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Probabilistic Accident Consequence Uncertainty – A Joint CEC/USNRC Study

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Abstract

The joint USNRC/CEC consequence uncertainty study was chartered after the development of two new probabilistic accident consequence codes, MACCS in the U.S. and COSYMA in Europe. Both the USNRC and CEC had a vested interest in expanding the knowledge base of the uncertainty associated with consequence modeling, and teamed up to co-sponsor a consequence uncertainty study. The information acquired from the study was expected to provide understanding of the strengths and weaknesses of current models as well as a basis for direction of future research. This paper looks at the elicitation process implemented in the joint study and discusses some of the uncertainty distributions provided by eight panels of experts from the U.S. and Europe that were convened to provide responses to the elicitations. The phenomenological areas addressed by the expert panels include atmospheric dispersion and deposition, deposited material and external doses, food chain, early health effects, late health effects and internal dosimetry.

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DISCLAIMER

1. Introduction

The assessment of the consequences resulting from a nuclear reactor accident involves the modeling of such phenomena including, but not limited to: the release of radioactive material to the atmosphere, its transport and deposition, the resultant exposure of the population by various pathways, emergency response and mitigative actions, deterministic and stochastic health effects, and economic costs. The models typically used to estimate the consequences involve varying degrees of complexity and there is a multitude of parameters used as input to the models. Significant uncertainties exist both in terms of the models and the model input parameters. This paper discusses consequence uncertainties from the perspective of the joint U.S. Nuclear Regulatory Commission (USNRC) / Commission of European Communities (CEC) consequence uncertainty study.

The joint USNRC/CEC consequence uncertainty study was chartered after the development of two new probabilistic accident consequence codes, MACCS in the U.S. [Chanin, 1990; Chanin, 1997] and COSYMA in Europe [CEC, 1991]. Both the USNRC and CEC had a vested interest in expanding the knowledge base of the uncertainty associated with consequence modeling, and teamed up to co-sponsor a consequence uncertainty study [Harper, 1994; Goossens, 1997; Brown, 1997; Little, 1997; Goossens, 1998; Haskin, 1997]. Formal expert elicitation is deemed appropriate and necessary if the available experimental database cannot provide the necessary information and if the analytical models that would provide information not observed experimentally are not indisputably correct.

This paper looks at the elicitation process implemented in the joint study and discusses some of the uncertainty distributions provided by eight panels of experts from the U.S. and Europe that were convened to provide responses to the elicitations. The phenomenological areas addressed by the expert panels include atmospheric dispersion and deposition, deposited material and external doses, food chain, early health effects, late health effects and internal dosimetry.

2. Uncertainty Issues Relating to the Assessment of Radiological Consequences

Each facet of consequence modeling has varying degrees of detail and complexity, rendering the potential for significant uncertainties to exist in the assessment to be performed. In performing an uncertainty analysis, a single model or set of models is typically chosen as the basis for the propagation of distributions of input parameters used to produce distributions of the model's output. Sometimes alternative models can be incorporated in an uncertainty analysis by weighting the distribution of results from each model by its expected probability with respect to the other models.

The choice of a particular model in a specific aspect of consequence modeling is never without controversy because the models currently used to represent the many complex processes in consequence analysis are generally quite rudimentary. This is illustrated in Figure 2.1, which compares the predictions of various models to actual behavior. Figure 2.1 shows the results from a test conducted in 1981 at the Idaho National Engineering Laboratory [Lewellen, 1985], in which a nonradioactive tracer (SF_6) was released and the resulting air concentrations were measured and compared with the predictions of three different atmospheric transport models. The plots in Figure 2.1 depict the air concentration patterns (the plots display isopleths of air concentrations on the site grid), as well as the estimated maximum dose for: (a) a simple straight-line Gaussian plume model, (b) a Gaussian-puff trajectory model with wind-shift, (c) a more sophisticated wind field

and topographic model used in the U.S. Department of Energy's Atmospheric Release Advisory Capability (ARAC) program, and (d) actual measured air concentrations. These plots illustrate that even the sophisticated ARAC model could not accurately reproduce the actual behavior.

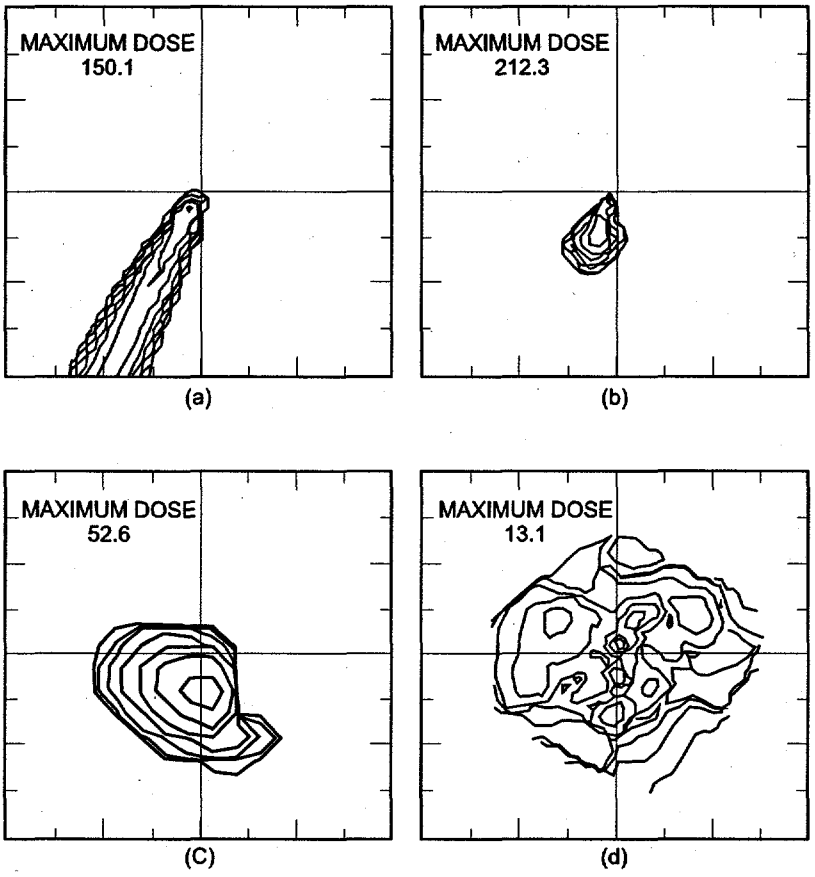

Figure 2.1 Predicted and actual one-hour doses: (a) Gaussian plume model, (b) puff-trajectory model, (c) complex numerical model, and (d) actual observations [Lewellen, 1985]

The assumptions that are adopted and the approach that is taken in an uncertainty analysis can be very important in the outcome and interpretation of results. In the sections that follow, different types of uncertainty are discussed and a historical perspective is provided on uncertainty analyses that have been performed in the area of probabilistic consequence assessment

2.1 Types of Uncertainty

There are many different ways to describe or define the types of uncertainty that exist in the application of phenomenological models used to estimate the impact of nuclear reactor accidents. The USNRC's Probabilistic Risk Analysis (PRA) Working Group [NRC, 1994] has defined two types of uncertainty that may be present in any calculation: 1) stochastic uncertainty caused by the natural variability in a parameter, and 2) state-of-knowledge uncertainty, which results from a lack of complete information about systems, phenomena or processes. The PRA Working Group further subdivides state-of-knowledge uncertainty into: 1) parameter uncertainty, which results from a lack of knowledge about the correct inputs to analytical models, 2) model uncertainty, which is a result of the fact that perfect models cannot be constructed, and 3) completeness uncertainty, which refers to the uncertainty as to whether all the significant phenomena and

relationships have been incorporated into the calculation (some analysts consider completeness uncertainty a subset of model uncertainty).

Stochastic uncertainty is inherent in a physical process and can therefore not be reduced. Additional data do not reduce stochastic uncertainty but provide more information about the distribution of the uncertainty associated with the stochastic variable. In the analysis of consequences of nuclear reactor accidents, the natural variability in the weather is typically characterized as stochastic uncertainty.

All three types of state-of-knowledge uncertainty are manifested in the assessment of consequences from nuclear reactor accidents. It is usually not known with complete certainty the correct value of model input parameters. Distributions that characterize parameter uncertainty can derive from sources such as experimental data, alternate phenomenological models, or may even appear to involve some component of stochastic uncertainty. Modeling uncertainty can result when models of physical processes have many underlying assumptions that are not valid for all possible cases. Completeness uncertainty can result when interactions and dependencies among the elements of the process are inadequately considered. It is not always easy to differentiate the types of uncertainty associated with the analysis of a complex physical process. In fact, there can be significant disagreement between experts in a specific field not only about the distribution of the uncertainty, but also about the types of uncertainty involved.

Figure 2.2 provides another illustration of the differences between actual plume behavior and plume behavior that is simulated by an analytical model. The simulation in this example applies a straight-line Gaussian plume model and predicts average concentrations for constant weather conditions. While the simulation might not predict the localized plume behavior at the monitor locations, it may provide an acceptable prediction on a global scale. If an uncertainty analysis were to be performed for this simulation, both stochastic and state-of-knowledge types of uncertainty would most likely be applied, and alternate models might even be implemented. The uncertainty analysis will probably not provide a better estimation of localized effects, but may provide some insight regarding important features of the simulation.

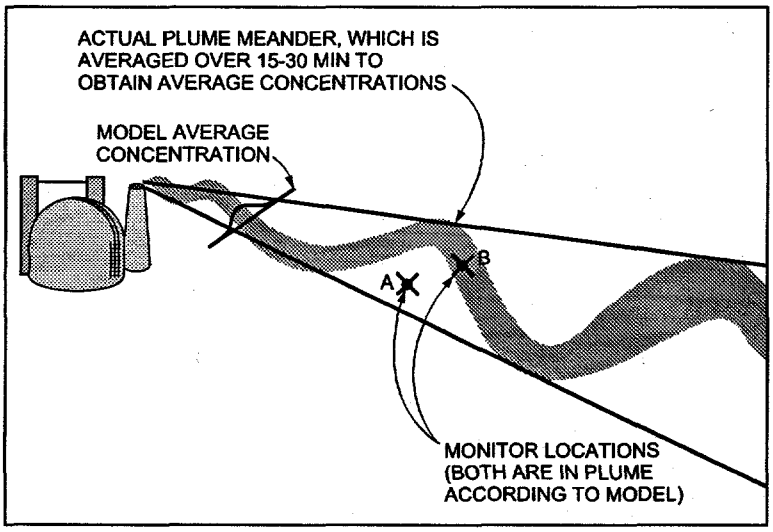

Figure 2.2 Model Simulation and Actual Plume Behavior [Sjoreen, 1994]

Typically, when an uncertainty analysis involves both stochastic and state-of-knowledge uncertainties, the two types of uncertainties are separated. This is demonstrated in Figure 2.3,

which shows a family of complementary cumulative distribution functions (CCDFs) of population dose. A CCDF displays the probability of exceeding a consequence value, conditional on the specific accident under analysis. The stochastic variability in the weather produces a single CCDF curve (the variability in the curve is a result of the weather trials from a year of meteorological data that were sampled to perform the calculation). The distribution of CCDF curves is generated by sampling distributions of state-of-knowledge uncertainties, typically in model input parameters. Regression analysis can be performed to determine the main contributors to the variability across the distribution of CCDFs in terms of the variability in each of the model input parameters.

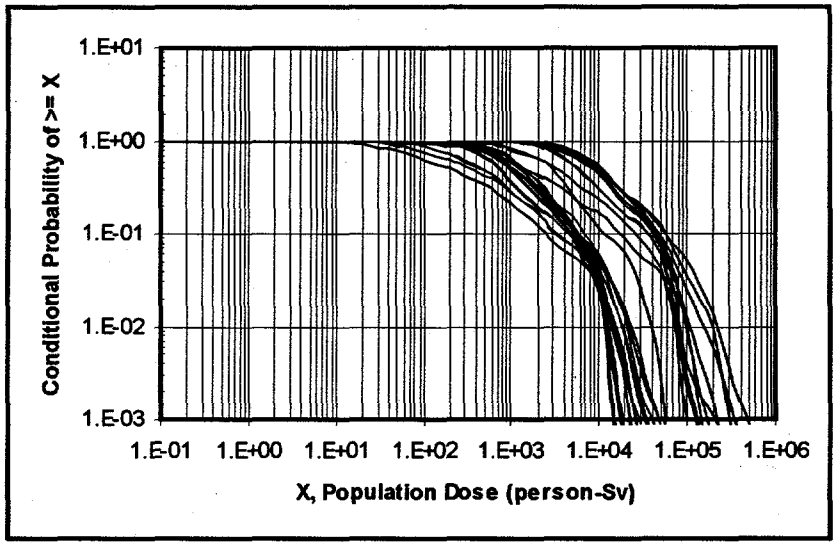

Figure 2.3 CCDF Curves Representing Stochastic and State-of-Knowledge Uncertainty

2.2 Historical Perspective of Consequence Uncertainty Analyses

Uncertainty analysis with respect to potential public risks from nuclear power reactors was introduced in a broad decision-making context with the Reactor Safety Study (WASH-1400), a study sponsored by the USNRC [NRC, 1975]. Since that study, the techniques used in similar uncertainty analyses have undergone significant development, yet the essential elements and goals remain the same. The intent of uncertainty analysis is to estimate the uncertainty in the output of quantitative models in order to provide the decision-maker with a measure of the robustness or accuracy of the model predictions.

Since the Reactor Safety Study, many new uncertainty analysis methods and techniques have been developed under the sponsorship of the USNRC for integrated risk assessments. These involved both the geologic disposal of radioactive waste [Campbell, 1980; Helton, 1980; Helton, 1981; Cranwell, 1987] as well as the landmark NUREG-1150 PRA [NRC, 1990] that was performed for five commercial U.S. nuclear power plants (two boiling water reactors and three pressurized water reactors). The NUREG-1150 analysis used techniques based on an extensive expert review process to characterize the uncertainty in many important input parameters. Uncertainty and sensitivity studies were conducted in NUREG-1150 for the systems analysis, accident progression analysis and source term analysis components of the PRA; however, the effects of the uncertainty in the consequence analysis component was only incorporated in application of stochastic variability in the weather. Concern about the limited knowledge of uncertainty in consequence analysis led the USNRC to sponsor further uncertainty/sensitivity investigations of the consequences associated with a reactor accident [Helton, 1994a; Helton, 1994b; Helton, 1994c] for

early exposure, chronic exposure and the food chain exposure pathway. These studies incorporated only uncertainties in model input parameters, with the distributions developed primarily by the model developers.

The CEC has also developed methods and techniques for performing uncertainty and sensitivity studies associated with assessing the consequences of nuclear reactor accidents. The German Nuclear Research Center Karlsruhe (KfK), the German Institute for Reactor Safety (GRS), and the United Kingdom's National Radiation Protection Board (NRPB) sponsored the CEC research program, Methods for Assessing the Radiological Impact of Accidents (MARIA). The KfK has published studies on uncertainty and sensitivity studies for the UFOMOD consequence model and submodels [Fischer, 1990] for the near range and early phase of an accident. The NRPB has performed uncertainty studies for the MARC consequence model and submodels that examined uncertainty in the calculation of atmospheric dispersion and deposition, food chain modeling, health effects and economic costs [Jones, 1991]. Like the USNRC-sponsored consequence uncertainty studies, the CEC-sponsored studies incorporated only uncertainties in model input parameters, with the distributions developed primarily by the model developers.

3. The Joint USNRC/CEC Consequence Uncertainty Study

After the development of two new probabilistic accident consequence codes, MACCS in the U.S. [Chanin, 1990; Chanin, 1997] and COSYMA in Europe [CEC, 1991], both the USNRC and CEC had a vested interest in expanding the knowledge base of the uncertainty associated with consequence modeling. Hence, they teamed up to co-sponsor a consequence uncertainty study [Harper, 1994; Goossens, 1997; Brown, 1997; Little, 1997; Goossens, 1998; Haskin, 1997]. The information acquired from the study was expected to provide understanding of the strengths and weaknesses of current models as well as a basis for direction of future research. The study was to focus on the formal elicitation of expert judgment. Formal expert judgment methods are deemed appropriate and necessary if the available experimental database cannot provide the necessary information and if the analytical models that would provide information not observed experimentally are not indisputably correct. The study had the following broad objectives:

1. *to formulate a generic, state-of-the-art methodology for uncertainty estimation which is capable of finding broad acceptance;*
2. *to apply the methodology to estimate the uncertainties associated with the predictions of probabilistic accident consequence codes designed for assessing the consequences of commercial nuclear power plant accident; and*
3. *to better quantify and obtain more valid estimates of the uncertainties associated with probabilistic consequence codes, thus enabling more informed and better judgments to be made in the areas of risk comparison and acceptability and therefore to help set priorities for future research.*

The approach in this study adopted two important ground rules. The first ground rule was that the existing code models would not be modified as a result of the expert elicitations, and thus it was necessary to elicit distributions over variables that could be processed in order to produce code input variables. The second ground rule was that the experts would be asked to assess physical quantities that could potentially be measured in experiments. This rule was adopted to avoid ambiguity in the definition of the variables to be elicited, as well as to provide for a broader application of the variables beyond the context of the joint study.

The choice of the variables to be elicited was based on their assessed importance in prior sensitivity and uncertainty studies performed in the U.S and Europe. The phenomenological areas and the

general topics for code input variables addressed by the experts are presented in Table 3.1. There were eight panels consisting of 70 experts convened to provide elicitations of the uncertainty in the variables. The expert panels assessed distributions for literally hundreds of parameters since there were different initial and boundary conditions to be considered for each variable, and at times it was important to derive separate distributions for different chemical elements. Table 3.1 lists the number of elicitation questions, or variables, assessed by each panel (each expert may not have provided assessments for every question; however, several experts assessed every single question). The expert panel members and their national affiliations are listed in Tables 3.2 through 3.5.

Table 3.1 Consequence Variables for Expert Panels

Phenomenological Area	Number of Experts	Number of Elicitation Questions	Code Input Variables
Atmospheric Dispersion	8	77	Plume spread parameters
Deposition	8	86	Dry deposition velocity Wet deposition parameters
Behavior of deposited material and external doses	10	505	Decontamination Shielding factors Penetration factors
Internal dosimetry	9	332	Breathing rate Dose conversion factors
Early health effects	10	489	Lethal dose thresholds
Late health effects	10	106	Dose rate effectiveness factors Risk coefficients (cancer)
Food chain on animal processes	9	115	Intake by inhalation/ingestion Metabolism and human consumption
Food chain on plant/soil processes	7	224	Transfer mechanisms Resuspension factors

Table 3.2 Atmospheric Dispersion/Deposition Panels

Dispersion	Country	Deposition	Country
Pietro Cagnetti	Italy	John Brockmann	U.S.A
Frank Gifford	U.S.A	Sheldon Friedlander	U.S.A
Paul Gudiksen	U.S.A	John Garland	U.K.
Steve Hanna	U.S.A	Jozef Pacyoa	Norway
Jan Kretzschmar	Belgium	Jorn Roed	Denmark
Klaus Nester	Germany	Richard Scorer	U.K.
Shankar Rao	U.S.A	George Sehmel	U.S.A
Hans van Dop	Netherlands	Sean Twomey	U.S.A

Table 3.3 Dosimetry Panels

External Dosimetry	Country	Internal Dosimetry	Country
Mikhail Balonov	Russia	Michael Bailey	U.K.
Andre Bouville	U.S.A.	Keith Eckerman	U.S.A.
Joanne Brown	U.K.	Anthony James	U.S.A.
Malcolm Crick	Austria	Richard Leggett	U.S.A.
Eduardo Gallego	Spain	Ilya Likhtarev	Ukraine
Peter Jacob	Germany	Henri Metivier	France
Olof Karlberg	Sweden	Dietmar Nosske	Germany
Ilya Liktarev	Ukraine	Nick Priest	U.K.
Kevin Miller	U.S.A.	David Taylor	U.K.
Jorn Roed	Denmark		

Table 3.4 Health Effects Panels

Early Health Effects	Country	Late Health Effects	Country
Johan Broerse	Netherlands	Maria Blettner	Germany
Marvin Goldman	U.S.A.	Monty Charles	U.K.
Jolyon Hendry	U.K.	Florent de Vathaire	France
John Hopewell	U.K.	Ethel Gilbert	U.S.A.
Fred Mettler	U.S.A.	Lothar Kreienbrock	Germany
Natalja Nadejina	Russia	Jerry Puskin	U.S.A.
Bobby Scott	U.S.A.	Warren Sinclair	U.S.A.
Elizabeth Travis	U.S.A.	Bob Ullrich	U.S.A.
Niel Wald	U.S.A.	Michael Vaeth	Denmark
Bob Young	U.S.A.	Richard Wakeford	U.K.

Table 3.5 Food Chain Panels

Soil and Plant	Country	Animal	Country
Martin Frissel	Netherlands	Peter Coughtrey	U.K
John Garland	U.K.	Francois Daburon	France
Rene Kirchmann	Belgium	Owen Hoffman	U.S.A.
Gerhard Prohl	Germany	Brenda Howard	U.K.
George Shaw	U.K.	Jack Pierce	U.K.
Ward Whicker	U.S.A	Per Strand	Norway
Lynn Anspaugh	U.S.A	Cristian Vandecasteele	Belgium
		Gaby Voigt	Germany
		Gerry Ward	U.S.A.

3.1 Dispersion and Deposition Panel

The members of the dispersion expert panel were asked to assess normalized and relative concentrations in a plume and other plume features at various distances for four meteorological conditions and a combination of both urban and rural surface roughness. They were asked to include in their uncertainty assessments consideration of phenomena such as plume meander, mixing height, minor terrain variability, uncertainty in the definition of synoptic weather conditions, directional wind shear, vertically changing turbulence, roughness height variability, wind profile and leaky inversion layers. They were not to consider complex meteorology in their assessments.

The Gaussian dispersion models in MACCS and COSYMA define the spread of the plume by using horizontal and vertical dispersion parameters, σ_y and σ_z, which are defined by the power law:

$$\sigma_y = a_y x^{by} \qquad \sigma_z = a_z x^{bz}$$

where

x = the distance from the segment's release point to its current location

a_y, b_y, a_z, b_z = dimensionless constants, required as code inputs that define the spread of the plume.

The distributions that the experts provided were not in a format that was readily compatible with the codes. The distributions were therefore processed in order to provide that compatibility. Figure 3.1 displays "5-95 boxplots" of distributions of σ_y for moderately stable meteorological conditions at three downwind locations. The boxplots display the 5th, 50th and 95th percentile values of the aggregate distributions obtained by equally weighting the assessments of the eight panel experts. Also displayed in Figure 3.1 are the single values of σ_y predicted by the MACCS and COSYMA power law models for the same assumptions. Note that the values predicted by MACCS and COSYMA are between the 5th and 50th percentile values of the elicited data.

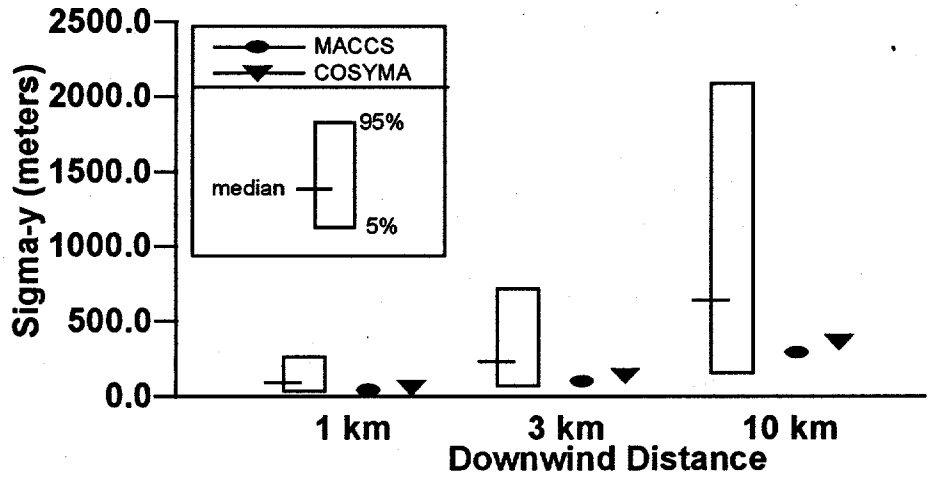

Figure 3.1 Aggregate Expert Distributions of σ_y Compared with σ_y as Defined in the MACCS and COSYMA Codes for Moderately Stable Meteorological Conditions

The deposition expert panel was asked to provide distributions of dry deposition velocities for different combinations of environmental factors:

- four surface types (urban, meadow, forest and human skin),
- three particulate forms (aerosol, elemental iodine, and methyl iodide),
- five particle sizes (0.1 μ, 0.3 μ, 1.0 μ, 3.0 μ, and 10.0 μ), and

- two average wind speeds (2 m/s and 5 m/s).

The experts were asked to consider in their assessments such effects as humidity, ambient and surface temperatures, variations within surface types, meteorological conditions except the wind speed, chemical reactions with aerosol surfaces, electrostatic effects, and day and night differences. They were instructed not to include variability due to vapor to particle conversion or resuspension.

The elicitation variable for wet deposition is the fraction of material removed from the plume. The deposition expert panel provided distribution for combinations of these important factors:

- five rain intensities (0.3 mm and 2.0 mm in an hour, and 0.05 mm, 0.33 mm and 1.67 mm in 10 minutes),
- three particulate forms (aerosol, elemental iodine, and methyl iodide), and
- four particle sizes (0.1 μ, 0.3 μ, 1.0 μ, and 10.0 μ).

The experts were asked to consider electrostatic effects, vertical concentration profiles, rain intensity, hydrophobic and hydrophilic effects in the assessment of their distributions; however, they were asked not to include the variability introduced by snow, mist, fog or rainout.

3.2 Internal Dosimetry Panel

The internal dosimetry expert panel was requested to provide distributions for elicitation variables in the following areas: inhalation, ingestion, systemic distribution and retention, and organ dose coefficients. For inhalation, the experts were asked to consider exposure to unit air concentration of radioactive aerosols for a short duration, e.g., 1 Bq/m^3 for 1 minute. The questions addressed parameters primarily for adults but with additional information requested for 5-year-old children. The inhalation parameters elicited were:

- ventilation rates,
- deposition in the respiratory tract as a fraction of what is inhaled for three particle sizes (0.1 μm, 1 μm and 10 μm AMAD),
- distribution of deposited material between the extrathoracic, tracheobronchial, and pulmonary regions of the respiratory tract for the three particle sizes,
- retention of material in the tracheobronchial and pulmonary regions at times after deposition that varied between 10 minutes and 10 years, and
- the absorption by blood for seven elements (Sr, I, Cs, Pu, Ru, Ce, and Te) at times after deposition that varied from 1 hour to 10 years.

Other factors noted to be important for the estimation of uncertainty in the distributions included the location of sensitive cells in different regions, the relative radiosensitivity of the different regions, tissue mass and geometric considerations.

The ingestion variables elicited were limited to absorption by blood as a fraction of the total ingested for Sr, I, Cs, and Pu for adults, 5-year-old children, and 3-month-old infants. The experts were asked to consider the chemical forms most likely to be ingested after an accident. Additional factors to be considered in the assessments included gut transit times, doses to sensitive cell from activity in gut contents (particularly for alpha emitters), retention in intestinal tissue, tissue mass and geometric considerations.

The questions posed to the expert panel that were related to systemic distribution and retention are concerned with the uncertainty in calculating dose from the radionuclides that enter the blood. For the elements Sr, Pu, Ce, and Te, the elicited variables were: total retention in the liver and skeleton, and distribution between the liver and skeleton at times that varied between 1 day and 50 years after entry to blood. For Pu only, the experts were asked to assess for the same time regimes the uncertainty associated with the distribution within the skeleton on endosteal and trabecular

bone surfaces and in red bone marrow. For the elements Ru and Cs, the elicited variables involved whole-body retention at times ranging from 1 day to 5 years after entry into the blood. For iodine, retention in the thyroid was elicited at times ranging from 1 day to 3 months after entry into blood. Factors considered important to the uncertainty included the location of sensitive cells in bone, absorbed fractions for alpha and beta emitting bone-seekers, and tissue mass and geometric considerations. The experts were also asked to consider the behavior of the elements and take no account of the radioactive half-lives of the various isotopes of the elements.

Because dosimetry input to accident consequence analysis codes is generally in the form of dose coefficients, the experts were also asked, if possible, to provide uncertainty distributions for the dose coefficients for inhalation and ingestion. The information that was elicited included absorbed doses per unit intake in terms of committed doses to 70 years of age. The isotopes considered for both inhalation and ingestion were ^{90}Sr, ^{131}I, ^{137}Cs, and ^{239}Pu. Inhalation only was considered for ^{132}Te and ^{144}Ce. The distributions were provided for the most important organ or organs. Figure 3.2 displays the boxplots for the equally-weighted aggregate distributions of dose conversion factors (DCFs) provided by the expert panel for the lung and red marrow inhalation doses for ^{90}Sr and for the thyroid inhalation dose for ^{131}I. Also displayed in Figure 3.2 are data for the same DCFs obtained from the EPA's Federal Guidance Report (FGR) 11 [Eckerman, 1988]. The FGR11 DCF database is provided as part of the MACCS2 software package. The FGR11 data falls within the ranges of the experts' uncertainty assessments. However note that the FGR11 Sr lung dose is in the lower 50 percentile of the distribution, the Sr red marrow dose is in the upper 50 percentile of the distribution, and the I thyroid dose is close to the 50 percentile value of the distribution. For the DCFs shown in Figure 3.2, the Sr lung dose exhibits the greatest uncertainty (nearly 4 orders of magnitude between the 5th and 95th percentiles).

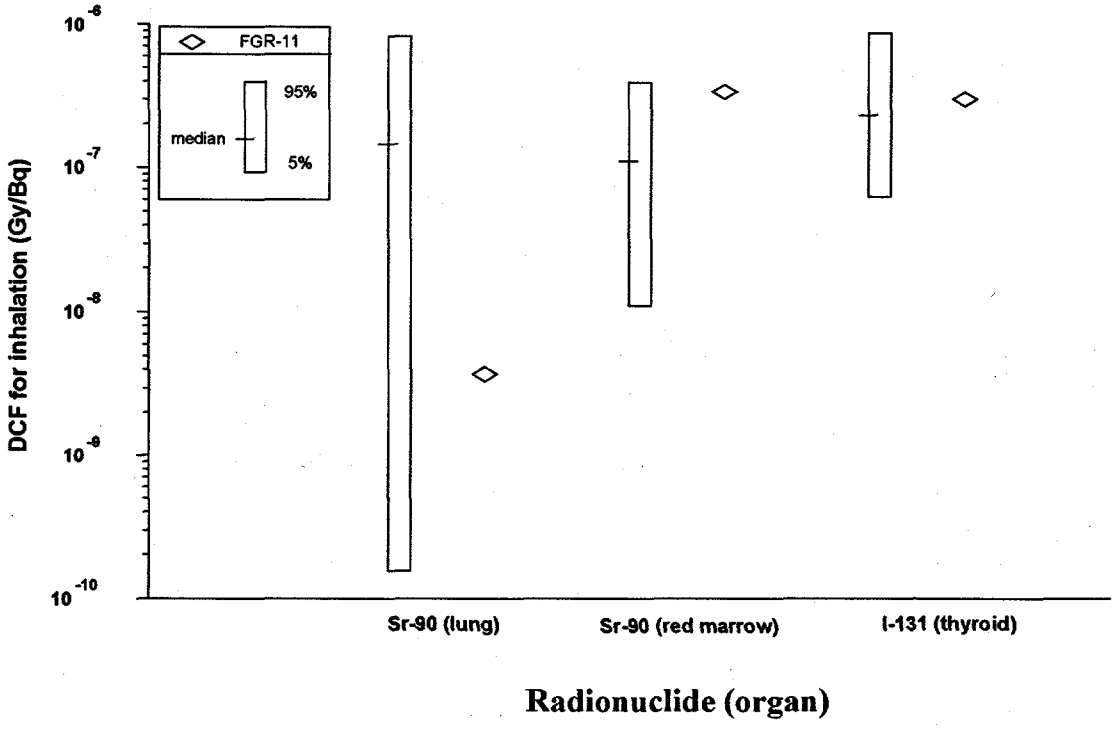

Figure 3.2 Aggregate Expert Distributions and FGR11 Values of DCFs – Absorbed Committed Dose per Unit Activity Inhaled for an Adult

3.3 Deposited Material and External Doses Panel

The expert panel for deposited material and external doses was asked to assess uncertainties related to the estimation of external doses to individuals outdoors and indoors and in urban or rural environments, together with various assumptions about population behavior. The experts were requested to provide distributions of variables for the areas of external gamma dose, indoor inhalation dose, and population behavior.

Elicited variables concerned with external gamma doses included absorbed and effective doses, dose rates and location factors. The absorbed dose rate in air 1 m above a uniform, flat and open lawned area was assessed for various times after an initial deposit on the ground of 1 Bq/m^2 of several isotopes (^{95}Zr/^{95}Nb, ^{106}Ru/^{106}Rh, ^{131}I and ^{137}Cs/^{137m}Ba). The effective dose and dose rate to an adult outdoors in typical urban and rural environments were elicited for various times after an initial deposit to the lawned areas of the ground of 1 Bq/m^2 of various isotopes (^{95}Zr/^{95}Nb, ^{106}Ru/^{106}Rh, ^{131}I and ^{137}Cs/^{137m}Ba). The ratio of the dose indoors, or at any given location to that at 1 m above an open lawn surface is often called a location factor. Indoor location factors were elicited for adult external dose shortly after an initial deposit on the ground of 1 Bq/m^2 of several isotopes (^{95}Zr/^{95}Nb, ^{106}Ru/^{106}Rh, ^{131}I and ^{137}Cs/^{137m}Ba) for buildings of various shielding levels and typical means of transportation.

Figure 3.3 provides the boxplots of the equally-weighted aggregate distributions of gamma dose rate for a deposit of 1 Bq/m^2 of ^{137}Cs on a lawned area for various times after deposit. Figure 3.4 provides the boxplots of the equally-weighted aggregate distribution of indoor location factors shortly after an initial deposit on the ground of 1 Bq/m^2 of ^{137}Cs on a lawned area for various locations. The locations are a low shield building, a medium shield building, a high shield building, a house basement, a building basement, a typical car and a typical bus.

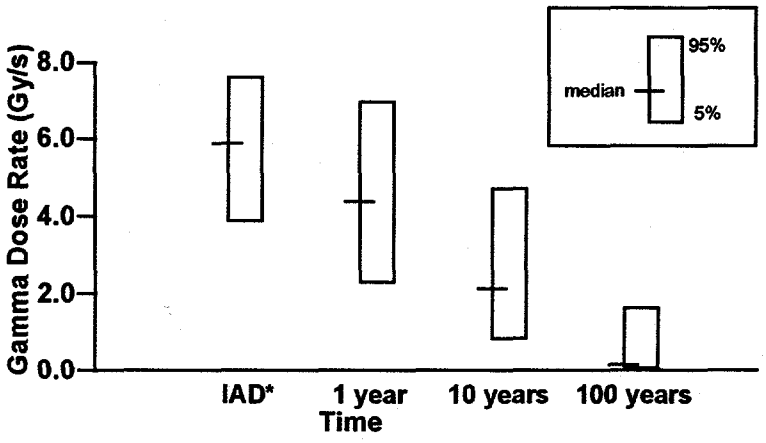

Figure 3.3 Aggregate Expert Distributions of gamma dose rate above an open lawned area following an initial dry deposit of 1 Bq/m^3 of ^{137}Cs (*Immediately after deposit).

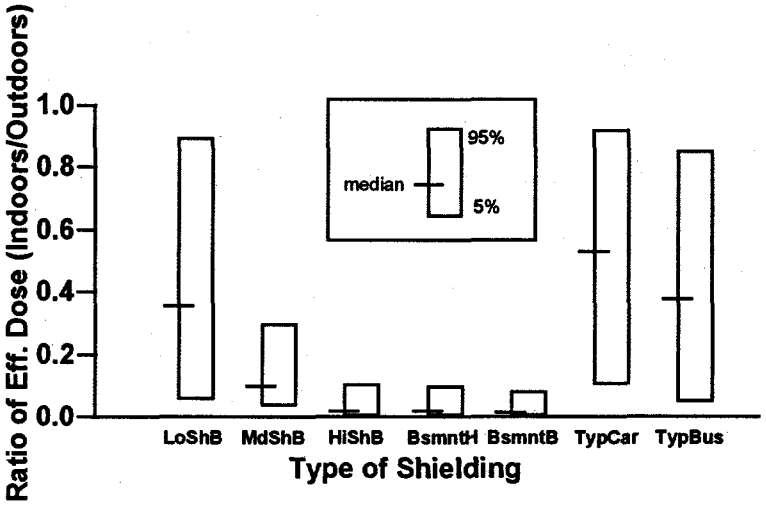

Figure 3.4 Aggregate Expert Distributions for indoor location factors shortly after an initial uniform deposit of 1 Bq/m^3 of ^{137}Cs to outdoor open lawned areas.

The elicited variables for indoor inhalation doses included the ratio of the time-integrated air concentration indoors to that outdoors given an outdoor concentration of 1 Bq-s/m^3. The isotopes to be considered were ^{240}Pu, ^{137}Cs and ^{131}I, for two different situations: doors or windows normally open for ventilation and all doors and windows closed.

The experts were asked to provide assessments of population behavior. One of the elicited variables was the fraction of the average population in the expert's own country that would be classed as:

- agricultural or outdoor workers,
- indoor workers,
- nonactive adult population, and
- schoolchildren.

Other information to be elicited was the fraction of time each of these four population groups spends indoors in various types of buildings and in vehicles, considering both an urban and rural environments. This was also to be provided for an additional hypothetical "average" person living in the expert's country.

Factors that were asked to be considered in the uncertainty assessments included: climate variations, variations with wet and dry deposition, particle size distribution, relative contamination levels on different surfaces (lawns, paved areas, roofs, etc.), weathering in both rural and urban areas, surface roughness effects on dose rate, and proximity of buildings and trees to the dose reference point. The experts were asked to include any other factors believed to be important contributors to uncertainty.

3.4 Early Health Effects Panel

The early health effects expert panel provided distributions for the lethal dose LD_{10}, LD_{50} and LD_{90} values, i.e., the dose that is fatal to 10%, 50% and 90%, respectively, of the population that receives it. Distributions of the LD values were provided for different exposure conditions:

- the organ(s) exposed – lungs, whole body, red marrow, gastrointestinal tract, or skin;
- the radiation source – internal or external; gamma, beta, alpha, or mixed;

- the dose rate or exposure period – 0.2 to 100 Gy/hr; two-step dose rates in a given time period (e.g., 10:1 relative dose rate 1 hour:1 day); and
- other variations such as minimal versus supportive treatment; age group differences; and different skin exposure fractions.

Other factors believed to contribute to the uncertainty were to be addressed within the distributions themselves. These include things such as uncertainties in dose reconstruction, underreporting in the databases, sparse information in the databases, efficacy of medical treatment, variable health states among members of the population, extrapolating from animal data, and limited data on synergistic effects.

To assist in the formulation of the distributions, many of the experts cited published data on early health effects, particularly the Nagasaki and Chernobyl data. Where human data was neither available nor sufficient, the experts applied extrapolations from animal data, or relied on statistical and/or mechanistic models, and one expert relied on an available biokinetic model.

Figure 3.5 provides boxplots of the equally-weighted aggregate expert panel distributions of LD_{50} for three health effects at a dose rate of 100 Gy/hr assuming minimal medical treatment. Also shown in Figure 3.5 are values obtained from a study performed at the Inhalation Toxicology Research Institute (ITRI) and documented in NUREG/CR-4214 [Evans, 1993]. The NUREG/CR-4214 work provides three estimates believed to be at the lower, central and upper limits of the range of possible values. Note that for both studies, the least uncertainty is associated with the hematopoietic syndrome, followed by the pulmonary syndrome and the values display the largest uncertainty for the gastrointestinal syndrome. The uncertainty bands from these two studies seem to be in overall agreement; however the current study data demonstrate a bit more conservatism by including lower LD_{50} values for the pulmonary and gastrointestinal syndromes.

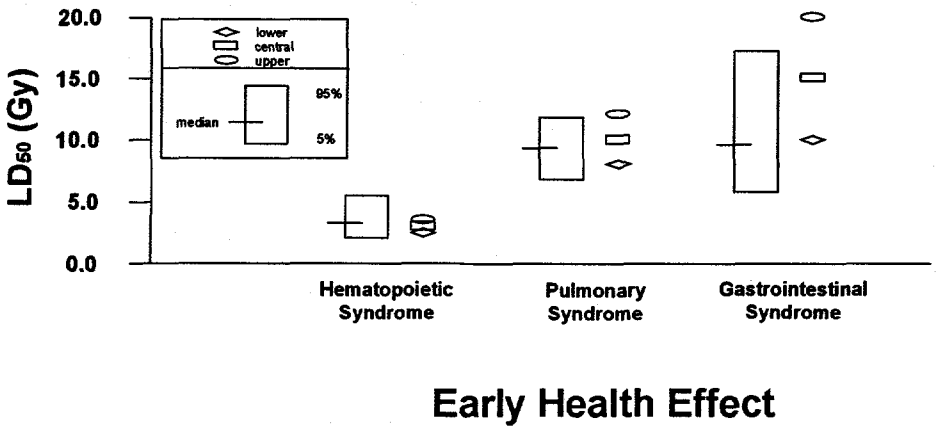

Figure 3.5 Aggregate Expert Distributions of LD_{50} at 100 Gy/hr versus NUREG/CR-4214 Values Assuming Minimal Medical Treatment

3.5 Late Health Effects Panel

The expert panel for late health effects provided distributions for the number of radiation exposure induced cancer deaths in a given population. The panel chose to assess all late effects with the exception of genetic health effects. The distributions were assessed for up to twelve cancer sites (bone, colon, breast, leukemia, liver, lung, pancreas, skin, stomach, thyroid, all other cancers, and all cancers) considering various conditions:

- a given population distribution – general, children, in utero,

- high or low levels of exposure conditions – dose, dose rate, and level of radiation linear energy transfer (LET), and
- number of years after exposure – 0-20, 0-40, or 0-∞.

The experts also provided for each of the twelve cancer sites, a distribution of the number of years of life lost in the general population due to radiation induced cancer deaths and the dose threshold for high dose-rate radiation. With the exception of one question relating to ingestion of ^{90}Sr and ^{239}Pu, the population was assumed to be exposed to whole body doses or to uniform doses to specific organs from internal exposure. In utero doses were assumed to be delivered uniformly to all tissues of the embryo and fetus.

Other factors believed to contribute to the uncertainty were to be addressed within the distributions themselves. These include things such as uncertainties in variable health states among members of the population, modeling of cancer risk (e.g., relative vs. absolute), sampling variability in risk coefficients and dosimetric errors in existing datasets, relative biological effectiveness, dose dependent reduction factors, transport of risks across populations, time/age variability in risk, data quality, and synergistic effects.

To assist in the formulation of distributions, many of the experts made extensive use of data contained in the latest Japanese atomic bomb survivor mortality and cancer incidence datasets. Other datasets that were accessed include the latest UNSCEAR [UNSCEAR, 1994] and BEIR [NAS, 1990] reports.

Figure 3.6 displays boxplots of the equally-weighted aggregate expert panel distributions of radiation-induced cancer deaths for twelve types of cancer. Figure 3.6 shows the number of deaths expected in a population of 100 million persons (half male, half female) for up to 40 years following exposure (assumed to be whole body dose of 1 Gy low LET radiation at a uniform rate over 1 minute). The results indicate that large uncertainties exist in the evaluation of radiation-induced incidence of death from bone, liver, pancreatic, skin, stomach, thyroid and other cancers; whereas there is less uncertainty associated with the evaluation of the incidence of death from colon, breast, leukemia, lung, and all cancers.

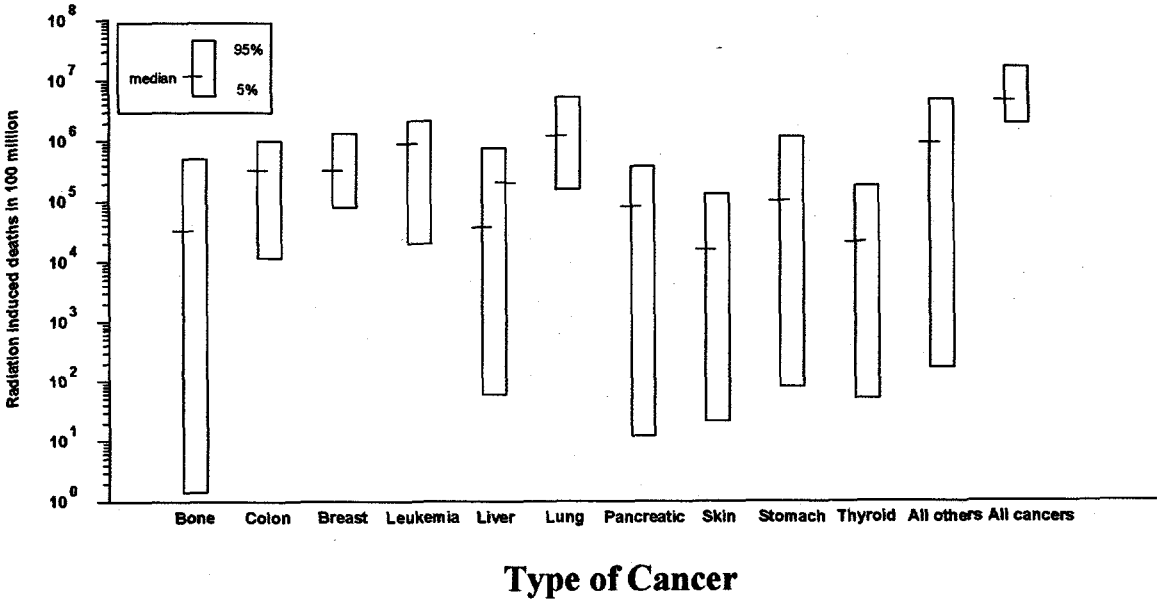

Figure 3.6 Aggregate Expert Distributions of Radiation-induced Cancer Deaths in a Population of 100 Million Persons up to 40 yrs Following Exposure (see text)

3.6 Food Chain Panels

The food chain expert panel was divided into its two main fields of study, i.e., soil and plant transfer processes and animal processes. The panel for soil and plant transfer processes provided distributions for various transfer mechanisms:

- migration of Sr and Cs for four soil depths (below 1, 5, 15, and 30cm) for four types of soil,
- fixation of Sr and Cs for four time periods (1, 3, 5 and 10 years) for four types of soil,
- root absorption of Sr and Cs for four types of soil for five crops,
- interception by plant foliage of ground-deposited material for five crops,
- retention of activity on the plant surface (retention half-life) for five crops,
- resuspension by wind driven processes of ground-deposited material for two crop types (surface crop and pasture grass), and
- concentration of Sr and Cs (translocation) in grain and root crops at harvest when the deposition has occurred at four specified times (15, 30, 60 and 90 days) before harvest.

The four soil types considered were generic European, generic U.S., sandy and highly organic. The five crop types were green vegetables, grains, root vegetables, pasture grass, and either potatoes (for root absorption) or hay/silage grass (for interception and retention).

Figure 3.7 displays the concentration ratio for Sr and Cs in grains from the equally-weighted aggregate expert distributions as well as the default values used in the COSYMA foodchain models, ECOSYS and FARMLAND. The concentration ratio is the ratio of Bq/kg for fresh plant mass to Bq/kg for dry soil mass. The values applied in ECOSYS and FARMLAND show good agreement with the 50 percentile values of the distributions provided for the current study.

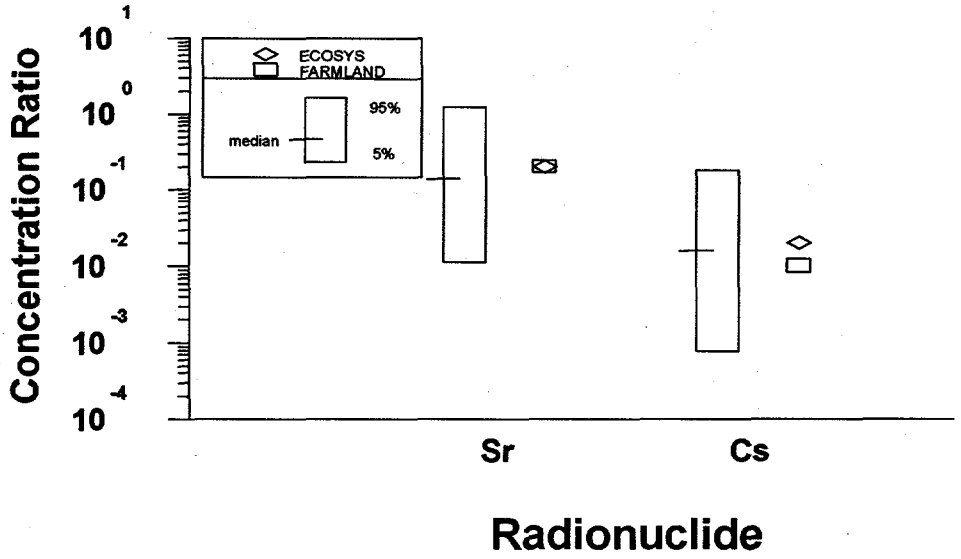

Figure 3.7 Aggregate Expert Distributions and COSYMA Foodchain Model Values of Concentration Ratios of Sr and Cs for Grains

The panel for animal processes addressed the two main stages for transfer of radionuclides, i.e., the intake of radionuclides by ingestion or inhalation, and the subsequent metabolism and transfer to animal tissues and products that are consumed by humans. This panel provided distributions for the following information:

- daily consumption rates of pasture grass, hay, cereals, and soil (if applicable) for dairy cows, beef cattle, sheep, pigs and poultry,

- availability of radioactivity associated with ingested feed for transfer across the gut for Sr, Cs, and I,
- the fraction, F_f, of Sr and Cs intake that is transferred to the meat of dairy cows, beef cattle, sheep, pigs and poultry,
- the fraction, F_f, of Sr and Cs intake that is transferred to the eggs of poultry
- the fraction, F_m, of Sr, Cs and I intake that is transferred to the milk of dairy cows, sheep and goats, and
- the biological half-life of Sr, Cs and I in dairy cows, beef cattle, sheep, pigs and poultry.

Because the animal husbandry practices differ significantly in the US and Europe, the European and US experts were given slightly different questions where appropriate.

Figure 3.8 displays the milk transfer fraction of Sr, Cs and I for dairy cows from the equally-weighted aggregate expert distributions as well as the default values used in the COSYMA foodchain models, ECOSYS and FARMLAND. The values applied in ECOSYS and FARMLAND for Sr show good agreement with the 50 percentile values of the distributions provided for the current study, and for Cs and I, the values fall between the 50 and 95 percentile values and the 5 and 50 percentile values respectively.

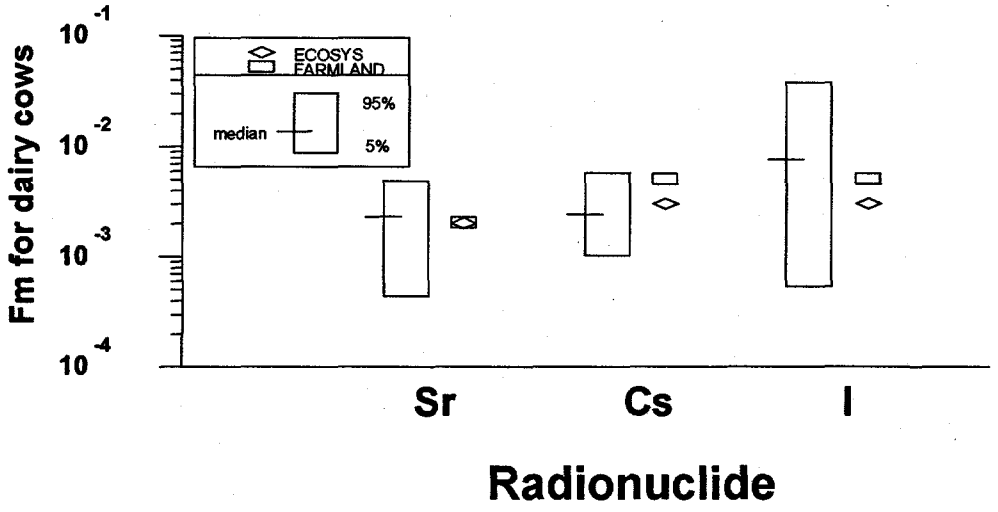

Figure 3.8 Aggregate Expert Distributions and COSYMA Foodchain Model Values of Milk Transfer Fraction F_m for Sr, Cs and I in Dairy Cows

4. Summary

Consequence modeling for nuclear reactor accidents consists of a multitude of submodels that have varying degrees of complexity and that typically require many input parameters. A recent joint USNRC/CEC consequence uncertainty study has provided a wealth of information about the uncertainty associated with parameters that are used as input to consequence models. In this paper, we have described that study and how the results can be interpreted by risk analysts.

The second phase of the uncertainty study is currently in progress and will implement in existing consequence codes the distributions that were provided by the expert panels in the first phase. The results from such a study can provide important information about the important contributors to consequence variability as a result of model input variability. In the U.S., the USNRC has sponsored an uncertainty/sensitivity study at Sandia National Laboratories using the MACCS2 code. The MACCS2 software package has the flexibility to be used in an uncertainty analysis that

would utilize the most current information. Upon completion of that study, the consequence uncertainties will then be implemented in an existing PRA (NUREG-1150), to study the impact of consequence uncertainty in a fully integrated risk analysis. This information may enable more informed and better judgments to be made in the areas of risk comparison and acceptability and may help to set priorities for future research.

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