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Sensitivity and Uncertainty Studies of the CRAC2 Code for Selected Non-meteorological Models and Parameters*

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ABSTRACT

We have studied the sensitivity of health impacts and economic costs from hypothetical nuclear reactor accidents, as predicted by the CRAC2 computer code, to uncertainties in selected non-meteorological models and parameters. The sources of uncertainty include (1) dose conversion factors for inhalation as affected by uncertainties in the particle size of the carrier aerosol and clearance of radionuclides from the respiratory tract, (2) the weathering half-time for external ground-surface exposure, and (3) transfer coefficients for terrestrial foodchain pathways. Uncertainties in inhalation dose conversion factors affected predicted early injuries by as much as 1-2 orders of magnitude in runs with fixed weather sequences, whereas the effects on early fatalities were less than a factor of 2 and on latent cancer fatalities less than 10%. Uncertainties in the weathering half-time for ground-surface exposure affected latent fatalities by a factor of 2-3 but economic costs by less than a factor of 2. Uncertainties in the transfer coefficients for terrestrial foodchain pathways affected latent fatalities by less than 15% and had no effect on economic costs.

INTRODUCTION

The computer code CRAC2[1,2] is a revised version of CRAC, which was developed for the Reactor Safety Study[3] to estimate health impacts and economic costs that could result from hypothetical nuclear reactor accidents. Of considerable interest is the sensitivity of CRAC2 predictions to uncertainties in models and parameters used in the code.[4]

This paper presents a study of the sensitivity of CRAC2 results to uncertainties in selected non-meteorological models and parameters. The sources of uncertainty that were studied include (1) the variability in dose conversion factors for inhalation (i.e., the dose to the lungs and other body organs per unit activity of an inhaled radionuclide) due to uncertainties in the particle size of the carrier aerosol and the clearance of radionuclides from the respiratory tract, (2) the uncertainty in the weathering half-time for estimating external exposures to radionuclides deposited on the ground surface, and (3) uncertainties in the transfer coefficients for estimating exposures via terrestrial foodchain pathways. Uncertainties in inhalation dose conversion factors can affect the number of early fatalities, early injuries, and latent cancer fatalities calculated by CRAC2, whereas uncertainties in the weathering half-time for external ground-surface exposure and the transfer coefficients for terrestrial foodchain pathways can affect only latent cancer fatalities and economic costs.[1]

DESCRIPTION OF SENSITIVITY AND UNCERTAINTY ANALYSES

The sensitivity studies of the CRAC2 code were performed using a set of meteorological data representing one year's observations, a nonuniform population distribution, a set of representative land-use data, and a single evacuation model. Either a "large" or a "small" release of radionuclides (i.e., source term) was assumed. Except for noble gases and organic iodine, the release fractions for the different radionuclide leakage groups were a factor of 3-5000 less for the small release than the corresponding values for the large release. A zero release height and a sensible heat release of 10^4 cal/s were used in most calculations; zero release height was often required to obtain nonzero early fatalities. When studying the effects of a particular source of uncertainty, all other models and parameters were fixed at the default conditions usually assumed in CRAC2 calculations.[1,2]

The sensitivity studies of the inhalation dose conversion factors and the transfer coefficients for terrestrial foodchain pathways involved repeated runs of the code with selected fixed weather sequences and statistical sampling over assumed distributions of model input parameters.* The fixed weather sequences were selected to give a variety of atmospheric stability categories, wind speeds, and precipitation conditions, so that we could investigate the sensitivity of CRAC2 calculations for representative meteorological conditions that give different concentrations of radionuclides in the atmosphere and on the ground. Meteorological bin sampling[1] was used in the sensitivity study of the weathering half-time for external ground-surface exposure, because only a single parameter was varied and, thus, only a few runs were required to estimate the variability in code output.

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* The large number of input parameters to be varied and, thus, the large number of runs required to define the resulting distributions of CRAC2 output precluded the use of statistical sampling of weather sequences from one year's data in these two studies.

ANALYSIS FOR INHALATION DOSE CONVERSION FACTORS

Except for noble gases, inhalation dose conversion factors depend on two parameters that reflect the physical and chemical form of the released radionuclides: (1) the particle diameter of the carrier aerosol, expressed as Activity Median Aerodynamic Diameter (AMAD); and (2) the respiratory clearance class for each radionuclide, expressed as Class D (clearance from the respiratory tract within days), W (weeks), or Y (years).[5] The value of AMAD determines the fraction of the inhaled material which is deposited in each of the three regions of the respiratory tract, and the clearance class affects the dose to the lungs and other body organs per unit deposition in each region.[5] Default CRAC2 calculations assume a single value of AMAD (1 μm) and a single clearance class for each element.[2]

In our analysis, uncertainties in particle size were represented by a uniform distribution of AMAD values between 0.2 and 10 μm with mean value of 5 μm. In order to represent uncertainties in respiratory clearance class, we replaced the discrete assignments of Class D, W, or Y for each element by a continuum over the interval [0,1], with 0, 1/2, and 1 corresponding to D, W, and Y, respectively. The probability density along this continuum was taken to be triangular with mode at D, W, or Y according to the clearance class assigned in CRAC2.[2]

From the assumed probability distributions for AMAD and clearance class, Latin hypercube sampling[6] was used to generate a sequence of 25 random vectors, each of which has 24 stochastically independent components — the value of AMAD and 23 numbers between 0 and 1 which determined the relative admixtures of the three clearance classes for each of the 23 elements in the release that are not noble gases (all isotopes of a given element are assumed to have the same clearance). Radionuclide-specific dose conversion factors for the lungs and other body organs corresponding to the components of each random vector were calculated as linear combinations of values for unit deposition in each region of the respiratory tract and each clearance class. The latter values were obtained from the ICRP deposition and retention model,[5] as implemented by the RADRISK computer code.[7] The sensitivity of CRAC2 output to uncertainties in the dose conversion factors was then determined by running the code for each of the 25 random vectors of input data for selected fixed weather sequences.

The most striking effects of varying the dose conversion factors were found in the predicted number of early injuries. For two weather sequences, mean early injuries were factors of 15 and 150 greater than the default CRAC2 results. We attribute this effect to the presence of thresholds in the dose-response model for early injuries.[1] For the remaining weather sequences, the increases in mean early injuries were a factor of 2-3. For all weather sequences, mean early fatalities increased by 20-80% compared with the default results, and mean latent fatalities changed by less than 20%. The coefficient of variation (i.e., the standard deviation relative to the mean) due to the variability in dose conversion factors was 10-30% for early fatalities, 10-40% for early injuries, and 10% or less for latent fatalities.

ANALYSIS FOR WEATHERING HALF-TIME FOR GROUND-SURFACE EXPOSURE

In calculating external exposures from radionuclides deposited on the ground surface, the CRAC2 code assumes that the photon dose rate decreases with time according to a weathering half-time as well as the half-life for radioactive decay.[1] The weathering half-time in CRAC2 is based on data for ^{137}Cs in soils[8] and is assumed to apply to all radionuclides that contribute to this exposure pathway.

From the measured weathering half-time of 23 ± 12 years,[8] we generated a lognormal distribution of half-times with the same arithmetic mean and standard deviation, and we selected the 5th and 99.9th percentiles as bounding values. These percentiles correspond to half-times of 9 and 93 years, respectively. The bounding values were used in CRAC2 runs with meteorological bin sampling.[1] Predicted latent cancer fatalities varied by a factor of 2-3 over the range of weathering half-times, depending on the source term. Economic costs varied by 25-60%, depending on the source term and whether or not decontamination was assumed.

ANALYSIS FOR TERRESTRIAL FOODCHAIN PATHWAYS

The CRAC2 code considers exposures to radionuclides via terrestrial foodchain pathways following deposition onto vegetation and root uptake from soils. Calculated doses for each radionuclide and foodchain pathway are proportional to an equilibrium concentration factor, CF, which gives activity ingested per unit initial ground concentration.[1]

We studied the sensitivity of CRAC2 calculations to uncertainties in the foodchain concentration factors. The mean and standard deviation for each CF were obtained from published uncertainty analyses.[9,10] Latin hypercube sampling was used to generate 25 stochastically independent sets of CF values. These sets of input data were then used to obtain distributions of CRAC2 output for selected fixed weather sequences.

Differences of as much as a factor of 6 were found between the mean CF values obtained from random sampling and the default values contained in the CRAC2 code. However, these differences had little effect on code output. In all cases, mean latent fatalities changed by less than 15%, and the coefficient of variation was less than 10%. Economic costs were insensitive to uncertainties in the CF values, because crop interdiction and land decontamination were always determined by doses from external ground-surface exposure.

CONCLUSIONS

The most important result from this analysis is the apparent sensitivity of early injuries calculated by the CRAC2 code to uncertainties in the dose conversion factors for inhalation. Increases of 1–2 orders of magnitude in early injuries compared with default CRAC2 results were found for selected fixed weather sequences. Increases of nearly a factor of 2 in early fatalities were also found, but the effects on latent cancer fatalities were somewhat less. Uncertainties in the weathering half-time for external ground-surface exposure affected latent fatalities by a factor of 2–3, but the effects on economic costs were somewhat less. Uncertainties in transfer coefficients for terrestrial foodchain pathways apparently have an insignificant effect on latent fatalities and economic costs.

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