MACCS2 DEVELOPMENT AND VERIFICATION EFFORTS

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ABSTRACT

MACCS2 represents a major enhancement of the capabilities of its predecessor MACCS, the MELCOR Accident Consequence Code System. MACCS, publicly released in 1987, was developed to estimate the potential impacts to the surrounding public of severe accidents at nuclear power plants. The principal phenomena considered in MACCS/MACCS2 are atmospheric transport and deposition under time-variant meteorology, short-term and long-term mitigative actions and exposure pathways, deterministic and stochastic health effects, and economic costs. MACCS2 was developed as a general-purpose analytical tool applicable to diverse reactor and nonreactor facilities. The MACCS2 package includes three primary enhancements: (1) a more flexible emergency response model, (2) an expanded library of radionuclides, and (3) a semidynamic food-chain model. In addition, errors that had been identified in MACCS version 1.5.11.1 were corrected, including an error that prevented the code from providing intermediate-phase results. MACCS2 version 1.10 beta test was released to the beta-test group in May, 1995. In addition, the University of New Mexico (UNM) has completed an independent verification study of the code package. Since the beta-test release of MACCS2 version 1.10, a number of minor errors have been identified and corrected, and a number of enhancements have been added to the code package. The code enhancements added since the beta-test release of version 1.10 include: (1) an option to allow the user to input the σ_y and σ_z plume expansion parameters in a table-lookup form for incremental downwind distances, (2) an option to define different initial dimensions for up to four segments of a release, (3) an enhancement to the COMIDA2 food-chain model preprocessor to allow the user to supply externally calculated tables of tritium food-chain dose per unit deposition on farmland to support analyses of tritium releases, and (4) the capability to calculate direction-dependent doses. The table-lookup option allows the user to bypass the power-law functions for σ_y and σ_z. The capability of defining four segments of a release was added to better model stem and cap type releases associated with explosive releases. The direction-dependent dose option was added as a result of UNM verification work relating to the network evacuation model and requests for these calculations from U.S. Department of Energy facilities. Public release of the code is planned for the last quarter of 1996. MACCS2 was developed under the sponsorship of the U.S. Department of Energy and the U.S. Nuclear Regulatory Commission. Installation of the code, written in FORTRAN 77, requires a 486 or higher IBM-compatible PC with 8 MB of RAM.

OVERVIEW OF MACCS CODE

MACCS[1,2,3,4] was developed at Sandia National Laboratories (SNL) under U.S. Nuclear Regulatory Commission (NRC) sponsorship to estimate the offsite consequences of potential severe accidents at

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nuclear power plants (NPPs). MACCS, publicly released in 1987, was developed to support the NRC's probabilistic safety assessment (PSA) efforts.

MACCS models the transport and dispersion of plumes of radioactive material released to the atmosphere. The deposition of radioactive material from the plume to the ground is modeled for both wet and dry deposition processes. The dispersion of the plume in the vertical and horizontal directions during downwind transport is estimated using an empirical Gaussian plume model. In this model, dispersion, downwind transport, and deposition depend on the prevailing meteorological conditions following the atmospheric release. Meteorological conditions can be modeled as time invariant or may vary hour by hour. They may be specified in the ATMOS user input file or through a weather data file that contains a year of historical hourly weather data. The user may specify that meteorological conditions at the time of release vary on an hourly basis through the sampling of a year of historical hourly meteorological data. This sampling allows the uncertainty in meteorological conditions at the time of the accident to be included in code calculations. Variability in consequences due to weather may be obtained in the form of a complementary cumulative distribution function (CCDF).

MACCS models seven pathways through which the general population can be exposed to radiation: cloudshine, groundshine, direct and resuspension inhalation, ingestion of contaminated food and water, and deposition on skin. Emergency response and protective measures for both the short and long term may also be modeled as means to mitigate the extent of the exposures. Dosimetry models calculate doses resulting from both prompt and long-term exposures. Acute health effects and cancers may be estimated. As a final step, the economic costs that would result from mitigative actions may also be estimated.

MACCS is organized into three modules. The ATMOS module performs atmospheric transport and deposition calculations. The EARLY module estimates the consequences of the accident during the emergency phase immediately following the accident (usually within the first week). The CHRONC module estimates the intermediate and long-term phase consequences of the accident.

MACCS has been used in a variety of applications since its initial application in the NUREG-1150 study.[5] Two examples of the diverse types of analyses that have utilized MACCS are the U.S. Department of Energy (DOE) Defense Programs Safety Survey[6] (DPSS) and the evaluation of a proposal to amend 10 CFR 100 to include population density limit criteria for the siting of new commercial reactors.[7] The DPSS was a survey-level evaluation of 27 nonreactor nuclear facilities conducted to gain insights into the relative risks posed by these highly diverse facilities. 10 CFR Part 100 is the section of the U.S. Code of Federal Regulations (CFR) that delineates reactor siting criteria. MACCS has also been used for the probabilistic consequence assessment of advanced reactor designs, i.e., the ABWR[8] and SBWR[9] designs.

MACCS has been applied in two international collaborative efforts; the Second International Comparison of Probabilistic Accident Consequence Codes[10] organized by the Nuclear Energy Agency of the Organization for Economic Cooperation and Development (OECD) and the European Commission (EC), and a probabilistic consequence uncertainty study[11] jointly sponsored by the NRC and EC.

MACCS has been widely used in National Environmental Policy Act (NEPA) studies by the DOE since the use of version 1.5.11 for the New Production Reactor (NPR) environmental impact statement

(EIS).[12] A number of large-scope EISs utilizing MACCS have recently been issued by the DOE, including EISs relating to:

- Tritium supply and recycling,[13]
- Foreign research reactor fuel,[14]
- Stockpile stewardship and management,[15]
- Pantex plant site-wide EIS (SWEIS),[16]
- Storage and disposition of fissile materials.[17]

MACCS2 DEVELOPMENT EFFORTS

MACCS2 represents a major enhancement of the capabilities of its predecessor MACCS. MACCS2 was developed to supersede MACCS as a general-purpose analytical tool applicable to diverse NRC-licensed and DOE reactors and nonreactor nuclear facilities. This effort was initiated in 1991. The MACCS2 package includes three primary enhancements over MACCS: (1) a more flexible emergency response model, (2) an expanded library of radionuclides and the ability to handle long decay chains, and (3) a semidynamic food-chain model developed by M.L. Abbott and A.S. Rood.[18] A detailed overview of these three enhancements was provided at the 1994 International MACCS User's Group Meeting.[19]

These enhancements were developed through cooperation and joint efforts with the technical staff at Brookhaven National Laboratory, Idaho National Engineering Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, the Rocky Flats Environmental Technology Site, the Savannah River Site, and the Hanford Reservation. These enhancements have also benefited from ongoing NRC research, as well as the joint NRC and EC consequence uncertainty study.[20]

The new code features allow detailed evaluation of risks to workers at nearby facilities on large DOE reservations and allow the user to assess the impacts of 765 radionuclides that cannot be readily considered with MACCS. The new emergency response model allows the user to model nonradial evacuation paths, evacuation speeds that vary with time, and up to three different evacuee groups. The code package allows the user to access and utilize dose conversion factors (DCFs) from three different databases, including the DCFs and radioactive decay data of Federal Guidance Reports 11 and 12 published by the Environmental Protection Agency.[21,22] The semidynamic food-chain model allows the user to evaluate consequences for accidents postulated to occur throughout the year, and, once the data have been assembled, to readily include a diverse range of radionuclides in the analysis. In addition, a number of new output measures have been added to the code that increase its usefulness as a research tool and facilitate the verification of its results. Code errors were corrected before each successive beta-test release of MACCS2.

MACCS2 version 1.01 was released to a small group of DOE beta-test users in 1993. Some of these participants have utilized code results to support facility authorization basis and NEPA studies. For examples, see the work of S.E. Fisher and K.E. Lenox[23] and V.L. Peterson.[24,25,26,27] The semidynamic food-chain model was redesigned and rewritten after the beta-test release of MACCS2 version 1.01. MACCS2 version 1.10 was released to both the original DOE beta-test group and IMUG members in 1995. MACCS2 is scheduled to be publicly released in the last quarter of 1996.

MACCS Version 1.5.11.1 Coding Errors Corrected in MACCS2 Version 1.01

Corrections were implemented in MACCS2 for three errors in MACCS version 1.5.11.1. These errors involved the (1) implementation of the dose and dose rate effectiveness factor (DDREF), (2) the specification of Type 3 results, and (3) the calculation of intermediate-phase doses.

DDREF Calculations

According to the Linear No-Threshold Hypothesis promulgated by the International Commission on Radiological Protection (ICRP), low doses delivered at low dose rates are assumed generally to have risk coefficients that are half of those associated with high doses and dose rates. ICRP 60 recommended the reduction of absorbed doses by a DDREF of two for doses below 0.2 Gy or a dose rate below 0.1 Gy per hour.[28] An error was discovered in the implementation of the DDREF in MACCS version 1.5.11.1 emergency-phase calculations. The error resulted in the underestimation of cancer fatalities by approximately 30 percent. However, for applications where a single cancer risk factor is typically used, such as those using the ICRP 60 risk factor of 0.05/sievert effective dose, the error has no impact as long as the MACCS DDREF input parameter is set to a value of one.

Type 3 Results

The Type 3 results allow the user to obtain information on how many individuals receive doses exceeding user-specified thresholds. There were several problems with the MACCS implementation of this feature which have been corrected in MACCS2 as follows. MACCS failed to report an input error when Type 3 acute doses were requested for organs for which the user had not provided acute dose DCFs and, instead of diagnosing an input error as is done by MACCS2, the code reported zeroes for the results. In addition, although the MACCS documentation stated that 10 results of this type could be generated, a coding error in MACCS allowed only 9 results to be generated; and, if 10 results were requested, either erroneous results would be generated or the code would bomb. MACCS2 allows 10 results of this type to be generated without error.

Intermediate Phase Doses Not Being Calculated

All versions of MACCS failed to store intermediate-phase doses for later use. Health effects and collective doses for the intermediate phase were consequently always reported to be zero. The option to print doses and health effects for the intermediate phase is not a commonly used feature of the code and the error was not identified until after the initiation of the MACCS2 effort. The code was corrected and MACCS2 now provides intermediate phase results.

MODIFICATIONS OF MACCS2 AND VERIFICATION EFFORTS SINCE VERSION 1.10 BETA-TEST RELEASE

Feedback from the MACCS2 beta-test group has been of great value to the code development process, identifying errors and making suggestions on additional enhancements. Enhancements and corrections to the code have been ongoing since 1993. In addition to the *ad hoc* verification efforts of the beta-test group, the University of New Mexico (UNM) has completed a formal independent verification study of the code package. This study included detailed hand calculations. The UNM verification effort was performed on version 1.11 of the MACCS2 code package.

Enhancements to MACCS2 Version 1.10 Implemented in MACCS2 Version 1.11
The code enhancements added after the beta-test release of version 1.10 include (1) an option to allow the user to provide externally calculated values of sigma-y and sigma-z for a range of downwind distances in a table-lookup form, (2) an option to define different initial dimensions for up to four segments of a release, and (3) an enhancement to the COMIDA2 food-chain model preprocessor to allow the user to supply externally calculated tables of tritium food-chain dose per unit deposition on farmland to support analyses of tritium releases.

The table-lookup option allows the user to bypass the power-law functions for the sigma-y and sigma-z interpolation algorithm in a manner that avoids the numerical instabilities often observed with cubic spline fits. This new table-lookup algorithm can be used to implement alternative dispersion parameterizations such as the Briggs models, or to utilize fits to site-specific tracer data.

The user-specified definitions of initial plume dimensions on the ATMOS User Input File, BUILDH, SIGYINIT and SIGZINIT, are now included in the set of source term specification results, allowing these parameters to be varied for each of the up to four plume segments comprising a source term. This allows modeling, for example, of "stem-and-cap" models of initial cloud sizes for explosive releases.[29] Whereas in previous versions, a user specification of plumes that overlapped each other in time was a fatal input error, the current code now allows overlapping plumes, but prints a warning to the terminal and the list output file.

MACCS does not allow the atmospheric parameters to be reported as CCDFs. The Type 0 results, a feature added with MACCS2, allow examination of the atmospheric dispersion parameters as a function of distance in CCDF form. For the MACCS2 version 1.10 Type 0 results, CCDFs of the ATMOS parameters, the result "Adjusted Source Strength, Q (Bq)" representing the effective source strength of the plume upon entering the spatial interval, now has been modified to reflect depletion due to deposition over the interval. The other results of this output are unchanged. The Type 0 results for air and ground concentrations are calculated after adjusting the effective source strength by subtracting out half of the total material lost during traversal of the interval. This change to the adjusted source strength result, makes it consistent with the reported air and ground concentrations. In addition, for Type 0 results, the user can now specify a different nuclide for each source term of a multiple-source-term run for which atmospheric CCDFs are to be generated.

Corrections to MACCS2 Version 1.10 Implemented in MACCS2 Version 1.11
The variable DLBCST defined on the CHRONC User Input File specifies the dollar per person-year cost of labor for personnel involved in decontamination. In all prior versions of MACCS and MACCS2 the user was allowed to specify a value of zero for this parameter. The value of DLBCST is used in the denominator of an expression, and thus the specification of a zero value leads to a floating-point exception due to divide-by-zero. The minimum allowable value for this parameter in MACCS2 version 1.11 has been changed to 1.0.

Errors were identified in COMIDA2 1.10 and the MACCS2 version 1.10 implementation of the COMIDA2 food model. COMIDA2 1.10 was not correctly calculating "accumulated" doses. When the COMIDA2 food model was implemented, MACCS2 version 1.10 was assigning a farmland fraction of one regardless of the information contained in the site data file. These errors affected the economic cost results and were corrected in MACCS2 version 1.11.

Enhancements and Corrections to MACCS2 Version 1.11 in Response to UNM Verification Effort
A number of code and documentation improvements were implemented as a result of the UNM verification effort. Documentation improvements primarily consisted of explaining code models in more detail. The code input parameters which define the duration of the emergency, intermediate, and long-term phases were modified. The user is now required to input the duration of these phases directly. In prior versions of the code, the duration of these phases was defined indirectly, relative to other MACCS2 input parameters.

Minor errors were corrected in the network evacuation model. A direction-dependent dose option was added as a result of UNM verification work relating to the network evacuation model, as well as the need for these calculations to support authorization basis studies of DOE nuclear facilities. Direction-dependent doses can be of great interest at facilities where the distance to the site boundary varies significantly with direction from the release point, or where authorization basis calculations make use of the 95 percent direction-independent dose and the 99.5 percent direction-dependent dose as defined in NRC Regulatory Guide 1.145.[30] In addition, the column of results previously used to report the 99.9th percentile was changed so that it now shows the 99.5th percentile.

An option was added which allows the user to specify the movement of evacuees from interval centerpoint to centerpoint rather than from interval endpoint to endpoint. The plume travel algorithm implemented in the MACCS/MACCS2 dose calculations is based on the model of plume movement from interval centerpoint to centerpoint. This option simplifies the modeling of scenarios intended to specify the evacuation of the population relative to the movement of the plume.

MACCS2 OPERATING SYSTEM REQUIREMENTS

Initial installation of the code, written in FORTRAN 77, requires a 486 or higher IBM-compatible PC with 8 MB of RAM. No other software is required for code operation on a PC. MACCS2 has been found to operate correctly under various versions of DOS as well as the DOS window of WINDOWS 3.1. The source code is provided. After installation on a PC, migration to other computer systems having a FORTRAN 77 compiler is straightforward.

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