

## **MELCOR Accident Consequence Code System, Version 2 (MACCS2)**

The U.S. Nuclear Regulatory Commission (NRC) developed MELCOR Accident Consequence Code System, Version 2 (MACCS2) specifically to evaluate offsite consequences from a hypothetical release of radioactive material into the atmosphere [1], [2]. The code models atmospheric transport and dispersion (ATD), emergency response actions, exposure pathways, health effects, and economic costs. This enclosure provides an overview of the MACCS2 code.

### **History**

MACCS2 evolved from predecessor codes MACCS, Calculation of Reactor Accident Consequences, Version 2 (CRAC2), and CRAC. MACCS was used to support NUREG-1150, "Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants," issued December 1990; CRAC2 was used to estimate consequences in the 1982 Siting Study, and CRAC was initially developed for WASH-1400, which was published in 1975. These codes were developed mainly as tools to assess the risk and consequences associated with accidental releases of radioactive material into the atmosphere in probabilistic risk assessment (PRA) studies.

The MACCS2 code has gone through additional improvements since its original release in 1997. Version 2.5 of the code has been released recently together with the graphical user interface (GUI), WinMACCS version 3.6 [3]. WinMACCS was developed to facilitate routine uses of MACCS2. The three most important modeling features implemented in WinMACCS are (1) the ability to easily evaluate the impact of parameter uncertainty, (2) the ability to manipulate input parameters for network evacuation modeling, and (3) the ability to model alternative dose-response relationships for latent cancer fatality evaluation (e.g., linear with threshold model). Uncertainty in the source term and in most of the other MACCS2 input parameters, including parameters related to emergency response, can be treated through WinMACCS. WinMACCS invokes the Latin Hypercube Sampling (LHS) code to prepare a user-specified number of MACCS2 input decks to reflect variations of the uncertain parameters specified [4]. The output from multiple runs of "equally likely" MACCS2 input sets is evaluated by the WinMACCS postprocessor to provide expectation values and statistical information.

### **Current NRC Uses**

The MACCS2 code is currently used by U.S. nuclear power plant license renewal applicants to support the plant specific evaluation of severe accident mitigation alternatives (SAMAs) that may be required as part of the applicant's environmental report for license renewal (as discussed further in enclosure 6). Applicants follow guidance provided in NEI-05-01, Revision A, "Severe Accident Mitigation Alternatives (SAMA) Analysis Guidance Document," which is endorsed by NRC License Renewal Interim Staff Guidance LR-ISG-2006-03, "Staff Guidance for Preparing Severe Accident Mitigation Alternatives Analyses." NEI-05-01 refers to both NUREG/BR-0058, "Regulatory Analysis Guidelines of the U.S. Nuclear Regulatory Commission," and NUREG/BR-0184, "Regulatory Analysis Technical Evaluation Handbook." The NRC's regulatory analysis guidelines in NUREG/BR-0058 and NUREG/BR-0184 specifically recommend the use of MACCS2 to estimate the averted "offsite property damage" cost (benefit) and the offsite averted dose cost elements. The information from MACCS2 code runs supports a cost-benefit assessment for various potential plant improvements as part of SAMAs. MACCS2 is also routinely used in severe accident mitigation design alternative

(SAMDA), or severe accident consequences analyses for environmental impact statements (EISs) supporting design certification, early site permit, and combined construction and operating license reviews for new reactors (as discussed in more detail in Enclosure 6). In another recent example, the MACCS2 code was used in the State-of-the-Art Reactor Consequence Analysis (SOARCA) study to estimate consequences in terms of early fatality risk and latent cancer fatality risk. Staff made numerous enhancements to the code for the SOARCA study including the capability for more plume segments (up to 200), a potassium iodide ingestion model, and the ability to model alternative dose-response relationships for latent cancer fatality. Staff continues to enhance the code as part of its update and maintenance program, for example, incorporating an alternative ATD model and economic consequence model as discussed below.

Previous Commission papers have indicated limitations associated with MACCS capability to evaluate land contamination and economic consequences. In SECY 00-0077, "Modifications to the Reactor Safety Goal Policy Statement," the staff considered whether a land contamination goal should be added to the safety goal policy but recommended against it. Part of the justification was that the current analytical tools have weaknesses in predicting land contamination and collective dose at significant distances. NRC staff continues to acknowledge that uncertainties increase for consequence projections at significant distances, but a 2004 benchmarking study provides increased confidence in the ATD model results from MACCS2 for distances out to 100 miles. The MACCS2 ATD model was compared against two Gaussian puff codes (Radiological Assessment System for Consequence Analysis (RASCAL) and Regional Atmospheric Transport Code for Hanford Emission Tracking (RATCHET)) and a Lagrangian particle tracking code (Lagrangian Operational Dispersion Integrator (LODI) from the National Atmospheric Release Advisory Center (NARAC)) [5]. The study showed that the MACCS2 mean results (over weather) were within a factor of 2 for arc-averages and a factor of 3 at a specific grid location out to 100 miles from the point of release.

In addition, as described in SECY-05-0233, "Plan for Developing State-of-the-Art Reactor Consequence Analyses," dated December 22, 2005, the State-of-the-Art Reactor Consequence Analysis (SOARCA) project's original scope included calculating offsite consequences of severe accidents in terms of (1) health effects and (2) land contamination. Subsequently in an April 3, 2007 memo to the Commission, the staff indicated that the MACCS2 code's capabilities with respect to land contamination and economic impacts of severe accidents should be updated before attempting a best-estimate, realistic calculation of those outcomes. The Commission directed the staff, in SRM-COMPBL-08-002/COMGBJ-08-0003, not to delay reporting the results of the SOARCA project in order to include an assessment of land contamination and the economic consequences of land contamination. In the April 3, 2007 memorandum, the staff noted to the Commission that "LC [land contamination] and EC [economic consequence] cost are interrelated and depend on models for rehabilitation and clean up. There is some evidence that the models may be excessively conservative." It is not obvious to current MACCS2 experts at both the NRC and Sandia National Laboratories (SNL) that rehabilitation and clean up, land contamination area, or economic models and results are excessively conservative. Economic results and some land contamination area results are controlled by user inputs and could be biased to be either conservative or nonconservative, depending on the input values selected by the user. A MACCS2 user's guide and code manual is available for reference when deciding various parameter inputs [1]. Other land contamination areas produced by MACCS2 are influenced chiefly by the Gaussian plume and deposition modeling. Based on the 2004 benchmarking study, these values do not appear to have either a

conservative or nonconservative bias. Current MACCS2 experts do note that a conservative result produced by the code is likely to be the peak centerline dose, due to the use of the Gaussian plume ATD model. This particular result is not used in current MACCS2 applications (such as cost-benefit analyses and SAMA analyses), which rely on the mean results out to 50 miles.

Most recently, the Pilgrim nuclear power plant license renewal proceeding included a contention related to the SAMA analyses and the use of the MACCS2 code. The issue was whether the ATD model was adequate for the Pilgrim site, and whether a potential existed for underestimating offsite property damage. After the hearing in March 2011, the Atomic Safety and Licensing Board (ASLB) ruled that SAMA analyses and use of MACCS2 were adequate (NRC testimony available at [6] and [7]; final ASLB ruling available at [8]).

### **MACCS2 Steps for Estimating Consequences**

MACCS2 estimates consequences in four steps: (1) atmospheric transport and deposition onto land and water bodies, (2) the estimated exposures and health effects for up to seven days following the beginning of release (early phase), (3) the estimated exposures and health effects during an intermediate time period of up to one year (intermediate phase), and (4) the estimated long-term (e.g., 50 years) exposures and health effects (late-phase model). The assessment of offsite property damage in terms of contaminated land and economic consequences use all four parts of the modeling. An overview of the code is provided below to explain the assessment of offsite property damage in MACCS2.

#### **Atmospheric Transport and Dispersion Model**

MACCS2 models dispersion of radioactive materials released into the atmosphere using the straight-line Gaussian plume model with provisions for meander and surface roughness effects. The ATD model treats the following: plume rise resulting from the sensible heat content (i.e., buoyancy), initial plume size caused by building wake effects, release of up to 200 plume segments, dispersion under statistically representative meteorological conditions, deposition under dry and wet (precipitation) conditions, and decay and ingrowths of up to 150 radionuclides and a maximum of six generations. The model does not treat in detail irregular terrain, spatial variations in the wind-field, and temporal variations in wind direction.

The user has the option to select meteorological sampling, such as a single weather sequence or multiple weather sequences. The latter of these weather sampling options is used in PRA studies to evaluate the effect of weather conditions at the time of the hypothetical accident.

The results generated by the ATD model include contaminant concentrations in air, on land, and as a function of time and distance from the release source; these results are subsequently used in early, intermediate, and late-phase exposure modeling.

A new and alternative ATD model, with the capability to model three-dimensional, time-dependent wind-fields, is planned as part of the MACCS2 update and maintenance program. The updates for the model, including documentation, will be developed and tested during the fiscal year (FY) 2013 to FY 2014 timeframe subject to available funding.

### Early Phase Model and Exposure Pathways

The early-phase model in MACCS2 assesses the time period immediately following a radioactive release. This period is commonly referred to as the emergency phase and it can extend up to seven days after the arrival of the first plume at any downwind spatial interval. Early exposures in this phase account for emergency planning (i.e., sheltering, evacuation, and relocation of the population). The early-phase modeling in MACCS2 is limited to seven days from the beginning of release. MACCS2 models sheltering and evacuation actions within the emergency planning zone (EPZ). Different shielding factors for exposure to cloudshine, groundshine, inhalation, and deposition on the skin are associated with three types of activities: normal activity, sheltering, and evacuation.

Outside the sheltering/evacuation zone, dose-dependent relocation actions may take place during the emergency phase. That is, if individuals at a specific location are projected to exceed either of two dose thresholds over the duration of the emergency phase, they are relocated at a specified time after plume arrival.

For a radioactive release containing radioiodine, some of the iodine is highly likely to be absorbed by the thyroid. As a consequence the chance of thyroid cancer to the individual may be increased. Potassium iodide (KI) can saturate the thyroid with iodine and thereby reduce the amount of radioiodine that can be absorbed. KI is distributed near some nuclear power plants. MACCS2/WinMACCS has implemented a KI model to account for the beneficial effect of taking KI. This model accounts for the fraction of the population taking KI and the efficacy, or dose reduction, provided by the KI.

### Intermediate Phase and Exposure Pathways

MACCS2 can model an intermediate phase with duration of up to one year following the early phase. The only mitigative action modeled in this phase is relocation. That is, if the projected dose leads to doses in excess of a threshold, the population is assumed to be relocated to an uncontaminated area for the entire duration of this phase, with a corresponding per-capita economic cost defined by the user. The intermediate phase duration can be modeled as being zero (i.e., no intermediate phase).

If the projected dose does not reach the user-specified threshold, exposure pathways for groundshine and inhalation of resuspended material are treated.

### Long-Term Phase Model and Exposure Pathways

In the long-term phase (e.g., 50 years of potential exposure), protective actions are defined to minimize the dose to an individual by external (groundshine) and internal (food consumption and resuspension inhalation) pathways. Decisions on mitigative actions are based on two sets of independent actions (i.e., decisions relating to whether land, at a specific location and time, is suitable for human habitation ("habitability") or agriculture production ("farmability")). Habitability is defined by a maximum dose and an exposure period to receive that dose. Habitability decisionmaking can result in four possible outcomes: (1) land is immediately habitable, (2) land

is habitable after decontamination, (3) land is habitable after decontamination and interdiction<sup>1</sup>, or (4) land is not deemed habitable after 30 years of interdiction (i.e., it is condemned). Land is also condemned if the cost of decontamination exceeds the value of the land. The dose criterion for the MACCS2 modeling of individuals returning back to the affected (i.e., contaminated) area is a user input and is typically taken from the U.S. Environmental Protection Agency (EPA) protective action guides (PAGs).<sup>2</sup>

Decisions on decontamination are made using a decision tree. The first decision is whether land is habitable. If it is, then no further actions are needed. The population returns to their homes and receive a dose from any deposited radionuclides for the entire long-term phase. If land is not habitable, the first option considered is to decontaminate at the lowest level of dose reduction, which is also the cheapest to implement. If this level is sufficient to restore the land to habitability, then it is performed. Following the decontamination, the population returns to their homes and receives a dose based on the residual contamination for the duration of the long-term phase. If the first level of decontamination is insufficient to restore habitability, then successively higher levels are considered. MACCS2 considers up to three decontamination levels. If the highest level of decontamination is insufficient, then interdiction for up to 30 years is considered following the decontamination. During the interdiction period, radioactive decay and weathering work to reduce the dose rates that would be received by the returning population. If the highest level of decontamination followed by interdiction is sufficient to restore habitability, then it is employed and the population is allowed to return. Doses are accrued for the duration of the long-term phase. If habitability cannot be restored by any of these actions, then the land is condemned. The land is also condemned if the cost of the required action to restore habitability is greater than the value of property.

The decision on whether land is suitable for farming is first based on prior evaluation of its suitability for human habitation. That is, land cannot be used for agriculture unless it is habitable. Furthermore, farmland must be able to grow crops or produce dairy products that meet the requirements of the Food and Drug Administration (i.e., it must be farmable). If farmland is habitable and farmable, a food chain model is used to determine doses that result from consuming the food grown or produced on this land. The COMIDA2 food chain model is the latest model developed for use in MACCS2. COMIDA2 represents a significant improvement over the older food chain model embodied in the original MACCS code and used in NUREG-1150. The capability of bypassing (not modeling) the food chain/ingestion model has been recently implemented in MACCS2 because it is generally thought that food availability in the United States would preclude the need for individuals to consume contaminated food or water.

MACCS2 values of total long-term population dose and health effects account for exposures received by workers performing decontamination. While engaged in cleanup efforts, workers are assumed to wear respiratory protection devices; therefore, they only accumulate doses from groundshine.

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<sup>1</sup> In this context, interdiction generally refers to the period of time in which residents are not permitted to return to live on their property because the radiation doses they would receive (from external sources and inhalation) exceed the habitability criterion. Interdiction allows for radioactive decay, decontamination, and weathering to potentially bring these doses to a point where they would no longer exceed the habitability criterion.

<sup>2</sup> EPA developed the PAG Manual to provide guidance to State and local authorities on actions to help protect the public during emergencies. The manual can be found at <http://www.epa.gov/rpdweb00/rert/pags.html>.

### Land Contamination Areas

Land areas contaminated above a threshold level can be calculated in several ways. The simplest is to report land areas that exceed activity levels per unit area for one or more isotopes. This is the approach used to report contaminated areas following the Chernobyl accident (i.e., land areas exceeding threshold levels of cesium-137 activity were reported). The process to estimate land contamination areas based on activity is very simple and depends only on the atmospheric transport and deposition modeling employed in the analysis. Currently, MACCS2 estimates such areas based on the Gaussian plume model; in the future, higher fidelity models will become available upon which to base land contamination areas.

MACCS2 also allows calculation of land contamination areas based on doses. For example, land areas can be calculated that exceed the habitability criterion. Land areas based on doses or projected doses are for a specific set of dose pathways. Habitability is generally based on two dose pathways, groundshine and inhalation of resuspended aerosols. Clearly, this approach is more complex than activity-based estimates and involves estimating doses for specific dose pathways. Finally, land contamination areas based on an economic model (e.g., areas that are decontaminated or condemned) are the most complex to evaluate and are tied to the assumptions and parameters in the economic model.

### **MACCS2 Economic Model**

#### Current Model

The economic model in MACCS2 includes costs associated with various actions or modeling as follows:

- evacuation and relocation costs (e.g., a per diem cost associated with displaced individuals)
- moving expenses for people displaced (i.e., a onetime expense for moving people out of a contaminated region) and loss of wages, if chosen
- decontamination costs (e.g., labor, materials, equipment, and disposal of contaminants), *if* decontamination is cost effective
- cost from loss of land use of property (e.g., costs associated with lost return on investment and for depreciation of property that is not being maintained)
- disposal of contaminated food grown locally (e.g., crops, vegetables, milk, dairy products, and meat)
- cost of condemned lands (i.e., land that cannot be restored to usefulness or it is not cost effective to do so)

Nearly all of the values affecting the economic cost model are user inputs and thus can account for a variety of costs and can be adjusted for inflation, new technology, or changes in policy.

### New Alternative Economic Model

The new and alternative economic model for MACCS2 is under development. The new model is based on the existing Regional Economic Accounting Tool (REAcct), which SNL developed for the U.S. Department of Homeland Security (DHS). REAcct uses an economic model that is built upon the well-known and extensively documented input-output modeling technique initially presented by Leontief [9] and more recently further developed by numerous contributors. The model is widely accepted and used within the community of economists. In response to SECY-09-0051, "Evaluation of Radiological Consequence Models and Codes," the Commission approved the staff's recommendation to enhance the MACCS2 code with insights that may be learned from the DHS/National Nuclear Security Administration (NNSA) economic consequence model recently developed for radiological dispersion devices. A comparison of the new and alternative economic model for MACCS2 with the DHS Radiological and Nuclear Terrorism Risk Assessment (RNTRA) economic consequence model is also underway.

REAcct is used to rapidly estimate approximate economic impacts for disruptions caused by natural (e.g., hurricanes) or manmade events. The tool estimates the following:

- The model estimates direct losses (gross domestic product (GDP) losses) within the grid using county-level economic-sector (e.g., manufacturing, tourism, and agriculture) data.<sup>3</sup>
- The model estimates indirect losses using the national-level Regional Input-Output Modeling System (RIMS) multipliers to estimate indirect GDP losses (representing the remainder of the United States outside the grid).
- The model can be used to account for potential multiple-year disruption to economy in terms of present value.

The metric of concern is reduction in GDP, which can be reported at the industry, region, and U.S. levels.

The cost of decontamination in the new model is the same as the old model and is computed separately. The cost of evacuation, relocation, and condemned land do not directly contribute to GDP losses and are not included in the new model.

An internal peer review for the new model is planned to evaluate the model developments. The work is being documented in the WinMACCS draft documentation [3]. Planned activities include review of draft documentation during the FY 2013 timeframe. A workshop will be conducted to introduce the modeling concepts to NRC users of MACCS2.

Table 1 through Table 3 below summarize (1) the basis for current and new economic models, (2) comparison of current and new economic models, and (3) databases used for current and new economic models.

The current schedule envisions a new version of MACCS2/WinMACCS during early FY 2014 that gives the user the option to choose the new economic model.

<sup>3</sup> GDP data are from the U.S. Bureau of Economic Analysis and can be found at <http://www.bea.gov/regional/index.htm>.

**Table 1 Basis for Current and New Economic Models**

<b>Original MACCS2 Model</b>	<b>REAcct Model</b>
Cost-Based Accounting of Losses	GDP-Based Accounting of the Effect Accident on Economy
Based on Model Dating Back to CRAC and CRAC2 Codes Developed for the NRC	Based on Input-Output Economic Model Developed by Economists
Accounts for Losses to Local Residents	Accounts for GDP Losses, Both within Region and to Entire Country

**Table 2 Comparison of Current and New Economic Models**

<b>Original MACCS2 Model</b>	<b>REAcct Model</b>
Evacuation & Relocation Per Diem Expenses	Excluded from Model—These Are Transfer Payments Which Do Not Affect GDP
Loss of Use of Property during Interdiction	GDP Losses* Direct—Within MACCS2 Grid Indirect—Impact on Rest of the Country
Condemnation of Property	
Disposal of Contaminated Farm Products	
Decontamination of Property	
Cost of Population Exposure Estimated by Multiplying Population Dose by Cost per Person-Rem	

\* GDP losses in REAcct account for property that cannot be used, either temporarily or permanently. Permanent loss is over the entire time period treated by the REAcct model, which can be up to 30 years. Losses for each economic sector, including agriculture, are tabulated separately in the REAcct model and summed to represent the total economy.

(Note: Rows shown across the tables denotes that the value is accounted in both models.)



**Table 3 Databases Used for Current and New Economic Models<sup>4</sup>**

<b>Original MACCS2 Model</b>	<b>REAcct Model</b>
Fraction of Area That Is Land (i.e., Excluding Water Bodies)	
Fraction of Land Devoted to Farming	
Fraction of Farm Sales from Dairy	
Average Annual Farm Sales	
Average Farm Land Value	
Average Nonfarm Land Value	
	County-Level GDP Data (Direct GDP Losses)
	RIMS II Multipliers (Indirect GDP Losses)

**References**

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All data are from the U.S. Department of Commerce, Bureau of Economic Analysis and Census Bureau.

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