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FORECASTING CONSEQUENCES OF ACCIDENTAL RELEASE: HOW RELIABLE ARE CURRENT ASSESSMENT MODELS?

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Models to simulate environmental transport of radionuclides and estimate radiation dose to man are not something new. However, their proliferation and combination for assessment applications is fairly recent. Even more recent is the intense interest in quantifying uncertainties in predictions obtained with such model combinations. This paper is focused on uncertainties in model output used to assess accidents. We begin by reviewing the historical development of assessment models and the associated interest in uncertainties as these evolutionary processes occurred for us in the United States. That is followed by a description of the sources of uncertainties in assessment calculations. Next we identify types of models appropriate for assessment of accidents. Then we provide a summary of results from our analysis of uncertainty in results obtained with current methodology for assessing routine and accidental radionuclide releases to the environment. We conclude with discussion of preferred procedures and suggested future directions to improve the state-of-the-art of radiological assessments.

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Historical Development

Our development of assessment models at Oak Ridge National Laboratory (ORNL) dates back to the 1960s when we were participating in the U.S. PLOWSHARE Program which explored the feasibility of potential peaceful applications of nuclear explosives [1]. Our role was to estimate the total potential radiological impact to man. An exposure pathway diagram became a useful tool to demonstrate the comprehensive assessment methodology being developed. Figure 1, taken from a previous publication [2], is representative of many such depictions available in the assessment literature today. Simple multicompartment models and associated data bases were developed to implement all of the pathways shown for each of the dozens of radionuclides comprising the projected source terms. The level of model complexity and data completeness varied among radionuclides and exposure pathways. Uncertainties in the resulting model predictions were little questioned and order-of-magnitude estimates were sufficient to gauge the reasonableness of PLOWSHARE projects and to facilitate qualitative comparisons of potential radiological insults among suggested project sites and among application concepts.

Aroused environmental concerns in the U.S. and other parts of the world contributed to waning interest in peaceful uses of nuclear explosives. The same environmental concerns were being voiced regarding the growing list of nuclear power reactors in operation or under construction. The changing social and political climate led to the advent of the U.S. National Environmental Policy Act of 1969 (NEPA) and other environmental legislation. Among the specific manifestations of that

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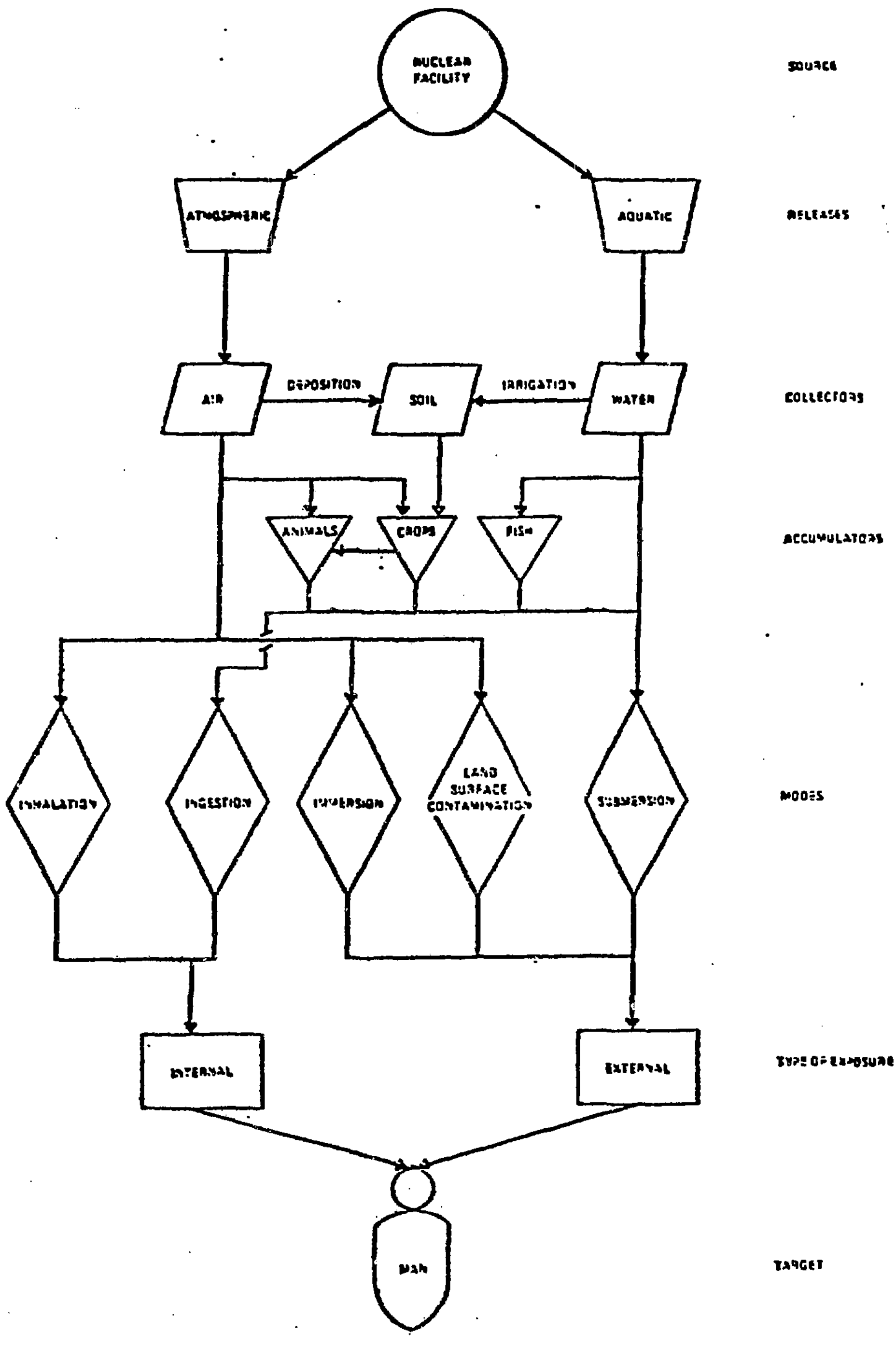


Figure 1.

movement in the radiological safety area was the initiative to quantify the fundamental tenent, "As Low As Reasonable Achievable" (ALARA). Compliance with NEPA also includes the preparation of environmental impact statements and other environmental documents. Implicit in such documents are radiological impact analyses used in cost-benefit balances to compare the proposed project with all reasonable alternatives to that project. The detailed radiological safety analyses emphasized assessment of routine environmental releases more than potential accidents. Again, uncertainties were not a principal focus, and somewhat qualitative estimates of potential radiological impact were sufficient because the results were utilized in a largely comparative process. However, a definite trend was obvious which would insure increasing need for predictive methodology to assess potential human health impacts of nuclear and nonnuclear pollutants released to the environment.

Out of the environmental movement came widespread public concern over risk regardless of source, and within that concern developed serious questioning of any enhancement of radiation exposure, however small, attributable to man's activities. Although the universally acccepted radiation safety guidelines of the International Commission on Radiological Protection (ICRP) remained unchanged [3], standard setting and regulatory bodies began to set exposure and dose limits at much lower levels largely in response to social and political pressures [4]. In some cases the reduced limits are such that the radiation levels and radioactivity concentrations are below the detection limits of monitoring instrumentation. In such instances demonstrations of compliance must be accomplished with theoretical model calculations. In this type of application models and values used to parameterize them have come under severe scrutiny leading to the present-day interest in estimating the uncertainties in model predictions.

To this point we have not emphasized the increased complexity of assessing accidents as contrasted with routine releases. Early radiological assessments of nuclear facilities largely were limited to routine environmental releases. The estimated doses were low in comparison to the accepted limits [5-7]. Thus, the models and selected parameter values could accommodate large safety factors in the form of conservative, and often unrealistic, assumptions. Prediction and assessment of impacts due to accidental or episodic releases of radionuclides is a much greater challenge for developers of assessment models and model parameter data bases. The estimation of time-dependent exposure rates requires dynamic models, and such flexible models require extensive data bases. At the present time nuclear programs in many countries are slowed, and one reason is concern over possible accidents and the potential radiation exposures which could accompany them. The U.S. experience at Three-Mile Island did nothing to relieve this concern although resultant exposures have been shown to be small and followup effects studies are underway [8]. Rather, the post Three-Mile Island reaction has been one of enhanced questioning of uncertainty levels in models and parameter values used to evaluate and compare accident scenarios. The message to us appears clear that although the accident probabilities may be low and radioactivity release source terms highly uncertain, the potential radiological impacts of accidents are large and the reliability of the methodology available to assess them must be demonstrated.

Sources of Model Uncertainty

The sources of uncertainty are similar in assessments of routine releases and assessments of accidents although the relative magnitude of uncertainty will reflect the complexity of the respective assessments. Rather than enumerate all possible sources of model uncertainty, we have found it convenient to place them into four major categories: (1) model bias, (2) parameter bias, (3) parameter variability, and (4) common errors in calculation, computation, and computer programming. We limit our discussion here to the first three of these categories.

Model bias. This is the primary underlying source of uncertainty, as all models are at their very best only abstractions of real systems. The complexities of physical dispersion, food chain bioaccumulation, and human dosimetry are such that no model can be expected to exactly reproduce the processes affecting radionuclide transport in the environment and the subsequent impact on exposed individuals and populations. Model bias may result from unwarranted assumptions of steady-state conditions or first order kinetics, unrecognized relationships between model parameters and extrinsic variables, exclusion of significant exposure pathways or important physical processes, and multiple redundancies of distinct processes due to inconsistencies within the formulation of the model structure and the derivation of parameter values.

Parameter bias. Parameter bias results from improper estimation (quantification) of a model's independent variables. A clear distinction between parameter bias and model bias is not possible since many model parameters represent empirical relationships combining a number of interacting processes.

Proper parameter estimation is difficult because appropriate data are seldom available. Estimates must often be made from published data derived from experiments designed for other purposes, and dependencies on site-specific factors are not commonly determined [6,9-12]. All current radiological assessment models employ a data base of "default values" recommended for use in the absence of site-specific or population-specific data [9,13-18]. The degree to which these recommended "default values" are applicable to a specific situation is not usually stated, although they are frequently assumed to be conservative, i.e., they lead to overpredictions rather than underpredictions of dose [6,7]. It is our experience that model predictions are highly dependent on the judgement of the individual investigator or group of individuals responsible for estimating values for model parameters [19].

Parameter variability. As a source of uncertainty, parameter variability is related to the general reliance on deterministic models in radiological assessments [20,21]. Because parameter estimates and measurements are imprecise and ecological systems are afflicted with perpetual variability, model parameters are best represented by a range, or distribution, of values for any given assessment situation. This range of model parameters translates into a range, or distribution, of model predictions. Deterministic models by contrast use a single value for each parameter to produce a single prediction (Figure 2). Heavy reliance on deterministic models fosters the common misconception that the single number thus generaged is "the" dose to be expected under a given set of exposure conditions. Keep in mind also the much more generic application such single numbers receive once generated. By ignoring the stochastic nature of radiological assessments, deterministic models also

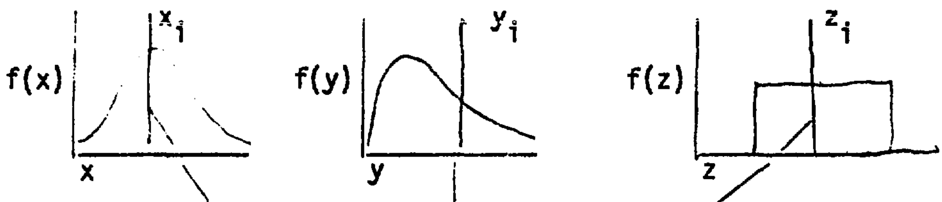
Deterministic Modeling

A range, or distribution, of possible values exists for parameter input for each assessment situation.

DETERMINISTIC ASSESSMENT MODELS

- Although a range of values are possible for input,

INPUT PARAMETERS X, Y, and Z



- Parameters are represented as a single quantity, and

MODEL

$$D_i = f(x_i, y_i, z_i)$$

- A single value is produced as model output,

$$D_i = 0.3756 \text{ rem/yr}$$

Figure 2.

present a misleading impression of accuracy. This is especially evident when order-of-magnitude estimates of parameters are used to predict values given to four significant digits (Figure 2).

Types of Accident Assessment Models

Although various classifications of models are possible, we recognize two basic categories of models developed to study the fate of radionuclides in the environment: assessment models and research models [22].

Assessment models serve as tools for decision making, whereby research models emphasize the ability to explicitly simulate the function and structure of real systems. In assessment models, underlying processes and mechanisms may be aggregated into general transfer coefficients that relate the concentration of a radionuclide in a donor model compartment to that of a receptor compartment. Therefore, assessment models, as a rule, tend to be less complex in structure than process-level research models. Although we have often substituted research models for assessment models in order to quantify key parameters for which empirical relationships are non-existent or inappropriate, we recognize that increased model complexity does not guarantee increased accuracy in model predictions [7,21-24]. For the assessment of consequences due to accidental releases of radionuclides from nuclear facilities, a variety of modeling approaches can be taken. The approach taken will be dictated by the question asked of the model.

Equilibrium and/or Quasi-equilibrium models. If the assessment is primarily concerned with time-integrated dose resulting from exposure to acute releases of radionuclides, then concentration factors (equilibrium models) or quasi-equilibrium models will suffice, provided that the conditions prevailing at the time of the release are taken into account [21,22,25]. This is the type of model commonly used to assess routine releases. The primary source of error in applying these models for accident analysis will be the bias involved in properly quanitfying model parameters.

Dynamic models. If, however, the conc rn is with the time following an acute release in which specific dose rates or environmental concentrations will occur, then dynamic models must be used. Mathematically, dynamic models have the advantage of calculating both time-integrated exposures and time-dependent exposure rates [22]. These models are usually composed of donor controlled linear systems described by coupled first-order differential equations. The primary disadvantage of dynamic models is that their mathematical flexibility may be misinterpreted as implying an additional level of accuracy.

Loss of accuracy is implicit in the calculation of time-dependent dose rates or environmental concentrations because of the absence of the normalizing effect of time-integration or time-averaging. In addition, transfer coefficients must often be estimated from very limited data. Estimates of those transfer coefficients are most frequently derived from steady-state relationships or from experiments in which considerable time averaging and time integration has been performed [14,17,26-28]. Therefore, even though it is possible for these models to mathematically predict dose rates and environmental concentrations as a function of time, the reliability of these predictions must be seriously questioned.

The amount of data needed to improve the reliability of time-dependent predictions for accident assessments is enormous. The derivation of parameter values relevant to acute releases requires a time series of measurements that must be repeated both temporally and spatially. If these data were to eventually become available, dynamic models would take the form of a system of partial differential equations with coefficients varying as joint functions of time and location [29].

Stochastic models. From our experience, we now consider the most realistic modeling approach to be a stochastic approach. Stochastic models treat uncertain input parameters as random variables and predict environmental concentrations, exposures, or doses as random variables (Figure 3). In this modeling approach, uncertainties in parameter estimation are translated directly into uncertainties in model predictions. The approach may be applied with either quasi-equilibrium models [30,31] or dynamic models [32]. The primary sources of error are related to bias in the formulation of the model structure and bias in estimating the range of uncertainties for model parameters. These biases are best detected by testing the model against an independent set of field data (i.e., model validation). Another approach is to compare the results of independently developed stochastic models.

Estimates of Uncertainty

We have used the best available information and reasoned scientific judgement to suggest ranges of uncertainty for model-predicted radiological consequences of nuclear accidents. The suggested ranges of uncertainty for accident assessments (Table 1) are more qualitative than quantitative. To help place these estimates of uncertainty in proper

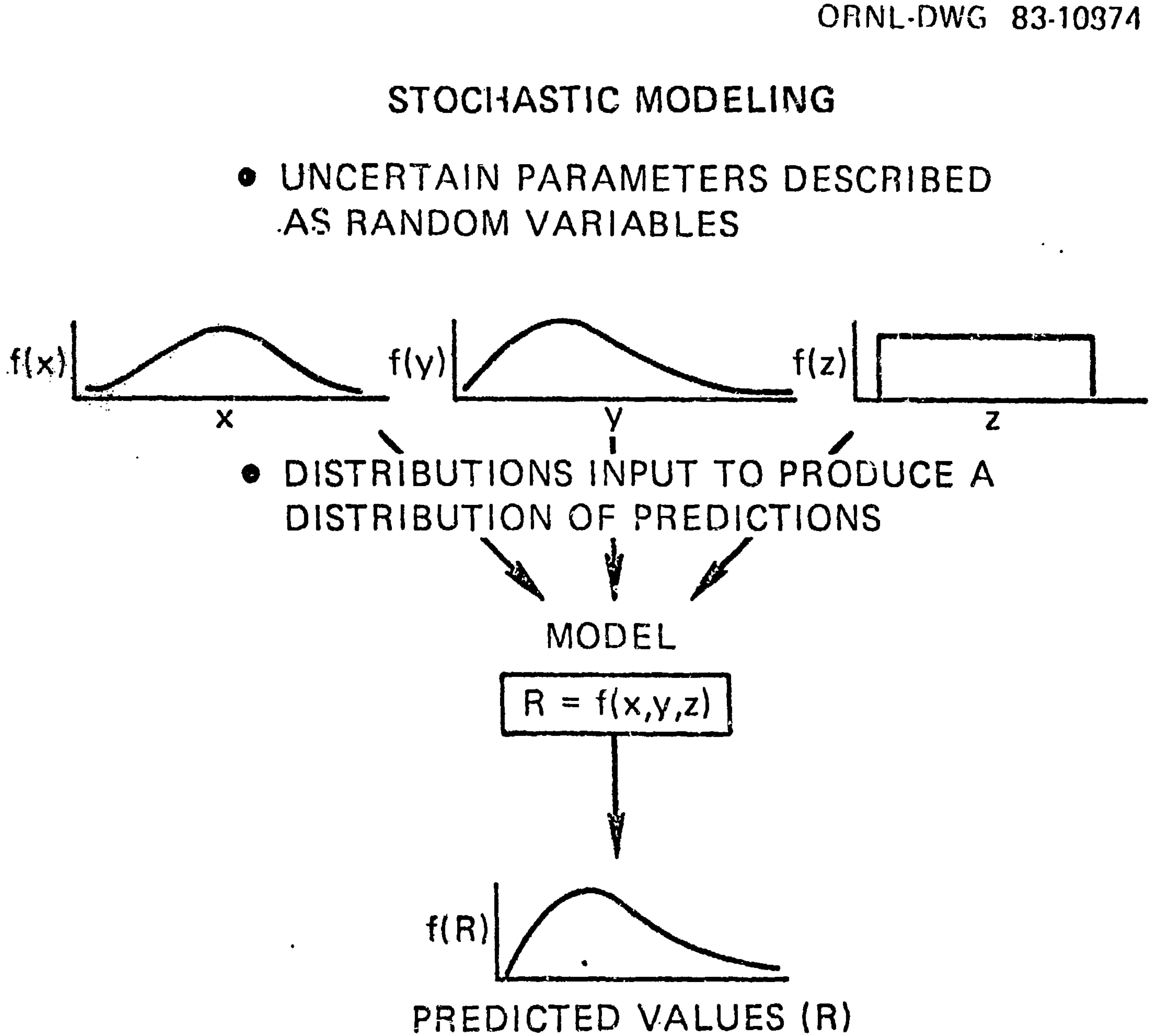


Figure 3. A description of the basic procedure of stochastic modeling in uncertainty analyses [20].

Table 1. Semi-quantitative estimates of the relative magnitude of the uncertainties associated with calculations of the radiological impact of accidental releases

Model component	Uncertainty factor[a]		References
	Individual[b]	Population[c]	
Release (source term)	$10-10^4$?[d]	$10-10^4$?[d]	[34-6]
Physical dispersion[e] (atmosphere and surface water)	3-100	2-10	[7,8,25,33,34]
Food chain transport[f]	5-100	2-10	[25,34,37-39]
Usage factors[g]	3-10	2-4	[21,40-42]
Dose factors[h]	2-30	1.5-10	[34,43-45]
Risk factors[i]	2-20	1.2-10	[34,45-50]

[a]The ratio of a likely maximum or minimum value to the expected median value; estimated using judgement in concert with information given in the cited references.

[b]Includes estimates for critical groups of the population.

[c]Includes estimates for average individuals.

[d]Uncertainties primarily due to conservative bias in engineering estimates of source terms; question marks indicate a lack of consensus among consulted experts.

[e]Does not include uncertainties due to precipitation events.

[f]It is expected that environmental monitoring will serve to reduce this uncertainty in the event of an actual accidental radionuclide release.

[g]We assume that following an actual relase, emergency response measures will reduce the number of pathways through which the population may be exposed, with the possibl exception of inhalation and initial exposure to contaminated surfaces.

[h]Includes errors due to extrapolations from animal data.

[i]Excludes potential bias due to exrapolations to low doses; uncertainties are expected to decrease as exposure rates increase

context, we have provided for comparison purposes, our estimates of uncertainties in assessments for routine radioactivity releases (Table 2). In preparing Tables 1 and 2, we have identified and begun to quantify *the principal uncertainties in assessment model results* [19]. We have also made a number of observations. Our experience with stochastic modeling has shown that generally only a few radionuclides and exposure pathways will dominate the overall uncertainty in the predicted quantity and that uncertainties will increase with decreased time and space averaging [7,20,31,33]. Therefore, uncertainties will be greater for accident assessments than for routine emission evaluations, and where predictions are made for maximally exposed individuals or critical population groups rather than for average individuals or entire populations [19]. Uncertainties are expected to be less in estimates of risk for the more extensively studied radionuclides and exposure pathways [19]. Estimates of external exposure are expected to be less uncertain than estimates of internal exposure [24,33]. Uncertainties tend to be less for near-term (<30 years) assessments compared to far-term (>100 years) [12,21,56], and generally less when multiple exposure pathways and radionuclides are involved as compared to single-radionuclide single-exposure-pathway estimates [19]. Values presented in Tables 1 and 2 summarize these relationships and attempt to identify the components of an assessment calculation which are of dominant importance to the overall uncertainty in model predictions.

Prior to an actual release of radionuclides, the uncertainties in the assessment of accident consequence appears to be dominated by the uncertainty in the source term or release rate. If the release rates are well known, the remaining uncertainties are dominated by

Table 2. Semi-quantitative estimates of the relative magnitude of the uncertainties associated with calculations of the radiological impact of routine releases

Model component	Uncertainty factor[a]		References
	Individual[b]	Population[c]	
Release (source term)	10–100[d]	10–100[d]	[51,52]
Physical dispersion (atmosphere and surface water)	2–4	1.5–2	[7,21,23,33]
Food chain transport	3–50	1.5–10	[6,9–12,21,22,24,30,54,55]
Usage factors (rates of intake)	1.3–7	1.2–2	[21,40–42,53]
Dose factors[e]	1.5–30	1.3–10	[33,34,43–45]
Risk factors[f]	2–20	1.2–10	[45–50]

[a] The ratio of a likely maximum or minimum value to the expected median value; estimated using judgement in concert with information given in the cited references.

[b] Includes estimates for critical groups of the population.

[c] Includes estimates for average individuals.

[d] Uncertainties primarily due to conservative bias in engineering estimates of source terms.

[e] Includes errors due to extrapolations from animal data.

[f] Excludes potential bias due to exrapolations to low doses.

meteorological dispersion, provided that environmental monitoring can feasibly reduce the magnitude of uncertainties associated with the contamination of surfaces and agricultural products.

Preferred Procedures and Suggested Future Directions

It is well established that models are very useful assessment tools and that we have many appropriate uses for them. Those uses range from comparative analyses used in policy making and decisions on technology selection and placement to quantitative estimation of exposure and risk to demonstrate compliance with regulatory guides and statutory limits. Accident evaluations are becoming integral parts of these comparative and quantitative modeling applications. Accepting in principal that the levels of uncertainty in model predictions suggested here are the proper result of a thorough and reasonable analysis of the best available information, where do we go from here to further refine these estimates of uncertainty and thus improve the reliability of model applications for assessments of accidental releases?

When preparing to evaluate potential accidents for a facility, develop emergency plans, etc., it is important to carefully select an appropriate model and site-specific data. We suggest a "screening model" as a logical starting point. A screening model is conservative, i. e., it is likely to overpredict potential impact, by design. Such a model is useful for rapidly defining a level of contamination not likely to be exceeded and the maximum extent of the potentially affecdted geographic area. Screening models can be used to rapidly define areas where emergency action and intensified environmental surveillance may be needed. A properly designed monitoring system, a system in which monitoring data output and model input data requirements are compatible, will serve as backup to an initial screening calculation to fine tune preevent-generated base-case predictions with monitoring observations recorded during the course of an accident should one occur.

Models available for selection are numerous in the literature and they vary in complexity [56]. In general it is best to select for use the simplest model which will do the job in an acceptable manner [21]. First, the more simple model will have less input data requirements. This is important to the model user because the probability of successful application of any model is optimized whenever site-specific data are used in preference to the default generic parameter values commonly provided by the author(s) of the model. Second, studies have shown that a more complex model may not necessarily provide results which are more accurate [7,21-24].

Model selection should also include realization of a responsibility to avoid misuse of the model. Once they are developed, models are subject to many applications for which they were not designed or intended. Often this is done by the user out of desperation because of pressures to provide quantitative answers to questions previously addressed in more qualitative ways. One example of model misuse is the growing tendency to use deterministic model results to establish the basis for regulatory dose limits and guides while ignoring the inherent uncertainties in the model results. Thus, situations may arise whereby the reduction of radiological impact is not commensurate with the economic costs associated with regulatory actions.

It is clear that validation studies covering ranges of exposure conditions are needed to improve confidence in the application of models for accident assessments [7,15,21,24,57]. We must realize, however, that even after such efforts have been completed some uncertainties will remain essentially irreduceable for a number of reasons including biological variability and our limited ability to measure some parameters.

In the absence of extensive model validation results, other alternatives should be explored. We recommend increased development and application of stochastic models to supplement validation studies, because stochastic models will provide ranges of dose or risk estimates reflecting the ranges of values which characterize model input parameters. Studies completed with that type of model will assist in prioritizing future efforts to establish an improved basis for the limitation and control of radiation exposures, and to better define the extent to which models can be used as tools for decision making when evaluating the potential consequences of accidental releases.

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