ANALYSIS OF UNCERTAINTIES IN CRAC2 CALCULATIONS: THE INHALATION PATHWAY

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ABSTRACT

CRAC2 is a computer code for estimating the health effects and economic costs that might result from a release of radioactivity from a nuclear reactor to the environment. This paper describes tests of sensitivity of the predicted health effects to uncertainties in parameters associated with inhalation of the released radionuclides. These parameters are the particle size of the carrier aerosol and, for each element in the release, the clearance parameters for the lung model on which the code's dose conversion factors for inhalation are based. CRAC2 uses hourly meteorological data and a straight-line Gaussian plume model to predict the transport of airborne radioactivity; it includes models for plume depletion and population evacuation, and data for the distributions of population and land use. The code can compute results for single weather sequences, or it can perform random sampling of weather sequences from the meteorological data file and compute results for each weather sequence in the sample. For the work described in this paper, we concentrated on three fixed weather sequences that represent a range of conditions. For each fixed weather sequence, we applied random sampling to joint distributions of the inhalation parameters in order to estimate the sensitivity of the predicted health effects. All sampling runs produced coefficients of variation that were less than 50%, but some differences of means between weather sequences were substantial, as were some differences between means and the corresponding CRAC2 results without random sampling. Early injuries showed differences of as much as 1-2 orders of magnitude, while the differences in early fatalities were less than a factor of 2. Latent cancer fatalities varied by less than 10%.

KEY WORDS: Consequence Analysis; Nuclear Reactor; Dose Conversion Factor; Particle Size; Respiratory Clearance; Latin Hypercube Sampling; ICRP Lung Model

1. INTRODUCTION

In this paper we discuss some sensitivity tests of calculations performed with the CRAC2 computer code to uncertainties in parameters for inhalation dose. CRAC2 estimates early and latent health effects and economic costs that might result from a hypothetical release of radioactivity from a nuclear reactor to the environment.

The CRAC2 code (Ritchie et al., 1983; Ritchie et al., 1984) is a revision of CRAC (Calculation of Reactor Accident Consequences), which was developed for use in the Reactor Safety Study (U.S. Nuclear Regulatory Commission, 1975). Consequence analysis codes such as CRAC2 are normally used in conjunction with the last stage of a Probabilistic Risk Assessment (PRA) of the engineered safety design of a nuclear reactor. CRAC2 uses hourly meteorological data (wind speed and direction, atmospheric stability class, and precipitation rate) and a straight-line Gaussian plume model to predict the transport of airborne radioactivity; models for plume depletion by wet and dry deposition; a model of population evacuation; and data for the distributions of population and land use. The data base also includes dose conversion factors for external and internal exposure to radionuclides, risk data for converting estimates of collective dose to numbers of radiation-induced health effects, and economic data for land use. The code can compute results for single weather sequences, or it can perform random sampling from a data file containing one year's weather data and simulate the release repeatedly for each weather sequence in the sample. In this paper, where meteorology is concerned, we are interested only in the former nonrandom mode; we describe simulations in which the meteorology is fixed, but random sampling is introduced in connection with uncertainties in the dose conversion factors for inhalation of radionuclides.

Sensitivity studies reported in this paper were carried out using meteorological data from a file containing one year's observations, a nonuniform distribution of population, a set of representative land use data, and a single evacuation model. Both a "large" and a "small" release of radionuclides were used as source terms. With the exception of the 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 for the large one. Most of our calculations were carried out with the large release. A zero release height and a sensible heat release of 10^4 cal/s were used in all of our calculations; the zero release height was sometimes required to obtain nonzero early fatalities.

In our analyses, we consider uncertainties in the particle size of the carrier aerosol and in the rates of clearance of the various radionuclides from the respiratory passages. In the standard CRAC2 data base, the particle size is fixed at 1 μm. This parameter determines the deposition of inhaled particulate material in each of the major regions of the respiratory passages. The rates of clearance from the lungs are based on estimates of the solubility of the expected chemical forms of released radionuclides; these estimates represent a consensus of groups of experts (Morrow et al., 1966; U.S. Nuclear Regulatory Commission, 1975). The relevant portion of the CRAC2 data base consists of dose conversion factors (rems to target organs per curie of inhaled radionuclide) in which these assumptions are implicit and fixed. In effect,

the fixed particle size and clearance rates have been replaced by probability distributions, and for three fixed weather sequences, repeated runs of CRAC2 have been performed with joint random sampling from these distributions. Thus, we are able to compile corresponding probability distributions of output quantities (numbers of early and latent health effects) and assess their sensitivity to uncertainties in the inputs. Details and results of these calculations are discussed in the following sections.

2. DOSE CONVERSION FACTORS FOR INHALATION

Factors for converting unit amounts of inhaled radionuclides to dose to thirteen target organs are part of the data base of CRAC2. These dose conversion factors depend on two parameters that characterize the physical and chemical properties of the radionuclide and the carrier aerosol. The first of these parameters is the aerosol particle size, expressed as activity median aerodynamic diameter, or AMAD (μm), which determines the deposition of the inhaled particles in the regions of the respiratory tract. The second parameter has three discrete values that characterize the rate of clearance of inhaled particulate material from the respiratory passages as rapid, intermediate, or slow. These clearance rates have been estimated from considerations of solubility of particular chemical compounds of each radionuclide. The appropriate values for these parameters in a CRAC2 analysis are subject to some uncertainty, and we have carried out sensitivity studies to determine how these uncertainties propagate into the estimates of health effects.

In order to be more precise about the nature of these parameters and the sensitivity tests, it is necessary to give some details of the dose conversion factors and the respiratory deposition and clearance model on which they are based. For each particulate radionuclide in the source term, the CRAC2 data base contains factors for dose to thirteen target organs due to inhalation of the radionuclide. These factors have been calculated for brief periods of acute exposure (1 year for lungs; 7 days for marrow, bone, endosteal cells, stomach wall, small intestine, upper large intestine, and lower large intestine; and 2 days for thyroid, whole body, testes, ovaries, and other tissues); and for the time intervals 0-1, 1-10, 10-20, 20-30, 30-40, and 40-50 years for chronic exposure. Corresponding factors are included for noble gases, but these factors are not dependent upon the parameters that concern us and therefore were not varied in the sensitivity analyses to be discussed.

Each dose conversion factor for inhalation of particulate matter depends on the particle size of the carrier aerosol, AMAD, (μm). The dependence is expressed in terms of deposition fractions for the major respiratory regions (nasal pharynx or NP, tracheobronchial tree or TB, and pulmonary region or P). For any value of AMAD in the applicable range, the deposition fractions may be read from the curves in the graph of Fig. 1. In general, we note that larger particles tend to be trapped in the nasal pharynx, while smaller particles are breathed into the pulmonary region and tend to deposit there. The tracheobronchial tree receives the same fraction throughout the size range. But a point of particular importance is this: the total respiratory deposition fraction (i.e., the sum of the fractions for the three regions) is larger for

large particles than for small ones (98% for 10-μm particles compared with 63% for 0.2-μm). Figure 1 shows the total deposition fraction for several values of AMAD. Thus, while larger particles tend not to penetrate deeply into the respiratory passages, a larger fraction of those inhaled are retained than is the case for small particles. Some dose conversion factors, such as those routinely used in CRAC2, do not include the dose to the nasaopharyngeal tissues in computing the dose to the lungs; but the material deposited in the nasal pharynx is available for absorption into the blood and thus contributes to the dose to other systemic organs. Hence the effect of the greater total deposition in the respiratory passages resulting from larger particle sizes is increased dose to some organs and therefore potentially higher estimates of numbers of health effects. In Section 4, we shall return to the question of how the lung dose is computed and how an alternate definition changes the CRAC2 estimates of health effects.

FIGURE 1 ABOUT HERE

The first parameter that concerns us, then, is the measure of aerosol particle size or AMAD. All dose conversion factors for particulate inhalation that are contained in the CRAC2 data base were calculated for AMAD = 1 μm. Our sensitivity analysis deals, in part, with uncertainty about the choice of this parameter's value.

Once the radioactive material is deposited in the respiratory passages, its rates of clearance from the respective regions are strongly dependent upon the physical and chemical composition of the material. The lung model on which the calculation of the dose conversion factors was based was developed by the International Commission on Radiological Protection (ICRP) (Morrow et al., 1966; ICRP, 1972; ICRP, 1979). Figure 2 summarizes the compartmentalization and parameterization of the model. Rather than treating a multidimensional continuum of dynamic behaviors, the ICRP, in defining its lung model, has simplified the complex topic of respiratory clearance by assuming three discrete classes of materials. These classes are labeled as class D (in which clearance is accomplished in a matter of days), W (weeks), and Y (years). The clearance-rate coefficients of the model depend on the class that is assumed for a particular radionuclide. These clearance-rate coefficients are related in Fig. 2 to the clearance pathways labeled a, b, c, ..., i by way of which the deposited radioactivity is moved from the sites of deposition into the blood, the lymph nodes, and the GI tract. The table in Fig. 2 quantifies the rates at which these migrations of radioactivity are assumed to take place. Each pathway out of a region is assigned a fraction F and a half-time T (days). For each region, the values of F sum to one. The radioactivity remaining after t days is

$$A = DF \exp[-((\ln 2)/T + \lambda_R)t]$$

where λ_R is the radioactive decay-rate coefficient (day^{-1}) for the radionuclide, and D is the deposition fraction D_3, D_4, or D_5 that corresponds to the particular region from which the clearance pathway emerges. The parameters T and F vary with the choice of clearance class

(D, W, or Y); the deposition fraction D is determined by the value of AMAD. In practice, the lung model is translated into a system of ordinary differential equations which can be solved by numerical methods.

FIGURE 2 ABOUT HERE

To illustrate the notations of Fig. 2, we note that in the case of Class D material deposited in the nasal pharynx, 50% is available for direct absorption into the blood with half-time 0.01 days, while the other 50% is swallowed into the gastrointestinal (GI) tract with the same half-time. For a Class Y material in the nasal pharynx, only 1% is available to be absorbed into the blood with half-time 0.01 days, while 99% is cleared to the GI tract but at a much slower rate, with half-time 0.4 days. The contrasts in behavior among the D, W, and Y materials are substantial in all three major respiratory regions of the model. Because of these differences, the dose to the lungs is generally less for Class D than for Class Y materials; a factor-of-five difference is typical of short integration periods (comparable to those associated with the estimation of acute effects), but the variation from one radionuclide to another is substantial. The rapidly cleared and absorbed Class D materials are introduced more promptly into systemic organs and therefore tend to give a higher dose to those organs than do Class Y materials, which are detained for longer periods in the respiratory tract.

Each dose conversion factor for inhalation of particulate material that is stored in the CRAC2 data base has implicit in it the assumption of a particular respiratory clearance class: 23 of the 54 nuclides are assigned to Class Y, 11 to Class W, and 14 to Class D [the remainder are noble gases, for which the ICRP lung model is inappropriate and for which the factors for internal dose are based on an alternate model (Bernard and Snyder, 1975); these factors will not be included in our sensitivity analysis]. The clearance class assignments are based on assumptions about the chemical form of the material in a release and have generally been made from guidance offered by ICRP task groups and other experts (Morrow et al., 1966; ICRP, 1972) and from assumptions made about releases in the Reactor Safety Study (U.S. Nuclear Regulatory Commission, 1975). We should emphasize that all isotopes of the same element are considered to belong to the same respiratory clearance class. Even though the determination of clearance class depends on the particular chemical compound of the material, assumptions about the predominant chemical form of each element must be assumed to have been made when the CRAC2 data base was prepared. We note that this assumption might possibly be an implicit restriction on application of the code to releases of a kind not contemplated in the Reactor Safety Study.

Our sensitivity analysis is concerned with uncertainty about (1) the value of the particle diameter AMAD for the carrier aerosol and (2) the information that determined the D, W, or Y class for each element in the release.

Uncertainty in AMAD.

All dose conversion factors for inhaled particulates in the CRAC2 data base were calculated for AMAD = 1 μm. But there is considerable uncertainty in this value, and in consultation with NRC staff, we chose to replace it by a probability distribution that is uniform over the range 0.2–10 μm (Fig. 3), which is the normal range spanned by the deposition model shown in Fig. 1. It should be noted that this distribution has a mean value (5.1 μm) that is substantially greater than the CRAC2 default value, so that, on the average, the total fraction of inhaled radioactivity that is deposited in the respiratory passages will be greater than that associated with the default value of 1 μm.

FIGURE 3 ABOUT HERE

Uncertainty in D, W, Y.

The assignment of a radionuclide to class D, class W, or class Y depends on properties of the expected chemical form. Groups of experts (Morrow et al. 1966) have made such assignments for numerous chemical compounds, and these assignments have been applied to the radionuclides in the CRAC2 data base on the basis of assumptions about the probable chemical form of each element in the release (U.S. Nuclear Regulatory Commission, 1975). Hence, in the CRAC2 data base, all isotopes of a given element are assigned the same clearance class. Table 1 shows the assignment of class D, class W, or class Y to each radionuclide in the CRAC2 data base (no assignment is shown for noble gases, because the model is not applicable to them).

TABLE 1 ABOUT HERE

In place of the three discrete choices D, W, and Y, we have defined a continuum consisting of the interval [0,1], with correspondence as follows: $0 \rightarrow$ D, $0.5 \rightarrow$ W, and $1 \rightarrow$ Y. For each element, we define a triangular probability density function over [0,1] with its mode (sometimes called the "most probable value") at D, W, or Y according to the class assigned to the element by expert consensus (Fig. 4). Thus, for a class-D nuclide, we sample from the triangular density function with its mode at class D (i.e, zero). This arrangement expresses uncertainty in the assignment but biases the sampling toward the assigned clearance class. We note, however, that the mean of the class-D distribution is 1/3 rather than zero; similarly, the mean of the class-Y distribution is 2/3 and not 1. Thus, on the average, both extremes are shifted somewhat toward class-W.

FIGURE 4 ABOUT HERE

The Sampling Scheme and Resultant Dose Conversion Factors.

We have devised a scheme to sample a joint probability distribution of AMAD and a clearance value in [0,1] for each of the 23 particulate elements in the CRAC2 data base. Each trial in the sampling process results in a random vector of 24 stochastically independent components

from the joint distribution. A number N (= 25 in our investigations) of these random vectors is selected in the sampling. For each choice of a random vector, CRAC2 is executed with data from that vector; each execution produces an output value for each of the quantities of interest (numbers of early and latent health effects), and means and measures of dispersion (e.g., standard deviations) can be estimated from the aggregate of outputs resulting from the N random input vectors. Figure 5 shows the general arrangement of the random input vectors in relation to the rectangular distribution for AMAD and the triangular distributions for the clearance classes of the 23 elements.

From the variety of available sampling strategies, we have chosen Latin hypercube sampling. A detailed discussion of the theory and implementation of this technique has been given by Iman et al., 1980.

FIGURE 5 ABOUT HERE

The data base for our sampling scheme includes dose conversion factors for all three classes (not just for the class assigned to the element, as in the ordinary CRAC2 data base). Let us denote such factors generically by d_D, d_W, and d_Y. When our sampling scheme chooses the number x from the interval [0,1] for one of the elements, with probability density assigned by the triangular distribution that is appropriate for the particular element, the dose conversion factor d_x will be computed as a suitable combination of d_D, d_W, and d_Y as follows:

$$d_x = 2[d_D(1/2 - x) + d_W x] \quad \text{if} \quad 0 \leq x < 1/2 \ ,$$

$$= 2[d_W(1 - x) + d_Y(x - 1/2)] \quad \text{if} \quad 1/2 \leq x \leq 1 \ .$$

CRAC2 uses the dose conversion factors d_x in its computation of numbers of early and latent health effects resulting from the release. Each trial in the sampling scheme gives different numbers of effects because of the different value of AMAD and the perturbation of each element from its D, W, or Y lung clearance category.

It was not possible to complement the ordinary CRAC2 data base with dose conversion factors that would be entirely compatible with the methodology that produced the CRAC2 factors; consequently, we used an alternate data base derived from the the INREM II and RADRISK computer codes (Killough et al., 1978; Dunning et al., 1980). Some background for this data base is given in Sect. 5.

3. RESULTS OF THE SIMULATIONS

Table 2 collects the results of the CRAC2 consequence estimates for the Latin hypercube sensitivity runs and the corresponding "default" estimates that represent standard runs of CRAC2. The results that are based on Latin hypercube sampling are presented as follows in the tables:

$$\text{mean} \times (1 \pm \text{C.V.}),$$

where C.V. is the fraction (standard deviation)/mean. In one set of runs, AMAD was kept fixed at 1 μm, and the results are given in brackets in Table 2.

TABLE 2 ABOUT HERE

The measures of effect that we have chosen for display are the following:

EARLY FATALITIES — Number of fatalities occurring within one year due to initial exposure to the radioactive cloud

EARLY INJURIES — Number of injuries or illnesses occurring within one year due to initial exposure to the radioactive cloud

TOT. LATENT/INIT. — Total latent cancer fatalities occurring due to initial exposure to the radioactive cloud

TOT. LATENT/TOT. — Total latent cancer fatalities occurring due to both initial and chronic exposure.

The Latin hypercube simulations estimate substantially greater numbers of early injuries than the CRAC2 default runs, and in all categories of health effect (with one exception, where the effect is zero), the Latin hypercube calculation estimates a larger number. Some of the increase is due to the greater mean value of AMAD in the random sampling runs (a mean of 5.1 μm vs. a default value of 1 μm). The parenthesized quantities in Table 2 are the results of Latin hypercube sampling calculations in which the clearance classes were varied with each trial, as previously described, but AMAD was kept fixed at 1 μm. In this comparison, most of the difference disappears for early fatalities, but the mean value for early injuries still exceeds the default value by 58%. Fixing AMAD increases the mean latent cancer fatalities.

In the column of Table 2 under weather sequence #2, the Latin hypercube mean for early injuries exceeds the default value by two orders of magnitude. We attribute this large discrepancy to the effects of thresholds in the dose-response models used in CRAC2 (Ritchie et al., 1983). For the three weather sequences represented in Table 2, the early injuries show the most substantial increase over their default values of all health effects considered.

For each weather sequence and health effect studied, estimates of the variability arising from uncertainties in AMAD and respiratory clearance class are rather modest: the maximum coefficient of variation (standard deviation relative to the mean) is 42%. This variability is considerably exceeded by the differences between means and the corresponding default values, and by the variation of means among the weather sequences that were used.

4. RESPIRATORY REGIONS INCLUDED IN LUNG DOSE DEFINITION

Another aspect of the dose conversion factors that we considered is the extent of respiratory tissue to which the definition of lung dose is applied. Assumptions vary among different tabulations of dose conversion factors. The dose to the lungs is computed as some weighted average of doses to the major respiratory regions — NP (nasal pharynx), TB (tracheo-bronchial region), P (pulmonary region), and L (lymph nodes). The original INREM II tabulations (Killough et al., 1978; Dunning et al., 1978; Dunning et al., 1981) used the mass-weighted average of all four regions. The EPA-sponsored RADRISK work (Dunning et al., 1980) used the dose to the P region as its basis for health effects. The dose conversion factors prepared for the Reactor Safety Study (U.S. Nuclear Regulatory Commission, 1975) by W.S. Snyder and his co-workers used the mass-weighted average of TB, P, and L. The CRAC/CRAC2 data base is generally derived from the Reactor Safety Study numbers, although there are numerous discrepancies. Thus the lung dose numbers in this data base also use the mass-weighted average of TB, P, and L. ICRP Publication 30 (ICRP, 1979) has adopted the practice of computing the lung dose as the mass-weighted average of TB, P, and L. It should be understood that the question of the most appropriate interpretation is a matter of some controversy.

For this study, the INREM II and RADRISK computer codes were used to prepare special data bases of dose conversion factors for the sensitivity studies of CRAC2 involving the inhalation pathway. We prepared two data bases, one for each of the following assumptions:

- The lung consists of NP + TB + P + L
- The lung consists of TB + P + L (consistent with the CRAC2 data base).

The latter data base (without NP) is considered the standard one, but some results using the former (with NP) are included because of the significantly larger numbers of predicted health effects that are calculated when it is used. The number of early fatalities is the most affected measure of impact, differing by more than a factor of three when the two assumptions are applied. Table 3 gives the details. The INREM II/RADRISK numbers were generated with Latin hypercube sampling. The parenthesized numbers are results from runs in which AMAD was held constant at 1 μm.

TABLE 3 ABOUT HERE

Figure 6 shows a quantitative comparison of lung dose estimates based on the alternate assumptions displayed above. The ratio

$$\tilde{A}_{NP+TB+P+L} / \tilde{A}_{TB+P+L}$$

is plotted vs. the radioactive decay-rate coefficient, λ_R (day^{-1}), for various combinations of AMAD and clearance class. The symbols $\tilde{A}$ denote time integrals of the radioactivity burdens of the lung tissue indicated

by the respective subscripts. This ratio is equal to the ratio of doses to these tissues. The numerator uses all four regions of the respiratory tract, while the denominator omits the nasopharyngeal (NP) region. All values are larger than 1; the excess above 1 is a measure of the effect that the inclusion of the NP region has on the lung dose estimate. But we remind the reader that material deposited in the NP region, whether it is considered in the calculation of lung dose or not, contributes to the dose to other organs as a result of its absorption into the blood, either directly from the NP or indirectly by way of the gastrointestinal (GI) tract.

We conclude this section with several observations based on Fig. 6:

FIGURE 6 ABOUT HERE

- The importance of including NP in the dose-receiving lung tissue increases with increasing particle size.
- The effect of including NP is most sensitive to Class W and least sensitive to Class D for a given half-life.
- This NP effect, for a given clearance class and particle size, diminishes most rapidly for half-lives between about 100 minutes and seven days. For longer half-lives, the effect is negligible.
- For very short half-lives, the lung dose per unit intake of 5-μm particles exceeds that for 1-μm particles by a factor of about five.

5. SOME BACKGROUND FOR THE INREM II/RADRISK DATA BASE

The dose conversion factors for inhalation (dose to a reference adult at specified times following an acute unit intake) used in the sensitivity analyses of CRAC2 were computed using a computer code that was adapted from the computer codes INREM II (Killough et al., 1978) and RADRISK (Dunning et al., 1980). The model reference adult is based on the ICRP Reference Man Report (ICRP, 1975). The ICRP lung model (Morrow et al., 1966; ICRP, 1972; ICRP, 1979) was used to simulate the deposition and retention of inhaled aerosols in the respiratory tract. The GI tract is represented by a catenary model of four segments (ICRP, 1979). Retention of activity in systemic organs is modeled by linear combinations of exponential terms; all metabolic data conform to current ICRP recommendations (ICRP, 1980; ICRP, 1981a; ICRP, 1981b).

Estimates of dose were computed separately for activity deposited initially in the nasopharyngeal, tracheobronchial, and pulmonary regions of the lung; estimates of dose from inhalation of aerosols with activity median aerodynamic diameter (AMAD) of 0.2 to 10 μm can be computed from a function that relates deposition in each of the three regions to AMAD (Fig. 1). Doses were computed for each of the three clearance classes (D, W, and Y) of the ICRP lung model (Fig. 2). A complete tabulation of these dose estimates, as well as a more complete description of the methods, has been prepared (Dunning and Eckerman, 1984).

These dose estimates differ from those used previously in the CRAC and CRAC2 computer codes in several ways. For many of the radionuclides considered, the metabolic models and parameters have changed significantly as additional data have become available. Also, the quality factor recommended by the ICRP for alpha particles has been revised from $Q_\alpha = 10$ to $Q_\alpha = 20$, and the use of the additional modifying factor for alpha particles in bone ($N_\alpha = 5$) has been discontinued. Several discrepancies also exist in the definition of some of the thirteen organs used in the CRAC code: (1) estimates of dose to the active red bone marrow have been substituted for total marrow; (2) the effective dose equivalent as defined in ICRP Publication 26 (ICRP, 1977) has been used to represent the dose to whole body; (3) doses to skeleton have been approximated by multiplying the endosteal cell dose by the ratio of the bone dose to endosteal dose in earlier tabulations, because the total skeleton is not included in the current dosimetric data base (use of the endosteum rather than the skeleton is recommended for future revisions of the CRAC/CRAC2 data base); and (4) dose to the "organ" OTHER is computed as a mass-weighted mean of the doses to the remaining organs in our dosimetric data base not explicitly included in the CRAC2 organ list (adrenals, bladder wall, kidneys, liver, breast, pancreas, brain, skin, spleen, thymus, and uterus). The cumulative effect of these discrepancies between the current dose estimates and those used previously in CRAC2 is difficult to estimate, but differences exceeding a factor of two occur between some of the dose conversion factors.

6. SUMMARY AND CONCLUSIONS

We have described calculations with the CRAC2 computer code to examine the sensitivity of estimated health effects to uncertainties in particle size and rate of clearance of radionuclides from the respiratory passages. For two of the three fixed weather sequences that we examined, our results indicated increases of one to two orders of magnitude in early injuries, in comparison with calculations using the standard CRAC2 data base. We also obtained increases of nearly a factor of two in early fatalities in some of the runs. But changes in latent cancer fatalities were minor. Economic costs were not affected by changes in the dose conversion factors for the inhalation pathway.

It is possible that a more coherent picture of these sensitivities in predicted health effects might emerge from simulations that combine random sampling of the AMAD and clearance class distributions with random sampling of meteorological sequences. Such a sampling plan was beyond the reach of our resources for the present study, but the results we have obtained suggest that it merits future consideration.

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FIGURE CAPTIONS

Figure 1. Respiratory deposition model for particulate material. The radioactive fraction of an aerosol that is deposited in the nasopharyngeal (NP), tracheobronchial (TB), and pulmonary (P) regions is shown as a function of the activity median aerodynamic diameter (AMAD) of the particle size distribution. The model is intended for use with aerosol distributions that have an AMAD between 0.2 and 10 μm with geometric standard deviations less than 4.5. Provisional deposition estimates further extending the size range are given by the broken lines. For the unusual distribution having AMAD greater than 20 μm, complete deposition in the nasal pharynx can be assumed. The model does not apply to aerosols with AMAD below 0.1 μm. Several total deposition fractions are shown, some including and others excluding the nasal pharynx. While the dose to the nasal pharynx is not included in the lung dose in CRAC2 calculations, radioactive material deposited there is available for uptake to the blood. Therefore, the large total-fractional deposition associated with the larger particle sizes is potentially important if the code should be extended to include more realistic ranges (at present, AMAD is fixed at 1 μm). If the definition of lung dose were revised to include the nasal pharynx, the contribution of larger particle sizes would assume an even greater importance.

Figure 2. ICRP model for clearance of particulate material from the respiratory tract. The columns labeled "D," "W," and "Y" correspond, respectively, to rapid, intermediate, and slow clearance of the inspired material. The symbols T and F denote biological half-time (days) and fractional removal coefficient for the indicated clearance pathway. The regional deposition fractions are denoted by D_3, D_4, and D_5 for nasal pharynx, tracheobronchial tree, and pulmonary region, respectively. the values shown are for AMAD = 1 μm; values appropriate for other AMAD may be read from Fig. 1. The respiratory lymph nodes are denoted by L. Retention functions for radioactivity in the major regions depend on the foregoing parameters and are derived from systems of ordinary differential equations (e.g. Killough et al., 1978a; ICRP, 1979).

Figure 3. Probability density (or frequency) function for the uncertainty in AMAD. The default value of AMAD for CRAC2 calculations is 1 μm, but this value is subject to uncertainty. The probability density function shown above was chosen to express maximum uncertainty within the applicable range (0.2-10 μm). Notice that its mean value is 5.1 μm, a substantially larger value than the default assumption.

Figure 4. Triangular probability density functions of the sampling distributions for Class D, Class W, and Class Y inhaled particulates. Each element in the release is assigned to the distribution for which the mode (sometimes called the "most probable value") corresponds to the clearance class assigned to that element by expert consensus. This consensus is expressed in tables of D, W, and Y assignments to a variety of chemical forms (e.g., U. S. Nuclear Regulatory Commission, 1975). The assignments that are implicit in the dose conversion factors in the CRAC2 data base involve further assumptions about the expected chemical

forms of the nuclides in the release.

Figure 5. Schematic portrayal of the random sampling procedure. At each "trial," a random vector of 24 stochastically independent components is constructed by sampling the distribution of AMAD and, for each element in the release, the appropriate triangular distribution for the assumed clearance class of that element. At each trial, CRAC2 is executed with the data from the current random vector, and at the end of N trials, the aggregates of estimated health effects are compiled into probability distributions that represent their sensitivity to the uncertainties in the inputs.

Figure 6. Comparison of two definitions of dose to the lungs. The dose conversion factors in the ordinary CRAC2 data base estimate dose to the lungs as a weighted average of the doses to the tracheobronchial, pulmonary, and lymphatic regions (TB+P+L). If the dose to the nasal pharynx is included (NP+TB+P+L), the estimates of health effects by CRAC2 are increased significantly. The curves in this figure represent the ratio of time-integrated levels of a radionuclide in all four over TB+P+L; these ratios, which are equal to the corresponding dose ratios, are plotted as functions of the radioactive decay-rate coefficient for the radionuclide. Curves are shown for D, W, and Y materials and for a range of AMAD values (the numbers in parentheses, in μm). For radionuclides with long half-lives, the differences become unimportant. For extremely short-lived nuclides, the differences are pronounced and depend essentially on AMAD. In the intermediate range, the situation is more complex; for fixed AMAD, the values tend to be monotonic, increasing in the order D, W, Y.

Table 1. Respiratory clearance classes for the radionuclides in the CRAC/CRAC2 data base

Index	Nuclide	Clearance	Index	Nuclide	Clearance
1	Co-58	Y	28	Te-131m	W
2	Co-60	Y	29	Te-132	W
3	Kr-85	-	30	I-131	D
4	Kr-85m	-	31	I-132	D
5	Kr-87	-	32	I-133	D
6	Kr-88	-	33	I-134	D
7	Rb-86	D	34	I-135	D
8	Sr-89	D	35	Xe-133	-
9	Sr-90	D	36	Xe-135	-
10	Sr-91	D	37	Cs-134	D
11	Y-90	W	38	Cs-136	D
12	Y-91	W	39	Cs-137	D
13	Zr-95	Y	40	Ba-140	D
14	Zr-97	Y	41	La-140	W
15	Nb-95	Y	42	Ce-141	Y
16	Mo-99	Y	43	Ce-143	Y
17	Tc-99m	D	44	Ce-144	Y
18	Ru-103	Y	45	Pr-143	Y
19	Ru-105	Y	46	Nd-147	Y
20	Ru-106	Y	47	Np-239	Y
21	Rh-105	Y	48	Pu-238	Y
22	Sb-127	W	49	Pu-239	Y
23	Sb-129	W	50	Pu-240	Y
24	Te-127	W	51	Pu-241	Y
25	Te-127m	W	52	Am-241	Y
26	Te-129	W	53	Cm-242	Y
27	Te-129m	W	54	Cm-244	Y

Table 2. Sensitivity of predicted health effects to uncertainty in AMAD and D, W, Y classification of nuclides

		Weather seaquence #1		Weather sequence #2		Weather Sequence #3	
		Default	L. hypercube	Default	L. hypercube	Default	L. hypercube
A	Early fatalities	53.7	68.5×(1±.20) [52.1×(1±.09)]	0.413	0.748×(1±0.33)	2.31	2.82×(1±.11)
A	Early injuries	2450	4439×(1±.08) [3877×(1±.03)]	1.54	228×(1±.42)	150	403×(1±.10)
A	Latent/initial	1090	1202×(1±.12) [1336×(1±.11)]	1320	1420×(1±.10)	93.9	100×(1±.11)
A	Latent/total	2670	2787×(1±.05) [2929×(1±.05)]	2140	2227×(1±.07)	161	167×(1±.07)
B	Early fatalities	0	0				
B	Early injuries	4.35	69.4×(1±.20)				
B	Latent/initial	13.4	10.3×(1±.06)				
B	Latent/total	90.6	87.4×(1±.01)				

A = large release; B = small release.

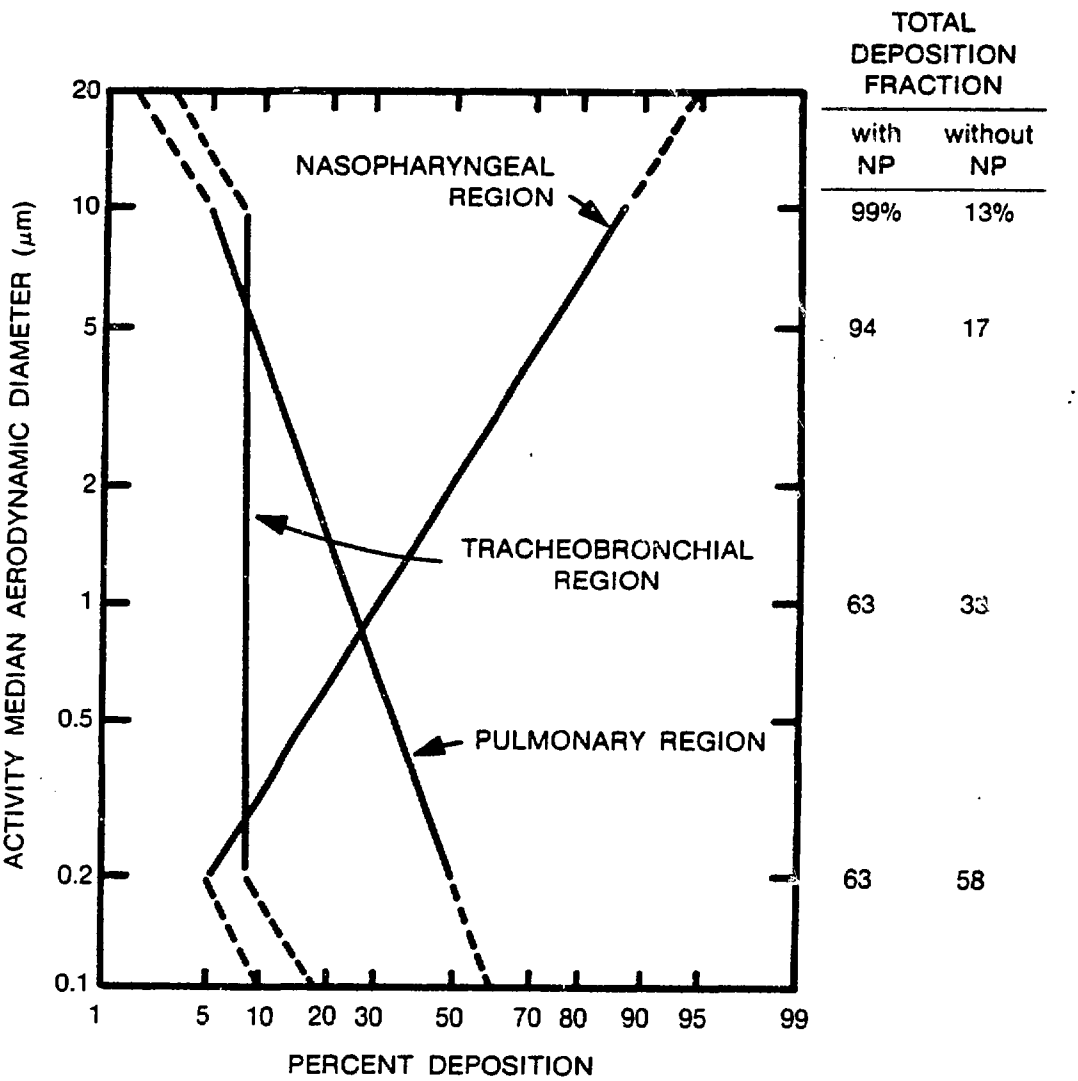
Latin hypercube results are given as mean×(1±C.V.), where C.V. = standard deviation/mean.

Numbers in brackets [] are results of Latin hypercube simulations in which AMAD was held constant at 1 μm.

Table 3. CRAC2 calculations with and without counting dose to nasal pharynx (NP) as part of lung dose

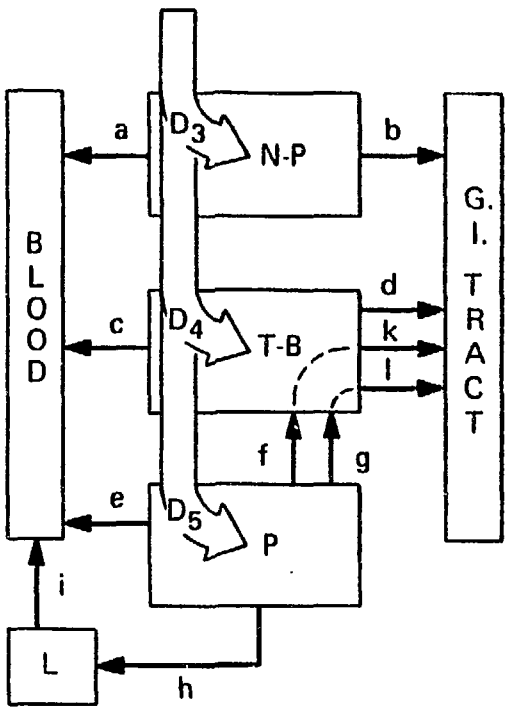
Large release, Weather sequence # 1			
	INREM II/RADRISK		
	With NP	Without NP	Default
Acute fat.	222 (121)	68.5 (52.1)	53.7
Acute inj.	4498 (3916)	4439 (3877)	2450
Latent/Init.	1451 (1754)	1202 (1336)	1090
Latent/Tot.	3069 (3377)	2787 (2929)	2670

ORNL-DWG 84-15031

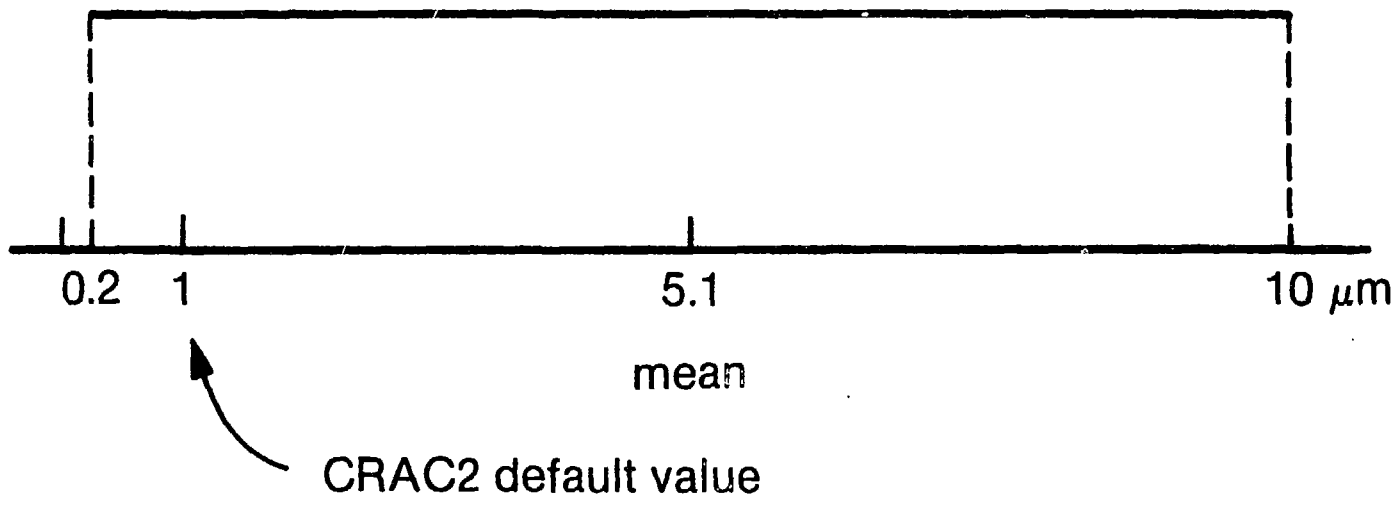


COMPARTMENT		CLASS					
		D		W		Y	
		T	F	T	F	T	F
N-P	a	0.01	0.5	0.01	0.1	0.01	0.01
(D_3 = 0.30)	b	0.01	0.5	0.4	0.9	0.4	0.99
T-B	c	0.01	0.95	0.01	0.5	0.01	0.01
(D_4 = 0.08)	d	0.2	0.05	0.2	0.5	0.2	0.99
	e	0.5	0.8	50	0.15	500	0.05
P	f	n.a.	n.a.	1.0	0.4	1.0	0.4
(D_5 = 0.25)	g	n.a.	n.a.	50	0.4	500	0.4
	h	0.5	0.2	50	0.05	500	0.15
L	i	0.5	1.0	50	1.0	1000	0.9

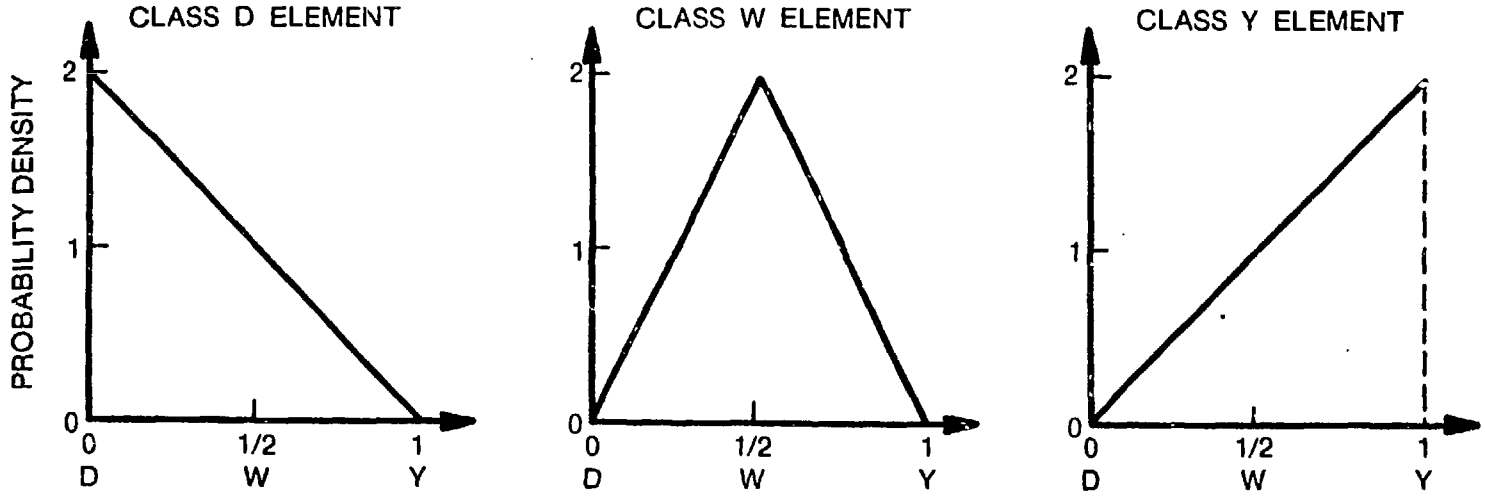
ORNL-DWG 77-2743



ORNL-DWG 84-15032



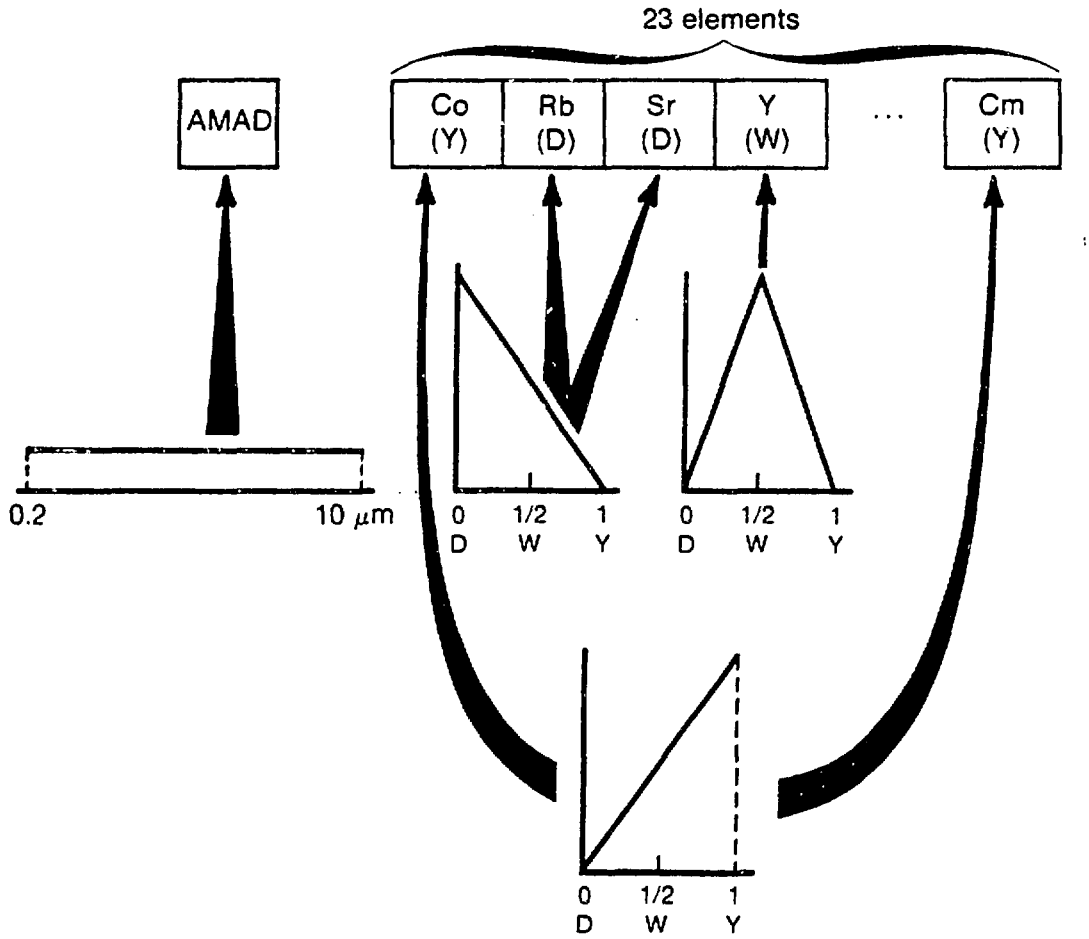
ORNL-DWG 84-15033



ORNL-DWG 84-15034

RANDOM SAMPLING SCHEME

We generate a sequence of *N* random vectors; each vector has 24 stochastically independent components:



Each component is sampled from the appropriate probability distribution, with Latin hypercube stratification.

ORNL-DWG 84-15036