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A REVIEW OF THE MELCOR ACCIDENT CONSEQUENCE CODE SYSTEM (MACCS): CAPABILITIES AND APPLICATIONS

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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 was publicly released in 1990. MACCS was developed to support the NRC's probabilistic safety assessment (PSA) efforts. PSA techniques can provide a measure of the risk of reactor operation. PSAs are generally divided into three levels. Level one efforts identify potential plant damage states that lead to core damage and the associated probabilities, level two models damage progression and containment strength for establishing fission-product release categories, and level three efforts evaluate potential off-site consequences of radiological releases and the probabilities associated with the consequences. MACCS was designed as a tool for level three PSA analysis. MACCS performs probabilistic health and economic consequence assessments of hypothetical accidental releases of radioactive material from NPPs. 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. The computer systems MACCS is designed to run on are the 386/486 PC, VAX/VMS, IBM RISC S/6000, Sun SPARC, and Cray UNICOS.

This paper provides an overview of MACCS, reviews some of the applications of MACCS, international collaborations which have involved MACCS, current developmental efforts, and future directions.

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

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schematic of these modules and the input files that provide information to them is shown in Figure 1. The phenomena modeled in MACCS are described in more detail below.

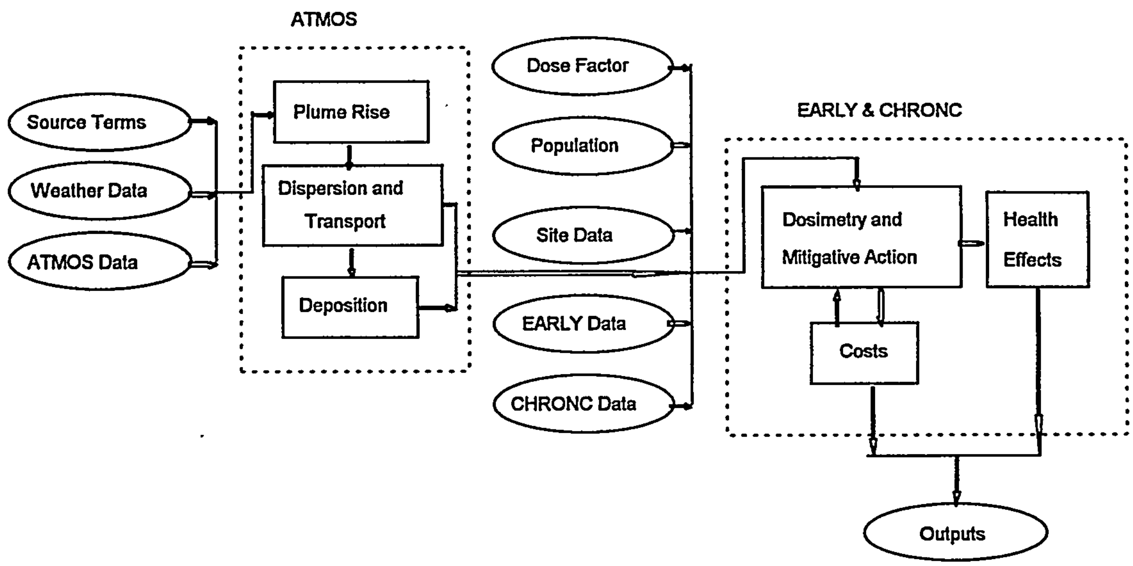

Figure 1. Progression of a MACCS Consequence Calculation.

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 segments 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 or not 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 (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 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 inclusion of the uncertainty in meteorological conditions at the time of the accident in code calculations. Variability in consequences due to weather may be obtained in the form of a complementary cumulative distribution function.

Two types of deposition are modeled in the MACCS. These types of deposition are wet and dry deposition. 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.

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 measure actions, and (3) 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 reduced 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.

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 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. 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.

Exposure pathways

MACCS models seven exposure pathways: (1) exposure to the passing plume (cloudshine), (2) exposure to materials deposited on the ground (groundshine), (3) exposure to materials deposited on skin, (4) inhalation of materials directly from the passing plume (inhalation), (5) inhalation of materials resuspended from the ground by natural and mechanical process (resuspension inhalation), (6) ingestion of contaminated foodstuffs (food ingestion), and (7) 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, water and food ingestion. Ingestion of contaminated food or water produces doses to people who reside at unknown locations both on and off of the computational grid.

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.

Health effects

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

Economic effects

In the MACCS model, economic consequences result from the implementation of mitigative actions. The following costs are considered in the model: (1) evacuation costs, (2) temporary relocation costs, (3) costs of decontaminating land and buildings, (4) lost return-on-investments from temporarily interdicted properties, (5) the value of crops destroyed or not grown, and (6) the value of condemned property. Costs associated with damage to the reactor, the purchase of replacement power, medical care, life-shortening, and litigation are not considered.

Applications

Since its most publicized application in the NUREG-1150[5] study, "Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants," MACCS has been used in a variety of applications. Two examples of the diverse types of analyses which have utilized MACCS are the U.S. Department of Energy (DOE) Safety Survey[6] and the evaluation of proposed changes to 10 CFR Part 100. MACCS has also been used for the Probabilistic Consequence Assessment (PCA) of advanced reactor designs, i.e., the ABWR[7] and SBWR[8] designs.

NUREG-1150

PSA, also referred to as probabilistic risk assessment (PRA), techniques were first applied in the Reactor Safety Study[9] sponsored by the NRC and completed in 1975. PSA and accident analysis techniques underwent a significant evolution and refinement between the mid-1970s and mid-1980s. The NRC published a PRA Procedures Guide and a summary of PRA perspectives in 1983 and 1984 respectively. In 1986 the NRC established safety goals against which risk values developed from PSAs could be compared. In response to these developments, the NRC initiated the NUREG-1150 study which consisted of PSAs of five commercial NPPs of different designs. MACCS was used for the PCA portion of the PSAs. Four alternative offsite emergency response assumptions were modeled. In addition, the uncertainty due to meteorological conditions was included in consequence calculations. The PCA portion of the NUREG-1150 study, in addition to serving as an essential component of the PSAs, also provided many important insights into the development of effective emergency response preparedness strategies for potential NPP accident scenarios.

DOE Safety Survey

The DOE's Defense Programs (DP) Office of Engineering and Operations Support contracted with Science Applications International Corporation (SAIC) to assess the safety of DOE DP non-reactor nuclear facilities and develop bounding accident consequences for hazards associated with these facilities. Radiological doses and potential health effects were estimated using MACCS. The survey results indicated that the DOE safety goals[10] for early fatalities and latent cancer were met and that the facilities surveyed do not represent a major hazard to the public relative to other industrial facilities.

Population Density Study

In 1992, the NRC proposed revisions[11] to 10CFR100 which included the codification of nuclear reactor site population density limits to 500 people per square mile, at the siting stage, averaged over any radial distance out to 30 miles. The proposed revisions also specified the requirement of a 0.4-mile exclusion zone for new reactor sites. DOE's Light-

Water Reactor (LWR) Safety & Technology Branch sponsored a study[12] at Sandia National Laboratories to evaluate the calculated health effects for various population distributions in the vicinity of a typical LWR NPP of the type currently operating, as well as a proposed advanced LWR design. MACCS was used to model the consequences to four different population distributions assuming two different evacuation rates. The results of the study indicated that measures which address the distribution of the population density, including emergency response conditions, could result in lower average individual risks to the public than the proposed guidelines that require controlling average population density.

International Collaborative Efforts

MACCS has participated in two international collaborative efforts; the Second International Comparison of PCA Codes[13] organized by the Nuclear Energy Agency of the Organization for Economic Cooperation and Development (OECD) and Commission of the European Communities (CEC), and a pilot probabilistic consequence uncertainty study[14] sponsored by the NRC and CEC.

Second International Comparison of PCA Codes

The second international comparison exercise compared consequences calculated by seven PCA codes. Examples of the consequences compared are collective doses, early and late health effects, economic costs, and the effect of countermeasures on people and agriculture. The codes compared in the study were ARANO (Finland), CONDOR (UK), COSYMA (CEC), LENA (Sweden), MACCS (USA), MECA2 (Spain) and OSCAAR (Japan). Comparisons were made between the predictions of the codes for a wide range of accidental release scenarios. Some of the conclusions of the comparison exercise were that the differences observed between the predictions of the codes were small in comparison to the overall uncertainty associated with the estimation of risk from postulated NPP accidents and that all of the codes assessed could be judged "fit-for-purpose" for the assessment of overall NPP risk. A number of recommendations for improving PCA codes were made by the authors of the comparison exercise at the completion of the study. These recommendations included the implementation of more comprehensive economic models in the codes, pursuing uncertainty to develop a better understanding of the uncertainties in PCA codes, and establishing users' groups to provide appropriate training to ensure proper use of the codes. Additional recommendations were offered and are contained in the project Overview Report.[15]

In parallel with the international comparison exercise, consequence predictions were compared between users of the same codes.[16] The codes used for this parallel study were MACCS and COSYMA.[17] Differences between predictions were obtained when different users input accident scenario specifications into the same code. The differences were found to be the result of different interpretations and simulations of the specifications, further emphasizing the importance of appropriate training in the use of the codes.

In response to the interest expressed in MACCS by numerous countries and organizations at the conclusion of the PCA code comparison study, an International MACCS Users

Group was formed to further enhance its applicability, identify potential improvements, and provide a forum for technical information exchange.

Joint NRC/CEC Uncertainty Study

In an attempt to quantify the uncertainty in consequence code predictions, the NRC and the CEC are jointly sponsoring an uncertainty study of their respective probabilistic consequence codes, MACCS and COSYMA. Although uncertainty analyses were performed for the predecessors of MACCS and COSYMA, the distributions for the code input parameters were largely developed by the code developers rather than the experts involved in the numerous phenomenological areas of consequence analysis. The joint CEC/NRC uncertainty study will use expert judgment techniques for the development of uncertainty distributions over the code input parameters indicated by sensitivity analyses to be the most important in terms of contribution to the uncertainty in code predictions. The formal elicitation of expert judgment is sometimes the only feasible alternative for obtaining information when it is impractical to perform experiments or the available experimental results do not lead to an unambiguous and a non-controversial conclusion. Less resource intensive methods will be used for the development of uncertainty distributions for the remainder of the code input parameters. After the development of the uncertainty distributions, the uncertainty in code input parameters is to be propagated through MACCS and COSYMA in order to quantify the uncertainty in code predictions.

In 1994, the joint CEC/NRC project completed an uncertainty analysis of the input parameters for the atmospheric dispersion and deposition modules of MACCS and COSYMA. Because of the magnitude and expense required to complete a full-scale consequence uncertainty analysis, the project was intended as a pilot uncertainty study for the assessment of the feasibility of a full NRC/CEC uncertainty study of MACCS and COSYMA. The primary goal of the joint study was to develop a library of uncertainty distributions in the areas of radionuclide dispersion and deposition by using a formal expert judgment elicitation process.

The NRC/CEC team developed a state-of-the-art approach for the elicitation of uncertainty distributions based on two important ground rules: (1) the current code models would not be changed because both the NRC and CEC were interested in the uncertainties in the predictions produced by MACCS and COSYMA, respectively, and (2) the experts would only be asked to assess physical quantities which could be hypothetically measured in experiments. The benefits of these ground rules were: (1) the codes have already been developed and extensively applied in US and EC risk assessments, and (2) eliciting physical quantities avoids ambiguity in variable definitions and, more importantly, the elicited physical quantities are not tied to any particular model and thus have a much wider application.

To ensure the quality of the elicited information, a formal expert judgment elicitation procedure, built on the process developed for and used in the NUREG-1150 study, was followed. Refinements were implemented based on the experience and knowledge gained from several formal expert judgment elicitation exercises performed in the US and EC since the NUREG-1150 study. In particular, significant experience and knowledge were gained from a trial dispersion and deposition expert elicitation exercise conducted by the CEC prior to the pilot uncertainty study.[18]

Distributions were developed over hypothetically measurable dispersion and deposition parameters from which were derived uncertainty distributions over code input parameters. Formal expert judgment elicitation served as a valuable vehicle to synthesize the best available information elicited from international experts. The uncertainty distributions developed in the pilot uncertainty study represent state-of-the-art knowledge in the areas of atmospheric dispersion and deposition. In addition to MACCS and COSYMA applications, the library of uncertainty distributions for atmospheric dispersion and deposition parameters potentially have many applications beyond code uncertainty analyses.

The results and experiences of the pilot uncertainty study support the feasibility of a full NRC/CEC uncertainty analysis of their respective PCA codes. In the pilot study, teams from the NRC and CEC staff with diverse experience and expertise and from different organizations allowed a creative and synergistic interplay of ideas which would not have been possible if they worked in isolation.

Current Development Efforts

The latest publicly available version of MACCS, MACCS 1.5.11.1 was released in 1992. MACCS 1.5.11.1 incorporated the latent cancer risk coefficients recommended by NRC sponsored research.[19] In 1994, the NRC sponsored the development of an updated and improved version of DOSFAC, the preprocessor which creates the file of dose conversion factors (DCFs) used in MACCS health effect calculations. The new version of the DOSFAC preprocessor, DOSFAC2, allows the user to define values for relative biological effectiveness, acute dose reductions factors, clearance class, and particle size. DOSFAC2 also allows the user to run the code without specification of a user input file, in which case the code utilizes values for parameters applied in DOSFAC. DOSFAC2 also provides DCF's for the ICRP 60 effective dose based on the updated tissue weighting factors.

In addition to NRC funded efforts, the DOE has sponsored major revisions of the MACCS code in order to expand the capabilities of MACCS to address the PCA needs of DOE facilities. The original MACCS package was developed specifically for the PCA of commercial NPP's and subsequently some difficulties were encountered when the code was used to evaluate DOE facilities. In order to address the specific needs of the DOE community, the capabilities of MACCS have been upgraded to include an expanded nuclide list and a more flexible emergency countermeasures modeling scheme. The capability of calculating potential health effects for the expanded list of nuclides was achieved by implementing an improved ingestion pathway model and a more powerful dose conversion factor preprocessor. The first beta test version of the updated code, referred to as MACCS2[20], was released in February 1993. The 1993 MACCS2 beta test version has been used in the PCA of a number of DOE facilities including the Oak Ridge

Ridge National Laboratory Highly Enriched Uranium Storage Facility Y-12 Plant[21] and the Savannah River Defense Waste Processing Facility.[22]

Overview Of MACCS2 beta release

This section reviews MACCS2 efforts originally reviewed in reference 20. When MACCS is used for assessments of DOE facilities, analyses are often hampered in two areas: (1) the original set of radionuclides was developed only for the assessment of commercial reactor accident scenarios and subsequently do not contain all of the nuclides important to the PCA of DOE nuclear facilities and (2) the MACCS evacuation model was developed to model an offsite population traveling radially outward, the evacuation path of onsite personnel from DOE facilities could be expected to be more complex than represented by the original MACCS evacuation model. The MACCS2 package expands the library of nuclides available to the user and provides a more flexible emergency response model.

Expanded Nuclide List

DOSFAC provides DCFs for 60 radionuclides. The database created by DOSFAC does not provide DCFs for all of the nuclides needed for DOE PCAs. It was therefore necessary to find an alternative source of DCFs for MACCS2. The 1993 MACCS2 beta test package accessed DCFs for immersion and groundshine for approximately 800 nuclides from DOE/EH-0070[23] and inhalation and ingestion DCFs for approximately 500 nuclides from the MACCS2 preprocessor IDCFMAX. IDCFMAX is based on the IDCF[24,25] code developed at the Idaho National Engineering Laboratory (INEL). IDCF calculates DCFs based on the recommendations of ICRP30.[26] In addition, MACCS2 allows the consideration of ingrowth and decay for chains with lengths up to six members. Decay and ingrowth in MACCS2 are calculated analytically using an iterative representation of the differential equation for first-order kinetics.

New Food-Chain Model

MACCS incorporates a food pathway model which requires the user to supply unitless transfer coefficients for each nuclide through each of the crop types considered by the code. These transfer factors define the fraction of material deposited on farmland that is eventually incorporated into edible portions of resultant foodstuffs. The derivation of these transfer factors is a difficult and labor intensive task and the sample problems distributed with MACCS include input parameter data for only six nuclides: Sr-89, Sr-90, I-131, I-133, Cs-134, and Cs-137. Input data for additional nuclides has never been developed. In addition, the original food pathway model did not contain dynamic modeling capabilities. No first year food pathway ingestion dose was calculated for releases outside of the growing season.

The MACCS2 package includes a new dynamic food chain model which does not require the derivation of complex input parameter values. The new model allows the user to include additional nuclides in the ingestion model through the input of nuclide/food chain data directly available in the literature. In addition, users can readily modify input parameters to reflect site-specific agricultural conditions.

The MACCS2 preprocessor for food ingestion modeling is based on INEL's COMIDA code.[27] COMIDA was developed to support accident analyses of fusion power test facilities.[28] COMIDA's modeling capabilities are similar to those of the PATHWAY code.[29,30] COMIDA determines nuclide concentrations in agricultural food products following an acute fallout event. COMIDA dynamically models plant growth and calculations are subsequently specific to the release date. COMIDA estimates yearly harvest concentrations for five human crop types and integrated concentrations for four animal products. A MACCS2/ COMIDA interface was developed which performs a number of functions including obtaining COMIDA results for each of the first 51 years after the accident, obtaining data for multiple accident dates so that MACCS2 can choose the date closest to the accident date in order to account for seasonality effects, and calculating the radionuclide decay and ingrowth which occurs between harvest and the time of consumption. For maximum flexibility, MACCS2 allows the use of either the COMIDA based pre-processor or the MACCS unitless transfer factor model.

Improved Emergency Response Model

MACCS 1.5 models evacuation radially outward. Many DOE nuclear facilities are sited at large reservations which may have a limited number of egress paths for worker evacuation.[31] The principal MACCS2 enhancements in this area are (1) allowance for evacuation paths that are non-radial, (2) allowance for evacuation travel speed that varies with time, and (3) allowance for specification of up to three population distributions, with each cohort following its own distinct pattern of emergency response. These new features allow (1) consideration of evacuation travel on road networks, (2) traffic jams causing slowdowns in travel speed, and (3) consideration of distinct population subgroups (e.g., security guards and health physics teams) responding to the accident. These additional features are implemented in such a way that any scenario that can be modeled with MACCS 1.5 can also be treated with MACCS2, though modification of existing input files will need to be performed.

Modifications to MACCS2 in Response to Beta Test User Comments

In response to beta test feedback the capabilities of both the food chain and dose conversion factor preprocessors are being expanded before the unlimited public release of MACCS2.

MACCS/COMIDA Interface

The original MACCS2/COMIDA interface program reported nuclide concentrations in foodstuffs for each crop category. Because of the large volume of data this framework required, the code design was limited to handling a maximum of ten nuclides (the same limit imposed by the original MACCS food model). The COMIDA/MACCS2 interface program was revised in order to reduce code storage requirements by reporting doses to individuals instead of foodstuff concentrations. COMIDA2, the revised COMIDA/MACCS2 interface, allows up to 75 nuclides to be processed in one run. In addition, COMIDA2 was designed so that it could be used as a stand-alone code or as a preprocessor for other consequence codes.

Dose Conversion Factors
A discrepancy was found between the inhalation and ingestion DCFs for Sr-90 generated by IDCFMAX and those recommended by the Environmental Protection Agency (EPA) in Federal Guidance Report (FGR) 11[32]. Review of IDCF indicated that it is possible to implement ICRP30 models in more than one way and obtain divergent results. No errors were found in IDCF. Nevertheless, the MACCS2 package was modified to allow the user a choice between the following three different sources for DCFs: (1) DOSFAC2, (2) IDCF/DOE-EH-0070, or (3) the EPA recommended DCFs from FGRs 11 and 12[33]. It is not practical to use FGRs 11 and 12 as the sole source of DCFs for MACCS because the data in these reports is insufficient for the calculation of acute health effects. In order to facilitate MACCS versus MACCS2 code comparisons, MACCS2 was modified to obtain DCFs in the same file format used by MACCS. IDCF and DOE-EH-0070 provide DCFs for nuclides not available in DOSFAC2.

Beta Release of Upgraded MACCS2

A June, 1995 release date is planned for the beta test version of the upgraded MACCS2 package. This release will include an updated User's Guide describing all operational features of the new code. Verification activities will continue through the 1995 calendar year. A December, 1995 public release is planned for MACCS2.

Future Directions

The U.S. NRC is sponsoring a re-evaluation and upgrade of the MACCS economic model within the context of recent NRC sponsored research.[34] The NRC has requested that the MACCS economic model be upgraded to include per person-rem health effect costs as well as the capability of including present-worth considerations in the dollar value assigned to health effect costs.

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