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OVERVIEW OF MACCS AND MACCS2 DEVELOPMENT EFFORTS

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ABSTRACT

The MELCOR Accident Consequence Code System (MACCS), publicly distributed since 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 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 of mitigative actions. At this time, no other publicly available code in the United States offers all these capabilities. MACCS2 represents a major enhancement of the capabilities of its predecessor MACCS. MACCS2 was developed as a general-purpose analytical tool applicable to diverse reactor and nonreactor Department of Energy (DOE) 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. The new code features allow detailed evaluations of risks to workers at nearby facilities on large DOE reservations and allow the user to assess the potential impacts of over 700 radionuclides that cannot be considered with MACCS.

I. INTRODUCTION

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 nuclear power plants (NPPs). MACCS, publicly released in 1987, was developed to support the NRC's probabilistic safety assessment (PSA) efforts. PSAs are generally divided into three levels. Level I efforts identify potential plant damage states that lead to core damage and the associated probabilities, Level II models damage progression and containment strength for establishing fission-product release categories, and Level III efforts evaluate potential off-site consequences of radiological releases and the probabilities associated with the consequences. MACCS was designed as a tool for Level III PSA analysis. MACCS was first used to perform the consequence calculations of the NUREG-1150[5] study which evaluated severe accident risks for five U.S. NPPs. The models included in the MACCS code are based largely on methodologies originally developed for the 1975 Reactor Safety Study,[6] as refined in the CRAC2 code.[7]

MACCS includes models for atmospheric dispersion and transport, wet and dry deposition, the probabilistic treatment of meteorology, environmental transfer, countermeasure strategies, dosimetry, health effects, and economic impacts. All results generated by MACCS/MACCS2 are available probabilistically, in the form of a complementary cumulative distribution function (CCDF) generated using a year of hourly meteorological data. In addition, single weather sequences can be utilized, with either constant or time-variant meteorology.

The computer systems MACCS is designed to run on are the 386/486/Pentium PC, VAX/VMS, IBM RISC S/6000, Sun SPARC, and Cray UNICOS.

II. OVERVIEW OF MACCS CODE

MACCS models the transport and dispersion of plumes of radioactive material released to the atmosphere. As the plumes travel through the atmosphere, material may be deposited on the ground via wet and dry deposition processes. 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 action guides for both the short and long term are also considered as means to mitigate the extent of the exposures. As a final step, the economic costs that would result from the mitigative actions are estimated.

MACCS is organized into three modules. The ATMOS module performs the atmospheric transport and deposition portion of the calculation. The EARLY module estimates the consequences of the accident immediately following the accident (usually within the first week) and the CHRONC module estimates the long-term consequences of the accident. A schematic of these modules and the input files

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that provide information to them is shown in Figure 1. The phenomena modeled in MACCS are described in more detail below.

A. Atmospheric Dispersion and Transport

MACCS allows the release of radioactive materials to the atmosphere to be divided into successive plume segments, which can have different compositions, release times, durations, release heights, and amounts of sensible heat. The 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.

A lift-off criterion based on a critical windspeed determines whether a plume is subject to buoyant plume rise. Momentum plume rise is not modeled. If the windspeed at release is greater than the critical windspeed, plume rise is prevented.

After release from the facility, windspeed determines the rates at which plume segments transport in the downwind direction, and the wind direction at the time of release determines the direction of travel. MACCS neglects wind trajectories as do most other consequence codes. Sixteen 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 the wind blows from the site into the sector.

During transport, dispersion of the plume in the vertical and horizontal directions is estimated using an empirical Gaussian plume model. In this model, dispersion depends on atmospheric stability and windspeed. Horizontal dispersion of the plume segments is unconstrained, however, vertical dispersion is bounded by the ground and by the mixing layer, which are both modeled as totally reflecting layers. A single value for the mixing layer is specified by the user for each season of the year and is constant during a calculation. Eventually, the vertical distribution of each plume segment becomes uniform and is so modeled.

Plume rise, dispersion, downwind transport, and deposition depend on the prevailing meteorological conditions. These conditions can be modeled as time invariant or may vary hour by hour. If they are variable, the user may specify them directly or through an input file. Meteorological conditions at the time of release are varied on an hourly basis through the sampling 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.

Wet and dry deposition are modeled. Dry deposition incorporates removal from the plume by diffusion, impaction, and settling and is modeled by use of a dry deposition velocity, which is a user input. The dry deposition velocity depends on particle size; therefore, if the aerosol size distribution is divided into ranges, a dry deposition velocity must be specified for each range. The washout of radioactive material from the plume, wet deposition, is modeled as dependent on the rain intensity.

Weathering, resuspension, washoff, and radioactive decay decrease the deposited concentrations of radioactive materials. Radioactive decay treats only first-generation daughter products and a branch ratio of unity is applied.

B. Dosimetry

The MACCS dosimetry model consists of three interacting processes: (1) the projection of individual exposures to radioactive contamination for each of the seven exposure pathways modeled over a user specified time period, (2) mitigation of these exposures by protective actions, and (3) calculation of the exposures incurred accounting for the implementation of protective actions. For each exposure pathway, MACCS models the radiological burden for the pathway as reduced by mitigative actions. The total dose to an organ is obtained by summing the doses delivered by each of the pathways.

C. Dose Mitigation

The time after accident initiation is divided into three phases: (1) an emergency phase, (2) an optional intermediate phase, and (3) a long-term phase. During the emergency phase, which can last up to 7 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. During the long-term phase, doses are reduced by decontamination of property that is not habitable, by temporary interdiction of property that cannot be restored to habitability by decontamination alone, by condemnation of property that cannot 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.

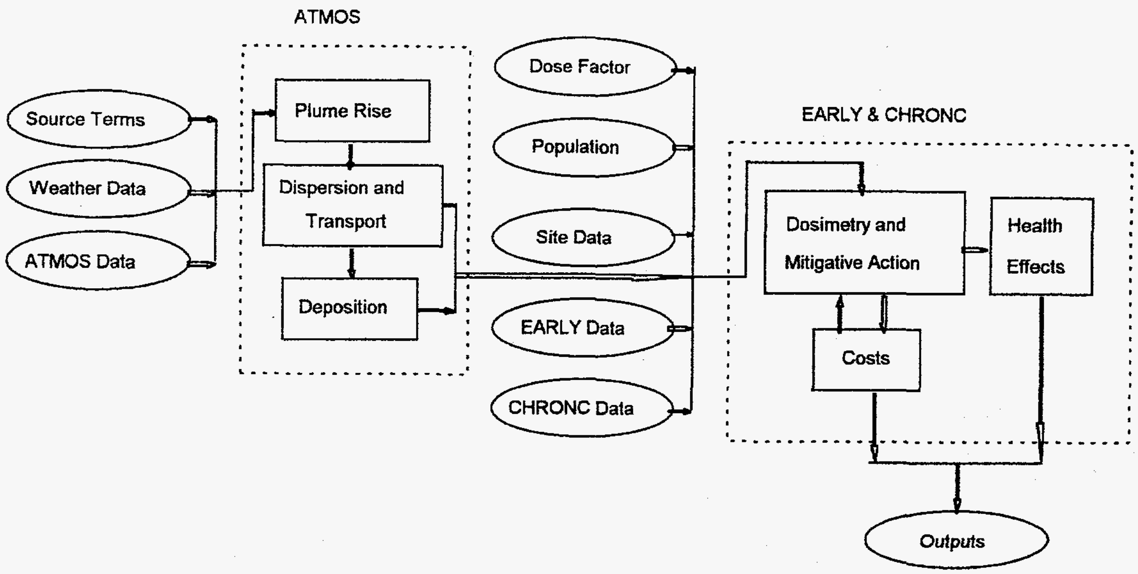

Figure 1. Progression of a MACCS Consequence Calculation.

D. 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,
- inhalation of materials directly from the passing plume (inhalation),
- inhalation of materials resuspended from the ground by natural and mechanical process (resuspension inhalation),
- ingestion of contaminated foodstuffs (food ingestion),
- 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, resuspension inhalation, and ingestion of contaminated food and water. Ingestion of contaminated food or water results in doses to people who reside at unknown locations both on and off of the computational grid.

E. Population Cohorts

People on the computational grid are assigned to three groups: (1) evacuees, (2) people actively taking shelter, and (3) people who continue normal activities. Shielding factors for each of the groups are specified by the user.

F. Health Effects

Health effects are calculated from doses to specific organs using dose conversion factors. Early injuries and fatalities (those that occur within 1 year of the accident) are estimated using nonlinear dose-response models. Latent cancers are estimated using a piecewise-linear dose-response model. Two equations are implemented in the code: one for high exposures and one for low exposures.

G. Economic Effects

In the MACCS model, economic consequences result from the implementation of mitigative actions. The following costs are considered in the model:

- evacuation costs,
- temporary relocation costs,
- costs of decontaminating land and buildings,
- lost return on investments from temporarily interdicted properties,
- the value of crops destroyed or not grown,
- the value of condemned property.

Costs associated with damage to the reactor, the purchase of replacement power, medical care, shortened life span, and litigation are not considered.

III. APPLICATIONS

MACCS has been used in a variety of applications since its pre-eminent application in the NUREG-1150 study. Two examples of the diverse types of analyses that have utilized MACCS are the DOE Defense Programs Safety Survey[8] and the evaluation of proposed changes to 10 CFR Part 100.[9] MACCS has also been used for the probabilistic consequence assessment of advanced reactor designs, i.e., the ABWR[10] and SBWR[11] designs.

MACCS has been applied in two international collaborative efforts; the Second International Comparison of PCA Codes[12] organized by the Nuclear Energy Agency of the Organization for Economic Cooperation and Development (OECD) and Commission of the European Communities (CEC), and a probabilistic consequence uncertainty study[13] jointly sponsored by the NRC and CEC.

MACCS has been widely used in DOE National Environmental Policy Act (NEPA) studies since the use of version 1.5.11 for the New Production Reactor (NPR) Environmental Impact Statement (EIS).[14] A number of large-scope EISs utilizing MACCS have recently been issued by the DOE:

- tritium supply and recycling,[15]
- foreign research reactor fuel,[16]
- stockpile stewardship and management,[17]
- Pantex plant site-wide EIS (SWEIS),[18]
- storage and disposition of fissile materials.[19]

In addition, beta-test MACCS2 was utilized for a large-scope environmental assessment (EA) pertaining to the Y-12 Plant.[20] Further, MACCS is currently being utilized for the forthcoming Los Alamos National Laboratory draft SWEIS and the forthcoming final version of the EIS on disposition of surplus highly enriched uranium.[21] Finally, both MACCS and beta-test MACCS2 have been utilized for the forthcoming Rocky Flats environmental technology site draft SWEIS.

IV. MACCS2 DEVELOPMENT EFFORTS AND BETA-TEST RESULTS

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 Department of Energy 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.[22]

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 Plant, the Savannah River Site, and the Hanford Reservation. They have also benefited from ongoing NRC research, as well as the joint NRC and CEC consequence uncertainty study.[23]

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 considered with MACCS. The code package incorporates the dose conversion factors and radioactive decay data of Federal Guidance Reports 11 and 12 published by the Environmental Protection Agency.[24,25] 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, primarily CCDFs of the results generated by the atmospheric model and a number of new dose measures.

MACCS2 has been in limited-distribution beta test by a small set of DOE users since April 1993 and 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[26] and V.L. Peterson.[27,28,29,30]

Feedback from this core group of long-term MACCS/MACCS2 users has been of great value to the code development process, identifying errors and making suggestions on additional enhancements. Over the course of the MACCS2 development process, a number of minor code errors were corrected; primarily an error that prevented the code from providing intermediate-phase results, and correction of the code's implementation of the dose and dose rate reduction factor (DDREF) used to estimate cancer risks. MACCS2 beta-test version 1.10 was released to the beta-test group in May 1995 and distributed to over thirty recipients in the United States and Europe.

In addition to the *ad hoc* verification efforts of the beta-test group, the University of New Mexico (UNM) is completing a formal independent verification study of the code package. This study includes performance of detailed hand calculations. The UNM effort is to be described in a published report. Enhancements and corrections to the code have been ongoing since 1993. In parallel, work on the documentation continues in order to address comments and suggestions from the recipients.

The code enhancements added since 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; (3) an enhancement to COMIDA2 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 the 99.5% direction-dependent dose as defined in NRC Reg. Guide 1.145.

The table look-up 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 capability of defining four segments of a release was added to better model "stem and cap" source terms associated with explosive releases as used in the Dual Axis Radiographic Hydrodynamic Test Facility (DAHRT) EIS.[31]

The direction-dependent dose option was added as a result of UNM verification work relating to the network evacuation model and 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% direction-independent dose and the 99.5% direction-dependent dose as stipulated in DOE Order 6430.1A.

Public release of the code and revised documentation is planned for the summer of 1996. 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 WINDOWS 3.1 and WINDOWS95. 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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