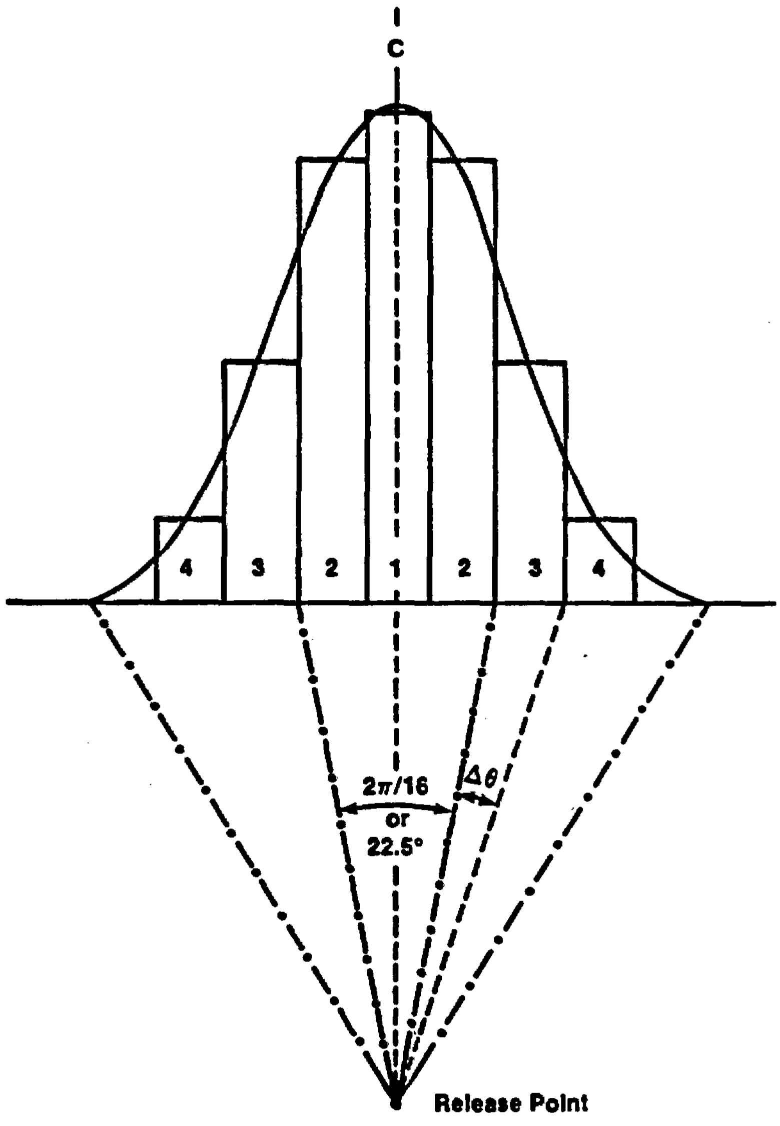


Figure 3.2 Approximation of a Gaussian Distribution by a Seven-Step Histogram (the number of fine grid divisions, $m_o = 3$)

The outermost histogram step, M, for the above off-centerline correction factor equation is determined as follows. Let θ_M be the angle between the outer edge of M-th histogram step and the plume centerline. Since the M-th histogram step is the outermost step and contains the point at which the crosswind distance is $2.15\sigma_{yr}$ from the plume centerline, therefore $\tan \theta_M \geq 2.15\sigma_{yr}/R_r$, where σ_{yr} and R_r have been previously defined. Then M is the integer portion of the following quantity: $(\theta_M/\Delta\theta + 1.5)$.

In order to simplify the subscript notation, the fine spatial element subscripts r and m are not used in the dose equations of early exposure pathways discussed in the following sections. Therefore, the off-centerline correction factors of a fine spatial element are C for the cloudshine and J for the other early exposure pathways instead of C_{rm} and J_{rm}.

3.1.2 Cloudshine

Estimates of doses from external exposure to the radioactive plume incorporate a "semi-infinite cloud" approximation [He84]. For a given plume segment, the cloudshine dose is calculated for each of the fine spatial elements using the following equation:

$$DC_k = \left[\sum_i AC_i^c \bullet DFC_{\infty ik}\right] \bullet C \bullet F \bullet SFC \tag{3.3}$$

where

- DC_k = cloudshine dose (Sv) to organ k from the passage of a plume segment over a fine spatial element,
- AC^c_i = time-integrated air concentration (Bq-s/m^3) of radionuclide i at the plume centerline, calculated by the ATMOS module,
- $DFC_{\infty ik}$ = semi-infinite cloud dose conversion factor (Sv-m^3/Bq-s) to organ k for radionuclide i, MACCS Dose Conversion Factors File,
- C = off-centerline correction factor (dimensionless) of the fine spatial element for the cloudshine dose, or the finite cloud dose correction factor, see Table 3.1,
- F = fraction of exposure duration during the plume passage, equal to TE/TO; where TE is the exposure time (s) of an individual in the fine spatial element and TO is the time duration (s) of a plume segment traversing the fine spatial element, and
- SFC = cloudshine shielding factor (dimensionless) specified by the user.

The semi-infinite cloud-dose conversion factors, $DFC_{\infty ik}$, were provided by Oak Ridge National Laboratory (see Appendix D). The off-centerline correction factor, C, is used to correct the calculated semi-infinite cloud doses for a finite cloud. This correction factor is for a spherical cloud, based upon formulations by Healy [He84], and dependent on the effective size of the plume and the distance from the plume centerline to the receptor. These finite cloud correction factors are hard-wired into the MACCS code and shown in Table 3.1.

Whereas Reactor Safety Study [US75] and CRAC2 use σ_z as the size of the plume, MACCS calculates the effective size of the plume to be $\sqrt{\sigma_y \sigma_z}$ for the purpose of calculating the cloudshine correction factor. A linear interpolation procedure is used to estimate values not given in Table 3.1. When uniform mixing in the vertical is achieved, the finite cloud correction factor, C, is no longer used. Instead, the off-centerline correction factor J (see Section 3.1.1) is used when mixing is uniform in the vertical direction.

Table 3.1

Finite Cloud Dose Correction Factors*

diffusion parameter $\sqrt{\sigma_y \sigma_z}$ meters	Distance to Cloud Centerline in Unit of Effective Plume Size $\sqrt{y^2 + z^2} / \sqrt{\sigma_y \sigma_z}$					
	0	1	2	3	4	5
3	0.020	0.018	0.011	0.007	0.005	0.004
10	0.074	0.060	0.036	0.020	0.015	0.011
20	0.150	0.120	0.065	0.035	0.024	0.016
30	0.220	0.170	0.088	0.046	0.029	0.017
50	0.350	0.250	0.130	0.054	0.028	0.013
100	0.560	0.380	0.150	0.045	0.016	0.004
200	0.760	0.511	0.150	0.024	0.004	0.001
400	0.899	0.600	0.140	0.014	0.001	0.001
1000	0.951	0.600	0.130	0.011	0.001	0.001

*Data from Reactor Safety Study Table VI 8-1 with correction of a typographic error of data. For 0.7 MeV gamma photons.

3.1.3 Groundshine

The MACCS groundshine dose model of the emergency phase represents an improvement over CRAC2 [Ri84] in the calculation of groundshine during the plume passage. Whereas CRAC2 assumes the ground concentration during plume passage to be one-half of its final value, MACCS takes account of the linear increase in contamination by performing a simple numerical integration.

The groundshine dose of the emergency phase is calculated by integrating groundshine dose rate over the period of exposure time. The groundshine dose rate is expressed by two different functions: a linear ramp function during the plume passage and an exponential decay function after the plume passage.

Figure 3.3 illustrates the groundshine dose rate, GDR, as a function of time and the relationships among different event times. In Figure 3.3(a), t_1 and t_2 are the times that people enter and leave a given spatial element during the plume passage, and t_e and t_o are the times that the plume enters and leaves a given spatial element. In Figure 3.3(b), t_1 and t_2 are the times that people enter and leave a spatial element after the plume passage. Once MACCS determines the relationship of t_1 and t_2 to t_e and t_o, the groundshine dose accumulation is then the area under the groundshine dose rate curve between t_1 and t_2. If $t_2 < t_e$, that is, people left a spatial element before the plume entered it, there would be no groundshine dose to these people.

The groundshine dose to organ k in a fine spatial element during the plume passage, DG_k^1, is the shaded area in Figure 3.3(a) and calculated by the following equation:

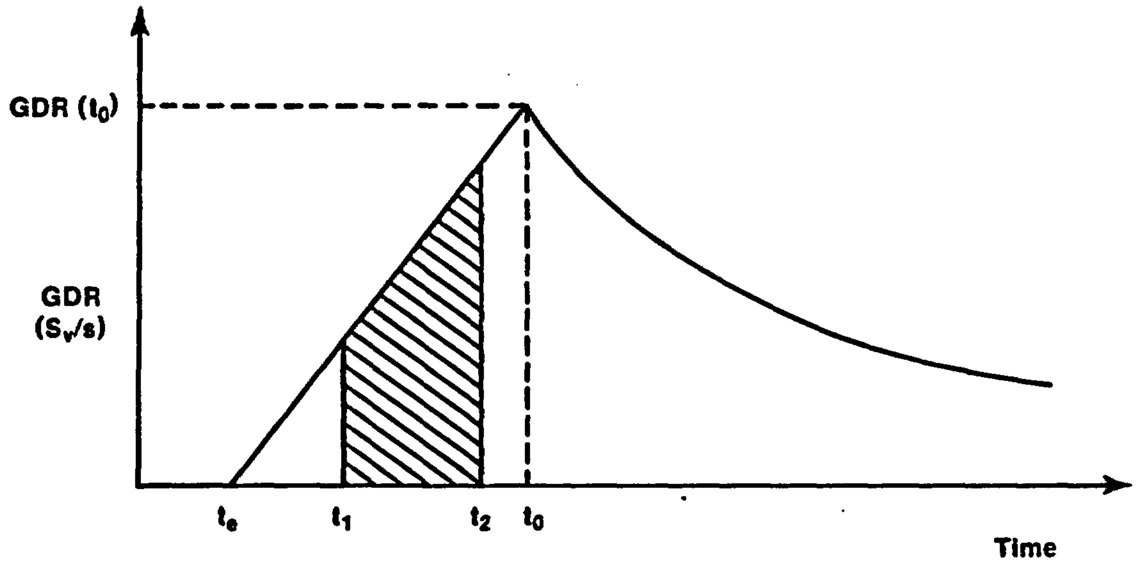
$$DG_k^1 = GDR_k(t_o) \bullet \int_{t_1}^{t_2} (t - t_e)/(t_o - t_e)\, dt \tag{3.4}$$

where

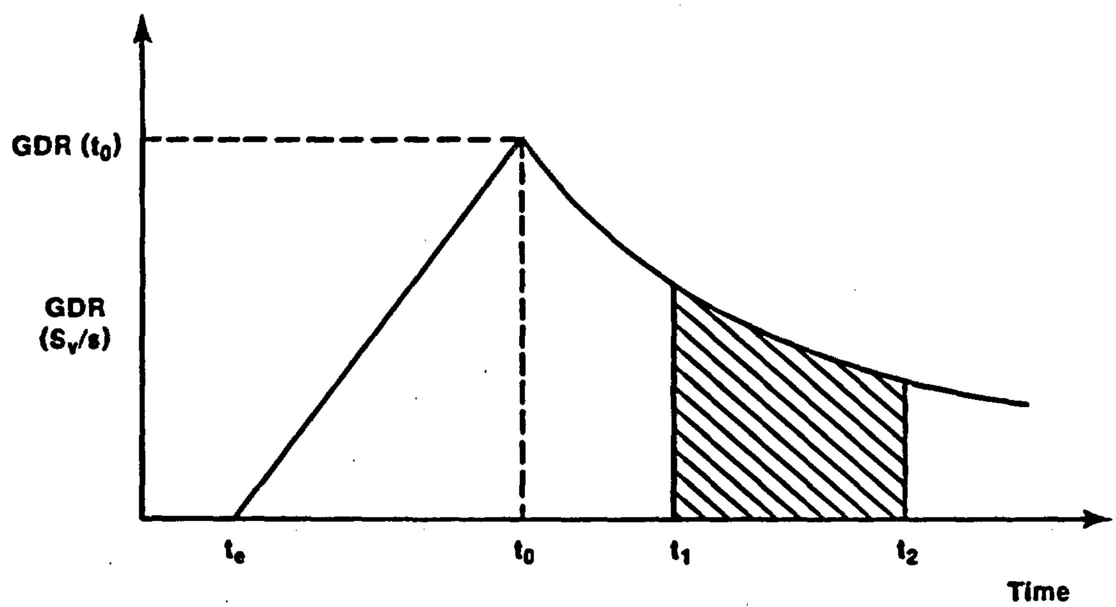
$GDR_k(t_o)$ = groundshine dose rate to organ k of a fine spatial element at time t_o (Sv/s), defined below.

The groundshine dose rate to organ k at t_o, $GDR_k(t_o)$, is calculated using the following equation:

$$GDR_k(t_o) = \left[\sum_i GC_i(t_o) \bullet DRFG_{ik}\right] \bullet J \bullet SFG \tag{3.5}$$



(a) Exposure During the Plume Passage



(b) Exposure After the Plume Passage

Figure 3.3 Illustration of Groundshine Dose Rate Function and Different Event Times

where

$GDR_k(t_o)$ = groundshine dose rate (Sv/s) to organ k at time t_o in a fine spatial element, after passage of a plume segment,

$GC_i(t_o)$ = ground concentration (Bq/m^2) of radionuclide i at t_o under the plume centerline, calculated by the ATMOS module,

$DRFG_{ik}$ = groundshine dose rate conversion factor ($Sv\text{-}m^2/Bq\text{-}s$) to organ k for radionuclide i, MACCS Dose Conversion Factors File,

J = off-centerline correction factor (dimensionless) for the fine spatial element,

SFG = groundshine shielding factor (dimensionless) specified by the user.

By substituting $GDR_k(t_o)$ into Equation (3.4), the groundshine dose during the plume passage, $DG^1{}_k$, can be calculated.

To calculate the groundshine dose for a time period after plume passage, MACCS first derives the effective decreasing rate λ_e of the groundshine dose rate after the plume leaves a spatial element using the two doses calculated by the following equation for two time periods: 8-hour dose and one week dose:

$$DG_k = \sum_i \left[GC_i(t_o) \bullet DFG_{ik} \right] \tag{3.6}$$

where

DG_k = groundshine dose (Sv) to organ k for a given time period (8 hours or one week) after t_o, under the plume centerline,

$GC_i(t_o)$ = ground concentration (Bq/m^2) for radionuclide i at t_o under the plume centerline, calculated by ATMOS module, and

DFG_{ik} = groundshine dose conversion factor ($Sv\text{-}m^2/Bq$) to organ k of radionuclide i for a given time period (8 hours or one week), MACCS Dose Conversion Factors File.

The integrated dose-conversion factors, DFG_{ik}, used in MACCS for exposure periods of eight hours and seven days are based on the data provided by ORNL and are given in Appendix D.10 of [Ch89].

Since Equation (3.6) calculates the dose to each organ by summing over all nuclides, this effective decay constant is an average value over all nuclides. The organ chosen in deriving λ_e is determined by the user-specified critical organ for emergency-phase relocation (e.g., effective whole body dose equivalent; see Section 5.1.3). Let D1 and D2 be the calculated 8-hour and one-week groundshine doses to the user-specified critical organ c using Equation (3.6), respectively. These two doses can also be expressed by the following two equations:

$$D1 = GDR_c(t_o) \bullet \left[1.0 - e^{-\lambda_e T1}\right] \Big/ \lambda_e \tag{3.7}$$

$$D2 = GDR_c(t_o) \bullet \left[1.0 - e^{-\lambda_e T2}\right] \Big/ \lambda_e \quad , \tag{3.8}$$

where

- $GDR_c(t_o)$ = groundshine dose rate (Sv/s) to the user-specified critical organ c at time t_o,
- D1 = groundshine dose (Sv) to critical organ c for eight hours (T1) after t_o,
- D2 = groundshine dose (Sv) to critical organ c for one week (T2) after t_o, and
- λ_e = effective decay constant of groundshine dose rate (s^{-1}).

By taking the ratio of Equations (3.7) to (3.8), we have

$$\frac{D1}{D2} = \frac{1.0 - e^{-\lambda_e T1}}{1.0 - e^{-\lambda_e T2}} \quad . \tag{3.9}$$

Since D1 and D2 were known from Equation (3.6), λ_e can be determined using Equation (3.9). A set of precalculated values of λ_e corresponding to D1/D2 ratio values ranging from 0.01 to 0.99 is used by MACCS to determine λ_e. After λ_e is determined, it is used in the groundshine dose calculation after the plume passage for all organs.

For each fine spatial element, the groundshine dose DG_k^2 to organ k for the time interval between t_1 and t_2 after the plume passage is the shaded area in Figure 3.3(b) and can be expressed by the following equation:

$$DG_k^2 = D2 \bullet \left[\frac{e^{-\lambda_e\left(t_1-t_o\right)} - e^{-\lambda_e\left(t_2-t_o\right)}}{1 - e^{-\lambda_e T2}}\right] \bullet J \bullet SFG \tag{3.10}$$

where

- DG_k^2 = groundshine dose to organ k (Sv) in a fine spatial element for a given time period between t_1 and t_2 after plume passage, D2 - the one week groundshine dose (Sv) to organ k under the plume centerline after plume passage,

T2 - one week of time (s),

J - off-centerline correction factor (dimensionless) of the fine spatial element, and

SFG - groundshine shielding factor (dimensionless) specified by the user.

Finally, the total groundshine dose to organ k of emergency phase is the sum of DG_k^1 in Equation (3.4) and DG_k^2 in Equation (3.10).

3.1.4 Inhalation

The internal radiation dose due to inhalation of radionuclides from the radioactive cloud is calculated for two different time periods following exposure. The two time periods are the early (or acute) exposure period and a lifetime dose commitment period (50 years). The acute inhalation doses are used for estimating early health effects (e.g., early fatality from lung exposure). The lifetime inhalation doses are used for estimating latent cancer fatality (e.g., lung cancer fatality). For each of these time periods, a corresponding radiation dose (dose commitment) is calculated from the internally deposited radionuclides.

For a given plume segment, the cloud inhalation dose of either acute or lifetime dose during the plume passage is calculated for each of the fine spatial elements using the following equation:

$$DI_k = \left(\sum_i AC_i \bullet DFI_{ik} \right) \bullet BR \bullet J \bullet F \bullet SFI \qquad (3.11)$$

where

DI_k - cloud inhalation dose (Sv) to organ k during passage of a plume segment over a fine spatial element,

AC_i - time-integrated ground level air concentration (Bq-s/m^3) of radionuclide i under the plume centerline,

DFI_{ik} - inhalation dose conversion factor (Sv/Bq inhaled) of either acute or lifetime dose to organ k for radionuclide i, MACCS Dose Conversion Factors File,

BR - breathing rate (m^3/s), user-specified,

J - off-centerline correction factor (dimensionless) of the fine spatial element,

F - fraction of exposure duration during the plume passage, equal to TE/TO; where TE is the exposure time (s) of an individual at the fine spatial element and TO is the time duration (s) of a plume segment traversing the fine spatial element, and

SFI - inhalation shielding factor (dimensionless) specified by the user.

The time integrated ground level air concentration under the plume centerline, AC_i, is integrated over the whole duration of plume passage. However, an individual may not be exposed to the full extent of the plume. Therefore, the accumulation of inhalation dose DI is adjusted by the duration of exposure.

The inhalation dose conversion factor DFI_{ik} (Sv/Bq inhaled) for radionuclide i and organ k is calculated using the data provided by ORNL and clearance class of each radionuclide suggested by ICRP 30 [IC79] (see Appendix D). The activity median aerodynamic diameter (AMAD) of the inhaled particle is assumed to be 1 micron.

3.1.5 Resuspension Inhalation

The inhalation dose of the emergency phase from the resuspended radionuclides after passage of a plume segment is calculated for each of the fine spatial elements using the following equation:

$$DR_k = \left[\sum_i GC_i \bullet DFI_{ik}\right] \bullet BR \bullet J \bullet RF \bullet SFI \qquad (3.12)$$

where

- DR_k = resuspension inhalation dose (Sv) to organ k after passage of a plume segment over a fine spatial element,
- GC_i = ground concentration (Bq/m^2) of radionuclide i under the plume centerline at the time that plume leaves the fine spatial element, calculated by the ATMOS module,
- DFI_{ik} = inhalation dose conversion factor (Sv/Bq inhaled) to organ k for radionuclide i, MACCS Dose Conversion Factors File,
- BR = breathing rate (m^3/s), user-specified,
- J = off-centerline correction factor (dimensionless) of the fine spatial element,
- RF = time-integrated resuspension factor (s/m) defined below, and
- SFI = inhalation shielding factor (dimensionless), specified by the user.

The resuspension factor, RF, is calculated using the following equation:

$$RF = RC \bullet \int_{t_1}^{t_2} e^{-\lambda t}\, dt = RC \bullet \left(e^{-\lambda t_1} - e^{-\lambda t_2}\right) / \lambda . \qquad (3.13)$$

where

- RC = the resuspension coefficient that relates ground concentration to air concentration (m^{-1}), user-specified,
- λ = the natural log of 2 divided by the resuspension half-life (s^{-1}), user-specified,
- t_1 = the time from plume departure to the entrance of the individual into the spatial element (s), and
- t_2 = the time from plume departure to the departure of the individual from the spatial element (s).

The values of t_1 and t_2 and hence the inhalation dose from resuspension in Equation (3.12) depend on the emergency response scenario. For example, if an individual in a given spatial element leaves the spatial element before the plume enters the spatial element, the resuspension inhalation dose is zero.

It should be noted that resuspension inhalation dose is calculated only after plume passage. During the passage of a plume, resuspension is ignored because it represents only a small fraction of the total inhalation dose. The resuspension factor in Equation (3.13) here is similar to that used in the CHRONC module (see Section 3.2.3), but it is simpler in two respects:

1. The EARLY module uses the one-term expression given above where there is a single resuspension coefficient and a single half-life associated with it. The CHRONC module can use up to a <u>three</u>-term expression for the resuspension factor.

2. The EARLY module does not treat the effect of radioactive decay on resuspension inhalation dose. If this were to be treated, exponential interpolation for all radionuclides would be required every time a new cohort entered a spatial element and the computing expense would be great.

3.1.6 Deposition to Skin

Exposed skin for people directly immersed in a radioactive cloud may be contaminated as a result of material deposited by the cloud. If this material remains on the skin, there is a potential for damage to the skin.

In calculating the dose to the skin, MACCS assumes that material is deposited from the cloud to skin using a hard-wired dry-deposition velocity of 0.01 m/s. For a given plume segment, the skin dose during the plume passage is calculated for each of the fine spatial elements using the following equation:

$$DS = \left[\sum_i AC_i \bullet V_d \bullet DFS_i\right] J \bullet F \bullet SFS \quad (3.14)$$

where

- DS = skin dose (Sv) during passage of a plume segment over a fine spatial element,
- AC_i = time-integrated ground level air concentration (Bq-s/m^3) of radionuclide i under the plume centerline,
- V_d = deposition velocity to skin, hard-wired value of 0.01 m/s,
- DFS_i = skin dose conversion factor (Sv-m^2/Bq) for radionuclide i, defined below,
- J = off-centerline correction factor (dimensionless) of the fine spatial element,
- F = fraction of exposure duration during the plume passage, equal to TE/TO; where TE is the exposure time (s) of an individual at the fine spatial element and TO is the time duration (s) of a plume segment over the fine spatial element, and
- SFS = skin shielding factor (dimensionless), specified by the user.

The skin dose conversion factor DFS_i is calculated inside the MACCS code according to the following assumptions:

1. every radioactive disintegration of material deposited on the skin results in the emission of a single beta particle,

2. there is no buildup of radioactive daughter products on the skin subsequent to the initial deposition of material, and

3. all material deposited on the skin remains there for eight hours following its deposition.

For multiple plume segment releases, the skin dose from each segment is accumulated independently. It is assumed that the radioactive materials deposited on the skin would be removed eight hours after deposition by decontamination procedure. Therefore, accumulation of the skin dose from each plume segment is terminated eight hours after its deposition.

Derivation of the skin dose conversion factors has been guided by information presented in an article by Healy in Atmospheric Science and Power Production [He84]. Because of the limited ability of beta radiation to penetrate skin, the dose will rapidly decrease with increasing distance from the surface. We are not interested in calculating the dose in the immediate surface layer, since the cells there are insensitive to damage.

The rapidly dividing basal cells below 0.09 mm are deemed most sensitive to damage according to the Health Effects Models for Nuclear Power Plant Accident Consequence Analysis [Ev89]. Therefore, we calculate the dose received by the tissue at that depth.

According to the Healy article, at the critical depth of human skin, the dose rate from material deposited on the skin surface does not show a significant variability over a range of decay energy from 0.2 to 2.0 MeV. For emissions in this range of energy, the dose rate at the critical depth of skin is roughly 0.2 rads/s for skin contaminated to a unit concentration of 1 Ci/m^2. Assuming a quality factor of 1 for β particles and converting to SI units, this is equivalent to (5.4×10^{-14} $Sv\text{-}m^2/Bq\text{-}s$).

The skin dose conversion factor DFS_i in Equation (3.14) is then calculated using the following equation,

$$DFS_i = 5.4 \times 10^{-14} \bullet \left[1.0 - e^{-\lambda_i T}\right] \Big/ \lambda_i \qquad (3.15)$$

where λ_i is the decay constant (s^{-1}) of radionuclide i and T is the residence time(s) of radionuclide material on the skin and assumed to be eight hours.

3.2 Intermediate and Long-Term Exposure Pathways

Four long-term exposure pathways are modeled in MACCS to predict the long-term radiation exposures from accidental radiological releases: groundshine, resuspension inhalation, ingestion of contaminated food, and ingestion of contaminated drinking water. The models utilized in predicting the doses from these four pathways are described individually below. The dose from each of the long-term pathways is evaluated for each spatial element surrounding the accident site. For the intermediate phase, only the groundshine and resuspension inhalation exposure pathways are considered.

The long-term ingestion models are based on the simple principle that the long-term dose produced by any radionuclide to an organ via a pathway is the product of (1) the ground concentration of the nuclide, (2) the integrated transfer factor for the nuclide to human intake for the pathway, and (3) the ingestion dose conversion factor.

The radiation dose for the exposure pathways of the intermediate and long-term phases is calculated for each of the coarse spatial elements using the initial ground concentration under the plume centerline calculated by the ATMOS module. Similar to the early exposure pathways, MACCS uses the off-centerline correction factor and the ground concentration under the plume centerline to estimate the initial ground concentration at the off-centerline region of various spatial elements. The following section discusses how to estimate the off-centerline factors for the intermediate and long-term phases.

3.2.1 Off-Centerline Correction Factor for the Intermediate and Long-Term Phases

A coarse spatial element, or spatial element, can be specified using the notation (r,s), where r indicates the radial interval number and s specifies the compass direction sector number. The initial ground concentration of a spatial element (r,s) as a result of deposition from a plume segment is the ground concentration under the plume centerline at a distance specified by the radial interval number r multiplied by the off-centerline correction factor of that spatial element. This off-centerline correction factor of a spatial element (r,s), called K_{rs}, is calculated using the values of the off-centerline correction factors of fine spatial elements, namely J_{rm}, discussed in Section 3.1.1. The value of K_{rs} is the sum of J_{rm} over the fine spatial elements within a coarse spatial element divided by the number of fine crosswind divisions (3, 5, or 7 as specified by the user). If there is more than one plume segment passing over a spatial element, the total initial ground concentration for radionuclide i in a spatial element (r,s) is then the sum of initial ground concentrations of all plume segments:

$$GC_{irs} = \sum_{n=1}^{N} GC_{in} \bullet K_{rsn} \tag{3.16}$$

where

GC_{irs} = initial ground concentration (Bq/m²) of radionuclide i in spatial element (r,s) as a result of dry and wet deposition from all plume segments,
GC_{in} = initial ground concentration (Bq/m²) of radionuclide i under the plume centerline, as a result of dry and wet deposition from plume segment n,
N = total number of plume segments, and
K_{rsn} = off-centerline correction factor of the spatial element (r,s) for plume segment n, defined above.

In order to simplify the subscript notation, the spatial element subscripts r and s are not used in the dose equations of the intermediate and long-term phases. The initial ground concentration of a spatial element (r,s), GC_{irs}, or GC_i, is used for the exposure pathways of the intermediate and long-term phases discussed in the following sections.

3.2.2 Groundshine

The basis for the intermediate and long-term groundshine dose used in the chronic exposure model is discussed in detail in Appendix VI of the Reactor Safety Study [US75]. Before calculating the groundshine dose to an individual, the model first determines whether protective actions should be taken (see Sections 5.2 and 5.3). These long-term actions can include decontamination, a combination of decontamination and temporary interdiction, or condemnation of the land. To make this determination, the model must compare the sum of the projected intermediate or long-term groundshine and resuspension doses to a dose criterion, that is, a dose level that would require protective actions. This projected groundshine and resuspension inhalation dose is integrated from the start of the intermediate or long-term period up to the end of the projection period.

The groundshine dose of the intermediate or long-term phase for a given time period is calculated for each of the coarse spatial elements using the following equation:

$$DG_k = \left[\sum_i GC_i \bullet DFG_{ik}\right] \bullet SFG \tag{3.17}$$

where

DG_k = groundshine dose (Sv) to organ k in a spatial element for a given time period,
GC_i = initial ground concentration (Bq/m^2) of radionuclide i in the spatial element, calculated by Equation (3.16),
DFG_{ik} = groundshine dose factor ($Sv\text{-}m^2/Bq$) to organ k for radionuclide i for a time period, defined below, and
SFG = groundshine shielding factor (dimensionless).

For the intermediate and long-term phases, the groundshine shielding factor for normal activity (user-specified) is used.

The computation of the groundshine dose factor DFG_{ik} for the specific time period from t_1 to t_2 requires the evaluation of the following function:

$$DFG_{ik} = DRFG_{ik} \bullet \int_{t_1}^{t_2} e^{-\lambda_i t} \bullet Gw(t)\, dt \tag{3.18}$$

where

$DRFG_{ik}$ = groundshine dose rate conversion factor ($Sv\text{-}m^2/Bq\text{-}s$) to organ k for radionuclide i, MACCS Dose Conversion Factors File,
λ_i = decay constant (s^{-1}) of radionuclide i, and
$Gw(t)$ = Gale's weathering function, defined below.

If a radionuclide decays to a radioactive daughter, the groundshine dose resulting from the daughter is added to the groundshine dose of the parent radionuclide.

Gale's equation [Ga64] for the loss of radioactivity by weathering is a two-term exponential decay function. That is,

$$Gw(t) = WC_1 \bullet e^{-\lambda_1 t} + WC_2 \bullet e^{-\lambda_2 t} \tag{3.19}$$

where

WC_1 and WC_2 = weathering coefficients (dimensionless), and
λ_1 and λ_2 = weathering decay constants (s^{-1}).

This equation is used in the MACCS groundshine exposure model with all variables on the right hand side of Equation (3.19) being user-supplied input data.

By combining Equations (3.17), (3.18), and (3.19), we can calculate the groundshine dose between two specified times t_1 and t_2. For example, in the intermediate phase, t_1 could be the end of the emergency phase, and t_2 could be the end of the intermediate phase if no relocation is needed for a given spatial element.

3.2.3 Resuspension Inhalation

In addition to calculating groundshine doses to individuals residing in the contaminated area, the chronic exposure model calculates doses from inhalation of resuspended radionuclides. These doses are calculated for all inhabitants living in areas that are not permanently interdicted.

The resuspension inhalation dose of the intermediate or long-term phase for a given time period is calculated for each of the coarse spatial elements using the following equation:

$$DR_k = \sum_i GC_i \bullet DFR_{ik} \bullet SFI \tag{3.20}$$

where

DR_k = resuspension inhalation dose (Sv) to organ k in a spatial element for a given time period,
GC_i = initial ground concentration (Bq/m^2) of radionuclide i in a spatial element, calculated by Equation (3.16),
DFR_{ik} = resuspension inhalation dose factor ($Sv\text{-}m^2/Bq$) to organ k for radionuclide i for a given time period, defined below, and
SFI = inhalation shielding factor (dimensionless).

For the intermediate and long-term phases, the inhalation shielding factor for normal activity (user-specified) is used in the resuspension inhalation dose calculation.

The computation of the resuspension dose factor, DFR_{ik}, for a specific time period t_1 to t_2 requires the evaluation of the following function:

$$DFR_{ik} = BR \bullet DFI_{ik} \bullet \int_{t_1}^{t_2} e^{-\lambda_i t} \bullet Rw(t)\, dt \qquad (3.21)$$

where

- DFI_{ik} = inhalation dose conversion factor (Sv/Bq inhaled) of either acute or lifetime dose to organ k for radionuclide i, MACCS Dose Conversion Factors File,
- BR = breathing rate (m^3/s),
- λ_i = decay constant (s^{-1}) of radionuclide i, and
- Rw(t) = resuspension weathering function, defined below.

If a radionuclide decays to a radioactive daughter, the resuspension inhalation dose resulting from the daughter is added to the resuspension inhalation dose of the parent radionuclide.

Similar to Equation (3.19) for the groundshine weathering, the resuspension weathering equation is a multiterm exponential decay function:

$$Rw\ (t) = \sum_{m=1}^{3} \left(RC_m \bullet e^{-\lambda_m t} \right) \qquad (3.22)$$

where

- RC_m = resuspension weathering coefficient (m^{-1}) for the m-th term, and
- λ_m = resuspension weathering decay constant (s^{-1}) for the m-th term.

All the above quantities are user-specified. By combining Equations (3.20), (3.21) and (3.22), the intermediate and long-term inhalation dose of resuspended radionuclides can be calculated for a period of time of interest.

3.2.4 Ingestion Doses from Contaminated Food

Long-term dose from ingestion of both contaminated food and water is modeled in the MACCS code. Contamination of food and water results from the dry and wet deposition of the radioactive plume as it is carried from the accident site by the wind. Ingestion doses are received by population who consume food or water originating in the area over which the radioactive plume has deposited.

When radioactive material is deposited onto farmland, an ingestion dose to the population can result from two pathways: (1) a growing season pathway resulting from the direct deposition of radionuclides onto the growing crops and (2) a long-term pathway resulting from root uptake and soil ingestion by animals of the material from contaminated soil. The growing season pathway can contaminate only those crops being grown at the time of the accident. The resulting dose to the population will depend on the day in the year when the accident occurs. If the accident occurs outside the growing season, there will be no resultant dose from the growing season pathway. In contrast, the long-term root uptake of radioactive material into food products may span many successive growing seasons. The dose resulting from the long-term pathway is independent of the time of the year when the accident occurs.

For both pathways, the material is transferred to the population via three means:

1. direct consumption of the crop by the population,

2. consumption of milk produced by animals that have consumed radioactive material, and

3. consumption of meat from animals that have consumed radioactive material.

The ingestion model does not attempt to ascertain the specific amount of radioactive material consumed by any individual, but rather determines the total amount of the material ultimately consumed by the population. The resulting health effects are therefore attributed to society as a whole. There is no provision in the model for examination of the ingestion dose incurred by specific individuals.

The food ingestion population dose from a spatial element that results from a single radionuclide is the product of its ground concentration in that spatial element, the transfer coefficients, its ingestion dose conversion factor, the land area within the element used for farming, and the portion of the farmland used for growing each crop. The population dose to organ k from a specific radionuclide i via the ingestion pathway for crop category j is calculated using the equation

$$D_{ijk} = GC_i \bullet DF_{ik} \bullet FA \bullet FAC_j \bullet TF_{ij} \tag{3.23}$$

where

D_{ijk} = food ingestion population dose to organ k of radionuclide i from a spatial element via crop category j (Sv),

GC_i = initial ground concentration of radionuclide i in the spatial element (Bq/m^2), calculated by Equation (3.16),

DF_{ik} - ingestion dose conversion factor for nuclide i to organ k (Sv/Bq), MACCS Dose Conversion Factors File,

FA - area in grid element which is devoted to farming (m^2),

FAC_j - fraction of the farmland area in the spatial element which is devoted to crop j (dimensionless), and

TF_{ij} - overall transfer factor (dimensionless) from soil to population for nuclide i via crop j.

All variables on the right side of the dose equation except GC_i are user supplied or are derived from user-supplied data as in the case of TF_{ij}. Three input files supply food pathway data for the MACCS code: the Site Data File, the Dose Conversion Data File, and the CHRONC User Input File [Ch89]. For a description of these files, consult the MACCS User's Guide. The total societal dose to any organ is determined by summing the derived doses over all of the nuclides and all crops. A description follows for the derivation of the transfer factors TF_{ij} for the MACCS food pathway.

Food Pathways Transfer Factors

At the heart of the food pathways model in the MACCS code is the determination of the fraction of the radioactive material deposited onto farmland that will ultimately be consumed by the population. The food pathways model is connected with the food pathways mitigative actions model described in Section 5.3.2. The MACCS ingestion model assumes that it will always be possible for the mitigative actions to reduce individual doses below the user-established criteria for maximum allowable radiological exposure of the public. Since these criteria should normally be set well below the threshold dose for inducing any type of acute health effects, only a lifetime dose commitment to the population at large is calculated. Another fundamental assumption in the MACCS ingestion model is the linearity of the dose-response relationship for cancers resulting from ingestion. For a description of the cancer induction model, refer to Section 6.2.

The transfer of radionuclides through the various pathways is affected not only by processes that will facilitate their transfer, but also by processes that will in some manner limit the amount actually consumed. The limiting processes considered are

1. radioactive decay between time of deposition and time of consumption of contaminated food,

2. movement of the nuclide downward through the soil compartment to a depth where it will no longer be taken up by the plant,

3. irreversible chemical binding of the nuclide with the soil that prevents it from being taken up by the plant,

4. food processing and preparation methods that will discard part of the contaminated portion of food, and

5. biological filtering of the radionuclides by meat- or milk-producing animals.

It should be noted that when farmland is decontaminated, no provision is made in the calculation of dose received via the food pathway for a possible decrease of contaminated material resulting from the decontamination process. It is assumed that farmland decontamination will consist of deep plowing to make the area habitable, but would not remove the radioactive material from the root zone. This material would still be available for uptake into the food supply. In addition, even though washoff is considered in the water ingestion dose calculations, the food pathway dose calculations do not account for washoff as a possible limiting process. These factors may lead to a small overestimation of the dose received via the food pathway.

The food pathway model implemented in the MACCS code is schematically depicted in Figure 3.4. It consists of a series of connected compartments. Between each pair of compartments is a transfer factor that defines the fraction of the radioactive material transmitted from one compartment to the next. In the MACCS code, each of these transfer factors are supplied as user input.

A definition of each transfer factor indicated in the overview of the food pathways is given in Table 3.2. All variables indicated are user-supplied data with the exception of CTD which is calculated within the code from user-supplied data. The variables TFSI (transfer factor from soil to animals by soil ingestion) and CTR are combined and supplied as the input variable TCROOT.

The current version of the ingestion pathway model has the capability to handle as many as 10 radionuclides and as many as 10 crop categories. Since the definition of the parameters describing the ingestion model is the responsibility of the user, refer to the MACCS User's Guide [Ch89] where a sample set of input files is presented. The relevant data files are the CHRONC User Input File and the Site Data File.

In the food pathways model, two processes are considered for the uptake of the radioactive material deposited on farmland into the food supply for man. The material may be deposited directly onto the plant surfaces of the growing crop. For some crops, this results in the direct contamination of the edible portion of that crop, while for others, the edible portions of the plants will be contaminated by biological translocation of the contaminants to the edible portions of plants. Alternatively, the material can be deposited onto the soil and subsequently enter the food chain either by being taken up by the plants themselves or by being ingested with soil by grazing animals. Nuclides deposited onto the soil can be taken up by plants via root uptake or by being deposited onto the plant surfaces through resuspension or rainsplash.

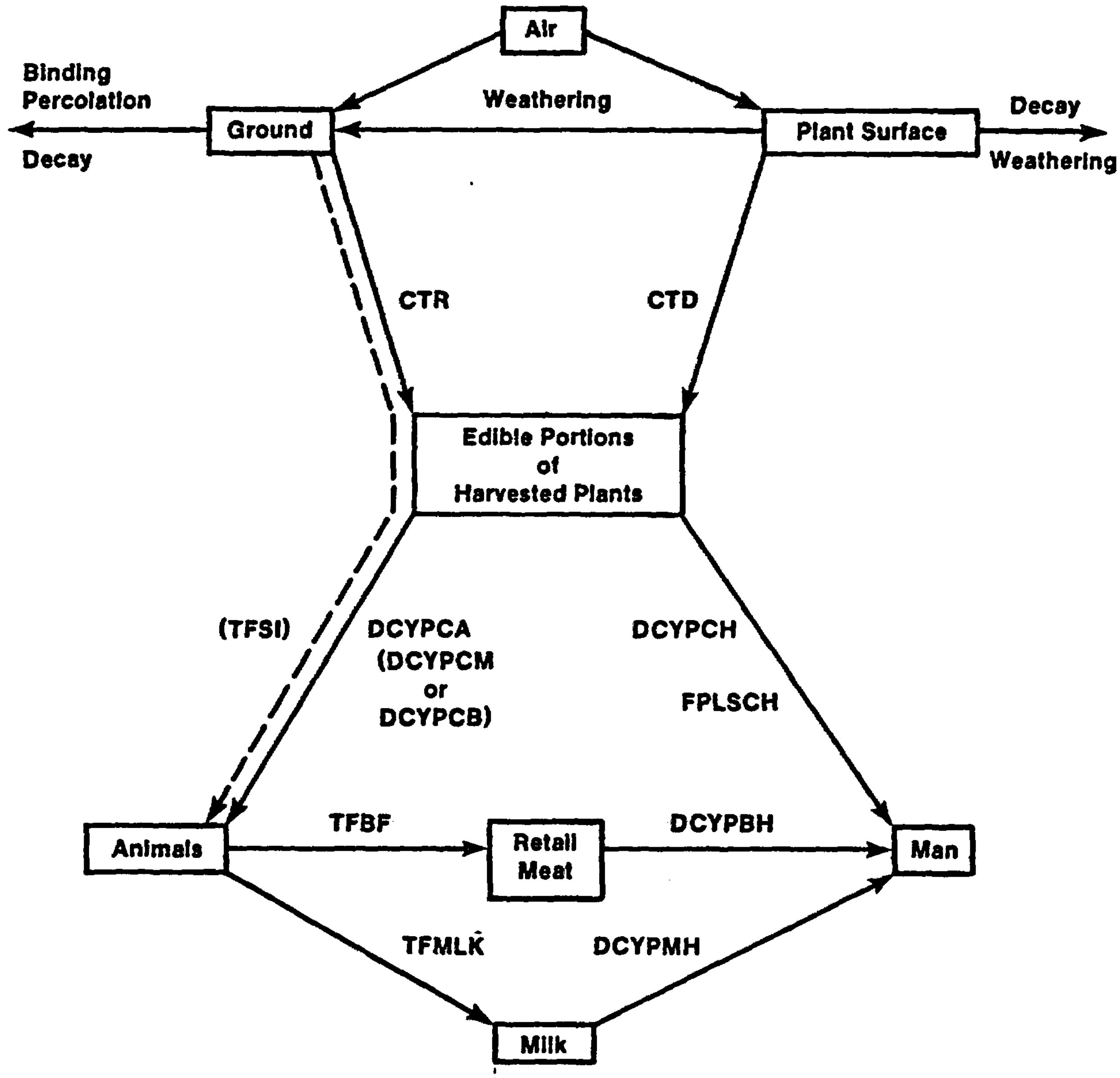


Figure 3.4 Food Pathways Model in MACCS Code

Table 3.2

Glossary of Transfer Factors
for Food Pathways Model

Transfer Factor*	Relevant Phenomena	Time Delay From	Time Delay To
CTD	weathering radioactive decay	deposition onto plants	harvest
DCYPBH	meat trimming radioactive decay	slaughter	consumption
DCYPCB	radioactive decay	harvest	consumption
DCYPCM	radioactive decay	harvest	consumption
DCYPCH	radioactive decay	harvest	consumption
DCYPMH	radioactive decay	production of milk	consumption
FPLSCH	food processing food preparation	harvest	consumption
CTR	radioactive decay percolation binding with soil	deposition onto soil	harvest
TFBF	biological filtration radioactive decay	feed consumption	slaughter
TFMLK	biological filtration radioactive decay	feed consumption	milk production
TFSI	radioactive decay binding with soil percolation	deposition onto soil of pastureland	consumption

*All transfer factors are dimensionless.

Radioactive material in the edible portions of plants can in turn be transferred to man by three routes: crop-man, crop-animal-milk-man, and crop-animal-meat-man. For each of these pathways, an overall transfer factor is determined that describes the fraction of the total amount of each radionuclide deposited onto the farmlands that is actually consumed by man. These transfer factors are defined for each crop-nuclide pair.

Transfer of Radionuclides Deposited Directly onto Plant Surfaces

The transfer of directly deposited nuclides to edible portions of the crop is dependent upon the time of the year in which the accident occurs. When an accident occurs outside the growing season, none of the radioactive material will be deposited onto growing crops, and the growing season transfer factor, CTD, will be zero. When an accident occurs during the growing season for a given crop, the amount of contamination present in the edible portion of the crop when it is harvested will depend on the point of time in the growing season when the accident occurs. For most types of crops, harvesting is assumed to occur at the end of the growing season. The important variable for these crops is the length of time between deposition and harvest. For pasture-type crops, continual harvesting over the entire growing season is assumed. The time between the beginning of the growing season and the time of the accident is also important for pasture-type crops.

A crop characteristic that affects the transfer of directly deposited contamination to the edible portions of that crop is the degree to which the edible portion of the plant is exposed to the outside environment. For some crops (e.g., grain) the edible portion of the plant is completely protected from the outside environment, and contamination of the edible portion requires the biological translocation of a radionuclide from the plant surfaces to the edible portions of the plant.

When the edible portion of the plant is exposed, an increase in the length of time between deposition and harvest will normally result in a decrease in the retention factor from weathering and decay processes. When the edible portion of a crop is unexposed, however, contamination is solely dependent on the biological process of translocation, and the transfer of a radionuclide will generally increase as the length of time between the accident and harvest is increased. Translocation is not modeled explicitly in the MACCS code, but can be implicitly considered in establishing the values of the variables CTCOEF, the weathering coefficients, and CTHALF, the weathering half-lives. Additional information regarding the variables CTCOEF and CTHALF can be found in the MACCS User's Guide [Ch89].

With regard to the categorization of crop types, pasture is treated uniquely within the MACCS model. It is assumed that pasture undergoes continual harvesting over the entire course of the growing season. It is also assumed that the entire pasture crop will be consumed by food-producing animals over the course of a single growing season.

The direct deposition transfer factor CTD_{ij} is defined for every nuclide i and crop category j pair. The number of terms n in the crop transfer function is currently limited to three (see Equation (3.24)). The first term represents the portion of the contaminating material that will be removed quickly by weathering processes, and the second and third, if specified, represent the more persistent contaminants. When considering crops in which the edible portion is not exposed to the environment, the first term of the crop transfer function can be set to a constant, and the second and third terms, if specified, can be set to zero.

For pasture, harvest is assumed to be a continuous process. Therefore, CTD_{ij} is derived by integrating the uptake function from the time of the accident to the end of the growing season. The uptake function is expressed as the grazing rate modified by the weathering loss rate. The grazing rate of pasture is assumed to be constant over the grazing period of time, $(TE_j - TS_j)$. Therefore, the grazing rate is $1.0/(TE_j - TS_j)$. The weathering rate is expressed by a three-term exponential decay function. Therefore, the direct deposition transfer factor of radionuclide i via pasture is calculated using the following equation:

$$CTD_{ij} = \frac{1}{TE_j - TS_j} \cdot \left[\sum_{n=1}^{3} CTCOEF_{ijn} \cdot \int_{o}^{T} e^{-H_{ijn}t}\, dt \right]$$

$$= \frac{1}{TE_j - TS_j} \cdot \sum_{n=1}^{3} \left[CTCOEF_{ijn} \cdot \frac{1 - e^{-H_{ijn}T}}{H_{ijn}} \right] \qquad (3.24)$$

where

CTD_{ij} = fraction of radionuclide deposited directly onto plant surfaces found in the edible portion of pasture at harvest (dimensionless),

T = time from accident to the end of growing season (s)

$CTCOEF_{ijn}$ = crop transfer coefficient (amount transferred/amount deposited)(dimensionless),

TE_j = time from the beginning of the year to the end of the growing season for crop j (s),

TS_j = time from the beginning of the year to the beginning of the growing season for pasture (s), and

H_{ijn} = total depletion rate of radionuclide i from surface of pasture due to weathering, grazing, and radioactive decay processes (s^{-1}).

And

$$H_{ijn} = \frac{\ell n\ 2}{CTHALF_{ijn}} + \frac{\ell n\ 2}{TE_j - TS_j} + \lambda_i \quad ,$$

where

$\ell n\ 2$ = natural logarithm of 2,
$CTHALF_{ijn}$ = half-life of weathering coefficient n (s) and,
λ_i = decay constant for radionuclide i (s^{-1}).

For pasture, the transfer of radioactive material deposited onto the surface of the growing crop is assumed to be limited to the period of time between the time of the accident TI and the end of the growing season. If the accident occurs outside the growing season for pasture (i.e., TI < TS or TI > TE_j), then T = 0 and no material will be consumed via this pathway. If, however, the accident occurs during the pasture growing season (i.e., TS_j < TI < TE_j), then the time T over which the transfer can occur is (TE_j - TI) and the direct deposition crop transfer factor for pasture in Equation (3.24) becomes

$$CTD_{ij} = \frac{1}{TE_j - TS_j} \bullet \sum_{n=1}^{3} \left[CTCOEF_{ijn} \bullet \frac{1 - e^{-H_{ijn} \bullet (TE_j - TI)}}{H_{ijn}} \right] \quad (3.25)$$

For all nonpasture crops, harvest is not a continuous process, and occurs only at the end of the growing season. The transfer function consists only of a weathering term. The fraction of the deposited material found in the edible portion of the plant will again be dependent on the amount of time between the time of the accident and the end of the growing season. Again, if TI < TS_j or TI > TE_j, then CTD = 0 for that nuclide-crop pair. If TS_j < TI < TE_j, then

$$CTD_{ij} = \sum_{n=1}^{3} CTCOEF_{ijn} \bullet e^{-L_{ijn} \bullet (TE_j - TI)} \quad (3.26)$$

where

L_{ijn} = the total depletion rate for weathering and radioactive decay processes (s^{-1})

and

$$L_{ijn} = \frac{\ell n 2}{CTHALF_{ijn}} + \lambda_i$$

where all variables are as previously defined.

Transfer of Radioactive Material Deposited onto Soil to Food Plants

Compared to direct deposition transfer processes, the transfer processes in which radioactive material is deposited onto the soil and subsequently taken up by plants are long-term mechanisms. Following deposition, the contaminants must be transferred to the plants via root uptake and other soil uptake processes such as soil ingestion by grazing animals for this pathway to be effective. The user-supplied input variable TCROOT incorporates the overall transfer of the radionuclides by all these long-term uptake processes. Because a number of disparate processes are being combined, the transfer factor may be most readily derived empirically using current fallout data.

The transfer factor $TCROOT_{ij}$ is defined in the CHRONC User Input File as a two-dimensional array. For each nuclide-crop pair, it represents the fraction of the radioactive material deposited onto the soil being used to grow that crop which will eventually be consumed by man. $TCROOT_{ij}$ is the sum of the following fractions: (1) the fraction of the material deposited onto the soil which will be incorporated into the edible portion of the crop via root uptake, CTR_{ij}, and (2) the fraction of the material deposited onto the soil which will be ingested directly by grazing animals, $TFSI_{ij}$. The only crop for which soil ingestion is a significant factor is pasture. The derivation of the root uptake transfer factors, CTR_{ij}, is discussed in Appendix C.

<u>Transfer of Radioactive Material from Harvested Crops to Man</u>

Up to this point, we have described the phenomena that determine the fraction of the radioactive material deposited on farmland, which will be incorporated into edible portions of plants at the time of harvest or be consumed directly by food producing animals. This has been done for the two pathways: growing season and long-term uptake. What remains is to specify the efficiency of the transport mechanisms during the time period between the crop harvest and the consumption of the contaminated food by the population. These mechanisms include the direct consumption of the contaminated crop by the population as well as the population's consumption of contaminated animal products.

For each nuclide-crop pair, a specific transfer factor is established for each pathway that describes the fraction of the radioactive material present in the crop at the time of harvest that will ultimately be consumed by man. These transfer factors are defined for the direct consumption of the crop by the population and also for the consumption of animal products (milk and meat) produced by animals fed the contaminated crops.

The transfer factors describing the fraction of radionuclide i present in the edible portion of crop j at harvest that would ultimately be ingested by the population for the growing season and long-term pathways are derived as follows:

Crop-to-man

$$CH_{ij} = DCYPCH_{ij} \bullet FPLSCH_{ij}$$

Crop-to-milk-to-man

$$CMH_{ij} = DCYPCM_{ij} \bullet TFMLK_i \bullet DCYPMH_i$$

Crop-to-meat-to-man

$$CBH_{ij} = DCYPCB_{ij} \bullet TFBF_i \bullet DCYPBH_i \tag{3.27}$$

All of these transfer factors on the right hand side of Equation (3.27) are user-supplied input variables described in Table 3.2.

Overall Transfer of Radionuclides from Deposition to Ingestion

To establish overall transfer factors for the radionuclides deposited onto farmland following an accident, TF_{ij}, it is necessary to multiply the following factors: (1) those describing the transfer of material to the edible portion of the crop and (2) those describing the transfer of each nuclide in the harvested crop to man via each possible route to man.

For the growing season pathway, the overall transfer factors for any nuclide i/crop j pair are derived as follows. The overall transfer factors TF_{ij} found in the dose Equation (3.23) can now be calculated as the product of an appropriate crop transfer factor (that is, CTD_{ij} or $TCROOT_{ij}$) and an appropriate transfer factor describing fraction of material in harvested crops ultimately eaten by man (that is, the appropriate quantity described in Equation set (3.28) or Equation set (3.29)). That is, for the growing season pathway these overall transfer factors, TF_{ij}, for any nuclide i/crop j pair will be as follows:

Crop-to-man

$$TF_{ij} = CTD_{ij} \bullet CH_{ij}$$

Crop-to-milk-to-man

$$TF_{ij} = CTD_{ij} \bullet CMH_{ij}$$

Crop-to-meat-to-man

$$TF_{ij} = CTD_{ij} \bullet CBH_{ij} \tag{3.28}$$

The analogous long-term soil to man uptake pathway overall transfer factors, TF_{ij}, are as follows:

Crop-to-man

$$TF_{ij} = TCROOT_{ij} \bullet CH_{ij}$$

Crop-to-milk-to-man

$$TF_{ij} = TCROOT_{ij} \bullet CMH_{ij}$$

Crop-to-meat-to-man

$$TF_{ij} = TCROOT_{ij} \bullet CBH_{ij} \qquad (3.29)$$

Using the overall transfer factor, TF_{ij}, of each radionuclide i/crop j for a given pathway in either Equation (3.28) or Equation (3.29) and the food ingestion dose equation (3.23), the ingestion dose can be calculated. The total population ingestion dose from a spatial element is the sum of ingestion doses from all pathways, all radionuclides, and all crop categories.

3.2.5 Doses from Contaminated Water

In addition to the population dose received via the agricultural pathways, an ingestion population dose can also result from consumption of contaminated drinking water. Contamination of surface water can result from either the direct deposition of the radionuclides onto surface water bodies, the initial washoff of contaminated rain that falls onto land over a short time period, or the slow washoff of radioactive material from contaminated land to the surface water bodies over all time following the accident [He85]. In MACCS, the transfer of radionuclides through the liquid pathway to the population involves only the direct ingestion of contaminated fresh surface water.

The water pathways in MACCS considers only fresh water transfers to population. The water bodies treated in MACCS are lakes, river systems, and estuaries, that is, fresh surface water only. The models in MACCS are simple and intended to provide "scoping" estimates of the impact of liquid pathways on doses and health effects. All material deposited from the plume is assumed to be either deposited directly onto fresh surface-water bodies or else on land surfaces from which the radioactive contamination may be carried to the fresh surface-water bodies by washoff. Transfer of radionuclides to population is only by direct ingestion of the contaminated water. Other exposure pathways such as contamination resulting from irrigation of farmland, ingestion of contaminated water by milk- and meat-producing animals, recreational activities in the contaminated water and on the shoreline, consumption of contaminated aquatic foods, etc., are not considered in MACCS.

The MACCS code handles a maximum of 10 radionuclides in the water pathway. These radionuclides must be a subset of the nuclides being considered in the food pathway.

The transfer of contaminated water to population is modeled in MACCS as follows. The water ingestion model assumes that the area surrounding the site is divided into water and land. The radioactive material deposited on a spatial element is apportioned between water and land according to the fraction of the region covered by land as defined by the user-supplied input variable, FRACLD. The fraction of nonland area, (1 - FRACLD), is assumed to be covered by surface water.

For coastal sites, where both fresh water and ocean need to be considered, the Site Data File may be used to overcome the limitation of having only one kind of water. The Site Data File can define up to four types of watersheds. One of these, the ocean, can be defined to have a zero uptake fraction.

The ingestion dose calculated by MACCS is a societal dose, and it is not possible to determine the dose to a given individual from the water ingestion pathway. The total dose received via the water pathway consists of three component doses: (1) dose received from the radioactive material deposited directly onto fresh surface-water bodies by the radioactive plume; (2) dose received from radioactive material deposited onto land carried to surface-water bodies by washoff within a short period of time (i.e., a time period short enough to preclude significant radioactive decay); and (3) dose received from radioactive material deposited onto land that is carried to surface-water bodies by long-term continuous washoff processes. The total dose from radionuclide i to organ k via the water pathway, DW_{ik} (Sv), can therefore be defined by the following equation:

$$DW_{ik} = DWD_{ik} + DWSI_{ik} + DWSL_{ik} \quad , \qquad (3.30)$$

where

DW_{ik} = population dose to organ k for radionuclide i from all drinking water pathways from a spatial element (Sv),

DWD_{ik} = the dose to organ k resulting from the direct deposition of radionuclide i onto fresh surface-water bodies of the spatial element (Sv),

$DWSI_{ik}$ = the dose to organ k resulting from the deposition of radionuclide i onto land surfaces of the spatial element followed by washoff into the fresh surface-water bodies within a short time period (Sv), and

$DWSL_{ik}$ = the dose to organ k resulting from the deposition of radionuclide i onto land surfaces of the spatial element that will be washed off at a constant rate over all time following the accident (Sv).

Each of the three doses to organ k from radionuclide i (i.e., DWD_{ik}, $DWSI_{ik}$, or $DWSL_{ik}$) is calculated using the following general equation:

$$DOSE_{ik} = GC_i \bullet AREA \bullet TF_i \bullet DF_{ik} \tag{3.31}$$

where

- $DOSE_{ik}$ = water ingestion dose for a water pathway (Sv),
- GC_i = initial concentration of radionuclide i in a spatial element (Bq/m^2), calculated by Equation (3.16), NOTE: The concentration per unit surface is assumed to be the same for surface-water bodies and land masses.
- AREA = appropriate surface area (m^2) for the spatial element, NOTE: When considering the radioactive material deposited directly onto surface water bodies, AREA is the product of the total area in the region considered and the fraction of the region covered by fresh surface-water bodies (i.e., 1 - FRACLD). When considering the radioactive material deposited onto land and subsequently washed off into the fresh surface-water bodies, AREA is the product of the total area in the region considered and the variable FRACLD.
- TF_i = transfer factor (i.e., the fraction of nuclide i deposited that will ultimately be consumed by man)(dimensionless), and
- DF_{ik} = ingestion dose conversion factor (Sv/Bq ingested), MACCS Dose Conversion Factors File.

The total area in the region is calculated using the user-supplied grid geometry information. Therefore, as was the case in the food pathway dosimetry model, the only variables requiring further definition are the transfer factors TF_i for nuclide i for each of the component pathways.

Transfer of Radionuclides Deposited Directly onto Fresh Water Surface

When radioactive material enters the fresh surface-water system, it is assumed that some fraction of each radionuclide, $WINGF_i$, will ultimately be consumed by the population, which is user-specified input data. When a radionuclide is deposited directly onto a surface-water body, it is assumed that ingestion occurs before significant radioactive decay can occur. Therefore, the transfer factor, TF_i, for the dose component resulting from direct deposition onto water surface in Equation (3.30), DWD_{ik}, is simply $WINGF_i$. That is,

$$TF_i = WINGF_i \tag{3.32}$$

Transfer of Radionuclides Deposited onto Land and Subsequently Washed Off

For the purpose of estimating water ingestion dose, all deposited material is assumed to fall either on surface-water bodies or on land surface comprising a watershed. For material deposited onto watershed land surface, the radionuclide wash-off model in MACCS is based on two assumptions. First, it is assumed that some fraction $WSHFRI_i$ of each deposited nuclide will be washed off so quickly that the radioactive decay will be negligible. Second, it is assumed that the rate at which each nuclide in the remainder of the material moves from the land surfaces to the surface-water bodies, the washoff rate, is constant and that the pool of available material is diminished by both the washoff itself and by radioactive decay. The washoff rate $WSHRTA_i$ for each nuclide is user-supplied input.

The transfer factors TF_i for each radionuclide in the material washed off quickly into the surface-water bodies is the product of (1) the fraction of nuclide i deposited onto land that will be washed off quickly, and (2) the fraction of the nuclide i reaching the surface-water bodies that will ultimately be consumed by man. Therefore, the transfer factor, TF_i, for the dose component resulting from deposition onto land followed by short-term washoff in Equation (3.30), $DWSI_{ik}$, is,

$$TF_i = WSHFRI_i \bullet WINGF_i \tag{3.33}$$

The transfer factor TF_i for each radionuclide in the remaining material washed off into surface-water bodies at a constant rate over all time following the accident incorporates the depletion of available material from the washoff process itself and decay. By letting $x_i(t)$ represent the amount of available radioactive nuclide i on land surfaces at time t (s), the long-term washoff model can be described as follows:

$$\frac{dx_i}{dt} = -\left[\lambda_i + WSHRTA_i \right] \bullet x_i \tag{3.34}$$

with the initial condition

$$x_i(0) = \left(1 - WSHFRI_i\right) \bullet x_{oi} \tag{3.35}$$

where

$x_i(t)$ = amount of radionuclide i on the land surfaces at time t after an initial deposition at time t = 0 (Bq),

λ_i = radioactive decay constant for radionuclide i (s^{-1}),

$WSHRTA_i$ = rate constant for the long-term movement of radionuclide i from land surfaces to surface-water bodies (s^{-1}),

$WSHFRI_i$ = fraction of the initial radionuclide deposition that moves from the land surfaces to surface-water bodies in a short time period after deposition (dimensionless), and

x_{oi} = total amount of radionuclide i that was deposited onto land surfaces following the accident (Bq). NOTE: $x_{oi} = GC_i \bullet FRACLD$.

Using Equations (3.34) and (3.35), the quantity $x_i(t)$ is found to be

$$x_i(t) = \left(1 - WSHFRI_i\right) x_{oi} \bullet e^{-(\lambda_i + WSHRTA_i)t} \tag{3.36}$$

The transfer factor, TF_i, for the long-term dose received from washoff of radionuclide i, $DWSL_{ik}$, in Equation (3.30), is the product of the following fractions: (1) the fraction of the material deposited on land surfaces that will eventually be washed off into surface-water bodies, $WSHFRC_i$, and (2) the fraction of that material ultimately consumed by man, $WINGF_i$. $WINGF_i$ is the user-supplied water ingestion factor as previously defined.

The fraction $WSHFRC_i$ is the ratio of the amount of radionuclide i washed off into surface-water bodies over a long period of time following the initial short-term washoff process to the total amount of radionuclide i deposited onto land surfaces x_{oi}. The amount of material washed off land surfaces over the long term, $WSHFRL_i$, is found by integrating the product of the washoff rate for radionuclide i, $WSHRTA_i$, and the amount of material on land surfaces at time t, that is, $x_i(t)$. The integration is performed for all time following deposition, that is, from $t = 0$ to $t = \infty$. That is,

$$WSHFRL_i = WSHRTA_i \bullet \int_0^\infty x_i(t) \, dt$$

$$= WSHRTA_i \bullet \int_0^\infty \left(1 - WSHFRI_i\right) x_{oi} \, e^{-[\lambda_i + WSHRTA_i]t} \, dt$$

$$= \frac{WSHRTA_i \left(1 - WSHFRI_i\right) x_{oi}}{\lambda_i + WSHRTA_i}$$

and

$$WSHFRC_i = \frac{WSHFRL_i}{x_{oi}} = \frac{WSHRTA_i \left(1 - WSHFRI_i\right)}{\lambda_i + WSHRTA_i}$$

The transfer factor for radionuclide i for the long-term washoff dose model then becomes

$$TF_i = WSHFRC_i \bullet WINGF_i = \frac{WINGF_i \bullet WSHRTA_i \left(1 - WSHFRI_i\right)}{\lambda_i + WSHRTA_i} \tag{3.37}$$

All quantities on the right-hand side of Equation (3.37) are user-specified.

By combining Equations (3.33) and (3.37), the total transfer factor of radionuclide i deposited onto land and subsequently washed off into the surface water and ultimately consumed by the population is,

$$TF_i = \frac{\lambda_i \bullet WSHFRI_i + WSHRTA_i}{\lambda_i + WSHRTA_i} \bullet WINGF_i \tag{3.38}$$

Finally, after substituting Equation (3.32), or (3.38) for the transfer factor TF_i in Equation (3.31), each of the two water ingestion doses on the right hand side of Equation (3.30) can be determined.

4.0 ECONOMIC COSTS

The economic effect models in MACCS are intended to estimate the direct offsite costs resulting from a reactor accident. The models used were assessed and selected by Burke [Bu84]. Two types of costs are modeled in MACCS: costs resulting from early protective (emergency response) actions and costs resulting from long-term protective actions. Protective action costs are dependent on the site of the accident, the actions taken during and after the accident, and the accident itself. The protective actions to be taken and the accident description are defined in the user input data. Supporting economic and demographic data associated with the accident site are supplied on the Site Data File [Ch89].

The following costs are treated in the economic models implemented in the MACCS code:

(1) food and lodging costs for short-term relocation of people who are evacuated or relocated during the emergency phase of the accident,

(2) decontamination costs for property that can be returned to use if decontaminated,

(3) economic losses incurred while property (farm and nonfarm) is temporarily interdicted by a period of time following decontamination to allow for radioactive decay to reduce ground concentrations to acceptable levels,

(4) economic losses resulting from milk and crop disposal, and

(5) economic losses due to permanent interdiction of property.

The estimation of costs associated with the number of radiation-induced deaths, injuries, and cancers has not been included in the MACCS economic model.

Three types of protective actions during the emergency phase can be defined by the user: evacuation, sheltering, and relocation. Evacuation refers to the movement of individuals out of a user-specified annular ring around the accident site during the time the accident is occurring. Sheltering refers to the action taken by individuals to stay indoors for a user-specified period of time. Temporary relocation refers to the movement of individuals out of an annular ring if the projected dose exceeds a user-specified dose limit. Section 5.1 provides a detailed discussion of the protective actions taken during the emergency phase. Models to estimate the costs resulting from early protective actions are described in Section 4.2.

An optional intermediate phase can be specified by the user. Temporary relocation may occur as a protective action during that time period. The intermediate phase begins at the end of the emergency phase and may last up to one year. A typical duration for the intermediate phase is one month. Models used to estimate the costs of protective actions of the intermediate phase are described in Section 4.2.

The long-term phase begins at the end of the intermediate phase. Long-term protective actions include decontamination, temporary interdiction to allow for radioactive decay to return land to habitability, crop disposal, control of food production, and condemnation of property. These actions would be taken following the accident with the intent of reducing the long-term radiation exposure in the most cost effective manner. The protective actions taken during the intermediate and long-term phases are discussed in Sections 5.2 and 5.3, respectively. Models used to estimate the cost of protective actions of the long-term phase are described in Section 4.3.

4.1 Costs Resulting from Early Protective Actions

The costs resulting from early protective actions of the emergency phase are calculated for the following three protective measures: evacuation, sheltering and relocation. Some people may be asked to take shelter by staying indoors while the accident is occurring. If they are in a spatial element over which the plume passed they will be evacuated at the end of the sheltering period. The cost associated with the shelterees is that incurred for their evacuation. 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 overall time period during which people are provided with temporary lodging, and daily cost of the protective actions per individual.

The MACCS economic model calculates the costs for both evacuation and relocation on a spatial element basis. For any spatial element, the cost of an early protective action is calculated in the following manner:

$$CE = P \bullet D \bullet I \tag{4.1}$$

where

CE	=	cost of the early protective action being taken ($),
P	=	number of individuals involved in the action (persons),
D	=	duration of the action being taken (days), and
I	=	daily cost of the action per individual ($/person-day).

<u>Evacuation Costs (For Evacuees and Shelterees)</u>

In MACCS the user can define as many as three evacuation zones. Evacuation can only occur from these evacuation zones. An evacuation zone is an annular region defined by the inner and outer interval boundaries of the zone (See Figure 5.1). Only people in the evacuation zones residing in a contaminated spatial element will be evacuated. The evacuation duration of the evacuees in calculating the cost in Equation (4.1) is the duration of the emergency phase which is user-specified with a typical value being seven days.

In MACCS the user can specify up to two sheltering zones. The population of the spatial elements are assumed to continue normal activity until a user-specified time when they take shelter inside their homes. For any spatial element over which the plume passed, the shelterees are evacuated at the end of the sheltering time period and the cost of evacuation is incurred by that population. The evacuation duration of the shelterees for calculating the cost in Equation (4.1) is the duration of the emergency phase.

The population residing within a spatial element which is involved in evacuation or sheltering is obtained from either user-supplied uniform population input data or user-supplied site specific population data from the Site Data File [Ch89]. The daily evacuation cost per person in Equation (4.1) is user-supplied as the CHRONC input variable EVACST ($/person-day) and can include the cost incurred for providing temporary lodging, meals, and lost income for an individual.

The cost of evacuation is calculated on a spatial element basis. The evacuation cost for the accident is the sum of the evacuation costs for all spatial elements from which evacuation or sheltering has occurred.

Relocation Costs

Two types of temporary relocation are treated in MACCS, hot-spot relocation and normal relocation. Both types of relocation can only occur at locations outside the evacuation and sheltering zones. Spatial elements are designated for relocation actions based on a projected dose criteria (see Section 5.1.3). The cost of both hot-spot and normal relocation is calculated on a spatial element basis.

The time period for hot-spot relocation extends from the time when the population within a spatial element is relocated, TIMHOT, to the end of the emergency action period, ENDEMP. The value of TIMHOT is user-specified. The time period for normal relocation extends from the time the population within a spatial element is relocated, TIMNRM, to ENDEMP. The value of TIMNRM is user-specified.

The daily cost per person in Equation (4.1) for normal or hot-spot relocation is user input data as the CHRONC input variable RELCST ($/person-day) and can include the cost of temporary lodging, meals, and lost income for that individual for the duration of normal or hot-spot relocation.

The MACCS code does not print out separately the cost of hot-spot and normal relocation. The overall cost of relocation incurred as a result of an accident is calculated as the sum of all hot-spot and normal relocation costs for all spatial elements outside the evacuation and sheltering zones.

4.2 Costs Resulting from Protective Actions of Intermediate Phase

An optional intermediate phase may be specified by the user. The duration of the intermediate phase extends from the end of the emergency phase to the user-supplied time following the accident at which the intermediate phase ends.

The only protective action which occurs during the intermediate phase is temporary relocation. The decision to extend relocation throughout the intermediate phase is based on an intermediate phase dose criterion (see Section 5.2). When the dose criterion is exceeded, every person in the spatial element is then relocated for the duration of the intermediate time phase, TMIPND, which is user-specified with a typical value of one month.

The costs for relocation during this phase are calculated using Equation (4.1) and the relocation duration in the same way as the relocation costs are calculated for the emergency phase. A single user-supplied daily cost per person of relocation is used for relocation during either the emergency phase or the intermediate phase.

4.3 Costs Resulting from Long-Term Protective Actions

The costs resulting from long-term protective actions are associated with five types of long-term actions: decontamination, decontamination followed by temporary interdiction of farm and urban areas, disposal of crops or products produced on farms, temporary prohibition of farm production, and condemnation of property. Each of these actions is taken in an effort to reduce the long-term health consequences of the accident in a cost-effective manner. The estimation of the long-term protective action costs in MACCS depends on the accident, the time of year when the accident occurs, the site of the accident (the land area and population impacted), the protective actions taken, and the duration of these actions.

The costs resulting from long-term protective actions are calculated on a spatial element basis. A record is kept of all protective actions taken within any spatial element and the record is used in the calculation of the cost incurred for all actions taken within that spatial element. The costs of each long-term protective action will be discussed separately.

Long-term protective action costs are divided into two groups, farm costs and nonfarm costs. Farm costs are always calculated per hectare of farmland (worth of farmland and improvements per hectare, crop worth per hectare). Nonfarm costs are always calculated per person (temporary and permanent relocation costs per person, tangible worth of nonfarm property per person, decontamination costs of nonfarm property per person), where nonfarm property includes residential, commercial, and public land, improvements, equipment, and possessions.

In general the cost of any long-term protective action is determined in the following way:

$$CL = CNF \bullet P + CF \bullet AF \tag{4.2}$$

where

CL	=	total cost incurred as a result of long-term protective action taken within a given spatial element ($),
CNF	=	per person cost of long-term protective action for nonfarm property ($/person),
P	=	population within spatial element (persons),
CF	=	per unit area cost of long-term protective action for farm property ($/hectare), and
AF	=	farmland area within the spatial element (hectares).

The population within a spatial element, P, is user-specified and the farmland area within the spatial element, AF, is calculated by MACCS using the geometric grid input data and site data [Ch89].

The per person cost of long-term protective action for nonfarm property, CNF, is either the per person cost of restoring habitability or the per person cost of condemning the nonfarm property if it is not possible or cost effective to restore habitability. The per unit cost of long-term protective action for farm property, CF, is the sum of (1) the unit cost of restoring habitability and farm production of the farm property or the unit cost of condemning the farm property and (2) the unit cost of disposal of growing season crops. The remainder of this chapter discusses the economic models used in MACCS for estimating the unit costs of different long-term protective actions.

4.3.1 Costs Resulting from Restoring Habitability of Nonfarm Properties

A spatial element may be declared to be uninhabitable based on a dose criterion for groundshine and resuspension inhalation exposures. Decontamination with interdiction, decontamination without interdiction, or condemnation may be required for nonfarm property within any spatial element.

Three different cost components are defined for decontamination or for decontamination followed by interdiction: (1) the cost of the minimum decontamination effort required to reduce doses in that grid element so they do not exceed the long-term habitability dose criterion, (2) the costs of relocating the people from the spatial element for the period of decontamination, and (3) the cost of temporary interdiction required in addition to the maximum decontamination effort to reduce doses in the spatial element so they do not exceed the long-term habitability dose criteria. Because decontamination precedes interdiction, its costs are independent of temporary interdiction. Decontamination costs are specified by the user for each level of decontamination effort defined in the protective actions.

The cost of restoring habitability for nonfarm property is the sum of the cost of the actual decontamination efforts, the cost of relocating people, and the cost incurred as a result of the loss of usage of the property. That is,

$$CNF = CD + CR + CC \tag{4.3}$$

where

CNF = unit cost of restoring habitability for nonfarm property (\$/person),
CD = unit cost of decontamination (\$/person for nonfarm property),
CR = unit cost of relocating the population (\$/person for nonfarm property), and
CC = unit cost of compensation as a result of loss of usage of the property (depreciation, deterioration, and losses) (\$/person for nonfarm property).

The costs incurred for decontamination of nonfarm property, CD, are user-supplied. A separate set of decontamination costs is provided for both farm and nonfarm property for each level of decontamination.

A per person cost for temporary or permanent relocation of the population during a period of interdiction, CR, is supplied by the user as the CHRONC input variable POPCST (\$/person). This relocation cost is provided only for the nonfarm population.

The unit cost of compensation as a result of loss of usage of the property during the period of interdiction of nonfarm property is calculated to be the difference between the initial unit value of wealth for the region and the unit value of wealth for the region at the time the land is declared habitable. That is,

$$CC = VALW - VALWP \tag{4.4}$$

where

VALW = unit value of wealth for the region at the time of the accident (\$/person for nonfarm property) and
VALWP = unit value of wealth for the region at the time the land is declared habitable (\$/person for nonfarm property).

To derive the unit value of wealth following the period of interdiction, VALWP, the following adjustments are made to the current unit value of wealth to reflect the following: (1) a decrease in the value of the improvements made to property resulting from depreciation over the period of loss of usage and (2) a general decrease in the value of the property resulting from decreasing return on the investment. Property improvements are subject to a loss of value due to both depreciation and loss of return on the investment. The land itself is subject only to a loss of return on the investment. The value of wealth at the end of loss of usage is the sum of the value of wealth resulting from property improvements and the value of wealth resulting from the land itself. That is,

$$VALWP = VALWPI + VALWPL \tag{4.5}$$

where

VALWPI = post-interdiction period unit value of wealth resulting from improvements made to the property ($/person for nonfarm property) and
VALWPL = post-interdiction period unit value of wealth resulting from the land itself ($/person for nonfarm property).

To derive the post-interdiction period unit value of wealth resulting from improvements made to the property, VALWPI, an exponential decay of the current value is assumed for both depreciation and loss of return on the investment. That is,

$$VALWPI = VALW \bullet FIM \bullet EXP(-RDP \bullet TH) \bullet EXP(-RIR \bullet TH) \tag{4.6}$$

where

VALW = unit value of wealth for nonfarm property in the region (includes the cost of the land, buildings, infrastructures, and any non-recoverable equipment or machinery ($/person),
FIM = fraction of the wealth in the region resulting from improvements (unitless),
RDP = depreciation rate (s^{-1}),
TH = time (s) at which the nonfarm property is returned to habitability, and
RIR = inflation adjusted rate of investment return (s^{-1}).

The post-interdiction period value of wealth due to the value of land, VALWPL, can be derived as follows:

$$VALWPL = VALW \bullet (1.0 - FIM) \bullet EXP(-RIR \bullet TH) \tag{4.7}$$

All variables in Equation (4.7) are as previously defined. After substituting Equations (4.6) and (4.7) into Equation (4.5), the unit value of wealth of a spatial element can be calculated as follows:

$$
\begin{aligned}
\text{VALWP} &= \text{VALWPI} + \text{VALWPL} \\
&= \text{VALW} \bullet \text{FIM} \bullet \text{EXP}(-\text{RDP}\bullet\text{TH}) \bullet \text{EXP}(-\text{RIR}\bullet\text{TH}) \\
&+ \text{VALW} \bullet (1.0 - \text{FIM}) \bullet \text{EXP}(-\text{RIR}\bullet\text{TH}) \\
&= \text{VALW} \bullet [(1.0 - \text{FIM}) + \text{FIM} \bullet \text{EXP}(-\text{RDP}\bullet\text{TH})] \\
&\quad \bullet \text{EXP}(-\text{RIR}\bullet\text{TH}).
\end{aligned} \tag{4.8}
$$

By substituting Equation (4.8) into Equation (4.4), the unit compensation cost of interdiction of nonfarm property can then be derived as follows:

$$
\begin{aligned}
\text{CC} &= \text{VALW} - \text{VALWP} \\
&= \text{VALW} - \text{VALW} \bullet [(1.0 - \text{FIM}) + \text{FIM} \bullet \text{EXP}(-\text{RDP}\bullet\text{TH})] \bullet \\
&\qquad \text{EXP}(-\text{RIR}\bullet\text{TH}) \\
&= \text{VALW} \bullet \{1.0 - [(1.0 - \text{FIM}) + \text{FIM} \bullet \text{EXP}(-\text{RDP}\bullet\text{TH})] \bullet \\
&\qquad \text{EXP}(-\text{RIR}\bullet\text{TH})\}
\end{aligned} \tag{4.9}
$$

The values of VALW and FIM are specified by the user as input data for nonfarm property. The values for RDP and RIR are user-supplied and apply to both farm and nonfarm property. The time at which the nonfarm property is restored to habitability, TH, is calculated by the MACCS code in the determination of the necessary protective actions. For example, if decontamination alone is sufficient to restore habitability, TH is the end of the decontamination period. If decontamination is not sufficient, TH, is the end of the decontamination period plus the additional time during which property usage is prohibited. See Section 5.3.1 for more detail.

By substituting Equation (4.9) into Equation (4.3), the cost of restoring habitability, CNF, for nonfarm property can then be obtained.

4.3.2 Costs Resulting from Restoring Habitability and Farm Production of Farm Properties

Similar to the nonfarm property, decontamination with interdiction, or decontamination without interdiction, may be required to restore habitability for farm property within any spatial element.

When the surface contamination of farmland is sufficiently high to exceed the maximum allowable ground concentrations, it may be deemed necessary to restrict farm production on that farmland until such time that the ingestion dose criteria can be met (see Section 5.3.3). The number of years the farmland in a spatial element is withheld from production determines the cost of this action. Whenever the period of prohibition exceeds eight years (hard-wired value), the farm areas are automatically condemned.

In the MACCS code, it is assumed that the farm property needs to be habitable in order to perform farming activity. Therefore, farm property needs to satisfy both the habitability criterion and the maximum allowable ground concentration criteria in order to return to farm production.

Since MACCS assumes that farmland is unpopulated, the cost of restoring habitability and farm production for farm property is the sum of the cost of the actual decontamination efforts and the cost incurred as a result of the loss of usage of the farm property. That is,

$$CF = CD + CC \tag{4.10}$$

where

- CF = unit cost of restoring habitability and farm production for farm property (\$/hectare),
- CD = unit cost of decontamination (\$/hectare for farm property), and
- CC = unit cost of compensation as a result of loss of usage of the property (depreciation, deterioration, and losses) (\$/hectare for farm property).

The costs incurred for decontamination of farm property, CD, are user-supplied.

The unit cost of compensation as a result of loss of usage of the farm property during the period of interdiction is calculated in a similar way as the nonfarm property in Equation (4.9). That is,

$$CC = VALW \bullet \{1.0 - [(1.0 - FIM) + FIM \bullet EXP(-RDP \bullet TF)] \bullet EXP(-RIR \bullet TF)\} \tag{4.11}$$

where

- VALW = unit value of wealth for farm property in the region (includes the cost of the land, building, infrastructure, and any non-recoverable equipment or machinery (\$/hectare)),
- FIM = fraction of the wealth for farm property in the region resulting from improvements (unitless),
- RDP = depreciation rate (s^{-1}),
- TF = time (s) at which the farmland is returned to habitability and farm production, and
- RIR = inflation adjusted rate of investment return (s^{-1}).

The values of VALW and FIM are specified by the user as input data for farm property. The time at which the farm property is restored for habitability and farm production, TF, is the larger of two time periods: (1) time at which the farmland is habitable (see Section 5.3.1), and (2) time at which the farmland is suitable for farm production (see Section 5.3.2).

By substituting Equation (4.11) into Equation (4.10), the cost of restoring habitability and farm production for farm property, CF, can then be obtained.

4.3.3 Costs Resulting from Disposal of Growing Season Crops

The model for growing season crops disposal estimates the costs of milk and other crop disposal that would be required following a reactor accident. These costs are associated with the current growing season crops and assessed only if the accident occurs during the growing season. See Section 5.3.2 for a more detailed discussion of crop disposal protective actions. If crop disposal is deemed necessary, it is required by MACCS that milk be discarded for a period of three months and that disposal of other crops occurs in a manner which discards any crop growing at the time of the accident. The three month time period used for milk disposal is based on the assumption that the growing season is about six months long, and if an accident were to occur during the growing season the average time of occurrence would be at the middle of the growing season. For the remainder of the year, milk cattle are fed on stored feed.

The unit cost of milk disposal within any spatial element, CMD, is calculated as follows:

$$CMD = FP \bullet FDP \bullet FMD \tag{4.12}$$

where

CMD = unit cost of milk disposal in the spatial element considered ($/hectare),
FP = average annual farm production value ($/hectare),
FDP = fraction of annual farm production value which comes from dairy farm production (dimensionless), and
FMD = fraction of the year over which milk disposal occurs (dimensionless).

The values of FP and FDP are user-supplied input data. the value of FMD is hard-wired and equal to 0.25, that is, milk disposal occurs for three months of a year.

The unit cost of disposal of non-milk crops in a spatial element, CNMD, is calculated as follows:

$$CNMD = FP \bullet (1 - FDP) \qquad (4.13)$$

The variables are as described above in Equation (4.12). The value of (1 - FDP) represents the fraction of annual farm production which comes from non-dairy crops.

4.3.4 Costs Resulting from Condemning Farm or Nonfarm Property

If the farm or nonfarm property is condemned, the cost of condemning the property is calculated. Section 5.3.1 discusses how to determine whether or not to condemn a farm or nonfarm property using the habitability criteria and Section 5.3.3 discusses how to determine whether or not to condemn a farmland using the maximum allowable ground concentration.

The per person cost to condemn nonfarm property, CCNF, is the sum of the cost to relocate that individual and the per person value of nonfarm wealth for the region. That is,

$$CCNF = CR + VALW \qquad (4.14)$$

where CR is the unit cost of relocating an individual ($/person) as defined in Equation (4.3) and VALW is the unit value of wealth for nonfarm property ($/person) as defined in Equation (4.4).

Since MACCS assumes that the farmland is unpopulated, the per unit area cost to condemn farm property, CCF, is the unit value of the farm wealth for the region. That is,

$$CCF = VALW \qquad (4.15)$$

where VALW is the unit value of wealth of the farm property ($/hectare) as defined in Equation (4.11).

5.0 MITIGATIVE ACTIONS AND DOSE ACCUMULATION

The accumulation of doses to individuals affected by a nuclear power plant accident must take into account the location of these individuals during and following the accident, as well as the time period during which the doses were received.

Actions to mitigate the effects of a release of radioactivity during a reactor accident can have a significant impact on accident consequences. Mitigative actions are protective measures designed to reduce radiation exposures, public health effects, and thereby result in economic costs from an accident. These actions include evacuation, sheltering, temporary relocation, disposal of contaminated crops, decontamination, temporary interdiction, condemnation, and restricting crop production.

The period over which these mitigative actions can occur is divided by MACCS into three phases: emergency phase, intermediate phase, and long-term phase.

Individuals residing in the grid elements surrounding the accident site, i.e., the direct cohort, can receive early doses from cloudshine, groundshine, cloud inhalation, deposition to the skin, and resuspension inhalation. These same individuals can receive long-term doses from groundshine and resuspension inhalation.

Evacuation, sheltering, and temporary relocation are associated with the emergency phase or time period immediately preceding and following the accident and are generally called emergency response actions. Plans for emergency response are the basis for radiological emergency preparedness programs in the United States. The emergency response models for evacuation, sheltering, and temporary relocation utilized in MACCS are described in Section 5.1.

After the emergency phase, the intermediate phase begins. During this phase, only one protective measure is considered: temporary relocation of people. This action is taken if the projected dose during the intermediate phase exceeds some dose limit specified by the user. Section 5.2 discusses the intermediate phase protective actions and dose accumulation.

Crop disposal, decontamination, temporary interdiction, condemnation, and restricted crop production are employed in the period following the intermediate phase, the long-term phase, and are generally called long-term actions. Models of each of these long-term actions are included in MACCS. The goal is to reduce the long-term public health effects for both direct and indirect cohorts. The actions of temporary relocation, decontamination, and temporary interdiction are aimed at controlling long-term radiation exposure from groundshine and resuspension inhalation for the people who reside in the region surrounding the accident site. The actions of crop disposal and of restricting the production of crops are aimed at controlling long-term radiation exposure from ingestion of contaminated food by people who consume food produced in the region surrounding the accident site. These long-term mitigation models of extended relocation, decontamination, temporary interdiction, crop disposal, and restricted crop production are described in Section 5.3.

5.1 Emergency Phase

The MACCS model of emergency response represents an extensive revision of the corresponding Reactor Safety Study [US75] model. For a given MACCS calculation, the user could specify up to three different emergency response strategies or scenarios and their corresponding weighting fractions. These weighting fractions could be specified as fractions of the people or fractions of the time and are summed to 1.0. The EARLY module is executed and the results are presented for each of the scenarios. The weighted sum of different emergency scenarios is then calculated for each early consequence measure using the specified weighting fractions.

For a given emergency response scenario, up to three different types of protective measures could be specified by the user: evacuation, sheltering, or temporary relocation. The emergency response model of MACCS has the capability of using an inner sheltering zone, up to three evacuation zones, and an outer sheltering zone. Figure 5.1 shows the schematic of different emergency response zones.

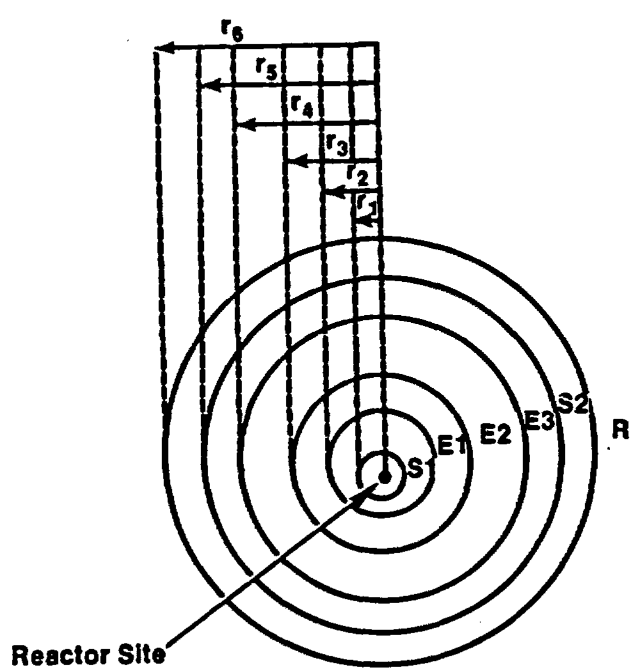


Figure 5.1 Schematic of Emergency Response Zones

The distance r_1 is the exclusion area boundary of the reactor site. The temporary relocation protective measure applies to all the spatial elements outside the evacuation or sheltering zone. The spatial elements of different protective measures shown in Figure 5.1 are defined as follows:

inner sheltering zone S_1: between r_1 and r_2
evacuation zone 1, E_1: between r_2 and r_3
evacuation zone 2, E_2: between r_3 and r_4
evacuation zone 3, E_3: between r_4 and r_5
outer sheltering zone S_2: between r_5 and r_6
relocation zone R: greater than r_6

The existence of an evacuation or sheltering zone is optional. For example, the user can define a scenario in which neither evacuation nor sheltering takes place anywhere in the region. For this case, temporary relocation applies to all spatial elements of the entire region.

A set of shielding factors is specified by the user for each of the three groups of people, evacuees, people taking shelter, and people continuing normal activity. The shielding factors are cloudshine shielding factor, groundshine shielding factor, inhalation shielding factor, and skin shielding factor. These shielding factors (less than or equal to 1.0) are used as multipliers in the dosimetry calculations for the corresponding pathways discussed in Section 3.1 to reduce the doses according to the protective measures taken at different times.

In deriving these user specified shielding factors, assumptions need to be made regarding the structural materials of buildings in the region of interest, the fraction of time people would be outdoors versus indoors, etc. Since shielding factors are used to reduce the calculated doses as linear scaling factors between 0 and 1.0, the smaller the shielding factor value, the better the protective measure. Typical relations among these shielding factors are:

$$1.0 \geq \text{shielding factors (evacuees)} \geq \text{shielding factors (normal activity)} \geq \text{shielding factors (sheltering)} \geq 0.0. \quad (5.1)$$

5.1.1 Evacuation

Warning times for an impending significant release of radioactive material could vary from essentially none to several hours. Depending on the accident scenario and the distance from the reactor, several more hours might pass before the released plume would reach a particular population group, depending on the windspeed following the release. Because of this available time, evacuation is given considerable attention as a public protective measure in most current radiological emergency preparedness programs in the United States. Evacuation is potentially the most effective method of avoiding radiation exposure and can provide total protection if completed prior to arrival of the plume.

The MACCS evacuation model incorporates a delay time before public movement, followed by evacuation radially away from the reactor at an effective radial constant speed. Different shielding factors and breathing rates can be used while evacuees await evacuation (normal activity) or are being evacuated (evacuees).

The user can specify up to three evacuation zones. Each evacuation zone has its own user-specified delay time before evacuation start. The evacuating people within the designated evacuation zone are assumed to move as a group after the specified delay time. However, all evacuees of the three zones have the same evacuation speed as specified by the user. Evacuating people are assumed to move to a user-specified distance (e.g., 20 miles) from the reactor site at which further exposure from the plume is assumed to be avoided. This model is similar to the one used in the Sandia Reactor Siting Study [A181].

If the plume did not pass over a given spatial element in an evacuation zone, it is as if those individuals in the spatial element are not evacuated. If the plume did pass over the spatial element of the evacuees, the evacuees might be moved back to their original spatial element at the end of the emergency phase specified by the user (for example, 7 days after the plume arrival). Whether the evacuees would be moved back or not depends on the habitability criterion evaluated by the CHRONC module (see Sections 5.2 and 5.3.1). Therefore, as far as dose accumulation is concerned, no further radiation doses to the evacuees are calculated by the EARLY module. Any additional radiation doses to the evacuees are calculated by the CHRONC module.

Before the evacuating people start moving, they are assumed to be in normal activity. Shielding factors (cloudshine, groundshine, inhalation, and skin) for normal activity apply to them during this period of time. After they start moving, they become evacuees and the shielding factors for evacuees apply to them during evacuation.

The MACCS plume transport model assigns the plume a finite length calculated using the assumed release duration and wind speed during the release (see Section 2.5). To simplify the treatment, the length of the cloud is assumed to remain constant following the release (i.e., the front and back of the plume travel at the same speed), and the concentration of radioactive material is assumed to be uniform over the length of the cloud. The radial position of evacuating persons, while stationary and while in transit, is compared to the positions of the front and back of the plume as a function of time to determine the period of exposure to airborne radionuclides.

MACCS accumulates the radiation doses for the evacuating people by adding the doses they received before they started moving and the doses received during evacuation out to a distance whereupon they are assumed to avoid further exposure.

5.1.2 Population Sheltering

In this model, the nonevacuating people residing within a sheltering region are exposed to radiation using the shielding factors defined for the sheltering region. Sheltering, as used by this emergency response model, is defined as the deliberate action by the public to take advantage of the protection against radiation exposure afforded by remaining indoors and away from doors and windows during and after the passage of the radioactive plume.

The shielding inherent in normally inhabited structures offers some degree of protection against external penetrating radiation from airborne and surface-deposited radionuclides. Furthermore, the exclusion of a significant amount of airborne radioactive material from the interior of a structure, either by closing windows and/or air circulation systems, can reduce the amount of inhaled radionuclides as well.

For the sheltering protective measure, the user specifies a sheltering delay time (from the alarm time) and the sheltering duration time [Ch89]. Before people take shelter by going indoors and closing windows, these people are assumed to be at normal activity and the shielding factors of normal activity apply to them during this period of time. After they take shelter, the shielding factors of sheltering apply to them for the duration of the sheltering period. MACCS accumulates the radiation doses by adding the doses they received before they take shelter and the doses received during the sheltering time. After the sheltering time, these people are assumed to be removed from their spatial element and no further exposure is calculated by the EARLY module.

If the plume passed over the spatial element, shelterees might be moved back to their original spatial element at the end of emergency phase (e.g., 7 days). Whether or not the shelterees would be moved back depends on the habitability criterion evaluated by the CHRONC module (see Sections 5.2 and 5.3.1). Therefore, as far as dose accumulation is concerned, any additional doses to the shelterees are calculated by the CHRONC module.

5.1.3 Population Relocation

Population relocation is defined in this emergency response model to be temporary relocation of nonevacuating people following deposition. The model provides two alternatives for temporary relocation (hot-spot relocation and normal relocation) at a user-specified time after plume arrival, each conditional on a projected dose from cloudshine, groundshine, cloud inhalation, and resuspension inhalation that exceeds a user-specified limit.

Population relocation is a post-accident protective measure designed to limit radiation exposure from radionuclides deposited on the ground and other surfaces. Since temporary relocation is a post-accident response, it can be implemented in a more selective manner than an immediate evacuation. In many instances, external exposure to contaminated surfaces would, in a relatively short time, result in a dose much greater than the dose from cloudshine and inhalation exposure pathways.

The user can specify a hot-spot relocation criterion and a normal relocation criterion. For both relocation criteria, the user specifies a dose limit, the critical organ for the dose limit, and a relocation time [Ch89]. For example, a dose criterion of 0.25 Sv effective whole body dose equivalent (EDE) [IC78] in one week and a relocation time of 24 hours after plume arrival are used for the normal relocation and 0.5 Sv EDE in one week and a relocation time of 12 hours after plume arrival are used for the hot-spot relocation.

For evaluating the need for normal and hot-spot relocation, the dose commitment received from the sum of the following pathways are considered: cloudshine and inhalation doses during plume passage, projected groundshine dose for the duration of emergency phase, and resuspension inhalation dose for the duration of emergency phase. The lifetime dose commitment is used for both types of inhalation dose.

The relocating people are assumed to be in normal activity before they leave their spatial element. The shielding factors for normal activity apply to them for the period of time before they are relocated (e.g., 24 hours after plume arrival for normal relocation). Once they are relocated, no further dose is calculated for them by the EARLY module. Additional doses for them could be calculated by the CHRONC module. The criterion for determining whether or not they would be moved back to their original spatial element depends on the habitability criterion evaluated in CHRONC (see Sections 5.2 and 5.3.1).

5.1.4 Dose Accumulation of Emergency Phase

As far as dose accumulation during the emergency phase is concerned, the key parameter is the duration of exposure for people originally residing in each of spatial elements in the entire region.

Before performing dose accumulation for people, MACCS determines t_1, the time that people enter a given spatial element, and t_2, the time that people leave that spatial element. This is done for each spatial element of the entire region. The time duration spent by people in a given spatial element equals $(t_2 - t_1)$. This time duration could be normal activity before evacuation or traveling time through a spatial element. For each spatial element, MACCS also determines the time that plume enters a given spatial element t_e and the time that plume leaves that spatial element t_o.

MACCS then calculates the dose accumulation for each organ during the emergency phase as follows.

The dosimetry equations for cloudshine and inhalation during plume passage, groundshine during and after plume passage, resuspension inhalation after plume passage, and skin dose during plume passage are described by (3.3), (3.4), (3.10), (3.11), (3.12), and (3.14), respectively. For each of these pathways, the dose received by an individual during the exposure time between t_1 and t_2 from each spatial element that he or she entered is first calculated using the corresponding equation. If the plume never entered a spatial element, the radiation dose from that spatial element would be zero for all pathways during the emergency phase.

During the emergency phase, two types of doses are calculated for the on-grid populations: the acute doses and the life-time doses (50-year dose commitments). The acute and life-time doses are calculated for a representative individual of a spatial element. The population dose for the on-grid populations is calculated by multiplying the individual dose by the number of people in a spatial element. The total population dose is the sum of population doses over all spatial elements.

The acute doses are used to calculate the early health effects (e.g., early fatalities and early injuries). The life-time doses are used for calculating the delayed (latent) health effects (e.g., cancer fatalities). See Chapter 6 of this report for more detail.

As discussed in Section 3.1.1, doses of early exposure pathways are calculated for each fine spatial element (r,m), where r is the radial interval number and m is the fine angular division number from the plume centerline. To calculate the dose to an organ received by the population of a fine spatial element, the dose to that organ received by that population group must be summed over all exposure pathways, over all plume segments that cause exposures in the population group, and over all locations where the group receives exposures (only evacuees receive dose at more than one location). Since MACCS approximates the crosswind distribution of plume segments using a histogram, all doses also depend on the off-centerline position where they are received. (See Section 3.1.1).

To express all of these dependencies mathematically, the dose to organ k of a population cohort located at a fine spatial element (r,m) must be expressed as a sum over nuclides i, plume segments n, and exposure pathways (cloudshine, cloud inhalation, groundshine, and resuspension inhalation). Thus, the dose to organ k of a population cohort in a fine spatial element (r,m) from plume segment n is given by

$$D_{krmn} = DC_{krmn} + DI_{krmn} + DG_{krmn} + DR_{krmn} \tag{5.2}$$

where DC is the cloudshine dose, DI is the dose caused by inhalation of materials directly from the passing plume segment, DG is the groundshine dose, and DR is the dose caused by inhalation of materials resuspended from the ground (see Section 3.1). Dose from materials deposited on skin is not included in this sum because radioactive materials deposited on the skin are assumed to deliver significant doses only to the skin and not to any other organ.

Equation (5.2) sums over exposure pathways. Since it is assumed that evacuation proceeds radially outward, to calculate the total dose received by a population cohort that receives dose at more than one location (evacuees only), the dose delivered at each radial interval number r where exposures are incurred must be summed:

$$D_{kmn} = \sum_{r} D_{krmn} \tag{5.3}$$

Finally, the total dose to organ k received by a representative member of cohort in a spatial element is obtained by summing the doses delivered to cohort by separate plume segments:

$$D_{krm} = \sum_{n} D_{krmn} \tag{5.4}$$

5.2 Intermediate Phase

The intermediate phase begins at the end of emergency phase specified by the user. The time period for the intermediate phase is specified by the user (e.g., 60 days). During the intermediate phase, only one mitigative action can be applied: temporary relocation of people.

The dose criterion and the critical organ used to determine the need for the intermediate phase mitigative action is specified by the user. For example, 0.05 Sv EDE may be the dose criterion. This criterion is compared against the sum of the projected groundshine dose and the projected resuspension inhalation dose during the intermediate phase. If the intermediate phase dose criterion is exceeded at a spatial element, all people in that spatial element are relocated for the duration of intermediate phase. At the end of the intermediate phase, the long-term habitability criterion is used to determine whether or not these people would be moved back to their original spatial element (see Section 5.3.1).

The user has the option of not specifying the intermediate phase and only specifying the long-term phase following the emergency phase. If the intermediate phase is not specified, the long-term phase begins at the end of the emergency phase.

Dose accumulation during the intermediate phase is performed if the people in a spatial element are not relocated. The pathways considered are groundshine dose and resuspension inhalation dose. The dose to organ k of a population in a spatial element is the sum of groundshine dose in Equation (3.17) and resuspension inhalation dose in Equation (3.20). The integration time period used in calculating these doses is the intermediate phase time period.

5.3 Long-Term Phase

The long-term phase begins at the end of intermediate phase if specified or at the end of emergency phase if the intermediate phase is not specified. Mitigative actions during the long-term phase depend on the projected doses received by the people, the pathways by which the doses are received, and the cost effectiveness of mitigative actions.

During the long-term phase, two types of pathways are considered for mitigative actions and dose accumulation: (1) direct doses or habitation doses from groundshine and resuspension inhalation (inhalation dose from inhaling resusupended particles from the ground) and (2) ingestion of food crops and milk produced from contaminated ground. No mitigative action for drinking water is considered in MACCS. Therefore, the dose accumulation for the drinking water pathway discussed in Section 3.2.5 need not be modified.

Actions taken as a response to excessive doses from groundshine and resuspension inhalation are aimed at reducing these doses so that people may remain in or return to their areas of residence (original spatial elements) within some time period. These actions include a combination of decontamination and temporary interdiction.

Actions could also be taken to limit the doses from the ingestion pathways. These include disposal of milk or food crops and restricting the use of farmland to grow food crops.

Section 5.3.1 discusses mitigative actions and dose accumulation for the long-term groundshine and resuspension inhalation doses. Section 5.3.2 discusses the worker doses for performing decontamination of non-farm properties. Section 5.3.3 discusses mitigative actions and dose accumulation for the long-term food pathways mitigative actions and dose accumulation. Section 5.3.4 discusses the work doses for performing decontamination of farmland.

5.3.1 Long-Term Habitation Doses

The long-term habitation dose is defined as the sum of long-term groundshine dose and resuspension inhalation dose. The need for mitigation of the long-term habitation exposure pathways is determined by examining the projected long-term doses from groundshine and resuspension inhalation (the sum of the groundshine and resuspension inhalation doses is called projected habitation dose). The chronic model requires mitigative actions whenever the projected habitation dose to the critical organ defined by the user exceeds the specified dose criterion for that organ in the time period of interest. Typically, this is defined by the user to be the effective whole body dose equivalent (EDE). A lifetime dose commitment period of 50 years is used for calculating the resuspension inhalation dose.

During the long-term 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 temporary interdiction of land and property for some period of time after decontamination until the property is restored to habitability; (3) permanent interdiction (condemnation) with removal and resettling of people.

5.3.1.1 Decontamination and Temporary Interdiction

The decision on whether the people residing in a given spatial element could return after temporary relocation or evacuation depends on the habitability criterion and cost effectiveness of protective actions such as decontamination and temporary interdiction. The habitability criterion is a dose limit to a critical organ within a specified time period. Both of these quantities and the critical organ name are user specified. An example of habitability criterion is 0.04 Sv EDE within a period of five years.

Two protective measures are considered for habitability: decontamination only and combination of decontamination and temporary interdiction. The decontamination model allows for decontamination strategies to be defined in terms of their effectiveness and cost. Each decontamination strategy is called a decontamination level and represents an alternative means to reduce the projected habitation dose by a factor called the decontamination factor. Decontamination levels are defined starting with the smallest effort and continuing to the most intense effort. Up to three different levels of decontamination and their corresponding decontamination factors could be specified by the user.

The decontamination goal is to reduce the habitation doses below the long-term dose criterion using the minimal decontamination effort that would be successful. Decontamination of a grid element serves to reduce the groundshine and resuspension doses of individuals living there by the dose reduction factor of the required decontamination strategy. For the duration of the decontamination period, the population is assumed to be relocated to an area free from radioactivity. If the decontamination measure fails to meet the dose limit, temporary interdiction is then evaluated.

Based on a dose projection over a user-specified period of time beginning at the end of the intermediate phase period, the code determines if a given spatial element is immediately habitable. A spatial element is considered to be habitable if the projected dose commitment to the critical organ for a user-specified time period does not exceed a user specified dose limit. If a spatial element is immediately habitable, the resident population is assumed to be present for the entire long-term phase period and no mitigative actions are taken to limit their exposure. The exposure pathways considered are groundshine and resuspension inhalation.

If the evaluation of the long-term phase dose criterion determines that the spatial element is not immediately habitable, it is necessary to take mitigative actions in order to assure that the criterion is not exceeded. The mitigative actions are evaluated in a predetermined sequence in order to select the least stringent action which will allow the dose criterion to be satisfied. The order of these actions is: (1) decontamination alone (up to three levels of decontamination can be specified by the user), (2) maximum level of decontamination followed by an interdiction period, and (3) permanent interdiction (condemnation) of the property.

The various levels of decontamination are evaluated in the order of their increasing effectiveness. That is, up to three different levels of decontamination can be evaluated beginning with the least effective and ending with the most effective decontamination level. The effectiveness of each level of decontamination is specified by the user as a dose reduction factor. The dose reduction factors specify the ratio by which the contamination level is reduced as a result of the decontamination process. For example, a dose reduction factor of three indicates that two-thirds of the radioactive material is removed as a result of the decontamination process. A given level of decontamination is considered to restore habitability if the projected dose over the projection period does not exceed dose limit.

The projection period in all cases starts at the time of prospective return of the resident population. For the case of decontamination alone, the projection period begins at the time when the decontamination process has been completed. The completion time of decontamination may be different for each different level of decontamination and all the relevant parameters are user-specified.

If the maximum level of decontamination by itself is not sufficient to restore habitability, a period of interdiction following the maximum level decontamination effort is evaluated to determine if the habitability criterion can be thereby satisfied. During the interdiction period, radioactive decay and weathering serve to reduce the contamination level over time. Based on dose projections beginning at 1, 5, and 30 years following deposition, a log-linear interpolation technique is used to estimate the time at which the element will satisfy the habitability criterion. These three time steps, namely 1, 5, and 30 years, are currently hard-wired in the MACCS code.

The log-linear interpolation is based on the assumption that the dose to the population following a period of interdiction follows a pattern of exponential decay as a function of time. The interpolation is linear on time and logarithmic on dose.

For temporary interdiction, the dose projection period begins at the time of the population's prospective return. The longest possible period of temporary interdiction is 30 years. If that is insufficient, the property is then automatically condemned. Please note that the interdiction model described here may select an interdiction duration of up to 30 years but an evaluation of its cost-effectiveness (Section 5.3.1.2) may determine that such an action would not take place. If the cost of interdiction and decontamination exceeds the cost of condemning the property, the property would be condemned instead of being interdicted.

5.3.1.2 Cost Effectiveness

To evaluate the cost effectiveness of decontamination or decontamination following temporary interdiction of nonfarm areas, the following steps are used in MACCS:

1. If a spatial element is condemned permanently according to the habitability criterion, the people originally residing in that element never return. The cost of condemnation is calculated for that spatial element. Cost effectiveness is not evaluated.

2. If a spatial element is not permanently condemned and the cost of decontamination and temporary interdiction of the property is less than the cost of condemning the property, then people residing in the spatial element are allowed to return after the interdiction period.

3. If a spatial element is not permanently condemned and the cost of decontamination and temporary interdiction of the property is greater than or equal to the value of the property, then the property is condemned permanently.

Decontamination cost of nonfarm areas is specified by the user (see Equation (4.3)). Temporary interdiction cost includes the cost of depreciation and loss of use of the properties during the time period that their usage was prohibited (Equation (4.9)).

5.3.1.3 Dose Accumulation

If the decontamination at level ℓ (ℓ = 1, 2 or 3) is sufficient to meet the habitability criterion, people originally residing in a given spatial element are assumed to move back at the end of decontamination period at level ℓ. The dose accumulation is calculated by adding the long-term groundshine dose in Equation (3.17) and long-term resuspension inhalation dose in Equation (3.20) together and dividing by the decontamination factor $DECON_\ell$. The integration times in Equations (3.18) and (3.21) for the long-term phase are defined as t_1 being the time that people return after decontamination is completed and t_2 being t_1 + one million years. For all the radionuclides considered in MACCS, their half lives are small compared to one million years. Therefore, the integration is effectively to an infinite time.

If the maximum decontamination effort fails to meet the dose criterion for immediate habitation and some temporary interdiction is cost effective to meet the habitability criterion, the dose accumulation is calculated by adding Equations (3.17) and (3.20) together and dividing by the maximum decontamination factor allowed, $DECON_{max}$, for dose reduction. For this case, the integration times in Equations (3.18) and (3.21) are defined as follows: t_1 is TDECON, the time people return to their original spatial element, and t_2 is t_1 + one million years.

5.3.2 Nonfarm Properties Decontamination Worker Dose

Decontamination workers engaged in the clean-up effort of nonfarm properties receive groundshine doses. Since the decontamination workers are assumed to wear respirators, their inhalation doses are not calculated in MACCS. These worker doses in a spatial element are calculated for the duration of decontamination at decontamination level ℓ:

$$DWNF_k = \sum_i GC_i \cdot DFG_{ik} \cdot NUMW_\ell \tag{5.5}$$

where

- $DWNF_k$ = worker population dose (persons-Sv) to organ k for performing nonfarm decontamination,
- GC_i = initial ground concentration of nuclide i in the spatial element (Bq/m^2),
- DFG_{ik} = groundshine dose factor of nuclide i to organ k for decontamination workers during the time period of performing decontamination ($Sv\text{-}m^2/Bq$), defined below, and
- $NUMW_\ell$ = number of workers required to perform level ℓ decontamination (persons).

The groundshine dose factor, DFG_{ik}, is calculated using Equation (3.18) with the integration time period being the time period of decontamination performance.

$NUMWV_\ell$ is calculated using the following equation:

$$NUMW_\ell = CSTDNF_\ell \cdot POPN \cdot FLBNF_\ell \,/\, \left(LBCST \cdot TIMD_\ell\right) \tag{5.6}$$

where

- $CSTDNF_\ell$ = level ℓ decontamination cost of nonfarm property in a spatial element (\$/person),
- POPN = number of persons in a given spatial element (persons),
- $FLBNF_\ell$ = fraction of nonfarm level ℓ decontamination cost is from labor at,
- LBCST = labor cost (\$/worker-s), and
- $TIMD_\ell$ = time required to perform level ℓ decontamination (s).

All the quantities on the right hand of Equation (5.6) are user-specified.

5.3.3 Long-Term Ingestion Doses

Radiation doses can result from the ingestion of contaminated food or water by the population at large. All food pathways are subject to mitigative actions. However, the water pathway model does not provide for any mitigative action to limit or prohibit the ingestion of contaminated water.

Three mitigative actions that affect the food ingestion pathway are modeled in MACCS: (1) the removal of farmland from production when the land is uninhabitable for any length of time, that is, temporary interdiction because of projected long-term groundshine and resuspension inhalation dose; (2) the temporary or permanent removal of farmland from production when the ground is too contaminated to grow crops on a long-term basis when user-established criteria are exceeded; (3) the disposal of contaminated milk and/or nonmilk crops for accidents during the growing season when user-established criteria are exceeded.

A fundamental constraint on food production in contaminated areas is that the land must be habitable for it to be farmable. Please refer to Section 5.3.1 for a discussion of the requirements for habitability.

5.3.3.1 Restricted Farmland Production

When farmland is immediately habitable at the beginning of the long-term phase, a need may exist for mitigation to restrict long-term production on farmland where the ground concentrations are too high. The allowable ground concentrations for long-term production are defined as variable $GCMAXR_i$ in the CHRONC User input data [Ch89].

In each grid element, the ratio of the actual surface concentrations to the permissible surface concentrations for each nuclide for long-term production is used for deciding whether to restrict long-term farm production. An overall ratio for any spatial element is calculated as the sum of ratios for the individual nuclides. That is,

$$RS = \sum_i \left\{ GC_i \bullet EXP(-\ YRS \bullet \lambda_i) \ /\ GCMAXR_i \right\} \tag{5.7}$$

where

- RS = sum of ratios of surface concentrations of all nuclides over the grid element considered,
- λ_i = weathering and radiological decay constant of nuclide i (yr^{-1}), user-specified input data as QROOT,
- GC_i = initial ground concentration of nuclide i in the spatial element being considered (Bq/m^2),
- YRS = number of years (an integer) during which the farmland production in that spatial element will be prohibited (yr), and
- $GCMAXR_i$ = user-specified maximum allowable ground concentration of nuclide i for long-term production (Bq/m^2).

The maximum allowable ground concentrations for long-term farmland production, $GCMAXR_i$, of all radionuclides considered in food pathway dose are user-specified. These values are derived using a dose criterion for the long-term farmland production. A detailed discussion on how $GCMAXR_i$ may be derived is included in Appendix C.

The value of RS in Equation (5.7) is calculated by setting the value YRS to an integer number starting from zero and ranging up to eight. When the value of RS is greater than one, action is taken to restrict long-term production on the farmland within that spatial element. When the value of RS is less than or equal to one, the corresponding integer value of YRS is the minimum number of years of restricting farm production, or MINYRS. The value of MINYRS is an integer between zero and eight (hard-wired value). If RS is greater than one for all integer values of YRS between zero and eight, the value of MINYRS is set to nine and the farmland is permanently condemned.

After the long-term farmland protective action is decided upon, that is, MINYRS is calculated using Equation (5.7), the next step is to see if the decontamination and temporary interdiction periods (MINYRS) of farmland are cost effective. The economic cost estimation models described in Section 4.3 are used to determine the cost effectiveness.

5.3.3.2 Cost Effectiveness

To be cost effective for decontamination of farmland or decontamination followed by temporary interdiction of farmland production, the following steps are used in MACCS:

1. If a spatial element is condemned permanently according to the habitability criterion (see Section 5.3.1) or the restriction of farmland production exceeds eight years (i.e., MINYRS greater than eight), farmland is assumed to be permanently condemned from crop production. The cost of farmland condemnation is calculated for that spatial element. Cost effectiveness is not evaluated.

2. If a spatial element is not permanently condemned (i.e. MINYRS is less than or equal to eight years) and the cost of farmland decontamination and temporary interdiction is less than the value of farm, then the farmland of that spatial element is allowed to return to production after a period of interdiction. This interdiction period is the larger one of two time periods: (1) the time that people return to their spatial element based on the habitability criterion (see Section 5.3.1.1), and (2) the time for the farmland to return to production, MINYRS.

3. If a spatial element is not permanently condemned and the cost of farmland decontamination and temporary interdiction is greater than or equal to the value of farm, i.e., it is not cost effective to allow the farmland to return to production, then the farmland is permanently condemned.

The economic cost models for farmland are discussed in Section 4.3.

5.3.3.3 Growing Season Crop Disposal

If the accident occurs during the growing season, an additional type of mitigative action is considered with the long-term actions described above. The action guides are specified by the user, and are defined in terms of a permissible surface concentration of each radionuclide separately and for both milk and the nonmilk pathways.

Growing Season Milk Disposal

Within each spatial element, the necessity for disposal of the milk crop is determined by using a milk dose ratio for each nuclide i as follows:

$$MDR = \sum_i \left[GC_i/PSCMLK_i\right] \tag{5.8}$$

where

MDR = milk dose ratio,
GC_i = initial ground concentration of nuclide i in the spatial element being considered (Bq/m^2), and
$PSCMLK_i$ = user-specified maximum permissible surface concentration of nuclide i for milk production (Bq/m^2).

When the milk dose ratio MDR exceeds a value of one, disposal of the milk crop will occur within that spatial element for one-fourth of a year. This is based on the assumption that the growing season is about one-half of a calendar year and on average that the accident would occur in the middle of the growing season if it does occur during the growing season. For any value of MDR less than one, there will be no disposal of the milk crop, and an ingestion dose can result from that spatial element. A derivation of $PSCMLK_i$ is included in Appendix C.

Nonmilk Crop Disposal

Within each spatial element, the necessity for disposal of the nonmilk crops is determined by using a nonmilk dose ratio for each nuclide i as follows:

$$NMDR = \sum_i \left(GC_i/PSCOTH_i\right) \tag{5.9}$$

where

$NMDR$ = nonmilk dose ratio,
GC_i = initial ground concentration of nuclide i in the spatial element being considered (Bq/m^2), and
$PSCOTH_i$ = user-specified maximum permissible surface concentration of nuclide i for nonmilk production (Bq/m^2).

When the nonmilk dose ratio NMDR exceeds a value of one, all nonmilk crops will be disposed of within that grid element for one growing season. For any value of NMDR less than one there will be no disposal of these crops, and an ingestion dose can result from that grid element. The derivation of $PSCOTH_i$ is included in Appendix C.

Coupled and Uncoupled Options of Growing Season Crop Disposal

The restriction of long-term farmland production is based on the maximum allowable ground concentration and is independent of the time in the year when the accident occurs. The disposal of growing season crops is evaluated only if the accident occurs during the growing season. To decide whether or not to dispose of the growing season crops, the user could choose either the COUPLED or UNCOUPLED option. For the COUPLED option, the decision on disposal of growing season crops is evaluated only if the farmland is not restricted for long-term production. For the UNCOUPLED option, the decision on disposal of growing season crops is independent of any restrictions for long-term production.

Figure 5.2 shows the logic diagram of the COUPLED option. In Figure 5.2, MDR and NMDR are the milk dose ratio and nonmilk dose ratio in Equations (5.8) and (5.9) and MINYRS is the minimum number of years for restriction of farmland production calculated by Equation (5.7). For the COUPLED option, the disposal of food crops for an accident during the growing season is automatically triggered if either of the following two conditions is met:

1. the land is not immediately habitable at the beginning of the long-term phase or

2. the restriction of farmland production is at least one year, that is, MINYRS $\geq$ 1.0.

If both of the above conditions are not true, the disposal of growing season milk and non-milk crops would be evaluated using Equations (5.8) and (5.9). Furthermore, it assumes that if both milk and nonmilk crops would be disposed of, the farmland production would be restricted for one year, even though the value for MINYRS calculated by Equation (5.7) is zero.

Figure 5.3 shows the logic diagrams for the UNCOUPLED options. In this option, the disposal of growing season food crops is totally independent of the restriction on long-term farmland production. That is, the growing season crops could be harvested even though farmland production of the same spatial element is prohibited in the following years. However, for the UNCOUPLED option, the disposal of growing season food crops is automatically triggered if the land is not immediately habitable. This is based on the assumption that if the farmland is not habitable, no crops could be produced.

5.3.3.4 Food Pathway Ingestion Dose Accumulation

If there is no restriction of farmland production, that is, MINYRS = 0 in Equation (5.7), or farmland interdiction time MINYRS is less than nine years, an ingestion dose can result from that spatial element.

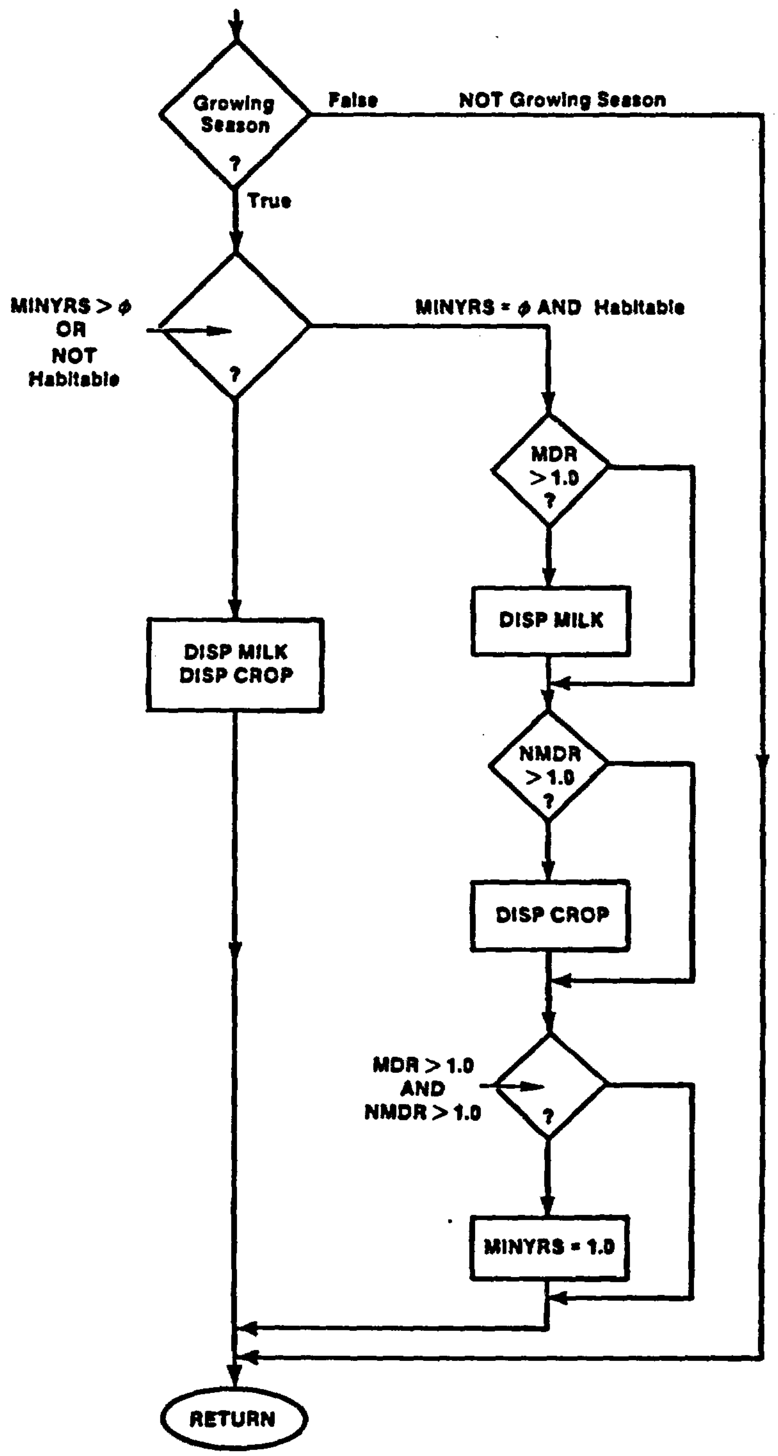


Figure 5.2 Logic Diagram of Growing Season Crop Disposal: COUPLED Option

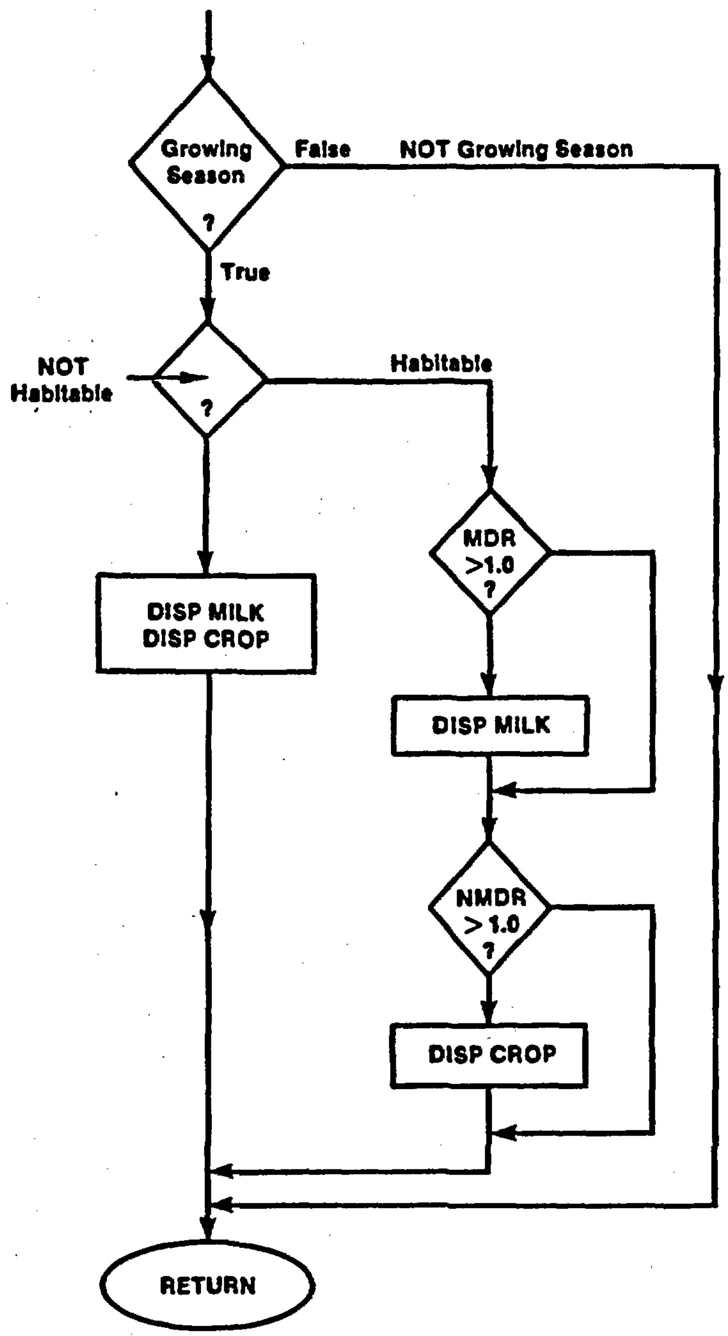


Figure 5.3 Logic Diagram of Growing Season Crop Disposal: UNCOUPLED Option

The long-term ingestion dose received from radionuclide i through root uptake and soil ingestion by animals is the product of the long-term transfer factor from the soil to man, the ground concentration in that grid element, the area in the grid element devoted to farming, a weathering term that reflects the losses from possible temporary interdiction, and the ingestion dose conversion factor. The dosimetry equation for ingestion pathway, Equation (3.23), is adjusted by multiplying by the weathering and radioactive decay which occurs during the temporary interdiction time period. The long-term dose commitment to any organ k is determined as follows:

$$DLT_k = \sum_i \left\{ EXP\left[-MINYRS \bullet \lambda_i\right] \right.$$

$$\left. \bullet \sum_j \left[TF_{ij} \bullet GC_i \bullet FA \bullet FAC_j \bullet DF_{ik}\right] \right\} \qquad (5.10)$$

where

- DLT_k = long-term ingestion population dose to organ k (Sv) from a spatial element,
- MINYRS = number of years during which temporary interdiction will occur (yr),
- λ_i = weathering and radiological decay constant for nuclide i (yr^{-1}), user-specified input data as QROOT,
- TF_{ij} = long-term overall transfer factor for radionuclide i to population via crop j, calculated by Equation (3.29); see Sections 3.2.3 and C-2,
- GC_i = initial ground concentration of radionuclide i in the spatial element being considered (Bq/m^2),
- FA = area of farmland contained in the spatial element being considered (m^2),
- FAC_j = user-specified fraction of the farmland area devoted to the growing of crop j, and
- DF_{ik} = ingestion dose conversion factor for nuclide i to organ k (Sv/Bq).

When there is no disposal of the growing season milk, the ingestion dose from the milk pathway during the first growing season will be calculated. The population dose to any organ k via the direct milk pathway during the first year is the sum of the doses received from all the food ingestion radionuclides. This dose is defined as follows:

$$DDM_k = \sum_i \left\{ GC_i \bullet DF_{ik} \bullet \sum_j \left[TF_{ij} \bullet FA \bullet FAC_j\right] \right\} \qquad (5.11)$$

where

DDM_k - growing season population ingestion dose to organ k (Sv) via milk pathway from a spatial element,

GC_i - initial ground concentration of nuclide i in the grid element being considered (Bq/m^2),

DF_{ik} - ingestion dose conversion factor for nuclide i to organ k (Sv/Bq),

TF_{ij} - overall transfer factor for crop nuclide pair (i,j), that is, the fraction of the material deposited on farmland during the growing season that will ultimately be consumed by man in the form of milk products, calculated by Equation (3.28),

FA - area of the farmland in the grid element being considered (m^2), and

FAC_j - fraction of the farmland area devoted to the growing of crop j, which, in this case, is the pasture.

When there is no disposal of the growing season nonmilk crops, the ingestion population dose from the nonmilk pathways during the first year will be calculated. The population dose to any organ k via the growing season nonmilk pathways during the first growing season will be the sum of the dose received from each of the food ingestion nuclides. It is defined as follows:

$$DDO_k = \sum_i \left\{ GC_i \bullet DF_{ik} \bullet \sum_j \left[TF_{ij} \bullet FA \bullet FAC_j \right] \right\} \tag{5.12}$$

where

DDO_k - growing season population ingestion dose to organ k (Sv) via nonmilk pathway from a spatial element,

TF_{ij} - overall transfer factor for crop-nuclide pair (i,j), that is, the fraction of the material deposited on farmland during the growing season that will ultimately be consumed by man in the form of nonmilk products, calculated by Equation (3.28), and

FAC_j - fraction of farmland area devoted to nonmilk crop j.

GC_i, FA, and DF_{ik} are the same as defined in Equation (5.11).

5.3.4 Farmland Decontamination Worker Dose

Decontamination workers engaged in the cleanup of farmland receive groundshine dose. These worker doses in a spatial element are calculated for the duration of decontamination at decontamination level ℓ:

$$DWF_k = \sum_i GC_i \bullet DFG_{ik} \bullet NUMW_\ell \tag{5.13}$$

where

- DWF_k - worker population dose to organ k for performing farmland decontamination (persons - Sv),
- GC_i - ground concentration of nuclide i (Bq/m^2),
- DFG_{ik} - groundshine dose factor of nuclide i to organ k for decontamination workers during the time period of performing decontamination ($Sv\text{-}m^2/Bq$), defined below, and
- $NUMW_\ell$ - number of workers required to perform farmland decontamination at level ℓ (persons).

The groundshine dose factor, DFG_{ik}, is calculated using Equation (3.18) with the integration time period being the period of decontamination performance.

$NUMW_\ell$ is calculated using the following equation:

$$NUMW_\ell = CSTDF_\ell \bullet FAREA \bullet FLBF_\ell \,/\, \left(LBCST \bullet TIMD_\ell\right) \tag{5.14}$$

where

- $CSTDF_\ell$ - level ℓ decontamination cost of farmland in a spatial element ($\$/m^2$),
- $FAREA$ - farmland area in a given spatial element (m^2),
- $FLBF_\ell$ - fraction of farmland level ℓ decontamination cost is from labor,
- $LBCST$ - labor cost ($/worker-s), and
- $TIMD_\ell$ - time required to perform level ℓ decontamination (s).

All the quantities on the right hand of Equation (5.14) are user-specified.

6.0 HEALTH EFFECTS MODELS

Release of radioactive materials to the atmosphere during the course of a severe reactor accident would cause downwind populations to be exposed to radiation. Both early fatalities (mortality) and injuries (morbidity) may occur in the exposed populations, if large exposures are delivered over short time periods. Persons who survive large exposures may later contract radiation induced delayed (latent) fatal or nonfatal cancers. Although small exposures or moderate exposures delivered at low dose rates are unlikely to cause early fatality or morbidity, they may induce latent fatal or nonfatal cancers in the exposed populations.

MACCS models the early mortality and morbidity and the latent cancers and cancer fatalities that would be caused by radiation exposures in the population, using models that are described in detail in [Ev85] and [Ev89]. The models presented in these reports provide estimates of the likelihood that an exposed individual may experience a specific health effect (e.g., lung impairment, breast cancer). After average individual risks have been estimated using the individual risk models, total cases of a specific health effect N_i are calculated in MACCS by multiplying the average individual risk r_i of experiencing an effect i by the number of people who receive similar dose that leads to the risk:

$$N_i = r_i f_i P \ , \qquad (6.1)$$

where

P = the total exposed population and
f_i = the fraction of the population that is susceptible to the risk r_i.

In MACCS, this equation is applied to the populations in individual spatial elements on the computational grid. Total cases of a health effect over the entire region covered by the grid are calculated by summing the results obtained for individual spatial elements.

This chapter describes the health effect risk models that are implemented in MACCS, and also discusses several approximations that are used to accumulate the doses received by exposed individuals. The models used to estimate risks of mortality or injury in the near-term are described first. Then the models used to estimate induced cancers and cancer fatalities are presented.[1]

6.1 Early Health Effects Models

The fatalities and injuries that result from substantial radiation exposures incurred during short time periods (usually within weeks,

1 A potential health effect, namely, the genetic effect in the succeeding generations due to radiation exposure of the parents is also discussed in [Ev89]. However, it is not modeled in MACCS.

though up to one year for pulmonary effects) are termed early health effects in MACCS. The early health effect risk models implemented in MACCS have sigmoid dependences of individual risk on dose to the target organ in an exposed individual. These models have the following form:

$$r = 1 - \exp(-H) \tag{6.2}$$

where, as recommended in [Ev89] the cumulative hazard H is expressed by a two-parameter Weibull function:

$$H = (\ell n\ 2) X^{\beta} \tag{6.3}$$

Ih Equation (6.3), X is a normalized and thus dimensionless, biologically effective dose (see quality factors below), and the exponent β is called a shape parameter, since it determines the steepness of the sigmoid dose-response curve. When the exposure that induces the health effect is delivered over a short time period (one day or less), the normalized dose X is computed as

$$X = D/D_{50} \tag{6.4}$$

where

- D = the biologically effective dose (Sv) delivered to the target organ, and
- D_{50} = the dose (Sv) that would induce the effect (impaired functioning of the target organ or fatality if the combined impairments are too large) in half the exposed population.

Note that when $D = D_{50}$, then $X = 1$, $H = \ell n\ 2$, and $r = 0.5$, as it should since the dose received was the D_{50} dose.

When the exposure is not delivered over a short time period, dose protraction, which is the lessened effectiveness of doses delivered at later times and lower dose rates compared to the effectiveness of doses delivered during earlier time periods at higher dose rates, must be addressed. When dose is delivered over long periods of time at rates that are not constant, the normalized dose X in Equation (6.3) could be calculated using the following equation,

$$X = \int_0^{\infty} \frac{R}{D_{50}(R)}\, dt\ . \tag{6.5}$$

In MACCS, the above integral is approximated by a sum over discrete time intervals,

$$X = \sum_{t} \frac{D_t}{D_{50,t}} \quad . \tag{6.6}$$

In Equations (6.5) and (6.6), R is the rate at which the dose is received with time, $D_{50}(R)$ is the dose-rate dependent dose that is expected to cause the health effect in half the exposed population, D_t is the dose received in time period t by individuals of exposed population, and $D_{50,t}$ is the dose that is expected to induce the effect in half of the exposed population that received the dose D_t in time period t.

If the dose delivered by short-lived nuclides is important compared to the dose from longer-lived nuclides, the first two terms in Equation (6.6) should have short time periods. Because one day is the shortest time period used for dose accumulation in standard MACCS calculations, these calculations might underestimate the risk induced by rapidly decaying nuclides (see Sections 6.1.1 and 6.1.3 below).

6.1.1 Accumulation and Protraction of Acute Doses

When calculating early health effects, all external dose (D_{ext}) delivered during the emergency phase of the accident is treated as though it had been delivered during the first day of the emergency phase (by definition the emergency phase commences upon plume arrival and lasts at least one and no more than seven days); and all materials in the plume or resuspended from the ground, that are inhaled during the emergency phase, are treated as though they were inhaled at the time of plume arrival. Thus, when Equation (6.6) is used to calculate the early health effect risks that are caused by external exposures (cloudshine and short-term groundshine exposures), only one term is used and the D_{50} value used with that term is chosen to be appropriate for intense exposures delivered over a 24-hour period.

Because many inhaled materials are not removed from the body within one day by decay or biologic clearance, the effects of dose protraction must be considered for inhalation doses. Thus, MACCS calculates normalized inhalation doses using Equation (6.7) with various numbers of terms, depending on the organ. When external and inhalation exposures both contribute to early health effects, X in Equation (6.6) is calculated using one term for the external exposure and several terms (two or more) for the inhalation exposure:

$$X = \frac{D_{ext}}{D_{50,t}} + \sum_{t=1}^{n} \frac{D_{inh,t}}{D_{50,t}} \tag{6.7}$$

where

D_{ext} = the external dose delivered to the target organ during the emergency phase of the accident by cloudshine or short-term groundshine,

$D_{50,t}$ = the dose to the organ that if delivered during the time period t would induce the health effect in half the exposed population, and

$D_{inh,t}$ = the dose delivered to the organ by materials that were inhaled during the emergency phase (because all inhaled materials are assumed to be inhaled at the time of plume arrival, one set of time periods applies to all inhaled materials).

6.1.2 Quality Factors

The damage done by energy deposited in an organ depends on the amount of energy deposited per unit length along the track of the particle that deposits the energy (α, β, or γ particle). Thus, the health effect models implemented in MACCS all express health effect risks as a function of biologically effective dose, which is expressed in sievert (Sv), rather than as a function of the energy deposited in a unit mass of the irradiated organ, which is expressed in gray (Gy) where 1.0 Gy = 1.0 J/kg. The conversion factor Q from gray to sievert is called a Quality factor. Thus, D(Sv) = Q • D(Gy) where D(Gy) is the absorbed dose in gray, D(Sv) is the dose equivalent in sievert and the Quality factor Q corrects for the biologic effectiveness of the damage done to the target organ by the energy deposited in the organ. For all health effects (acute fatalities and injuries; cancers and cancer fatalities), MACCS assumes that Q = 1 for β particles and γ-rays; for α particles, MACCS assumes that Q = 10 for acute effects and Q = 20 for cancer induction. Note that Quality factors do not appear directly in MACCS. Instead they are embedded in the dose conversion factors input to MACCS (i.e., dose conversion factors with dimensions Gy/Bq are multiplied by Quality factors with dimensions Sv/Gy to produce new factors with dimensions Sv/Bq input to MACCS (see Appendix D, Dose Conversion Factors).

6.1.3 Effective Inhalation Dose Conversion Factors

In Equation (6.7) $D_{inh,t} = C_{inh} F_{inh,t}$, where $C_{inh} = C_{air}R_b$ is the amount of material inhaled during plume passage, $F_{inh,t}$ is the dose conversion factor (Sv/Bq) for inhaled material applicable to time period t following the time of inhalation, C_{air} is the time-integrated air concentration of that material in the passing plume, and R_b is the average breathing rate of the exposed population. Because MACCS uses a fixed set of time periods t and a fixed set of $D_{50,t}$ values that apply to those time periods, Equation (6.7) can be recast [Ru85] as follows,

$$X = \frac{D_{ext}}{D_{50,1}} + \frac{C_{inh}}{D_{50,1}} \left[\sum_{t=1}^{n} \frac{D_{50,1}}{D_{50,t}} F_{inh,t} \right]$$

$$= \frac{D_{ext} + D_{inh}^{eff}}{D_{50,1}} = \frac{D_{tot}}{D_{50,1}} , \qquad (6.8)$$

where

$$D_{tot} = D_{ext} + D_{inh}^{eff} ,$$

$$D_{inh}^{eff} = C_{inh} F_{inh}^{eff} , \text{ and}$$

$$F_{inh}^{eff} = \sum_{t=1}^{n} \frac{D_{50,1}}{D_{50,t}} F_{inh,t}$$

And F_{inh}^{eff} is an effective dose conversion factor for dose caused by inhaled materials, which embeds the effects of dose protraction on inhalation dose. Note that the ratio $D_{50,1}/D_{50,t}$ is in effect a dose reduction factor [Ev89] for dose received during time period t.

Because MACCS uses effective dose conversion factors to calculate all inhalation doses that contribute to early health effects, acute (i.e., emergency phase) inhalation doses are protracted doses. A protracted dose is the dose that, if delivered over one day, would have the same effect as the actual dose accumulated over some longer time period (e.g., 7 days for the stomach, 30 for the red marrow, and 365 for the lungs) during which the dose contributes to the early health effects. Because they reflect the effects of dose protraction, the emergency phase acute doses calculated by MACCS can be considerably smaller than the unprotracted doses that would be predicted by a health physicist for emergency phase exposures (note that the lifetime doses caused by emergency phase exposures are calculated without protraction, since cancer induction is not modeled using protracted doses).

6.1.4 Dose Thresholds

When caused by brief (duration no longer than one day) intense exposures, most early health effects (thyroid and fetal injuries are exceptions) are observed to have dose thresholds that are about one-quarter to one-half of the D_{50} value for brief intense exposures [Ev89]. However, because of variability among individuals, early effect thresholds are not sharply defined for any population cohort. Instead, early effect thresholds for population cohorts are expected to asymptotically approach zero risk over some dose range. Because of its sigmoid shape, Equation (6.2) mimics this behavior (asymtotic approach to zero risk) except that zero risk is not reached until the dose delivered is also zero. Since this is not consistent with clinical observations, in MACCS an explicit early effect dose threshold (D_{th}) is introduced for each early health effect by setting H in Equation (6.2) to zero whenever the total dose delivered to the target organ is less than D_{th}. Thus, MACCS calculates all early health effect risks using the following equation:

$$r = 1 - \exp(-H), \text{ where } H = 0.693 \left[\frac{D_{tot}}{D_{50,1}} \right]^{\beta} \qquad (6.9)$$

$$D_{tot} = D_{ext} + D^{eff}_{inh}, \text{ and}$$

$$H = 0 \text{ if } D_{tot} \leq D_{th} .$$

Both D_{ext} and D^{eff}_{inh} are calculated using dose conversion factors which are constructed outside of the MACCS code, and which have embedded in them the effects of dose protraction on inhalation doses and of dose effectiveness (quality factors).

6.1.5 Early Fatalities

Standard MACCS calculations assume [Ev89] that early fatalites (fatalities that result from substantial exposures to radiation received during the emergency phase) are caused by impaired functioning of red (bone) marrow, the lungs, and the gastrointestinal tract (Since the number and identity of the organs used to calculate early fatalities is defined through input, more or fewer organs could be used.). Thus, for purposes of calculating early fatalities, the total cumulative hazard H used in Equation (6.2)(here denoted by H_{EF}) is taken to be the sum of the cumulative hazards for red marrow H_R, the lungs H_L, and the GI tract H_{GI},

$$H_{EF} = H_R + H_L + H_{GI} \qquad (6.10)$$

where each cumulative hazard is calculated using Equation (6.3), and each normalized dose is calculated using Equation (6.7) with D_{50} values replaced by LD_{50} (dose lethal to 50% of the exposed population) values and all values specific to the organ being treated. Because Equation (6.10) does not contain weighting factors or terms that are products of individual organ doses, it neglects both synergisms, which could increase the effect of simultaneous impairment of different organs (early fatality risks would exceed those predicted by the simple sum in Equation (6.10)), and the timing of organ impairments, which if not simultaneous could be less effective than predicted by Equation (6.10) (early fatality risks would be less than those predicted by the simple sum in Equation (6.10)).

6.1.6 Early Health Effect Target Organs and Model Parameters

Table 6.1 lists the early health effects that can be modeled by MACCS using the data on the sample input files and the organ whose impaired functioning leads to injury or contributes to the occurrence of early fatalites [Ev89]. The table also presents for each effect the parameter values provided on the sample EARLY input file distributed with MACCS.

Several comments about Table 6.1 are in order. First, the LD_{50} values for hematopoietic syndrome given in the table are appropriate for a population cohort that is randomly divided into two equal groups, one that receives minimal treatment and one that receives supportive treatment, where minimal treatment means provision only of basic first aid, and supportive treatment means hospitaliztion with routine isolation, antibiotic therapy, blood transfusions, electrolyte replacement, and parenteral feeding. Second, the shape parameter value given in the table for the pulmonary syndrome is appropriate for exposures comprised of about half external dose and half inhalation dose. Third, the parameter values given for pulmonary syndrome do not reflect the enhanced susceptibility to lung damage that normally is characteristic of older persons who have smoked extensively. And fourth, the dependence of $LD_{50,t}$ or $D_{50,t}$ values on the time period should be read (for example) as follows: for hematopoietic syndrome, LD_{50} equals 3.8 from day 0 through day 1, 7.6 from day 2 through day 14, and 15 from day 15 through day 30 (dose received after day 30 does not contribute to hematopoietic syndrome); for thyroiditis, D_{50} equals 240 for day 0 through day 21 (dose received after day 21 does not contribute to thyroiditis).

Table 6.1

Early Health Effects Modeled by the MACCS Sample Problem

Early Health Effect	End Result: Death	End Result: Injury	Impaired Organ	Shape Parameter	LD_{th} or D_{th} Threshold (Sv)	LD_{50} or D_{50} in Sv, Time Period End Point (days): 1	7	10	14	21	30	200	365
Hematopoietic Syndrome	x		Red Marrow	5	1.5	3.8			7.6		15		
Pulmonary Syndrome	x		Lungs	7	5	10			160			370	920
Gastro-intestinal Syndrome	x		Lower Large Intestine	10	8	15	35						
Prodromal Vomiting		x	Stomach	3	0.5	2	5						
Diarrhea		x	Stomach	2.5	1	3	6						
Pneumonitis		x	Lungs	7	5	10			160			370	920
Skin Erythema		x	Skin	5	3	6		20					
Transepidermal Injury		x	Skin	5	10	20		80					
Thyroiditis		x	Thyroid	2	40					240			
Hypothyroidism		x	Thyroid	1.3	2					60			

6.2 Delayed (Latent) Cancer

Figure 6.1 depicts the dependence of cancer risk on dose that is implemented in MACCS. The figure shows that cancer risk is expected to increase with increasing dose until the total dose becomes large enough to kill individual cells, whereupon the incremental risk begins to decrease with further increase of dose. The figure also shows that below the cell-killing region, the dependence of risk on dose is believed to be nonlinear and nonzero for any dose received (not characterized by a threshold). In the figure, the dose-response curve is dotted below 0.1 Sv (10 rem) because data concerning cancer risks are unavailable for doses that are this small and because extrapolation of data from larger exposures is questionable.

In MACCS, cancer risks below the cell-killing region are modeled using a linear-quadratic dependence of risk on dose; cancer risks in the cell-killing region are modeled using a linear dependence of risk on dose; and the transition from the linear-quadratic model to the linear model is assumed to occur at a dose of 1.5 Sv [Ev89]. Because chronic exposures are expected to be limited to doses less than a few hundredths of a sievert per year by imposition of some long-term dose limit (e.g., 0.04 Sv in 5 years), when chronic cancer risks are calculated in the CHRONC module of MACCS, the quadratic portion of the linear-quadratic dose-response equation is neglected. On the other hand, when cancer risks from exposures during the emergency phase are estimated in the EARLY module of MACCS, the linear-quadratic dose-response equation is used for total emergency phase exposures that are less than 1.5 Sv, and the linear dose-response equation is used when emergency phase exposures equal or exceed 1.5 Sv.

Thus, MACCS models the dependence of cancer risks on dose using the following three equations:

$$r_i = aD_i\left(b + cD_i\right) \tag{6.11a}$$

if $D_i < 1.5$ Sv and D_i is an emergency phase dose,

$$r_i = aD_i \tag{6.11b}$$

if $D_i \geq 1.5$ Sv and D_i is an emergency phase dose,

$$r_i = abD_i \tag{6.11c}$$

if D_i is a chronic dose,

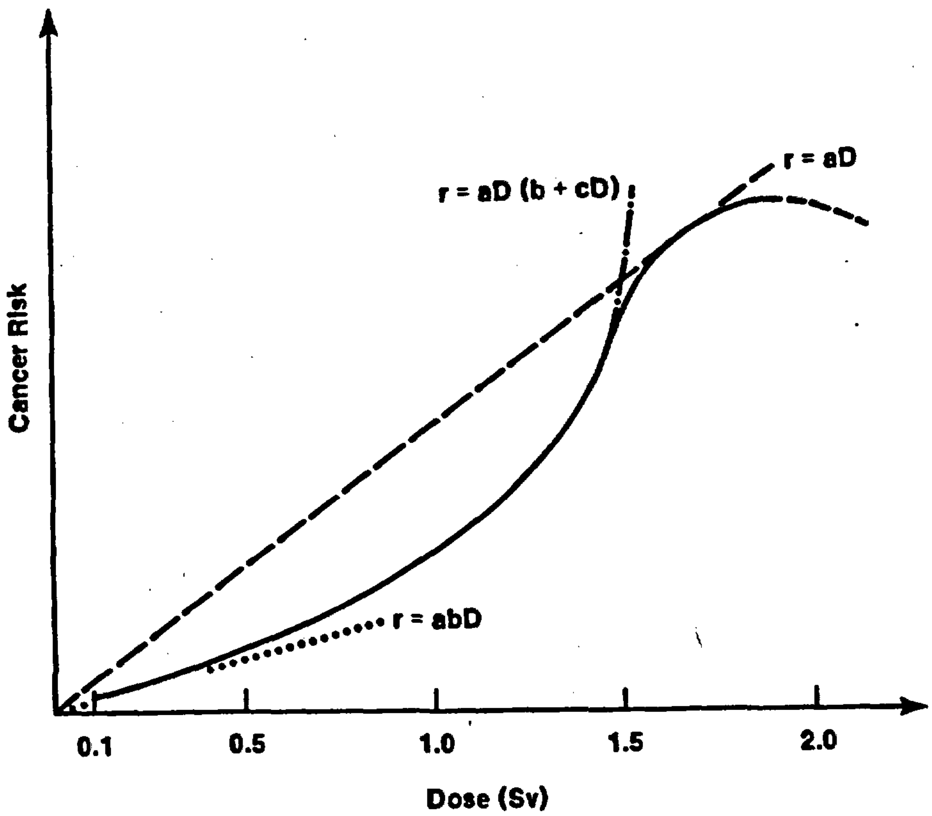


Figure 6.1 Dependence of Cancer Risks on Dose Implemented in MACCS

where

r_i - the risk of inducing cancer in a particular organ i and
D_i - the emergency phase or chronic dose to that organ.

Although MACCS does not directly model the decrease of cancer risk with increase of dose in the cell-killing region, MACCS partly corrects for this effect by subtracting the cases of early fatalities from the exposed population for calculating the cases of latent cancers in the surviving population. MACCS also partly corrects for the greater cell damage caused by high LET radiation by embedding quality factors in the dose conversion factors that are used to calculate the emergency phase and chronic doses from which the fatal and nonfatal cancer risks are estimated. For both emergency phase (acute) and long-term (chronic) exposures, unprotracted 50-year dose commitments are used to estimate chronic health effects, because an average exposed individual will be about 30 years old and at this age will have a life expectancy of about 50 years. For source terms that contain large quantities of nuclides that decay by emission of an α ray, the greater damage caused by high LET radiation is probably significantly underestimated by the models implemented in MACCS. High LET radiation would be better modeled by switching to the linear dose-response equation ($r = aD$) whenever some significant fraction (possibly 10 percent) of the total dose delivered is caused by high LET radiation.

6.2.1 Latent Cancer Target Organs and Model Parameters

Table 6.2 presents the latent cancer effects that can be modeled by MACCS using the data on the sample input files distributed with the code, the organ whose impaired functioning causes cancer in the organ, and the parameter values for each effect that are provided on the sample files.

In Table 6.2, the same "a" value for total cancer and for fatal cancer indicates that this form of cancer is considered incurable; and "other" cancers means cancers of organs not specifically modeled. Normally "other" cancers would include multiple myeloma, lymphoma, and cancers of the bladder, kidney, brain, ovary, uterus, and cervix. Because "other" cancer dose factors, which should be calculated as a weighted sum of the "other" organs dose factors, are not presently included in the MACCS dose conversion factor file, the lower large intestine is being used as a surrogate organ for the hypothetical "other" cancer organ. Since the risk of "other" cancers is not expected to exceed half the risk of GI cancer, "other" cancer is modeled using GI cancer model parameter values with the value of parameter "a" halved.

Table 6.2

Latent Cancer Health Effects Modeled by the MACCS Sample Problem

Chronic Health Effect	End Result: Cancer	End Result: Death	Impaired Organ	Model Parameters*: Total Cancer a_i	Fatal Cancer a_i	Both b_i	Both c_i
Leukemia	x	x	Red Marrow	3.7E-3	3.7E-3	0.39	0.61
Bone Cancer	x	x	Bone Surface	1.5E-4	1.5E-4	0.39	0.61
Breast Cancer	x	x	Breast	1.7E-2	6.0E-3	1	0
Lung Cancer	x	x	Lungs	5.7E-3	5.1E-3	0.39	0.61
Thyroid Cancer	x	x	Thyroid	7.2E-3	7.2E-4	1	0
Gastrointestinal Cancer	x	x	Lower Large Intestine	2.5E-2	1.5E-2	0.39	0.61
"Other" Cancers	x	x	Lower Large Intestine (surrogate)	1.3E-2	7.5E-3	0.39	0.61

*where $r_i = a_i D_i (b_i + c_i D_i)$ is the risk of inducing cancer in organ i.

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APPENDIX A

DATA BUILT INTO MACCS CODE

Even though most of the parameter values used in MACCS are user specified, there are still some parameter values built into the code. This Appendix summarizes those data that are currently built into the MACCS code.

A.1 ATMOS Module

1. The ambient temperature in the plume rise model is set to 288.16°K. The stability parameter S for stability classes E and F are set to 5.04E-4 and 1.27E-3, respectively, in the code. See Section 2.8.2.

2. The adiabatic lapse rate of the lower atmosphere g/C_p is set to 0.0098°C/meter. See Section 2.8.2.

3. The buoyancy flux parameter F (m^4/sec^3) in the plume rise model is set to 8.79E-6 • Q, where Q is the energy release rate (joules/sec). See Section 2.8.2.

4. The initial conditions for dry weather conditions, that is, initial wind speed and stability class, of weather category bins used in MACCS weather sampling are fixed in the code and shown in Table B.1. See Section B.1 of Appendix B.

5. The initial plume dispersion parameters σ_y and σ_z from building wake effects are calculated using Equation (2.2). The values 4.3 and 2.15 in these two equations are fixed in the code. See Section 2.5.

6. The variation of windspeed as a function of height above the ground level is described by Equation (2.9). The reference height z_o is assumed to be 10 m in the code. The values of the exponent p for six stability classes for rural area surfaces shown in Table 2.1 are hard-wired into the code. The maximum value of Z in Equation (2.9) is 200 m.

A.2 EARLY Module

1. The finite cloud to semi-infinite cloud dose correction factor is calculated using the data from Appendix VI of Reactor Safety Study [US75] for a 0.7 Mev gamma ray (see Section 3.1.2).

2. Unlike the other organs that have dose conversion factors pre-calculated and supplied as input data, the skin dose conversion factor is calculated in MACCS. The deposition velocity for the skin dose conversion factor calculation is assumed to be 0.01 m/sec. See Section 3.1.6.

A.3 CHRONC Module

1. The time periods for evaluating interdiction are hard-wired in MACCS as one, five, and thirty years after the accident, that is, the maximum time for temporary interdiction of habitation is 30 years. If the projected habitation dose over 30 years for a given spatial element, adjusted by the maximum decontamination factor, still cannot meet the habitability criterion, the spatial element is assumed to be condemned permanently. See Section 5.3.1.

2. The integration time for habitation dose is set to one million years. Since the half-lives of all 60 radionuclides considered in MACCS are much smaller than one million years, the integration is effectively to infinite time. See Section 5.3.1.

3. The maximum number of years for restriction of farmland production is eight years. If the number of years for restriction of farmland production is greater than eight, it is assumed that the farmland is permanently condemned. See Section 5.3.2.

4. The fraction of a year that the milk disposal action would be applied if an accident occurred during the growing season is assumed to be 0.25. See Section 4.3.3.

APPENDIX B

WEATHER BIN SAMPLING METHOD

The atmospheric dispersion of radioactive materials from a postulated accident depends on the weather from the start of the accident through a period of tens to hundreds of hours following the accident. The characteristics of the accident together with the weather conditions coincident with and immediately following the accident determine the transport and dispersion process that follows, and thus, the magnitude of the consequences that will result [US75]. Since the weather that could occur coincident with the accident is diverse, representative weather data sequences are selected as input to the dispersion model to reflect the dependence of the transport and dispersion process on the site weather. The selection process is done by means of sampling techniques from a full year of hourly weather data characteristic of the plant site.

B.1 <u>Weather Data Assessment</u>

The basis of the weather bin sampling method is an initial assessment of the full set of hourly weather data. This initial assessment provides information about the types of weather sequences contained in the data and the relative frequency of these weather types. With this information, weather sequences can be sampled to reflect the full year's weather data. This ensures representation of each type of weather sequence, those important to realistic representation of the weather data set, and those important to the occurrence of the most serious accident consequences.

The weather data assessment is done by sorting the weather data into weather bins that provide a realistic representation of the year's weather without overlooking those kinds of weather that can be instrumental in producing major consequence impacts. The method used by MACCS to sort weather into bins is based on the method used by CRAC2 [Ri84]. The only significant difference between the weather sorting of MACCS and CRAC2 is in the definition of the weather categories. Both codes use essentially the same sorting method described in Section B.2.

The weather bins used in MACCS are of two types: (1) those associated with rain events at distance intervals specified by the user and (2) those non-rain events determined by initial weather conditions, that is, initial wind speed and stability class.

The definition of the rain event bins, i.e., rain bins, is specified by the user as described in Section 1.16 of the MACCS user's guide [Ch89]. The number of rain bins can range from eight to twenty four, depending on the choice of the user. Two attributes are used in specifying the rain bins: rain intensity and rain distance intervals, the spatial intervals in which rain occurs. Rain intensity is specified in mm/h. Rain distance intervals are specified by distances in km. Since the meteorological data come from only one location (typically at the reactor site), MACCS assumes that rain occurs in the entire region when it rains at the reactor site.

The definition of the initial condition weather bins is currently hard-wired into the code. There are a total of sixteen initial condition weather bins defined by initial stability class and initial wind speed, as shown in Table B.1. Therefore, the total number of weather bins could range from twenty-four (if eight rain bins are specified) to forty (if twenty-four rain bins are specified).

Each weather sequence is described by a start-hour weather data followed by subsequent hourly weather data. In sorting the weather data into different weather bins, MACCS looks at each hourly weather data and uses the following algorithm:

1. If it rains in that hour, the weather sequence of this start-hour goes into the closest distance interval rain bin appropriate for the rain intensity of that hour.

2. If it does not rain in that hour, MACCS looks at the subsequent hourly weather data to see if there is rain within the distance intervals specified by the user. This is done by starting from the closest distance interval and going outward. If rain is found, the weather sequence of this start-hour goes into one of the rain bins at the distance interval of the first occurrence of rain. The initial intensity of the rain determines the bin to which it is assigned.

3. If the subsequent hourly weather data show no rain occurs within the farthest specified distance (the number of hours to reach the outer most distance of the specified intervals is determined by wind speed), this hourly data is classified as a no rain weather sequence. The weather sequence of this start-hour is then sorted according to its stability class and wind speed.

To illustrate the weather sorting and sampling methodology of MACCS, a set of parameters was chosen that define 32 weather bins.

Heuristic judgment played a significant role in the choice of the 32 weather bins into which the data are sorted. Experience with the CRAC and CRAC2 models revealed the impact of weather events on the consequence magnitudes resulting from accidents. Given a postulated large accident, significant numbers of early deaths and injuries are normally associated with relatively low probability weather events such as rainfall over urban/surburban areas as far as 40 kilometers from the plant site or with stable weather and moderate wind speeds at the start of the release. These weather data types have been selected to be among the 32 categories utilized in the assessment process.

The 32 weather bins are described in Table B.1. An example of weather data sorted into these weather bins is shown in Table B.2. The weather data for this example represent one year of meteorological data for the Grand Gulf plant site. The entire year of data, 8760 hourly recordings, are sorted into the 32 weather bins.

Using the three steps described above, MACCS looks at each start-hour weather data to determine the weather bin to which this weather sequence is assigned. For example, if a start-hour weather data is a rain event of 2 mm/hr, this weather sequence goes into bin number 21 shown in Table B.1. If the start-hour weather data is not a rain event and the wind speed is 15 km/h, MACCS looks at the subsequent weather data. If it rains at 0.4 mm/h in the next hour, this weather sequence goes into bin number 18 in Table B.1 because when the rain first occurs the plume already has traveled 15 km, which is the second distance interval (10,16). If neither the start-hour data nor the next three hourly weather data are rain events with wind speed of 6 km/h, 10 km/h, 10 km/h, and 8 km/h, this weather sequence is classified as one of the no rain bins, since there are no rain weather data out to the farthest distance interval (i.e., (24, 32)). This weather sequence is then sorted by the initial condition, the stability class and wind speed of the start-hour data.

Following the binning process, the start-hour of each weather sequence will have been assigned to one and only one weather category. Each of the weather categories then includes a set of weather sequences representing the corresponding weather type. The probability of occurrence of the weather type is the ratio of the total number of weather sequences in the bin to the total number of weather sequences in the year's weather data set, 8760 sequences.

B.2 Sampling Method

The sampling procedure has two key items of information available to it: (1) the weather bin of each weather sequence and (2) the probability of occurrence of each weather bin. Normally, four sequences are selected from each weather bin by the "Latin hypercube" sampling scheme [Im82]. With this sampling method, random samples are drawn from evenly spaced sets within a weather bin. This assures that the model uses a uniform representation of the weather data over the full year. Assume that a weather bin contains N_i weather sequences and that K_i samples are to be selected from each weather bin. Typically, K_i is less than N_i, $0 < K_i < N_i$. The N_i weather sequences are then grouped into K_i evenly spaced sets, $S_1, \ldots, S_{K_i}$.

The number of weather sequences contained in set S_j is

$$\mathrm{INT}\left[(j) \bullet (N_i/K_i)\right] - \mathrm{INT}\left[(j - 1) \bullet (N_i/K_i)\right] \qquad \text{(B.1)}$$

where INT[X] represents the integer function that returns the integer part of a real number X. For example, INT[2.5] = 2.

Since the N_i weather sequences of weather bin i have a natural order determined by the initial time of each of the weather sequences, the evenly spaced sets $S_1, \ldots, S_{K_i}$ are ordered. Thus, S_1 consists of the first $[N_i/K_i]$ elements of category i, S_2 consists of the next $\{[2(N_i/K_i)] - [N_i/K_i]\}$ elements of category i, and so on. One weather sequence is then randomly selected from each set.

If $K_i \geq N_i$ for a weather bin i, all the weather sequences in weather bin i, N_i, are selected. Since the total number of weather sequences selected from weather bin i is K_i, the total number of sequences selected from all 32 weather bins would be

$$\sum_{i=1}^{32} K_i$$

The assigned probability for a meteorological sequence sampled from weather bin i would be

$$\frac{1}{K_i} \cdot \frac{N_i}{\sum_{i=1}^{32} N_i} = \frac{N_i / K_i}{\sum_{i=1}^{32} N_i}$$

Consider a simple example. Let weather bin i contain ten weather sequences from which four are to be sampled. Then $N_i = 10$, $K_i = 4$, and using Equation (B.1) S_1 contains two sequences, S_2 contains three sequences, S_3 contains two sequences, and S_4 contains three sequences. One sequence is randomly drawn from each set S_j, j = 1,...,4, as in Figure B.1 below. In Figure B.1, an "x" denotes each weather sequence start hour in the bin and a circle around an x indicates the selection of that start hour by the sampling procedure.

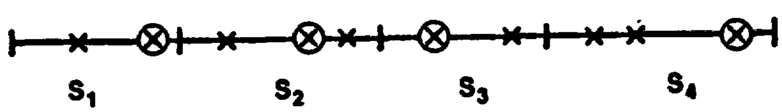

Figure B.1 Example of Sequences Selected

The assigned probability for a sequence chosen from this weather bin would be (10/4)/8760, since MACCS requires the year's weather data to contain 8760 sequences.

The technique of importance sampling described here selects weather sequences that accurately represent the range of weather sequences in the weather data and their probability of occurrence and assures selection of sequences that yield a representative range of accident consequences from insignificant to severe. The inclusion of these severe accident consequences and of weather sequence probabilities representing each weather bin is the key to a realistic representation of the probability distribution of consequences. The technique is simple and efficient in comparison to other sampling methods [Ri81].

Table B.1

Weather Bin Descriptions

Bin Number	Bin Notation*		Description of Weather Sequences in the Bin
1	B	3	Initial stability classes A and B, with initial windspeed ≤ 3 m/s.
2	B	4	Initial stability classes A and B, with initial windspeed > 3 m/s.
3	D	1	Initial stability classes C and D, with initial windspeed ≤ 1 m/s.
4	D	2	Initial stability classes C and D, with initial windspeed >1 and ≤ 2 m/s.
5	D	3	Initial stability classes C and D, with initial windspeed >2 and ≤ 3 m/s.
6	D	4	Initial stability classes C and D, with initial windspeed >3 and ≤ 5 m/s.
7	D	5	Initial stability classes C and D, with initial windspeed >5 and ≤ 7 m/s.
8	D	6	Initial stability classes C and D, with initial windspeed > 7 m/s.
9	E	1	Initial stability class E, with initial windspeed ≤ 1 m/s.
10	E	2	Initial stability class E, with initial windspeed > 1 and ≤ 2 m/s.
11	E	3	Initial stability class E, with initial windspeed > 2 and ≤ 3 m/s.
12	E	4	Initial stability class E, with initial windspeed > 3 m/s.
13	F	1	Initial stability class F, with initial windspeed ≤ 1 m/s.

Table B.1

Weather Bin Descriptions (Continued)

Bin Number	Bin Notation*	Description of Weather Sequences in the Bin
14	F 2	Initial stability class F, with initial windspeed > 1 and ≤ 2 m/s.
15	F 3	Initial stability class F, with initial windspeed > 2 and ≤ 3 m/s.
16	F 4	Initial stability class F, with initial windspeed > 3 m/s.
17	R1 10	First occurrence of rainfall of intensity 1 in the interval (0,10) kilometers from site.
18	R1 16	First occurrence of rainfall of intensity 1 in the interval (10,16) kilometers from site.
19	R1 24	First occurrence of rainfall of intensity 1 in the interval (16,24) kilometers from site.
20	R1 32	First occurrence of rainfall of intensity 1 in the interval (24,32) kilometers from site.
21	R2 10	First occurrence of rainfall of intensity 2 in the interval (0,10) kilometers from site.
22	R2 16	First occurrence of rainfall of intensity 2 in the interval (10,16) kilometers from site.
23	R2 24	First occurrence of rainfall of intensity 2 in the interval (16,24) kilometers from site.
24	R2 32	First occurrence of rainfall of intensity 2 in the interval (24,32) kilometers from site.
25	R3 10	First occurrence of rainfall of intensity 3 in the interval (0,10) kilometers from site.

Table B.1

Weather Bin Descriptions (Concluded)

Bin Number	Bin Notation*	Description of Weather Sequences in the Bin
26	R3 16	First occurrence of rainfall of intensity 3 in the interval (10,16) kilometers from site.
27	R3 24	First occurrence of rainfall of intensity 3 in the interval (16,24) kilometers from site.
28	R3 32	First occurrence of rainfall of intensity 3 in the interval (24,32) kilometers from site.
29	R4 10	First occurrence of rainfall of intensity 4 in the interval (0,10) kilometers from site.
30	R4 16	First occurrence of rainfall of intensity 4 in the interval (10,16) kilometers from site.
31	R4 24	First occurrence of rainfall of intensity 4 in the interval (16,24) kilometers from site.
32	R4 32	First occurrence of rainfall of intensity 4 in the interval (24,32) kilometers from site.

* Bin Notation

S V - Weather bin based on initial weather conditions with stability class S and windspeed interval V (bin numbers 1 through 16). Stability classes are B = A/B, D = C/D, E = E, and F = F. Windspeed intervals are in meters per second, 1 (0-1), 2 (1-2), 3 (2-3), 4 (3-5), 5 (5-7), 6 (GT 7).

RI XX - Weather bin based on rain intensity I within the interval ending at XX (bin numbers 17 through 32). Interval endpoints are in kilometers from the accident site, the four interval endpoints are 10, 16, 24, and 32 kilometers. Rain intensities are in millimeters of rain per hour; the three intensity breakpoints are 0.5, 2.5, and 15.0 mm/h.

Table B.2

One Year of Grand Gulf Site Meteorological Data
Summarized Using the Weather Bin Algorithms for MACCS

Weather Bin Definitions

See Table B.1.

Bin Number	Weather Bin		No. of Sequences	Percent
1	B	3	1250	14.27
2	B	4	384	4.38
3	D	1	200	2.28
4	D	2	560	6.39
5	D	3	501	5.72
6	D	4	564	6.44
7	D	5	84	0.96
8	D	6	1	0.01
9	E	1	498	5.68
10	E	2	604	6.90
11	E	3	306	3.49
12	E	4	192	2.19
13	F	1	1379	15.74
14	F	2	509	5.81
15	F	3	69	0.79
16	F	4	2	0.02
17	R1	10	457	5.22
18	R1	16	172	1.96
19	R1	24	203	2.32
20	R1	32	163	1.86
21	R2	10	197	2.25
22	R2	16	39	0.45
23	R2	24	41	0.47
24	R2	32	35	0.40
25	R3	10	191	2.18
26	R3	16	29	0.33
27	R3	24	46	0.53
28	R3	32	32	0.37
29	R4	10	36	0.41
30	R4	16	6	0.07
31	R4	24	5	0.06
32	R4	32	5	0.06
		TOTAL	8760	100.00

APPENDIX C

METHODOLOGY FOR CALCULATING THE MAXIMUM ALLOWABLE GROUND CONCENTRATIONS PSCMLK, PSCOTH, GCMAXR

The purpose of this appendix is to describe the method used to calculate the parameter values for the allowable ground concentrations: PSCMLK, PSCOTH, and GCMAXR. This method is implemented in the program MAXGC. These ground concentrations are used within the MACCS code to determine the necessity for taking actions which would mitigate the dose received via the food ingestion pathway. The main body of the appendix will give the overall methodology used and include derivation of the values of these parameters currently being used in consequence assessment. Addendum 1 and Addendum 2 describe in detail the methods used to derive specific complex input data required for the calculation of the maximum allowable ground concentrations. Addendum 3 gives an overview of the specific values used for the various component variables required for the calculations.

In the MACCS code, the dosimetry model for the food pathway is separated into two distinct submodels; (1) a "current growing season pathway" model and (2) a "long-term pathway" model. A total societal population dose to each organ considered is calculated for each of these distinct submodels. The societal dose from nuclide i to organ k via all crops j is found in the following way:

$$D_{i,k} = \sum_j \left(DF_{i,k} \bullet GC_i \bullet FA \bullet FAC_j \bullet TF_{i,j}\right)$$

$$= DF_{i,k} \bullet GC_i \bullet \sum_j \left(FA \bullet FAC_j \bullet TF_{i,j}\right) \qquad (C.1)$$

where

$DF_{i,k}$ = ingestion dose conversion factor for isotope i to organ k (Sv/Bq),

GC_i = ground concentration for isotope i (Bq/m²),

FA = area of farmland (m²),

FAC_j = fraction of the farmland area used to grow crop j (unitless), and

$TF_{i,j}$ = overall transfer factor for isotope i via crop j (i.e., the fraction of the material deposited ultimately consumed by population) (unitless).

Within the MACCS code, agricultural mitigative actions are taken to ensure that the dose received by any individual will not exceed the user-established dose criteria. These dose criteria are not actual input parameters to the MACCS code, but are utilized in the derivation of the maximum allowable concentrations for the various nuclides being considered.

Since the dosimetry model in MACCS consists of two discrete submodels the mitigative actions are also divided into two discrete groups: those that will limit the societal dose received from the consumption of food and animal products that originate from crops being grown at the time of the accident, and those which will limit the long-term doses received by society via the foods grown in the contaminated soil in the subsequent years. As a result of the separation of the dosimetry and mitigative action models within MACCS, it is necessary to establish three distinct sets of allowable ground concentrations as input parameters. The first two concern the "current growing season pathway" model and define the ground concentrations used to determine disposal of milk, $PSCMLK_i$, and the ground concentrations used to determine the disposal of non-milk crops, $PSCOTH_i$. The third allowable ground concentration required, $GCMAXR_i$, is that which is used by MACCS to determine the necessity to restrict farm production or condemn farmland over the long term.

The FDA protective action guides (PAG's) served as the basis for the dose limits used in the calculation of the allowable ground concentrations. These guidelines were stated in the Federal Register [Fr82]. The FDA emergency PAG is a 0.15 Sv (15 rem) projected dose commitment to the thyroid or a 0.05 Sv (5 rem) projected dose commitment to the whole body or any organ other than the thyroid. The FDA preventative PAG is a 0.015 Sv (1.5 rem) projected dose commitment to the thyroid or a 0.005 Sv (0.5 rem) projected dose commitment to the whole body or any organ other than the thyroid. The emergency PAG served as the standard for the growing season model (direct deposition), and the preventative PAG was used as the standard for the long-term uptake by plants and animals for all time following the accident. (Note: it is possible that perhaps the preventative PAG should instead apply to any year subsequent to the year in which the accident occurs.) For the strontium and cesium isotopes, the target organ used was the effective whole body dose equivalent (EDE), and the thyroid was used as the target organ for the iodine isotopes.

Since the PAG's are stated in terms of projected dose commitment to an individual, it is necessary to restate the dosimetry model equation (Equation (C.1)) in terms of an individual. In all cases, the calculations were done for a maximally exposed individual, that is, one whose entire annual intake of food is produced on contaminated ground. The revised equation then becomes:

$$DL_{i,k} = MXGC_i \bullet DF_{i,k} \bullet \sum_j \left[ADJA_j \bullet TF_{i,j} \right] \qquad (C.2)$$

where

$DL_{i,k}$ - dose limit for radionuclide i to organ k established for an individual (Sv),

$MXGC_i$ - maximum allowable ground concentration for radionuclide i (Bq/m^2),

$DF_{i,k}$ - ingestion dose conversion factor for the age group of the individual being considered (Sv/Bq),

$ADJA_j$ - land area required to grow crop j in sufficient quantity to provide the maximally exposed individual with a "typical" annual intake of food (m^2),

$TF_{i,j}$ - overall transfer factor for radionuclide i via crop j (i.e., the fraction of the material deposited onto the farmland that will ultimately be consumed by the individual.

The allowable ground concentration can then be derived by solving Equation (C.2) for the maximum allowable ground concentration. That is

$$MXCG_i = \frac{DL_{i,k}}{DF_{i,k} \bullet \sum_j ADJA_j \bullet TF_{i,j}} \tag{C.3}$$

C.1 Dose Limit Criteria

For the establishment of the maximum allowable ground concentrations, it is assumed that each nuclide being considered can contribute the entire dose limit. Within the MACCS code, the ratios of these allowable ground concentrations to the actual ground concentrations for each nuclide are used to derive the fraction of the dose limit criteria contributed by that nuclide. The dose limit criteria are considered to be met if the sum of the fractional contributions from all nuclides being considered remains less than unity. Therefore, in the derivation of the ground concentrations $PSCMLK_i$ and $PSCOTH_i$, the dose limit, $DL_{i,k}$, will be a 0.05 Sv (5 rem) EDE. In the derivation of the ground concentration $GCMAXR_i$, the dose limit, $DL_{i,k}$, will be a 0.005 Sv (0.5 rem) EDE.

C.2 Infant and Adult Ingestion Dose Conversion Factors

To establish the maximum allowable ground concentrations for the milk pathway a comparison was made for each nuclide between the ground concentration derived when the maximally exposed individual was an infant and the concentration derived when the maximally exposed individual was an adult. The more stringent ground concentration for each nuclide was then used as the parameter value for PSCMLK. To do this it is necessary to have ingestion dose conversion factors available for both the infant and the adult. To obtain ingestion dose conversion factors for infants, the current adult ingestion dose conversion factors from the MACCS Dose

Conversion File were modified using dose conversion factors recommended by the Nuclear Regulatory Commission [US77]. A transform factor for each nuclide-organ pair was established as the ratio of the NRC's infant ingestion dose conversion factor to the NRC's adult ingestion dose conversion factor. Each of the current adult ingestion dose conversion factors was then multiplied by the corresponding transform factor to derive an ingestion dose conversion factor for the infant.

C.3 Derivation of Areas Required to Grow Crops for Annual Dietary Intake

To obtain the areas, $ADJA_j$, an annual market basket approach was used. The basic market basket proposed by the NRC [US77] served as a basis for this evaluation. This market basket was expanded using current per capita consumption data [US84 - Table 696, p. 505] to include all crop categories currently being considered (i.e., the nonanimal food intake was defined for grain, legumes and nuts, green leafy vegetables, roots and tubers, and other foods). The expanded market basket was then converted into the farmland area required to grow each of the seven crops to provide the food contained in the basket. The areas required to grow pasture and stored forage for dairy and beef animals to provide the required milk and beef for the market basket were calculated separately. The areas to grow grain and legumes were also calculated independently for the following consumption classes: that required to feed dairy animals, that required to feed meat-producing animals, and that to provide foods to be eaten directly by man.

As a result of using this approach, a total of 13 crop categories emerged for the maximally exposed adult and 4 crop categories for the maximally exposed infant who is assumed to drink only milk produced from contaminated land. These crop categories are summarized as follows:

For the adult:

Pasture for milk animals
Stored forage for milk animals
Grain for milk animals
Legumes for milk animals
Pasture for beef animals
Stored forage for beef animals
Grain for meat animals
Legumes for meat animals
Grain to be consumed directly
Legumes to be consumed directly
Green Leafy vegetables to be consumed directly
Root vegetables to be consumed directly
Other food crops to be consumed directly

For the infant:

- Pasture for milk animals
- Stored forage for milk animals
- Grain for milk animals
- Legumes for milk animals

This procedure as well as the derived values are described in more detail in Addendum 1.

C.4 Overall Transfer Factors

The transfer factors $TF_{i,j}$ are defined uniquely for both the "current growing season pathway" and the "long-term pathway" submodels. Each submodel has a "component" of the transfer factor $TF_{i,j}$, which defines the fraction of the deposited nuclide i found in the edible portion of the crop j. For the "current growing season pathway" submodel, this component $CTD_{i,j}$ describes the part of the material deposited onto the plant surfaces that will be retained by the edible portion either by direct exposure to the fallout or by translocation into the edible portion from the plant surfaces. The deposition onto the plant surfaces can occur directly from the fallout or by resuspension or by rainsplash. In addition, the material on plant surfaces is subject to weathering losses and radioactive decay. Therefore, the transfer factor $CTD_{i,j}$ is dependent upon the time during the growing season at which the accident occurs.

For the "long-term pathway" submodel, the transfer factor $TF_{i,j}$ contains a component which describes the long-term root uptake of radioactive material deposited onto the soil. $CTR_{i,j}$ defines the fraction of nuclide i deposited onto the soil on which crop j is grown, which will ultimately be incorporated into the edible portion of the plant via root uptake over all time. For the pasture crop, the fraction CTR_i also contains a component that defines the fraction of nuclide i deposited onto the soil that will be ingested by grazing animals as a part of the soil they ingest.

The calculation of and the derived values for $CTD_{i,j}$ and $CTR_{i,j}$ can be found in Addendum 2.

In addition to the component of the transfer factor $TF_{i,j}$, which defines the fraction of deposited material found in the edible portion of the plant, each submodel contains components that define the following: (1) the fraction of the material that will remain after decay and processing losses and (2) the fraction of the material consumed by food-producing animals incorporated into the meat or the milk of those animals.

A summary of transfer factors $TF_{i,j}$ used by the MACCS code to calculate the dose received via each of the pathway submodels is given in Table C.1.

Table C.1

Summary of Transfer Factors TF Used by the MACCS Code

For the "current growing season pathway" submodel:

For milk

$$TF_{i,j} = CTD_{i,j} \bullet DCYPCM_{i,j} \bullet TFMLK_i \bullet DCYPMH_i$$

For meat

$$TF_{i,j} = CTD_{i,j} \bullet DCYPCB_{i,j} \bullet TFBF_i \bullet DCYPBH_i$$

For food crops eaten directly by man

$$TF_{i,j} = CTD_{i,j} \bullet DCYPCH_{i,j} \bullet FPLSCH_{i,j}$$

For the "long-term pathway" submodel:

For milk

$$TF_{i,j} = CTR_{i,j} \bullet DCYPCM_{i,j} \bullet TFMLK_i \bullet DCYPMH_i$$

For meat

$$TF_{i,j} = CTR_{i,j} \bullet DCYPCB_{i,j} \bullet TFBF_i \bullet DCYPBH_i$$

For crops eaten directly by man

$$TF_{i,j} = CTR_{i,j} \bullet DCYPCH_{i,j} \bullet FPLSCH_{i,j}$$

The following parameters are user-supplied input to MACCS:

$DCYPCB_{i,j}$ = fraction of nuclide i not lost by radioactive decay between harvest of crop j and consumption by meat-producing animal

$DCYPCH_{i,j}$ = fraction of nuclide i not lost by radioactive decay between harvest of crop j and consumption by man

$DCYPCM_{i,j}$ = fraction of nuclide i not lost by radioactive decay between harvest of crop j and consumption by milk-producing animal

$DCYPBH_i$ = fraction of nuclide i in meat at the time of slaughter that is not lost by radioactive decay or processing

$DCYPMH_i$ = fraction of nuclide i in milk at the time of production which is not lost by radioactive decay or processing

$FPLSCH_{i,j}$ - fraction of nuclide i in edible portion of crop j that is not lost by preparation and processing techniques

$TFBF_i$ - fraction of nuclide i consumed by a meat-producing animal that will be found in the meat at the time of slaughter

$TFMLK_i$ - fraction of nuclide i consumed by a milk-producing animal that will be found in the milk at the time of production

C.5 Ground Concentrations for the "Current Growing Season Pathway" Submodel

For the derivation of the permissible ground concentrations for the "current growing season pathway" model, both the dose to infants and adults must be considered in deriving values for PSCMLK and PSCOTH.

A permissible ground concentration for each nuclide being considered was derived for the infant by using Equation (C.3) with the following input values:

$DL_{i,k}$ - emergency PAG as applied to the target organ for the given nuclide

$DF_{i,k}$ - ingestion dose conversion factor for infants for the nuclide being considered to the selected target organ for that nuclide (Sv/Bq)

$ADJA_j$ - area of farmland required to grow the crops j in sufficient quantity to supply the infant's annual intake of milk (m^2)

$TF_{i,j}$ - "current growing season pathway" transfer factor (unitless)

In this way, a maximum ground concentration of the growing season milk pathway for the the maximally exposed infant $PSCMLK_i$ was derived.

To derive a maximum ground concentration for the maximally exposed adult it was necessary to determine the fraction of the dose limit for each ingested nuclide i that comes from milk, $FMLK_i$, for any given ground concentration. The fraction of the dose coming from nonmilk foods, $FOTH_i$, could then be found as follows

$$FOTH_i = 1 - FMLK_i \qquad (C.4)$$

These fractions were then used in conjunction with the appropriate crops to determine the allowable ground concentrations for each nuclide i being considered for the maximally exposed adult. To find the $FMLK_i$ for each nuclide i, the following method was used. Given that $DLMLK_{i,k}$ is the dose received from milk, then

$$FMLK_i = \frac{DLMLK_{i,k}}{DL_{i,k}} = \frac{PSCMLK_i \bullet DF_{i,k} \bullet \sum_m \left(ADJA_m \bullet TF_{i,m}\right)}{PSCMLK_i \bullet DF_{i,k} \bullet \sum_n \left(ADJA_n \bullet TF_{i,n}\right)} , \qquad (C.5)$$

where

m = represents all crop shares involved in the production of milk, and

n = represents all crop shares involved in the production of the total annual adult market basket.

Since both DLMLK and DL are given for an adult, the dose conversion factor for a given nuclide i for the selected organ k is identical. Assuming a single ground concentration for both expressions (by assuming that the total intake of food originates in a small local area), Equation (C.5) will then simplify to become

$$FMLK_i = \frac{DLMLK_{i,k}}{DL_{i,k}} = \frac{\sum_m \left(ADJA_m \bullet TF_{i,m}\right)}{\sum_n \left(ADJA_n \bullet TF_{i,n}\right)} \qquad (C.6)$$

By using the adjusted areas $ADJA_j$ as derived in Addendum 1 and using the transfer factors as derived in Section C.4, the following values were found for $FMLK_i$:

Nuclide	FMLK
Sr-89	.0547
Sr-90	.0387
Cs-134	.1178
Cs-137	.1112
I-131	.7838
I-133	1.0000

The dose limit for nuclide i to organ k for the adult milk pathway, $DLMLK_{i,k}$, then becomes

$$DLMLK_{i,k} = FMLK_i \bullet DL_{i,k} \qquad (C.7)$$

where

$DL_{i,k}$ = emergency PAG as applied to the target organ for the given nuclide.

A permissible ground concentration for each nuclide being considered was derived for the adult by using Equation (C.3) with the following input parameters:

$DL_{i,k}$ - $DLMLK_{i,k}$, (i.e., the fraction of the emergency PAG dose to to the target organ for the given nuclide that will be received by the adult via the milk pathway) (Sv),

$DF_{i,k}$ - ingestion dose conversion factor for adults for the nuclide being considered to the selected target organ for that nuclide (Sv/Bq),

$ADJA_i$ - area of farmland required to grow the crops j in sufficient quantity to supply the adult's annual intake of milk (m^2), and

$TF_{i,j}$ - "current growing season pathway" transfer factor, as calculated in Section C.3 (unitless).

A table of the values used for each of these variables can be found in Addendum 3. Using this method, the maximum ground concentrations for the maximally exposed adult $PSCMLK_i$ were derived.

A comparison of the ground concentrations derived for the infant $PSCMLK_i$ and for the adult $PSCMLK_i$ are then compared for each nuclide, and the most stringent concentration was selected for each isotope to be used as the ground concentration $PSCMLK_i$. These derived values of $PSCMLK_i$ are as follows:

Nuclide	PSCMLK
Sr-89	2.16E+07
Sr-90	2.41E+05
Cs-134	2.18E+05
Cs-137	2.66E+05
I-131	1.34E+06
I-133	1.05E+10

An examination of the methodology will show that when the adult standard for the permissible ground concentration is more stringent than that for the infant the associated value for PSCOTH will be the same. However, when the infant standard was more stringent than the ground concentration derived for the adult, the infant-based values of $PSCMLK_i$ were then used, and the values of adult $PSCOTH_i$ derived for the adult were used as the $PSCOTH_i$ values for those nuclides.

The derived values for $PSCOTH_i$ are as follows:

Nuclide	PSCOTH
Sr-89	2.16E+07
Sr-90	2.41E+05
Cs-134	2.18E+05
Cs-137	2.66E+05
I-131	7.95E+06
I-133	1.02E+11

It will be noted that the values for $PSCMLK_i$ and $PSCOTH_i$ are identical for the strontium and cesium nuclides, indicating that the ground concentration standards for these nuclides were based on adult food intake. On the other hand, the $PSCMLK_i$ and $PSCOTH_i$ values differ for both the iodine nuclides indicating the ground concentration standards for $PSCMLK_i$ were based on the infant milk intake.

C.6 Ground Concentrations for the Long-Term Pathway Submodel

The single permissible ground concentration for the "long-term pathway" submodel, $GCMAXR_i$, was derived from Equation (C.3) by using the following values for each variable:

$DL_{i,k}$ - preventative PAG dose criteria as applied to the target organ being considered for each nuclide

$DF_{i,k}$ - ingestion dose conversion factor for the appropriate nuclide i and a selected target organ k (Sv/Bq)

$ADJA_j$ - area utilized to grow crop j in sufficient quantity to provide all foods in the adult market basket (m^2)

$TF_{i,j}$ - "long-term pathway" transfer factor (unitless)

A table of the values used for each of these variables can be found in Section C.3. The resulting values for $GCMAXR_i$ were

Nuclide	GCMAXR (Bq/m^2)
Sr-89	1.79E+08
Sr-90	3.67E+04
Cs-134	4.07E+06
Cs-137	1.76E+06
I-131	9.40E+07
I-133	1.48E+13

It is deemed undesirable to have the ground concentrations for the two iodine nuclides trigger the interdiction of land for a year when their short half-life would make such an action questionable. Therefore, the permissible ground concentration for "long-term pathway" submodel for these two nuclides was set to 1.0E+20 to avoid such actions. The values derived for the user-specified input variable, GCMAXR, then became as follows:

Nuclide	GCMAXR (Bq/m^2)
Sr-89	1.79E+08
Sr-90	3.67E+04
Cs-134	4.07E+06
Cs-137	1.76E+06
I-131	1.00E+20
I-133	1.00E+20

Addendum 1

Calculation of the Ground Area Utilized to Provide the Maximally Exposed Individual with an Annual Market Basket of Foodstuffs

The problem being considered is that of defining a market basket (the total amount of food consumed in a year) by the maximally exposed individual and then using supporting data to convert that market basket into the required land area (m^2) required to produce those foodstuffs.

The Regulatory Guide 1.109 [US77] recommended the following market basket for the maximally exposed individuals

Foodstuff	Infant	Adult
Milk (l/yr)	330	310
Meat & Poultry (kg/yr)		110
Grain (kg/yr)		125
Leafy Vegetables (kg/yr)		64
Fruits (kg/yr)		114
Vegetables (kg/yr)		217

Because of the different crop utilization rates by the various meat animals, the meat and poultry category was further refined using recent agricultural data [US84 - Table 455, p.310 and Table 516, p.363], which indicate that beef accounts for 42 percent of the meat intake, pork accounts for 29 percent, and poultry for the remaining 29 percent. The poultry intake is comprised of 84 percent chicken and 16 percent turkey.

In a similar manner, the vegetable category was further refined using appropriate agricultural statistical data [US84] to the following:

Legumes and Nuts	32 kg/yr
Roots and Tubers	90 kg/yr
Other vegetables	95 kg/yr

The "other vegetables" (i.e., 95 kg/yr) are combined with the "fruits" to obtain the "other foods" category (i.e., 209 kg) in the following table.

As a result of these modifications the market basket used was as follows:

Foodstuff	Infant	Adult
Milk (l/yr)	330	310
Meat (kg/yr)		
Beef		46.2
Pork		31.9
Chicken		26.8
Turkey		5.1
Grain (kg/yr)		125
Legumes and Nuts (kg/yr)		32
Green Leafy Vegetables (kg/yr)		64
Roots and Tubers (kg/yr)		90
Other Foods (kg/yr)		209

In general, the annual ground area utilization for crop j was found in the following manner:

$$AGAU = AC/PRUA \ (m^2) \tag{C.8}$$

where

AC = annual consumption of crop j (ℓ or kg), and

PRUA = annual production of crop j per unit area (ℓ/m^2 or kg/m^2).

Equation (C.8) applies to both crops consumed by man directly and also to crops consumed by animals that in turn produce food which is consumed by man.

Animal Products (Milk, Beef, Pork, Etc.)

In the case of animal products, the consumption used was that of the animal producing the food. The grazing rate of 3.88 kg/day was used as developed by Boone et al. [Bo81]. This rate was applied to both dairy and beef animals for their consumption of pasture. Beef animals consume 7.4 kg of stored forage per day, and dairy animals consume 10.0 kg/day. It was assumed that the cattle graze on pasture 180 days of the year and are fed stored forage when not being pastured. None of the other animals being considered as a source of food will consume either pasture or stored forage. Using the given information the annual consumption by both groups of animals can be found for both pasture and stored forage.

	Annual Consumption (kg)	
	Dairy Cow	Beef Cow
Pasture	698.40	698.40
Stored Forage	1852.50	1370.85

Example:

annual consumption of pasture by dairy cow = 3.88 kg/d • 180 d/yr
= 6.98.4 kg/yr

stored forage by dairy cow = 10 kg/d • 185.25 d/yr
= 1852.5 kg/yr

It was assumed that both pasture and forage are produced at a rate of 0.7 kg/m² as indicated by the NRC [US77]. This suggests that the area utilized annually to produce the pasture and stored forage to feed a dairy cow and a beef cow utilizing Equation C.8 would be

	AGAU (m^2)	
	Dairy Cow	Beef Cow
Pasture	997.71	997.71
Stored Forage	2646.43	1958.36

Example:

pasture for dairy cow = (698.40 kg/yr) / .07 kg/m² = 997.7 m²/yr

It is also necessary to establish AGAU for all food animals that reflects their annual consumption of grains and legumes. The following daily consumption rates were established by Boone et al. [Bo81].

	Daily Consumption (kg)				
	Dairy Cow	Beef Cow	Hogs	Chickens	Turkeys
Grain	2.09	1.54	2.77	0.052	0.14
Legumes	0.46	0.34	0.61	0.012	0.030

It is assumed that all animals are fed grain and legume supplements every day, which leads to the following annual consumptions:

	Annual Consumption (kg)				
	Dairy Cow	Beef Cow	Hogs	Chickens	Turkeys
Grain	763.4	562.5	1011.7	19.0	51.1
Legumes	168.0	124.2	222.8	4.4	11.0

Example:

grain for dairy cow = 2.09 kg/d • 365.25 d/yr = 7.63.4 kg/yr

The production rates for these crops were derived using weighted averages and current agricultural data [US84]. Grain is produced at the rate of .46 kg/m^2, and legumes at the rate of .25 kg/m^2.

The annual ground area utilized to raise these crops to feed a single animal for a year are as follows:

	AGAU (m^2)				
	Dairy Cow	Beef Cow	Hogs	Chickens	Turkeys
Grain	1659.6	1222.8	2199.3	41.3	112.0
Legumes	672.0	496.8	891.2	17.6	44.0

Example:

grain for dairy cow = (763.4 kg/yr) / 0.46 kg/m^2 = 1659.6 m^2/yr

It will be recalled that the area derived for animals represent the area required to feed a single animal for one year. That area must be multiplied by the fraction of the total annual food production by that animal that will be eaten by a single individual. The annual food production per animal data were derived from recent agricultural data [US84].

The fractions for milk were based on the average annual production of a dairy cow. The fractions for meat were based on the quotient of average weight at the time of the animal slaughtered (kg) divided by the fraction of a year required to raise the animal for slaughter. The yearly fractions used were as follows:

Animal	Fraction of a Year
Beef Cow	2.0
Hog	0.42
Chicken	0.25
Turkey	0.50

These fractions, FPCI, can derived and summarized as follows:

Food	Annual Production by Single Animal	Annual Consumption by Single Individual	FPCI
Infant			
Milk	5844.0 liters	330.0 liters	.0565
Adult			
Milk	5844.0 liters	310.0 liters	.0530
Beef	114.5 kg	46.2 kg	.4035
Pork	170.4 kg	31.9 kg	.1872
Chicken	4.8 kg	26.8 kg	5.583
Turkey	12.0 kg	5.1 kg	.425

These values of FPCI are then multiplied by the area's AGAU to arrive at the area actually required to raise the food and animal feed required to produced the annual food intake for the maximally exposed individual.

Example:

$$\text{stored forage for beef consumed} = 1958.36 \text{ m}^2/\text{yr} \bullet 0.4035$$
$$= 790.2 \text{ m}^2/\text{yr}$$

Crops Consumed Directly by Man

The remaining values of AGUA for the crops eaten directly by man can be found by using the annual consumption rates and the production rates as found for grains and stored forage as well as these additional production rates: (1) 2 kg/m^2 for green leafy vegetables and for "other food" crop categories [US77], and (2) 2.98 kg/m^2 for roots and tubers as derived using weighted averages and agricultural data [US84].

	Grain	Legumes	Green Leafy	Roots and Tubers	Other Food
AGUA (m^2)	271.7	128.0	32.0	30.2	104.5

Example:

grain consumed by adult = 125 kg/yr

area utilized for grain for adult = (125 kg/yr) / (.46 kg/m^2)
= 271.1 m^2/yr

Summary of Land Area Utilized

The following table summarizes the areas utilized for each pathway based on the concepts of the market basket and the maximally exposed individual.

Crop	Area Utilized (m^2)	Crop	Area Utilized (m^2)
Pasture		Legumes	
Infant milk	56.4	Infant milk	38.0
Adult milk	52.9	Adult milk	35.6
Beef	402.6	Beef	200.5
Stored forage		Pork	166.8
Infant milk	149.5	Chicken	98.3
Adult milk	140.3	Turkey	18.7
Beef	790.2	Man	128.0
Grain		Green Leafy Vegetables	32.0
Infant milk	93.8	Roots and Tubers	30.2
Adult milk	88.0	Other Foods	104.5
Beef	493.4		
Pork	411.7		
Chicken	230.6		
Turkey	47.6		
Man	271.7		

Addendum 2

Calculation of the Transfer Factors for Radioactive Material Deposited onto Plant Surfaces and Soil to the Edible Portion of the Harvested Crops

To derive the overall transfer factors for radionuclides found in the soil to the edible portion of the plant requires the derivation of values for the following two variables:

$CTD_{i,j}$ = the fraction of the quantity of radionuclide i directly deposited on the field that is found in the edible portion of crop j at the time of harvest,

$CTR_{i,j}$ = the fraction of the quantity of radionuclide i deposited onto the soil which enters the edible portion of crop j via root uptake or is ingested with soil by grazing animals.

$CTD_{i,j}$ is time dependent since the amount of weathering that occurs from plants in which the edible portion is exposed as well as the amount of translocation that occurs will be determined by the time in the growing season when the accident occurs.

The derivation of values for these two variables will be discussed using the appropriate input variable names from the MACCS code.

<u>Current Growing Season Transfer Factor, $CTD_{i,j}$</u>

As a crop, pasture is handled in a different manner from all other crops. It is assumed for the model that pasture undergoes continual harvest throughout the growing season and that the entire pasture could be consumed at the end of the growing season. Therefore, the derivation of a value of CTD for pasture differs than the derivation of CTD for all other crops assumed to have a discrete harvest at the end of the growing season.

For pasture

$$CTD_{i,j} = \sum_{n} CTCOEF_{i,j,n} \bullet \left\{ \left[1 - e^{\left(-H_{i,j,n} \bullet Td_{j}\right)} \right] \right\} / H_{i,j,n}, \qquad (C.9)$$

where

$CTCOEF_{i,j,n}$ = fraction of the nuclide i on crop j which follows the weathering pattern n,

Td_j = time between the accident and the end of the growing season (sec),

Tt_j = total time in the growing season (sec), and

$$H_{i,j,n} = (\ln 2/CTHALF_{i,j,n}) + (\ln 2/Tt_j) + \lambda_i,$$

where

$CTHALF_{i,j,n}$ = weathering half life for nuclide i on crop j which follows the weathering term n (sec),

λ_i = the radiological decay constant for nuclide i (sec^{-1}).

The following values were derived for the depletion constants, $H_{i,j,n}$:

Nuclide	$H_{i,j,1}$	$H_{i,j,2}$
Sr-89	7.72E-07	3.59E-07
Sr-90	6.18E-07	2.06E-07
Cs-134	6.28E-07	2.16E-06
Cs-137	6.18E-07	2.06E-07
I-131	1.62E-06	1.20E-06
I-133	9.88E-06	9.47E-06

For nonpasture crops,

$$CTD_{i,j} = \sum_n CTCOEF_{i,j,n} \bullet e^{\left\{-\left[\left(\ln 2/CTHALF_{i,j,n}\right) + \lambda_i\right] \bullet Td_j\right\}}, \qquad (C.10)$$

where the variables represent the same quantities as for pasture.

The values for $CTD_{i,j}$ will always be equal to 0.0 for all time following the first growing season. The values derived for CTD are as follows:

Crop Category	Sr-89	Sr-90	Cs-134	Cs-137	I-131	I-133
Pasture	3.77E-02	4.99E-02	4.89E-02	4.99E-02	1.60E-02	2.47E-03
Stored Forage	2.66E-02	4.82E-02	4.64E-02	4.82E-02	9.94E-04	1.12E-17
Grains	5.50E-03	9.97E-03	4.79E-02	4.99E-02	0.0	0.0
Legumes and Nuts	2.75E-03	4.99E-03	9.59E-03	9.97E-03	0.0	0.0
Leafy Green Vegetables	3.19E-02	5.78E-02	5.56E-02	5.79E-02	1.19E-03	1.43E-17
Roots and Tubers	3.30E-04	5.98E-04	2.40E-02	2.49E-02	0.0	0.0
Other Foods	2.66E-02	4.82E-02	4.64E-02	4.82E-02	9.94E-04	1.12E-17

Long-Term Pathway Transfer Factor, $CTR_{i,j}$

In general, this transfer factor is the sum of two integrals taken over the period of time being considered. The first integral represents the fraction of the nuclide transferred from the soil to the edible portion of the plant via root uptake. The second integral represents the fraction of the nuclide on the surface of the soil consumed with the soil ingested by grazing animals.

$$CTR_{i,j} = RTRU_{i,j} \bullet \int_{t_1}^{t_2} e^{-SUMRU_{i,j} \bullet t} \, dt + RTSI_{i,j} \bullet \int_{t_1}^{t_2} e^{-SUMSI_{i,j} \bullet t} \, dt. \quad (C.11)$$

SUMRU is the overall depletion rate from the root zone of the soil compartment for nuclide i for crop j. SUMSI is the overall depletion rate from the surface soil compartment for nuclide i for crop j. Therefore, SUMRU can be expressed by the following equation:

$$SUMRU_{i,j} = RTRU_{i,j} + RTP_i + RTB_i + RTD_i + RTSI_{i,j}$$

and

$RTRU_{i,j}$ = rate at which nuclide i is lost from the root zone via root uptake,

RTP_i = rate at which nuclide i is lost from the root zone via percolation,

RTB_i = rate at which nuclide i is lost from the root zone via binding with the soil,

RTD_i = rate at which nuclide i is lost from the root zone via radiological decay,

$RTSI_j$ = rate at which nuclide i is lost from the root zone via soil ingestion,

t_1 = the beginning of the time period of interest,

t_2 = the end of the time period of interest.

Similarly, SUMSI is expressed by the following equation:

$$SUMSI_{i,j} = RTRU_{i,j} + SSRTP_i + SSRTB_i + RTD_i + RTSI_j$$

and

$RTRU_{i,j}$ = rate at which nuclide i is lost from the surface soil compartment via root uptake,

$SSRTP_i$ = rate at which nuclide i is lost from the surface soil compartment via percolation,

$SSRTB_i$ = rate at which nuclide i is lost from the surface soil compartment via binding with the soil,

RTD_i = rate at which nuclide i is lost from the surface soil compartment via radiological decay,

$RTSI_j$ = rate at which the nuclide is lost to root zone via soil ingestion,

t_1 = the beginning of the time period of interest,

t_2 = the end of the time period of interest.

Pasture is the only crop for which soil ingestion occurs; therefore, the second integral will be equal to 0.0 for all nonpasture crops.

For the current application of the MACCS code, the quantity of interest is the fraction of the material deposited onto the soil in cropland that will over time be taken up by plants and ultimately consumed by man. By adhering to that interpretation the values of t_1 and t_2 are defined: $t_1 = 0$ and $t_2 = \infty$, where $t_1 = 0$ represents the time of the accident.

The evaluation of the integrals in Equation (C.11) over this time period simplify to become

$$CTR_{i,j} = [RTRU_{i,j}/(RTRU_{i,j} + RTP_i + RTB_i + RTD_i + RTSI_{i,j})]$$
$$+ [RTSI_{i,j}/(RTRU_{i,j} + SSRTP_i + SSRTB_i + RTD_i + RTSI_{i,j})]$$

and the derived values for CTR are shown in the following table:

Crop Category	Sr-89	Sr-90	Cs-134	Cs-137	I-131	I-133
Pasture	4.06E-04	2.58E-02	1.30E-03	6.92E-03	1.59E-05	1.71E-06
Stored Forage	1.28E-03	9.01E-02	7.09E-04	1.52E-03	0.0	0.0
Grains	4.29E-05	3.29E-03	3.55E-05	7.63E-05	0.0	0.0
Legumes and Nuts	3.67E-04	2.75E-02	9.29E-05	2.00E-04	0.0	0.0
Leafy Green Vegetables	1.69E-04	1.29E-02	1.40E-05	3.02E-05	0.0	0.0
Roots and Tubers	1.10E-04	8.42E-03	5.57E-05	1.20E-04	0.0	0.0
Other Foods	8.57E-06	6.60E-04	1.06E-04	2.29E-04	0.0	0.0

Addendum 3

Input Parameters Used to Derived Current Values of Allowable Ground Concentrations PSCMLK, PSCOTH, and GCMAXR

This section summarizes all input parameters discussed in Addenda 1 and 2, that is, those parameters needed to calculate allowable ground concentrations.

"Growing Season Pathway" Submodel Input Parameters

To find the maximum allowable ground concentrations for the "growing season pathway" submodel, it was necessary to determine a single value for both PSCMLK and PSCOTH that would ensure that both the maximally exposed adult and the maximally exposed infant would be protected. To do this, it was necessary to use some input parameters that were not needed to calculate the maximum ground concentrations for the "long-term pathway" submodel $GCMAXR_i$. These input parameters are defined below.

DL = allowable dose limit for nuclide i to organ k for emergency PAG (used for both infant and adult) (Sv),

Nuclide	Target Organ	DL (Sv)
Sr-89	EDEWBODY	.05
Sr-90	EDEWBODY	.05
Cs-134	EDEWBODY	.05
Cs-137	EDEWBODY	.05
I-131	THYROID	.15
I-133	THYROID	.15

DF = ingestion dose conversion factor (Sv/Bq),

Adult:

NUCLIDE	THYROID	EDEWBODY
Sr-89	2.584E-10	2.503E-09
Sr-90	1.333E-09	3.518E-08
Cs-134	1.764E-08	1.975E-08
Cs-137	1.257E-08	1.355E-08
I-131	4.753E-07	1.434E-08
I-133	9.102E-08	2.800E-09

Adult dose conversion factors supplied by ORNL.

Infant:

A set of ingestion dose conversion factors for the infant was derived from those for the adult. By using the FDA dose conversion factors given in the Regulatory Guide 1.109 [US77] and assuming that the relative sizes of the conversion factors would remain unchanged, it is possible to derive a multiplier that can be applied to the ORNL adult dose conversion factors to arrive at a corresponding infant dose conversion factor. The multiplier was derived as being

$$\text{Multiplier} = (\text{FDA infant DF})/(\text{FDA adult DF}).$$

The following results were obtained.

		THYROID	TBODY
Sr-89			
	FDA infant DF	NO DATA	7.20E-05
	FDA adult DF	NO DATA	8.84E-06
	Multiplier	1.0	8.14480
Sr-90			
	FDA infant DF	NO DATA	4.71E-03
	FDA adult DF	NO DATA	1.86E-03
	Multiplier	1.0	2.53226
Cs-134			
	FDA infant DF	NO DATA	7.10E-05
	FDA adult DF	NO DATA	1.21E-04
	Multiplier	1.0	0.586777
Cs-137			
	FDA infant DF	NO DATA	4.33E-05
	FDA adult DF	NO DATA	7.14E-05
	Multiplier	1.0	0.606443
I-131			
	FDA infant DF	1.39E-02	1.86E-05
	FDA adult DF	1.95E-03	3.41E-06
	Multiplier	7.12821	5.45455
I-133			
	FDA infant DF	3.31E-03	5.33E-06
	FDA adult DF	3.63E-04	7.53E-07
	Multiplier	9.11846	7.07835

DFI = The derived infant ingestion dose conversion factors:

NUCLIDE	THYROID	EDEWBODY
Sr-89	2.584E-10	2.039E-08
Sr-90	1.333E-09	8.908E-08
Cs-134	1.764E-08	1.159E-08
Cs-137	1.257E-08	8.217E-09
I-131	3.388E-06	7.822E-08
I-133	8.300E-07	1.982E-08

ADJA = area utilized to grow given crop in sufficient quantity to provide all foods in adult market basket (m^2)

		Component Area		Total Area	
Crop	Components	Adult (m^2)	Infant (m^2)	Adult (m^2)	Infant (m^2)
Pasture	for milk	52.9	56.4		
	for meat	402.6		455.5	56.4
Stored Forage	for milk	140.3	149.5		
	for meat	790.2		930.5	149.5
Grain	for milk	88.0	93.8		
	for meat	1183.3			
	direct	271.7		1543.0	93.8
Legumes	for milk	35.6	38.0		
	for meat	484.3			
	direct	128.0		647.9	38.0
Green Leafy Vegetables	direct	32.0		32.0	
Roots and Tubers	direct	30.2		30.2	
Other Foods	direct	104.5		104.5	
		TOTAL		3743.6	337.7

TF - "growing season pathway" overall transfer factors (as defined in Table C.1)

	Sr-89	Sr-90	Cs-134	Cs-137	I-131	I-133
Pasture						
milk	5.48E-04	1.10E-03	5.38E-03	5.489-03	5.82E-04	3.06E-07
meat	6.39E-07	1.10E-05	1.12E-03	1.20E-03	6.91E-06	0.0
Stored Forage						
milk	1.43E-04	1.05E-03	4.69E-03	5.25E-03	2.28E-06	9.25E-24
meat	1.67E-07	1.05E-05	9.81E-04	1.15E-03	2.71E-08	0.0
Grain						
milk	1.60E-05	2.17E-04	4.48E-03	5.43E-03	0.0	0.0
meat	1.86E-08	2.17E-06	9.37E-04	1.195E-03	0.0	0.0
direct	2.47E-04	2.47E-03	1.01E-02	1.23E-02	0.0	0.0
Legumes						
milk	7.98E-06	1.09E-04	8.97E-04	1.09E-03	0.0	0.0
meat	9.31E-09	1.09E-06	1.88E-04	2.37E-04	0.0	0.0
direct	3.96E-04	3.95E-03	6.44E-03	7.90E-03	0.0	0.0
Green Leafy Vegetables	1.07E-02	2.89E-02	2.67E-02	2.89E-02	1.25E-04	0.0
Roots and Tubers	4.75E-05	4.74E-04	1.61E-02	1.97E-02	0.0	0.0
Other Foods	3.96E-03	3.39E-02	2.80E-02	3.39E-02	1.69E-05	0.0

"Long-Term Pathway" Submodel Input Parameters

DL - allowable dose limit for nuclide i to organ k for preventative PAG (Sv)

Nuclide	Target Organ	DL (Sv)
Sr-89	EDEWBODY	.005
Sr-90	EDEWBODY	.005
Cs-134	EDEWBODY	.005
Cs-137	EDEWBODY	.005
I-131	THYROID	.015
I-133	THYROID	.015

DF = ingestion dose conversion factor (Sv/Bq)

	THYROID	EDEWBODY
Sr-89	2.584E-10	2.503E-09
Sr-90	1.333E-09	3.518E-08
Cs-134	1.764E-08	1.975E-08
Cs-137	1.257E-08	1.355E-08
I-131	4.753E-07	1.434E-08
I-133	9.102E-08	2.800E-09

Dose conversion factors supplied by ORNL.

ADJA = area utilized to grow given crop in sufficient quantity to provide all foods in adult market basket

Crop	Components	Component Area (m²)	Total Area (m²)
Pasture	for milk	52.9	
	for meat	402.6	455.5
Stored Forage	for milk	140.3	
	for meat	790.2	930.5
Grain	for milk	88.0	
	for meat	1183.3	
	direct	271.7	1543.0
Legumes	for milk	35.6	
	for meat	484.3	
	direct	128.0	647.9
Green Leafy Vegetables	direct	32.0	32.0
Roots and Tubers	direct	30.2	30.2
Other Foods	direct	104.5	104.5
		TOTAL	3743.6

TF = "long-term pathway" overall transfer factors

Crop Category	Sr-89	Sr-90	Cs-134	Cs-137	I-131	I-133
Pasture						
milk	5.95E-06	5.72E-04	1.43E-04	7.59E-04	5.82E-06	1.224E-10
meat	6.95E-09	5.72E-06	2.99E-05	1.66E-04	6.91E-08	0.0
Stored Forage						
milk	6.98E-06	1.96E-03	7.19E-05	1.63E-04	0.0	0.0
meat	8.15E-09	1.96E-05	1.50E-05	3.56E-05	0.0	0.0
Grain						
milk	1.25E-07	7.19E-05	3.27E-06	8.28E-06	0.0	0.0
meat	1.46E-10	7.19E-07	6.84E-07	1.81E-06	0.0	0.0
direct	1.84E-06	8.17E-04	7.35E-06	1.88E-05	0.0	0.0
Legumes						
milk	1.07E-06	6.10E-04	8.70E-06	2.18E-05	0.0	0.0
meat	1.25E-09	6.10E-06	1.82E-06	4.75E-06	0.0	0.0
direct	5.33E-05	2.22E-02	6.25E-05	1.58E-04	0.0	0,0
Green Leafy Vegetables	5.70E-05	6.50E-03	6.72E-06	1.50E-05	0.0	0.0
Roots and Tubers	1.58E-05	6.65E-03	3.76E-05	9.50E-05	0.0	0.0
Other Foods	1.28E-06	4.64E-04	6.64E-05	1.62E-04	0.0	0.0

APPENDIX D

MACCS DOSE CONVERSION FACTORS

The dose conversion factor data used by MACCS are calculated using the program DOSFAC. The MACCS dose conversion factor data file includes 60 radionuclides and 12 organs compiled from three dose conversion factor data bases: external dose rate conversion factor data for all organs, external dose rate conversion factor data for effective whole body dose equivalent (EDE), and internal dose conversion factor data for all organs and EDE.

The names of 12 organs are shown in Table D.1. In this table, the dose conversion factor for thyroid is used in MACCS for calculating the actual dose for thyroid. And the dose conversion factor for thyroid-H is used for calculating thyroid health effects (e.g., thyroiditis and hypothyroidism of early injury, thyroid cancer for latent health effect) in the MACCS code. For the thyroid-H, I-131 radionuclide conversion factors are reduced by a factor of 5 for the short-term health effects by inhalation and by a factor of 3 for the long-term health effects by inhalation and ingestion [Ab89].

Table D.1

Organs Included in MACCS Dose Conversion File

Stomach	Small Intestine
Lungs	Red Marrow
Thyroid	Lower Large Intestine
Bone Surfaces	Breasts
Testes	Ovaries
EDE Whole Body	Thyroid-H

Dose conversion factors are computed for seven exposure modes:

1. external air immersion (cloudshine) dose rate,
2. external ground-surface exposure (groundshine) dose rate integrated for 8 hours of exposure time,
3. external ground-surface exposure (groundshine) dose rate integrated for 7 days of exposure time,
4. external ground-surface exposure (groundshine) dose rate,
5. inhalation dose for short-term health effects,
6. inhalation dose for long-term health effects (50-year commitment time), and

7. ingestion dose for long-term health effects (50-year commitment time).

The calculation scheme for the program DOSFAC is given in [Ru85]. Parameter values used in the calculation are set in the block data in DOSFAC. Parameters include the list of radionuclide names, organ names, lung clearance classes to be used for each radionuclide, weighting factors for time periods for each organ for use in calculating doses for short-term health effects, regional respiratory deposition fractions versus particle size, ground exposure integration times, long-term dose commitment time for internal exposure, and half-life cutoff for adding external daughter radionuclide dose factors to parent radionuclide dose factors.

The external dose-rate conversion factor data base was received from D. C. Kocher (ORNL) in January 1981. This data base contains external photon dose-rate conversion factors for air immersion, water immersion, and ground-surface exposure for 496 nuclides and 24 organs. External photon and electron dose-rate conversion factors for skin are also included for the three exposure modes. However, the skin dose rate conversion factor data are not used, because the MACCS code calculates the skin dose factors within the code. Radionuclide half-lives are also included.

The external effective dose equivalent rate conversion factor data base was received from K. F. Eckerman (ORNL) in July 1988. This data base contains external photon dose-rate conversion factors for air immersion, water immersion, and ground-surface exposure for 62 radionuclides. As many as two daughter products are also specified for each radionuclide with corresponding branching fractions.

The internal dose factor conversion data base was received from K. F. Eckerman (ORNL) in February 1988. This data base contains organ-specific dose conversion factors for a reference adult for 18 incremental time periods and 21 organs (including EDE) following acute inhalation or ingestion of each of 60 radionuclides. Ingestion dose conversion factors are tabulated for all appropriate gastro-intestinal absorption fractions for each radionuclide. Inhalation dose conversion factors are tabulated separately for depositions in the nasopharyngeal, tracheobronchial, and pulmonary regions for each TGLM clearance category (rapid (Days), intermediate (Weeks), and protracted (Years) clearance from the lung) and for 17 activity median aerodynamic diameters (AMAD) ranging from 0.2 to 10 microns. Dose conversion factors are tabulated separately for low- and high-LET radiation if high-LET radiation is present. The effective whole body dose equivalent conversion factors in this data base were computed using the weighting scheme recommended by the International Commission on Radiological Protection [IC78].

Deposition fractions for the nasopharyngeal (NP), tracheobronchial (TB), and pulmonary (P) regions of the lung as a function of activity median aerodynamic diameter (AMAD) plus the deposition fractions for gases are shown in Table D.2.

Table D.2

Deposition Fractions for Different Regions of Lung as a Function of AMAD

AMAD (micron)	Regional Deposition Fractions NP	TB	P
0.2	0.050	0.08	0.50
0.3	0.088	0.08	0.43
0.4	0.13	0.08	0.39
0.5	0.16	0.08	0.35
0.6	0.19	0.08	0.32
0.7	0.23	0.08	0.30
0.9	0.26	0.08	0.28
1.0	0.30	0.08	0.25
2.0	0.50	0.08	0.17
3.0	0.61	0.08	0.13
4.0	0.69	0.08	0.10
5.0	0.74	0.08	0.088
6.0	0.78	0.08	0.076
7.0	0.81	0.08	0.067
8.0	0.84	0.08	0.060
9.0	0.86	0.08	0.055
10.0	0.87	0.08	0.050
GASES	0.02	0.04	0.94

For the noble gases, the fractions are estimated from the relative volumes of the three regions. All inhalation dose conversion factors in the MACCS data base assume a 1 micron AMAD particle size. Dose conversion factors for gases are independent of AMAD and clearance class since gases do not deposit in the lung.

The incremental time periods used in the internal dose conversion factor data base are shown in Table D.3.

Table D.3

Incremental Time Periods Used in Internal Dose Conversion Factor Data Base

0- 1 days	18- 21 days	200-365 days
1- 2 days	21- 28 days	1-10 years
2- 7 days	28- 30 days	10-20 years
7-10 days	30- 50 days	20-30 years
10-14 days	50- 60 days	30-40 years
14-18 days	60-200 days	40-50 years

Lung clearance classes for each radionuclide in the MACCS dose conversion factor data base are defined in Table D.4 [Ru85].

Table D.4

Lung Clearance Class for Each Radionuclide in MACCS

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

In the MACCS code, the early health effect models do not have dose rate effects. To compute short-term inhalation dose conversion factors, organ-specific weighting factors for different time periods are used to compute a single factor for each organ and radionuclide combination as shown in Table D.5.

Low LET radiation internal dose conversion factors always use a quality factor of 1. For the short-term health effects from inhalation, high LET radiation dose conversion factors are multiplied by a quality factor of 10 before being added to the low LET radiation dose conversion factor. For the long-term health effects from inhalation and ingestion, high LET radiation dose conversion factors are multiplied by a quality factor of 20 before being added to the low LET radiation dose conversion factors.

For the calculation of air immersion (cloudshine) and ground surface exposure (groundshine) dose conversion rate factors, the dose conversion rate factors for daughter products are added to the parent dose conversion rate factors if the half-life of the daughter product is less than 1.5 hours. This is an assumption that, for this case, the decay rate for the daughter products is in equilibrium with the decay rate of the parent. The integrated ground-surface exposure dose conversion factors include daughter product dose conversion factors explicitly due to the use of the standard parent/daughter decay formula. The internal dose conversion factors data base includes the effects of any daughter products.

The dose conversion factor data calculated by DOSFAC are presented in Appendix D.10 of MACCS User's Guide [Ch89].

Table D.5

Multiplicative Factors of Different Time Periods for Calculating Single Short Term Inhalation Dose Conversion Factor

Short-Term Health Effects Organ	Time Period (Days)	Multiplicative Factor
Stomach	0 - 1	1.0
	1 - 7	0.37
Small Intestine	0 - 1	1.0
	1 - 7	0.43
Lung	0 - 1	1.0
	1 - 14	0.0625
	14 - 200	0.0270
	200 - 365	0.0109
Red Bone Marrow	0 - 1	1.0
	1 - 14	0.5
	14 - 30	0.25
Lower Large Intestine	0 - 1	1.0
	1 - 7	0.43
Thyroid-H	0 - 1	1.0
	1 - 28	0.2

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Nuclear Engineering Dept.
153 Engineering Research Bldg.
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San Jose, CA 95129

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GRAM, Inc.
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Arizona State University
Tempe, AZ 85287

Mr. Griff Holmes
Westinghouse Electric Co.
Energy Center East
Bldg. 371
P.O. Box 355
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Stone & Webster Engineering Corp.
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Mr. Ian Wall
Electric Power Reseach Institute
3412 Hillview Avenue
Palo Alto, CA 94304

Mr. Jim Meyer
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11821 Parklawn Dr.
Suite 100
Rockville, MD 20852

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NUMARC
1776 Eye St, NW
Suite 300
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Mr. S. Daggupaty
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Downsview
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Canada

Mr. Soren Thykier-Nielsen
Riso National Laboratory
Postbox 49
DK-4000 Roskilde
Denmark

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P.O. Box 169
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Mr. Joachim Ehrhardt
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Postfach 3640
D-7500 Karlsruhe 1
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Mr. John G. Kollas
Institute of Nuclear Technology and
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Austria

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Hong-Nian Jow, Jeremy L. Sprung, Judith A. Rollstin,
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11. ABSTRACT (200 words or less)

This report describes the MACCS computer code. The purpose of this code is to simulate the impact of severe accidents at nuclear power plants on the surrounding environment. MACCS has been developed for the U.S. Nuclear Regulatory Commission to replace the previous CRAC2 code and it incorporates many improvements in modeling flexibility in comparison to CRAC2.

The principal phenomena considered in MACCS are atmospheric transport, mitigative actions based on dose projection, dose accumulation by a number of pathways including food and water ingestion, early and latent health effects, and economic costs.

The MACCS code can be used for a variety of applications. These include (1) probabilistic risk assessment (PRA) of nuclear power plants and other nuclear facilities, (2) sensitivity studies to gain a better understanding of the parameters important to PRA, and (3) cost-benefit analysis.

This report is composed of three volumes. Volume I, the User's Guide, describes the input data requirements of the MACCS code and provides directions for its use as illustrated by three sample problems. Volume II, the Model Description, describes the underlying models that are implemented in the code, and Volume III, the Programmer's Reference Manual, describes the code's structure and database management.

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