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REACTOR ACCIDENT CONSEQUENCE ANALYSIS CODE (MACCS)*

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ABSTRACT

Sandia National Laboratories has been involved in the performance of risk assessments for the U.S. Nuclear Regulatory Commission for more than a decade. As part of this effort, Sandia developed the reactor consequence analysis codes, CRAC2, and more recently, MACCS. CRAC2 is an improved version of CRAC, which was used in the Reactor Safety Study (also known as WASH-1400) [1]. MACCS was used in recent risk assessments for five nuclear power plants (NUREG-1150) [2]. MACCS incorporates many model improvements over CRAC2. Some of these improvements are discussed. A comparison of results obtained with CRAC2 and MACCS is also presented.

INTRODUCTION

The Reactor Safety Study 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. CRAC2, released in 1982, incorporated significant improvements over CRAC in the areas of weather sequence sampling and emergency response modeling [3].

During the last ten years, as consequence models were used to evaluate severe accident risks, emergency response plans, and criteria for reactor siting, 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

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model parameters, and the capability for uncertainty and sensitivity analyses were widely recognized as desirable improvements. This led to the development of the MACCS code.

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

MACCS INPUT AND OUTPUT

MACCS calculations require the following input data [4,5,6]:

- the core inventory at accident initiation of those radionuclides important for ex-plant consequences,
- the atmospheric source term produced by the accident,
- dose conversion factors for various exposure pathways,
- parameter values used in health effects calculations,
- meteorological data of the reactor site,
- the population distribution about the reactor site,
- protective measure actions for the early, intermediate, and long-term phases of the accident,
- environmental transfer factors for radionuclides considered in the ingestion pathways, and
- land usage data and economic data for the region about the reactor site.

Given the preceding input data, MACCS estimates the following:

- the downwind transport, dispersion, and deposition of the radioactive materials released to the atmosphere,
- 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,
- the early fatalities and injuries expected to occur within one year of the accident (early health effects) and the latent cancer fatalities and injuries expected to occur over the lifetime of the exposed individuals, and
- 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 property.

OVERVIEW OF MACCS

The models in MACCS [5,6] are implemented in three modules: ATMOS, EARLY, and CHRONC. Figure 1 depicts the structure

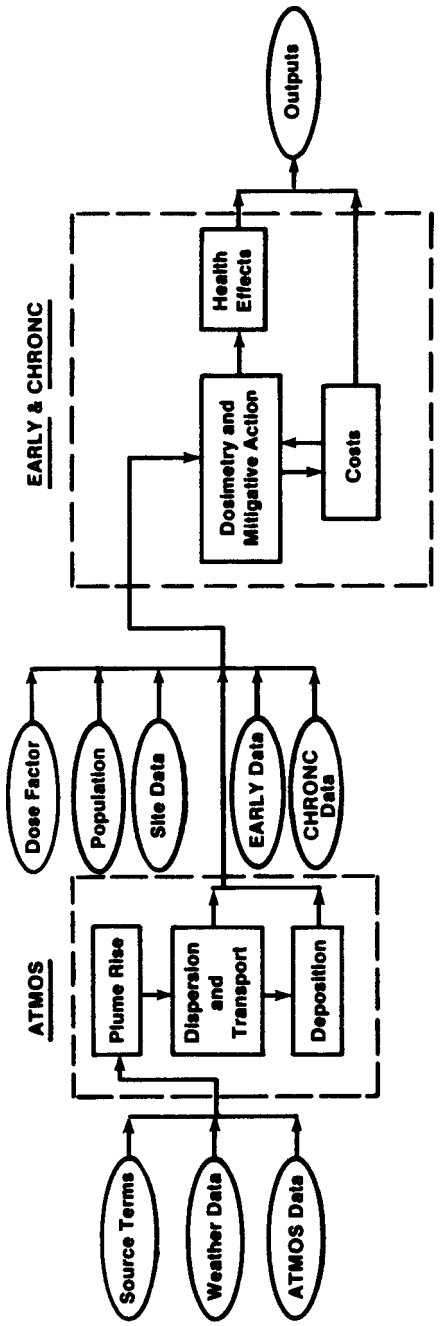

Figure 1 Progression of a MACCS Consequence Calculation

of a MACCS consequence calculation. The ATMOS module treats the atmospheric dispersion and transport of material and its deposition onto the ground. The EARLY module models exposure pathways, dosimetry, mitigative actions, and health effects during the emergency phase. The CHRONC module models the 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 due to mitigative actions during the emergency, intermediate, and the long-term phases.

Brief descriptions of models used in the MACCS code are presented in the following sections.

Atmospheric Transport

MACCS allows a release of radioactive materials to the atmosphere to be divided into successive plume segments, which can have different compositions, release times, durations, and energies (amounts of sensible heat). The plume rise models recommended by Briggs [7,8] are used in MACCS.

Dispersion of the plume in the vertical and horizontal (crosswind) directions during transport is estimated with a Gaussian plume model [9]. Although horizontal dispersion of plume segments is unconstrained, vertical

dispersion is bounded by the ground and by the top of the mixing layer, which are modeled as totally reflecting layers with mirror image sources [9].

Deposition, Weathering, Resuspension, and Decay

In MACCS, aerosols are removed from the plume by radioactive decay, by washout, which varies with rainfall rate, and by dry deposition [10].

Water bodies (rivers, the Great Lakes, oceans) are contaminated by direct deposition of radioactive materials onto their surfaces and by washoff from land [11].

Dosimetry

The MACCS dosimetry model involves of three interacting processes: projection of individual exposures over a given time period to radioactive contamination for each of the exposure pathways modeled, mitigation of these exposures by protective actions, and calculation of the actual doses incurred after dose mitigation by protective actions. The current dose conversion factors for various exposure pathways are based on data provided by Oak Ridge National Laboratory [5].

Dose Mitigation

MACCS divides the time after accident initiation into three phases: an emergency phase, an optional intermediate phase, and a long-term phase. During the emergency phase, which in MACCS can last up to seven days, doses are reduced by evacuation, sheltering, and temporary relocation of people. During the intermediate and long-term phases, doses are reduced by decontamination, by decontamination followed by temporary interdiction, by disposal of contaminated crops, by temporary interdiction of farmland, and by condemnation of property [5].

Exposure Pathways

MACCS models seven exposure pathways: exposure to the passing plume, exposure to materials deposited on the ground, exposure to materials deposited on skin, inhalation of materials directly from the passing plume, inhalation of materials resuspended from the ground, ingestion of contaminated foodstuffs, and ingestion of contaminated water [5,12].

Health Effects

Health effects are calculated from doses to specific organs. The early health effects models used in MACCS are based on a recent review [13,14] which recommended the use of hazard functions for the calculation of early fatalities and injuries. As also recommended by this review, MACCS calculates latent cancer fatalities and injuries using linear-

quadratic, zero-threshold, dose-response models.

Economic Effects

Economic consequences [15] are estimated by summing the following costs: evacuation and temporary relocation costs during the emergency phase, costs of decontamination and lost return-on-investments due to temporary interdiction of property, costs of crop disposal and temporary interdiction of farmland, and costs of condemning farm and nonfarm property.

SUMMARY OF MAJOR DIFFERENCES BETWEEN CRAC2 AND MACCS

The major differences between CRAC2 and MACCS can be summarized as follows:

(1) In CRAC2, a rectangular function (or the top-hat function, see Figure 2) is used to approximate the Gaussian crosswind (along the y-direction) distribution of the plume. This top-hat function has a width of 3 sigma-y and a height of 0.836 of the Gaussian peak. Air and ground concentrations are assumed to be constant within the top-hat function and zero outside the top-hat function. In MACCS, the atmospheric transport model calculates air and ground concentrations along the plume centerline. A correction factor to account for the off-centerline effect is calculated for each spatial element using the multi-step histogram approximation of the Gaussian crosswind distribution (see Figure 3) [5].

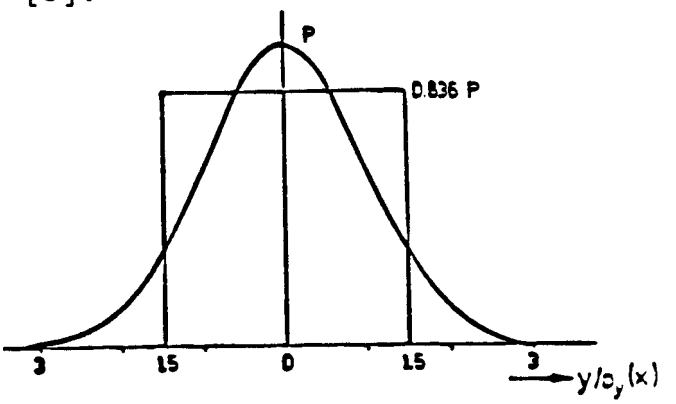

Figure 2 Top-Hat Approximation of the Gaussian Crosswind Distribution

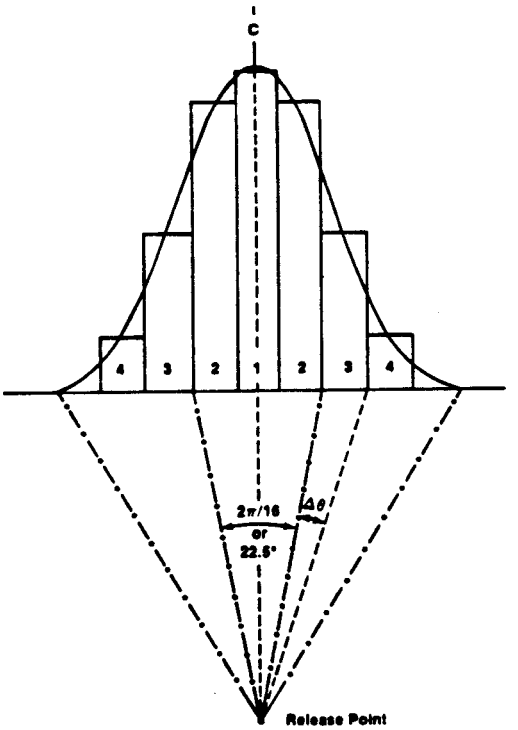

Figure 3 Approximation of a Gaussian Distribution by a Seven-Step Histogram (the number of Fine Grid Divisions is 3)

(2) For early health effects, CRAC2 uses piece-wise linear dose response models as in the Reactor Safety Study. MACCS uses the hazard function models recommended by [12,13]. Figure 4 illustrates the difference between CRAC2 and MACCS for early fatalities resulting from bone marrow irradiation. The piece-wise linear curve is for the supportive treatment typically assumed in CRAC2 calculations.

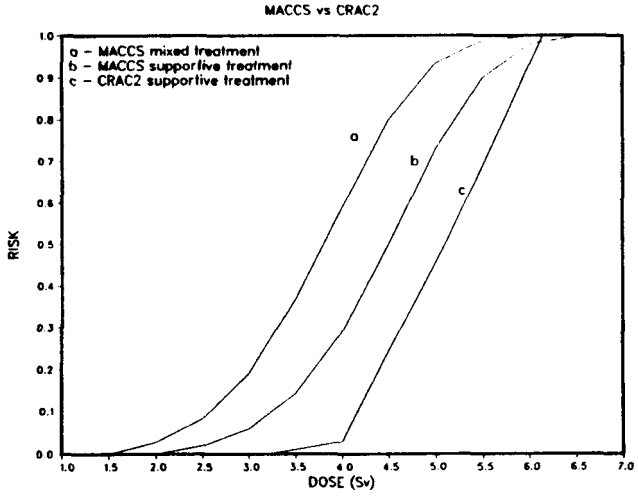

Figure 4 Comparison of Early Fatality Risk Versus Bone Marrow Dose Between MACCS and CRAC2

Two curves are presented for the MACCS model: (1) mixed treatment (50% minimum treatment and 50% supportive treatment) and (2) supportive treatment. The values of LD_{50} are 5.1 Sv for CRAC2, 3.8 Sv for MACCS mixed treatment, and 4.5 Sv for MACCS supportive treatment.

(3) For latent cancer health effects, CRAC2 uses the same models as the Reactor Safety Study, which used both the linear model in the BEIR report [16] and the central estimate model. The central estimate model modifies the BEIR linear model by using dose effectiveness factors for the reduction of latent cancer induction at low dose rates [1]. The central estimate models are typically used in CRAC2 calculations. MACCS uses the linear-quadratic, zero-threshold dose response model for the latent cancer health effects as recommended by a recent review [13,14].

(4) The long-term protective measures in CRAC2 are implemented independently for the two long-term pathways of resuspension inhalation and groundshine, whereas in MACCS the long-term dose criteria is compared against the sum of doses from the two pathways.

(5) In CRAC2, the user can specify only one plume for each source term (i.e., all of the radionuclides released come out as a single release), whereas in MACCS, the user can specify up to four successive plume segments for one source term. Each plume segment can have its own release fractions, release time, release duration, and energy release rate. Use of multiple plume segments in MACCS provides a better representation of the source term characteristics currently predicted in NUREG-1150 [2]. The source terms in the NUREG-

1150 severe accident risk assessments typically consist of two distinct release segments: one that characterizes the early releases (during the progression of core melt through vessel breach) and one that characterizes the later releases after vessel breach (during the molten core-concrete interaction).

(6) Since most input parameter values in MACCS are user-specified, the user is in a position to both understand and control the input parameter values and their impact on the calculated results. In CRAC2, many of the parameter values are hard-wired.

A COMPARISON OF CRAC2 AND MACCS USING A SAMPLE PROBLEM

To illustrate the differences in results obtained with CRAC2 and MACCS, this paper uses a problem originally analyzed with CRAC2 as part of the Sandia Siting Study [17]. The following input data are the same for both CRAC2 and MACCS:

(1) population distribution for the Indian Point reactor site,
(2) meteorological data for New York City,
(3) core inventory for the Sandia Siting Study,
(4) SST1 source term from the Sandia Siting Study, see Table 1 below, and
(5) the evacuation assumptions for the Sandia Siting Study, see Table 2 below.

Table 1

SST1 Source Term
Release Fractions
and Characteristics

Nuclides	Release Fraction
NG	1.0
I	0.45
Cs	0.67
Te	0.64
Ba-Sr	0.07
Ru	0.05
La	0.009

Release Time = 1.5 hrs,
Release Duration = 2 hrs,
Release Height = 10 m, and
Energy Release Rate = 0.

Table 2

Evacuation Assumptions

Probability of a Given Delay Time	Delay Time (hr)
0.3	1.0
0.4	3.0
0.3	5.0

Evacuation Speed = 4.47 m/s.

For the remaining parameters, the values used were those recommended in the documents distributed with the respective codes. All parameter values are not made identical for two reasons: (1) some parameters in CRAC2 are defined differently from MACCS; therefore, it is very difficult, if not impossible, to use the same values (e.g.,

long-term dose limits); (2) some models are completely different between CRAC2 and MACCS (e.g., health effects models).

Table 3 shows a comparison of the values for two consequence measures obtained with CRAC2 and MACCS.

Table 3

Comparison of Consequence Results* Obtained with CRAC2 and MACCS

CRAC2	MACCS	
Supportive Treatment	Mixed Treatment	Supportive Treatment
436	238	197
7490	9910	9950

*These numbers are conditional on the release of an SST1 source term. The numbers in the first row are for early fatalities, and the numbers in the second row are for latent cancer fatalities.

For early fatalities, CRAC2 predicts higher numbers than MACCS (about a factor of two for the supportive treatment case). There are many differences in models and input data between CRAC2 and MACCS. It not clear what parameters and models contribute the most to the differences in results between the two codes. For latent cancer fatalities, CRAC2 seems to predict slightly lower numbers than MACCS. Given the uncertainty of input parameter values and the impact of this uncertainty on consequence results [18,19], the differences between CRAC2 and MACCS shown in Table 3 are probably not significant.

SUMMARY

This paper presented a brief overview of the new consequence analysis code MACCS. The latest version of MACCS was used in the consequence analyses for NUREG-1150 [2]. It is expected that MACCS will be the primary consequence analysis tool used by the NRC for severe accident risk assessments.

A comparison between MACCS and CRAC2 was also presented using a trial problem. The results obtained with the two codes were similar but not the same. However, to understand the differences in consequence results obtained with CRAC2 and MACCS, a systematic evaluation would be needed. This would include comparison of the following intermediate results obtained with CRAC2 and MACCS : atmospheric transport, dry and wet deposition, individual and population doses, mitigative actions, and health effects.

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