Probabilistic Accident Consequence Uncertainty Analysis

A Joint Report Prepared by U.S. Nuclear Regulatory Commission and Commission of European Communities

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Uncertainty Assessment for Internal Dosimetry

Volume 1 Main Report

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Uncertainty Assessment for Internal Dosimetry

Main Report

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Abstract

The development of two new probabilistic accident consequence codes, MACCS and COSYMA, was completed in 1990. These codes estimate the risks presented by nuclear installations based on postulated frequencies and magnitudes of potential accidents. In 1991, the US Nuclear Regulatory Commission (NRC) and the European Commission (EC) began a joint uncertainty analysis of the two codes. The ultimate objective was to develop credible and traceable uncertainty distributions for the input variables of the codes.

The study was formulated jointly and was limited to the current code models and to physical quantities that could be measured in experiments. An elicitation procedure was devised from previous US and EC studies with refinements based on recent experience. Elicitation questions were developed, tested, and clarified. Internationally recognized experts were selected using a common set of criteria. Probability training exercises were conducted to establish ground rules and set the initial and boundary conditions. Experts developed their distributions independently.

After the first feasibility study on atmospheric dispersion and deposition parameters, a second expert judgment exercise was carried out on food chain and external dose (calculation) parameters. A third expert judgment exercise has been carried out on early and late health effects and internal dosimetry parameters. The goal again was to develop a library of uncertainty distributions for the selected consequence parameters. Nine experts from five countries were selected for an expert panel on internal dosimetry. Their results were processed with an equal-weighting aggregation method, and the aggregated distributions will be used to determine distributions on the code input parameters of the dose per unit intake (DUPI) models used in COSYMA and MACCS.

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Preface

This volume is the first of a two-volume document that summarizes a joint project conducted by the US Nuclear Regulatory Commission and the European Commission to assess uncertainties in the MACCS and COSYMA probabilistic accident consequence codes. These codes were developed primarily for estimating the risks presented by nuclear reactors based on postulated frequencies and magnitudes of potential accidents. This document reports on an ongoing project to assess uncertainty in the MACCS and COSYMA calculations for the offsite consequences of radionuclide releases by hypothetical nuclear power plant accidents. A panel of nine experts on internal dosimetry was selected to compile uncertainty distributions. The expert judgment elicitation procedure and its outcomes are described in these volumes. Other panels were formed to consider uncertainty in other aspects of the codes. Their results are described in companion reports.

Volume 1 contains background information and a complete description of the joint consequence uncertainty study along with a summary of the results of this aspect of the study. Volume 2 contains appendices that include (1) a summary of the MACCS and COSYMA consequence codes, (2) the elicitation questionnaires and case structures, (3) the rationales and results for the panel on internal dosimetry, (4) short biographies of the experts, and (5) the aggregated results of their responses.

Acknowledgments

The authors would like to acknowledge all the participants in the expert judgment election process, in particular the internal dosimetry expert panel. While we organized the process, processed the results, and wrote and edited the report, the experts provided the technical content that is the foundation of this report. Dr. Detlof von Winterfeldt is acknowledged for his contribution as elicitor in several expert sessions. We would also like to express our thanks for the support and fruitful remarks of Dr. G. N. Kelly (EC/DG XII).

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List of Acronyms

ACA	accident consequence analysis
CDF	cumulative distribution function
COSYMA	code system from MARIA (method for assessing the radiological impact of accidents)
DF	dose conversion factor
EC	European Commission
LHS	Latin hypercube sampling
MACCS	MELCOR accident consequence code system
NRC	Nuclear Regulatory Commission

Executive Summary

Introduction

The US Nuclear Regulatory Commission (NRC) and the European Commission (EC) have co-sponsored an uncertainty analysis of their respective probabilistic accident consequence codes, MACCS and COSYMA. Although uncertainty analyses have been performed for the predecessors of MACCS and COSYMA, the distributions for the input variables were largely developed by the code developers rather than experts involved in the specific phenomenological areas contributing to accident consequence analysis. In addition, both organizations were aware of the importance of using uncertainty analysis in making decisions on the prioritization of activities and research; they were also interested in initiating a comprehensive assessment of the uncertainty in the consequence calculations used for risk assessments and regulatory purposes. Therefore, the ultimate objective of the NRC/EC joint effort is to systematically develop credible and traceable uncertainty distributions for the code input variables using a formal expert judgment elicitation process.

This report focuses on the methods and results of the internal dosimetry study. The specific goal of this study was to develop a library of uncertainty distributions in the area of internal dosimetry by using a formal expert judgment elicitation process, addressing important aspects of the biokinetics of inhaled and ingested radionuclides. The use of the results obtained to determine distributions on dose coefficients, the required input to MACCS and COSYMA codes, will be considered in a separate publication.

Approach

To ensure the quality of the elicited information, a formal expert judgment elicitation procedure, built on the process developed for and used in the NUREG-1150 study, was followed.[1] Refinements were based on the experience and knowledge gained from several formal expert judgment elicitation exercises performed in the US and EC since the NUREG-1150 study. These include the pilot study on atmospheric dispersion and deposition published by Delft University of Technology for the EC, the joint NRC/EC study on atmospheric dispersion and deposition published as NUREG/CR-6244–EUR-15855, and performance assessments for waste repositories in the United States.

Expert judgment techniques are used only for the most important code input variables in terms of contribution to the uncertainty in code predictions. Less resource-intensive methods will be used to develop uncertainty distributions for the remainder of the code input variables. Each organization will then propagate and quantify the uncertainty in the predictions produced by their respective codes.

This approach was jointly formulated and was based on two important ground rules: (1) the current code models would not be changed because both the NRC and EC were interested in the uncertainties in the predictions produced by MACCS and COSYMA, respectively, and (2) the experts would be asked only to assess physical quantities that hypothetically could be measured in experiments. The reasons for these ground rules are that (1) the codes have already been developed and applied in US and EC risk assessments, and (2) eliciting physical quantities avoids ambiguity in definitions of variables; more important, the physical quantities elicited are not tied to any particular model and thus have a much wider potential application.

The study involved several phases: preparation stage, expert training meetings, preparation of the assessments and written rationale, expert elicitation sessions, and processing the elicited results. Each phase is summarized below.

Preparation Stage

For internal dosimetry, code input parameters for MACCS and COSYMA are dose coefficients for the inhalation or ingestion of radionuclides by children and adults. Elicitation variables were defined based on the results of past and contemporary probabilistic consequence code sensitivity/uncertainty studies, which screened for the important code input variables in the context of their contribution to the uncertainties in the code predictions. Elicitation questions, hereafter referred to as case structure, were developed so that sufficient information would be elicited from the experts to allow valid interpolation and extrapolation of the resulting uncertainty distributions. The proposed case structure was then tested with several

experts in the area of internal dosimetry and refined as considered appropriate. In accordance with the requirement that the parameters addressed should in principle be measurable rather than characteristics of models or their output, questions for the internal dosimetry panel concentrated on biokinetic parameters. Intakes of important radionuclides by inhalation and ingestion and their distribution and retention in tissues after entry into blood were considered. However, questions were also included on overall uncertainty in organ dose coefficients for selected radionuclides.

Two expert selection committees were established: one in the US and one in the EC. (The committees consisted of members predominantly external to the project although some project staff members took part.) The committees were charged with selecting experts using a common set of criteria, which included reputation in the relevant fields, number and quality of publications, familiarity with the uncertainty concepts, diversity in background, balance of viewpoints, interest in this project, and availability to undertake the task in the time scale prescribed. As a result of this process, the experts listed in the table were selected to participate in the formal elicitation process for internal dosimetry. Brief biographies are published in Volume 2. A short description of the objective of the joint program was sent to the selected experts before the training meeting to familiarize them with the project.

Expert Training Meetings

A joint training meeting was held for the European and American experts to provide background on the project and its objectives, the MACCS and COSYMA codes, and the treatment of the elicited information. A probability training session was conducted to familiarize the experts with the concept of uncertainty and the potential pitfalls in preparing subjective assessments; practice exercises followed. Material for the training exercise was drawn directly from the field of internal dosimetry. The training meetings were also used to ensure that the experts developed their respective uncertainty distributions based on common ground rules and initial and boundary conditions (it was considered critical that the experts all answer the same question). The full proposed case structure was presented to them for discussion, and when necessary, was modified in accordance with their feedback to ensure that all given problem conditions were clear, reasonable, and agreeable to them. In particular, the number of questions was reduced at the experts' request, primarily by reducing the number of nuclides for which information was requested and limiting requirements to consider different ages at intake.

Experts on internal dosimetry

Michael Bailey	UK
Keith Eckerman	US (jointly with Leggett)
Anthony James	US
Richard Leggett	US (jointly with Eckerman)
Ilya Likhtarev	Ukraine
Henri Métivier	France
Dietmar Nosske	Germany
Nick Priest	UK
David Taylor	UK

Preparation of the Assessments and Written Rationale

The experts were instructed to use any information sources available to assist them in developing their distributions, such as analytical models and experimental databases, between the first and second expert meetings. For each of the elicitation variables in the case structure, three percentile values (5th, 50th, and 95th) from the cumulative distribution functions were requested from each of the experts. A written rationale was also required from each expert so that the bases of the assessments could be traced.

Expert Elicitation Sessions

A joint videoconferenced meeting was held on February 29, 1996, followed by individual elicitation sessions. During the videoconference, held in Brussels and Albuquerque, a common session was conducted in which the experts presented the technical approach and rationale behind their assessments. No distributions were provided in the common sessions to avoid biasing the other experts. The elicitation of each expert took place privately with a normative specialist and a substantive assistant.

In both cases, the experts were allowed to change their elicitation results at any point. The elicitation interviews allowed for significant interaction between the assessment team and the expert. The issue of anonymity was discussed and the American experts agreed to preserve anonymity, as did their European counterparts.

Processing the Elicited Results

Because multiple assessments were elicited without requiring consensus, the elicited assessments were aggregated for each variable. Although many different methods for aggregating expert judgments can be found in the literature, investigating alternative weighting schemes was not the objective of this joint effort. A decision was therefore made to assign all experts equal weight (i.e., all experts on each panel would be treated as being equally credible). One of the primary reasons that the equal-weighting aggregation method was chosen was to ensure the inclusion of different modeling perspectives in the aggregated uncertainty distributions. However, additional information was elicited from the experts that would allow performance-based weighting schemes to be applied to the elicited internal dosimetry results. These results will be reported separately.

Mathematical processing of the aggregated elicited data will be necessary to produce distributions on the dose coefficients in use in the COSYMA and MACCS code; these results will be published separately. The experts also provided dose coefficient distributions directly for intakes of the most important nuclides. The estimates provided by the experts will be compared with those obtained by postprocessing of distributions on biokinetic parameters.

Results and Conclusions

Input from a group of highly qualified experts was used to develop uncertainty distributions for internal dosimetry. These distributions concern physically measurable quantities, conditional on the case structures provided to the experts. The experts were not directed to use any particular modeling approach but were free to use whatever models, tools, and perspectives they considered appropriate for the problem. The elicited distributions obtained were developed by the experts from a variety of information sources and the aggregated distributions therefore include variations resulting from different modeling approaches and perspectives. The distributions for the elicitation and code input variables are available on computer media and can be obtained from the project staff.

The elicited variables concentrated on biokinetic parameters, considering intakes of important radionuclides by inhalation and ingestion, and distribution and retention after entry into blood. However, experts were also invited to assess overall uncertainty in organ dose coefficients for selected radionuclides. The experts also provided quantitative data on dependencies between the elicited variables.

This exercise provided valuable information. Thus, the goal of creating a library of internal dosimetry uncertainty distributions, which will have many applications outside of this project, has been fulfilled. In this project, teams supported by the NRC and EC were able to work together successfully to create a unified process for developing uncertainty distributions on consequence code input variables. Staff with diverse experience and expertise and from different organizations provided a creative and synergistic interplay of ideas—something that would not have been possible if they had worked in isolation. Similarly, potential deficiencies in processes and methodologies were identified and addressed in this study. The final product, therefore, is more rigorous than an independent study produced by either organization would be.

Finally, in this exercise, formal expert judgment elicitation has proven to be a valuable vehicle for synthesizing the best available information from a highly qualified group. With a thoughtfully designed elicitation approach that addresses such issues as selection of parameters for elicitation, development of case structure, probability training, communication between the experts and project staff, and documentation of the results and rationale, expert judgment elicitation can play an important role when it is followed by an appropriate application of the elicited information. Indeed, it possibly becomes the only alternative technique for assembling the information required to make a decision at a particular time when it is impractical to perform experiments or when the available experimental results do not lead to an unambiguous and noncontroversial conclusion.

1. Nuclear Regulatory Commission, Severe Accident Risks: An Assessment for Five Nuclear Power Plants, Final Summary Report, NUREG-1150, Washington, DC, 1990.

1. Background of Joint Program

1.1 Introduction

The development of two new probabilistic accident consequence codes—MACCS[1] by the US and COSYMA[2] by the European Commission (EC)—was completed in 1990, and both codes have been distributed to a large number of potential users. These codes have been developed primarily, but not solely, to enable estimates to be made of the risks presented by nuclear installations, based on the postulated frequencies and magnitudes of potential accidents. This is the definition of risk referred to throughout this report. These risk estimates provide one of a number of inputs into judgments on risk acceptability and areas where further reductions in risk might be achieved at reasonable cost. They also enable comparisons with quantitative safety objectives. Knowledge of the uncertainty associated with these risk estimates has an important role in the effective prioritization and allocation of resources and the appropriate use of the results of risk assessments in regulatory activities.

This document describes part of a project designed to assess uncertainties in the MACCS and COSYMA calculations for offsite consequences of radionuclide releases in hypothetical nuclear power plant accidents. The first exercise consisted of uncertainty assessments for atmospheric dispersion and deposition modeling in the accident consequence analysis (ACA) codes.[3] The part of the project reported in this document was designed to elicit from experts uncertainty distributions on important parameters in the code calculations for internal doses. Other reports describe the elicitation of uncertainty distribution variables in other code areas. The elicited distributions will be used in consequence uncertainty analyses using the MACCS and COSYMA codes.

Fairly comprehensive assessments of the uncertainties in the estimates of the consequences of postulated accidental releases of radioactive material have already been made, both in the US and by the European Commission, using predecessors of the MACCS and COSYMA codes (i.e., CRAC-2,[4] MARC,[5] and UFOMOD[6]). Fundamental to these assessments were estimates of uncertainty (or more explicitly, probability distributions of values) for each of the more important model parameters. In each case these estimates were largely done by those who developed the accident consequence codes, as opposed to experts in the different scientific disciplines featured within an accident consequence code (e.g., atmospheric sciences, radioecology, metabolism, dosimetry, radiobiology, and economics). In addition, the underlying uncertainties in the submodels that constitute the consequence codes were addressed only to a limited extent.

The formal use of expert judgment has the potential to circumvent this problem. Although the use of expert judgment is common in resolving complex problems, it is most often used informally and has rarely been made explicit. The use of a formal expert judgment process has the considerable advantages of an improved expression of uncertainty, greater clarity and consistency of judgments, and an analysis that is more open to scrutiny. Formalized expert elicitation methods have been used for other applications. For a short overview, see Harper et al.[3]

In terms of probabilistic nuclear accident analyses, formal expert elicitation methods were used extensively in assessing core damage frequency and radionuclide transport from the melt to the environment in the NUREG-1150[7] study of the risks of reactor operation. The use of these methods was not without criticism or difficulties, but a special review committee[8] judged them to be preferable to the current alternative (i.e., risk analysts making informal judgments).

Formal expert judgment has found increasing use in recent years within the EC. A pilot study[9] in which the techniques were applied to the atmospheric dispersion and deposition module of the COSYMA code acted as a forerunner of the first phase of the current joint project.[3]

1.2 Establishment of Joint European Commission/Nuclear Regulatory Commission Uncertainty Study

In 1991, both the European Commission and the US Nuclear Regulatory Commission (NRC) were considering initiating independent studies to obtain better quantification and more valid estimates of the uncertainties associated with the predictions of accident

consequence codes. The data acquired in such a study were expected to significantly expand the knowledge and understanding of the strengths and weaknesses of current models, providing a basis and a direction for future research. In both cases the formal elicitation of expert judgment was intended to play an important role. Both organizations recognized that (given the similar purpose, scope, and content of both studies) several advantages could be gained from their integration. The primary advantages listed below were identified as reasons for conducting a joint consequence uncertainty study:

1. To combine the knowledge and experience of the EC and US in the areas of uncertainty analysis, expert elicitation, and consequence analysis, and to establish an internationally recognized probability elicitation protocol based on the NUREG-1150 probability elicitation methodology.

2. To gain access to a greater pool of experts. Experts in the areas relevant to consequence calculations are located in both Europe and the United States. A joint project presents an opportunity to identify and use a larger pool of world-class experts than would be available to a project conducted solely by the US or EC.

3. To capture the potentially greater technical and political acceptability of a joint project. Because of the different technical approaches of the two teams, there is an opportunity to consider alternative approaches together and to develop a final product that would be better than either team could produce in isolation.

4. To share project costs. Expert elicitation projects require significant resources because of the staff and outside experts required.

1.3 Objectives

The broad objectives of the NRC and EC in undertaking the consequence code uncertainty study are:

1. To formulate a generic, state-of-the-art methodology for estimating uncertainty that is capable of finding broad acceptance;

2. To apply the methodology to estimates of uncertainties associated with the predictions of probabilistic accident consequence codes (COSYMA and MACCS) designed for assessing the consequences of commercial nuclear power plant accidents;

3. To obtain better quantification and more valid estimates of the uncertainties associated with probabilistic accident 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.

Within these broad objectives, small differences in emphasis exist between the two organizations about the subsequent use of these results. The EC emphasizes the methodological development and its generic application, whereas the NRC is also interested in the potential use of the methods and results as contributions to the regulatory process. This work would complement the NRC-sponsored NUREG-1150 study in which the detailed analysis of uncertainty in risk estimates was confined to uncertainties in the probability, magnitude, and composition of potential accidental releases.

The ultimate goal of the NRC/EC joint effort is to systematically develop credible and traceable uncertainty distributions for the respective code input variables using a formal expert judgment elicitation process. Each organization will then propagate and quantify the uncertainty in the predictions produced by their respective codes.

1.4 Project Development

The primary phenomenological areas included in accident consequence calculations, which were identified as appropriate for consideration by a joint study, are listed in Table 1.1. The areas have been slightly modified since the first phase of the study. Plume rise is no longer considered a primary area. The calculations for countermeasures were considered to be specific for the European countries and the US, and will be not be subjected to a joint expert elicitation exercise.

Atmospheric dispersion and deposition parameters were the focus of the first phase of the study. The results are published in a multivolume main report[3] and an additional report.[10] The overall objective of the first phase was to determine the efficacy and feasibility of the joint effort before spending resources on the additional phenomenological areas (health effects, ingestion pathways, dosimetry, etc.).

Table 1.1 Phenomenological areas for the joint NRC/EC study

Atmospheric dispersion of radionuclides
Deposition of radionuclides
Behavior of deposited material and calculation of external doses
Food chain (soil/plant processes and animal processes)
Internal dosimetry
Early or deterministic health effects
Late or somatic health effects

This report provides the results of the expert judgment exercise on parameters used in internal dosimetry calculations. It had the following project goals:

1. To develop a library of uncertainty distributions for biokinetic parameters, considering both inhalation and ingestion of radionuclides, and their tissue distribution and retention after entry into blood. These data will provide a valuable resource for the calculation of uncertainties in dose coefficients for intakes for radionuclides, for use in MACCS and COSYMA codes and more generally.

2. To present uncertainty distributions on dose coefficients for intakes of selected radionuclides as elicited from experts; these will be compared with uncertainty distributions on dose coefficients as calculated from distributions on biokinetic parameters in a separate publication.

The approach explored in this study was jointly formulated and was based on two important ground rules:

1. The current code models would not be changed because both the NRC and the EC were interested in the uncertainties in the predictions produced by MACCS and COSYMA and in the codes used to provide the associated databases to use the MACCS and COSYMA codes.

2. The experts would be asked to assess only physical quantities that hypothetically could be measured in experiments.

Because of the stricture against modifying MACCS and COSYMA, it was necessary to elicit distributions either over consequence code input variables or over variables from which distributions for code input variables could be developed. In addition, the uncertainty distributions developed were constrained by the flexibility of the fixed models in the consequence codes. If any of the uncertainty distributions contain values prohibited by the fixed models, either the uncertainty distribution needs to be truncated (thereby neglecting part of the uncertainty range provided by the experts) or the fixed models need to be reevaluated.

Eliciting physical quantities avoids possible ambiguity in definition of variables. In addition, elicited variables that are derived from physical parameters have the advantage of not being tied to any particular analytical model and thus have a much wider application.

1.5 Brief Chronology of Joint Effort

May 1995	A kickoff meeting was held in the UK to proceed with three more areas of the study: internal dosimetry, early deterministic health effects, and late health effects.
November 1995	Meetings were held for the internal dosimetry and late health effects panel in Europe and for the early deterministic health effects panel in the United States.
December 1995	An internal dosimetry, early and late health effects expert training meeting was held in Annapolis, Maryland.
February 1996	Videoconferenced elicitation meetings and sessions were held in Brussels and Albuquerque for the internal dosimetry and late health effects panels.
March 1996	Videoconferenced elicitation meetings and sessions were held in Brussels and Albuquerque for the early deterministic health effects panels.

1.6 Structure of Document

This report summarizes the achievements of the joint effort for the internal dosimetry panel. Section 2 dis-

cusses the technical issues that were considered prior to the actual expert elicitation process. Section 3 provides a short characterization of consequence uncertainty studies, briefly describes why uncertainty information is necessary for decision making, summarizes the MACCS and COSYMA codes, describes the process used for selecting the variables that were assessed, explains why formal expert elicitation methods were chosen, and delineates the scope of the project.

Section 3 summarizes the methods used to acquire the distributions for the elicitation variables and to process the distributions into a form usable by MACCS and COSYMA. The results are summarized in Section 4 and the conclusions are presented in Section 5.

Volume 2 of this report contains the technical appendices. Appendix A contains a summary of the MACCS and COSYMA consequence codes. Appendix B contains the case structure and the elicitation questionnaire. Appendix C contains the rationales and responses of the expert panel. Appendix D contains short biographies of the experts and Appendix E contains their aggregated results.

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2. Technical Issues Considered Relevant

2.1 Introduction

Uncertainty analysis with respect to potential public risks from nuclear power installations was introduced into a broad decision-making context with the Reactor Safety Study (WASH-1400).[1] Although the technique has undergone considerable development since this study, the essentials have remained unchanged. The intent of uncertainty analysis is to estimate the uncertainty in the output of quantitative decision support modeling in order to provide the decision maker with a measure of the robustness or accuracy of the conclusions based on the model. To accomplish this, distributions are placed on the input variables of models and propagated through the model to yield distributions on the model's output.

Uncertainty analysis is performed in situations in which the uncertainties in model predictions have the potential to significantly affect the decision-making process and when "stakeholders" have differing interests and perceptions of the risks and benefits of possible decisions. There is no formula dictating how the results of quantitative models should be used to support such decision making; hence, there can be no formula for the use of uncertainty analyses either. Rather, uncertainty analysis provides a tool that stakeholders can use to express both negative and positive opinions. In this sense, it can contribute to a rational discussion of proposed courses of action. As a collateral benefit, it provides a perspective for assessing the quality of the quantitative decision-support modeling and can help direct resources for reducing uncertainties in the future.

Uncertainty analyses using expert elicitation techniques have been done primarily for Level 1 (core damage frequency assessment) and Level 2 (assessment of radionuclide transport from the melt to the environment) portions of reactor risk assessments. For the Level 3 (consequence analysis) portion of the risk assessments, uncertainty and sensitivity analyses have primarily consisted of parametric sensitivity studies in which the uncertainty distributions of the code input variables are estimated by code developers and not by experts in the different scientific fields of interest.

This section briefly summarizes the types of uncertainties and describes the need for uncertainty analyses in decision making. It also sketches the methods and issues that arise in carrying out an uncertainty analysis for accident consequence models.

2.2 Types of Uncertainty

The NRC Probabilistic Risk Analysis (PRA) Working Group[2] has defined two types of uncertainty that may be present in any calculation. These are (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 phenomena. The latter may be further divided 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 considered.

An example of stochastic uncertainty is the natural variability in the dimensions of animals or plants. Parameter uncertainty arises because we rarely know with certainty the correct values of the code input variables. Moreover, this lack of knowledge contributes also to modeling uncertainty. Models of physical processes generally have many underlying assumptions and are not valid for all cases. Alternative conceptual and mathematical models are proposed by different analysts. Completeness uncertainty is similar to modeling uncertainty, but occurs in the stage of adequate identification of the physical phenomena.

A common method of uncertainty analysis is based on the propagation of a distribution over an input variable, rather than a point value. In the past, distributions over code input variables have typically been estimated by code developers, with informal guidance from phenomenological experts in the appropriate field. The resulting distribution over the model output provides insight regarding the impact of uncertainty in input variables on model predictions.

2.3 Use of Uncertainty Analyses for Decision Making

Section 2.3 of Volume 1 of the main report on atmospheric dispersion and deposition[3] briefly describes the history of consequence uncertainty analyses. The US and European developments are sketched and summarized as lessons learned from past uncertainty analyses.

The use of uncertainty analyses in decision-making processes is required when some or all of the following conditions occur:

- Decision making is supported by quantitative model(s),
- The modeling is associated with potentially large uncertainties,
- The consequences predicted by models are associated with costs and benefits in a nonlinear way (such as threshold effects),
- The choice between alternative courses of action might change as different plausible scenarios are fed into the quantitative models, and
- The scenarios of concern are low-probability, high-consequence events.

In the context of most current regulatory decision making, the full problem is not dealt with. The regulatory authority is typically charged with regulating the risks from one type of activity. The choice between alternatives is made at a different level, where the trade-off of benefits against costs to different stakeholders is factored in. It is, nonetheless, incumbent upon the regulatory authority to provide such information as is deemed necessary for responsible decision making. Nuclear regulatory agencies have pioneered the use of uncertainty analysis and continue to set the standards in this field.

Accident consequence codes compute many quantities of interest to the decision maker, including time-varying radiation levels over a large spatial grid, numbers of acute and chronic fatalities, number of persons evacuated, amount of land lost to use, and economic and environmental damage. In the "point value" mode of calculation, the consequence codes compute distributions over the quantities that result from uncertainty in meteorological conditions at the time of the accident. In performing a full-scope uncertainty analysis, distributions over code variables other than those related to weather are generated for each quantity.

The question of how best to compress the information into a form that can be used by decision makers requires considerable attention. In some applications of the information, it may be important for the decision maker to distinguish stochastic uncertainty resulting from variation in meteorological conditions or other sources from state-of-knowledge uncertainty in code variables. Stochastic uncertainty is here to stay, whereas state-of-knowledge uncertainty may change as knowledge grows; distinguishing between stochastic and state-of-knowledge uncertainty could be helpful in setting research priorities. In allocating future research resources, it is important to know the contribution of each variable's uncertainty to the overall risk uncertainty, and to identify those variables for which uncertainty can be significantly reduced by future research efforts.

2.4 Brief Description of the Treatment of Dosimetry for MACCS and COSYMA

Doses are calculated within ACA codes either for presentation as an endpoint of the assessment or for use in further calculations of health effects. Both individual and collective doses can be evaluated and include external exposures and internal exposures from the inhalation and ingestion of radionuclides. Doses are generally calculated for an average adult member of the population although age-dependent doses and doses to members of critical groups can be calculated using more detailed models.

Material can be inhaled either directly from the radioactive cloud as it passes overhead, or following resuspension of material that has been deposited. This second pathway can lead to intakes over prolonged periods of time. Inhalation doses are calculated as the product of the inhalation rate, the time-integrated air concentration, and dose per unit activity inhaled.

Ingestion doses are calculated from the amount of activity deposited, the concentration of material in different food types for unit deposition, the consumption rate, and the dose per unit activity ingested.

ACA codes use precalculated values of dose per unit intake by either inhalation or ingestion (dose coefficients) for exposure of adults and children of different ages to all radionuclides of conceivable concern. The values used are those published by the International Commission on Radiological Protection (ICRP), the internationally recognized source of models for the calculation of inhalation and ingestion dose coefficients. The ICRP values provide the basis of legislation in Europe and the United States.

Uncertainties in calculated dose coefficients for intakes of radionuclides depend on uncertainties in biokinetic parameters and in calculations of absorbed dose in tissues. A brief outline of the principal parameters likely to influence dose is given below.

2.4.1 Inhalation

For inhaled radionuclides, it is important to estimate total deposition in the respiratory tract, distribution among the different regions of the tract, removal by mechanical clearance, and dissolution and entry into blood.

Intake per unit exposure will depend on ventilation, breathing frequency, and tidal volume, which will change according to the level of exercise and may differ appreciably between children and adults. Ventilation may also influence total deposition and the distribution of deposited material.

A major factor determining total deposition and distribution within the respiratory tract is the particle size of the inhaled material. The respirable range is taken to be from an activity median thermodynamic diameter (AMTD) of 6 nm to an activity median aerodynamic diameter (AMAD) of 100 μm. In general, a greater proportion of larger particles deposit in the upper airways of the nose and throat. Conversely, a greater proportion of smaller particles reach the alveolar region of the lung, with variable fractions depositing in the bronchiolar airways.

Removal of material from the respiratory tract by mechanical clearance includes nose blowing and escalation of particles from the lungs. Escalated material is normally swallowed and enters the gastrointestinal tract. As a competing process, material from the lungs is subject to dissolution, the rate depending on the chemical characteristics of the material.

2.4.2 Ingestion

For ingested materials, the main factors determining radiation dose will be the rate of movement of material through the different regions of the gastrointestinal tract and the proportion absorbed and transferred to blood. There is good evidence that absorption of many elements and their radioisotopes will be increased in newborn infants and in some cases may also be higher during later childhood than in adulthood.

2.4.3 Behavior of Systemic Radionuclides

For radionuclides reaching blood, the distribution among tissues and the duration of retention need to be taken into account. In some cases, distribution within individual tissues may be important. Distribution and retention in the body may be age dependent and in general retention half-times tend to be shorter at younger ages.

Some radionuclides are retained at similar concentrations throughout body tissues, and uniform distribution can be assumed; this applies, for example, to cesium isotopes. Other radionuclides concentrate in a specific organ or tissue, as is the case for isotopes of iodine accumulating in the thyroid gland.

For radionuclides for which the skeleton is a significant site of retention, behavior within bone may need to be taken into account. Thus, a number of elements deposit initially on bone surfaces but differ in the rate at which they are subsequently transferred within the volume of bone mineral. For example, the alkaline earth element, strontium, behaves similarly to calcium and while it is initially deposited on bone surfaces, it progressively transfers to bone volume. In contrast, the actinide element, plutonium, deposits initially on bone surfaces, and subsequent burial within bone depends on bone growth in the region of deposition. Bone resorption on surfaces with plutonium deposits may lead to transfer to bone marrow. Such differences in behavior are important because they can affect the dose received by sensitive cells; the target for osteosarcoma induction is thought to be cells near bone surfaces, and leukemia is thought to arise from cells distributed within red bone marrow.

2.4.4 Radiation Dose

When the distribution of activity in different organs or tissues is known, the resulting distribution of the

absorbed energy and absorbed dose, defined as absorbed energy per unit mass, can be calculated. For nonpenetrating radiations, in most cases energy will be deposited largely in the tissue in which the radionuclide is deposited. For penetrating radiations, however, it is necessary to take account of cross-fire between tissues. This is done using a "mathematical phantom" that describes the geometric relationship between the different tissues and organs of the body (i.e., a phantom that can be described with simple mathematical equations). Such phantoms have been developed for different ages. Different mathematical methods, including Monte Carlo techniques, may then be used to calculate the absorbed dose in a given organ from decays taking place in the same or another organ, making the assumption that the radionuclides in the source regions are homogeneously distributed. Absorbed dose in a tissue or organ is expressed in units of grays (1 Gy = 1 J kg^{-1}).

2.5 Selection of Variables for Presentation to Formal Expert Elicitation Panels

During the selection of the elicitation variables, it was necessary to consider the two ground rules of the methodology: (1) The current codes (MACCS and COSYMA) could not be modified to facilitate the uncertainty studies, and (2) the experts would only be asked to assess parameters that could (in principle) be determined experimentally (observable quantities).

Because accident consequence codes operate using precalculated organ dose coefficients (Gy Bq^{-1} ingested or inhaled), it was necessary to decide whether to select parameters that are (1) the basic input data for the calculation of organ doses, or (2) the input to the ACA codes (organ dose coefficients).

To fulfill the requirement of the second ground rule, elicitation parameters were selected that represent input data for the calculation of organ dose coefficients. Thus, the experts were asked to address measurable quantities such as deposition of inhaled material in the respiratory tract at different times after inhalation and absorption of ingested radionuclides. Consideration was also given to possible correlation between parameters. For example, the level of retention of a radionuclide in one organ might be negatively correlated with retention in another organ.

By addressing biokinetic parameters, the information obtained would be applicable to different modeling approaches rather than apply specifically to current internal dosimetry models. Additional effort would be required to process the data obtained to determine uncertainties in organ absorbed doses, the ACA code inputs. However, this work would provide valuable information on the relative importance of contributory uncertainties associated with individual input parameters.

Although the majority of questions asked of the experts related to uncertainties on measurable input parameters, the experts were also invited to assess uncertainties in organ dose coefficients for selected radionuclides in a final question. For some of the radionuclides addressed, this exercise would have involved some degree of numerical analysis of constituent uncertainties. The distributions obtained will be compared with uncertainty distributions on dose coefficients as calculated from distributions on biokinetic parameters in a separate publication.

The number of parameters used to calculate doses to body tissues after inhalation or ingestion of a range of radionuclides by adults and children of different ages is potentially very large. Parameters considered to be the most important were selected on the basis of information from previous sensitivity analyses and further evaluation of the processes involved. A further substantial reduction in the number of questions resulted from input from the expert panel.

2.6 Formal Expert Judgment Methods

The panel on internal dosimetry and related doses used the same formal expert judgment method as the atmospheric dispersion and deposition panels. The reasons are further specified in Section 2.8 of the main report on atmospheric dispersion and deposition.[3]

2.7 Scope of Analysis

It was important that the scope of the problem to be assessed be clearly defined for the experts to avoid inconsistencies of response on the basis of differing assumptions. Many general assumptions were straightforward. Thus, the experts were asked to consider average individuals representative of the group under consideration. For both inhalation and ingestion, the experts were asked to consider chemical

forms which they considered most likely to be encountered after a lightwater reactor accident. Table 2.1 shows the scope of the analysis.

2.8 References

1. NRC (US Nuclear Regulatory Commission), Reactor Safety Study—An Assessment of Accident Risks in US Commercial Nuclear Power Plants, WASH-1400 (NUREG-75/014), Washington, DC, October 1975.

2. NRC (US Nuclear Regulatory Commission), PRA Working Group, A Review of NRC Staff Uses of Probabilistic Risk Assessment, NUREG-1489, Washington, DC, March 1994.

3. Harper, F.T. et al., Probabilistic Accident Consequence Uncertainty Analysis, NUREG/CR-6244, EUR-15855EN, SAND94-1453, Vol. 1, Sandia National Laboratories, Albuquerque, NM, 1995.

Table 2.1 Examples of treatment of phenomenological uncertainty

Uncertainty is handled through specification of initial conditions (case structure). This uncertainty is not addressed in distributions.	**Uncertainty is addressed quantitatively in distributions.**	**Out of project scope: not to be considered in uncertainty distributions or in case structure.**
Inhalation due to exposure to air concentrations - 1 Bq m^{-3} for 1 min Ingestion - single intake Particle size Age at intake Chemical form of intake[a]	Health status of population group Ventilation rates Deposition in regions of the respiratory tract (hygroscopic growth) Particle clearance Chemical form of intake[a] Absorption to blood after inhalation Absorption to blood after ingestion Tissue distribution and retention of elements Distribution within skeleton - Pu	Location of sensitive cells in different regions of the respiratory tract, gut, skeleton and other tissues[b] Radiation transport[b]

[a]Information was given on assumptions to be made regarding chemical form of intakes. However, this information was necessarily imprecise and distributions on absorption to blood would include uncertainties associated with lack of knowledge on chemical form.

[b]Assumptions regarding the location of sensitive cells and radiation transport were implicit in the estimated distributions provided by the experts for organ dose coefficients.

3. Summary of Expert Elicitation Methods for Internal Dosimetry Panel

3.1 Introduction

This section summarizes the joint methodology used to develop uncertainty distributions for the consequence calculations in this project. It is a combination of methods from previous US and EC studies as well as methods developed specifically for this project. Table 3.1 summarizes some of the major contributions to the joint methodology from previous US and EC studies and Figure 3.1 summarizes the methodology. The definition of goals and philosophies for uncertainty assessment, the prioritization of the consequence code input parameters, and the selection of the code input variables to be addressed were accomplished prior to the initiation of the joint project as a whole and are discussed in Section 2 of this document. This chapter reviews the methodology specifically as it pertains to the development of distributions over biokinetic parameters for inhaled and ingested radionuclides which provide input data for the calculation of dose coefficients used in MACCS and COSYMA codes.

3.2 Definition of Elicitation Variables and Case Structures

Elicitation variables are the variables presented to the experts for assessment. They were asked to provide distributions over variables within a set of initial and boundary conditions. Each set of conditions was termed a "case." The ensemble of all cases for the elicitation variable was termed the "case structure." The primary consideration in developing elicitation variables, cases, and case structures was the importance of designing elicitation questions that were not dependent on specific analytical models.

It was the responsibility of the probability elicitation team to develop elicitation variables that were physically measurable parameters (rather than eliciting on a fitted exponent having no interpretation in terms of the underlying mechanisms). This constraint was imposed so that there would be no ambiguity when the elicitation variables were defined. If the experts assess poorly defined variables, the potential for incompatible assessments is high. Also, assessments on physically measurable parameters are not inherently dependent on any given theoretical model and therefore may be developed from a combination of relevant information sources.

As discussed earlier, the uncertainties addressed were those considered to be of greatest importance in assessing overall uncertainties in organ doses after inhalation or ingestion of the selected radionuclides. The case structure was developed with the objective of providing a data library of uncertainty distributions that can be used for different analyses.

Table 3.1 Contributions to the joint methodology from US and EC studies

Contributions from previous US studies	Contributions from previous EC studies
Philosophy of choosing high-quality experts and paying them	Ready-made processing methodology and software for dispersion and deposition
Formal elicitation protocol developed for NUREG-1150	Concept of elicitation on variables that can be conceived as being experimentally observable
Probabilistic training and help in encoding probabilities during elicitation session for experts	Techniques for assessing performance of experts in encoding probabilities
Aggregation techniques using equal weighting for experts	

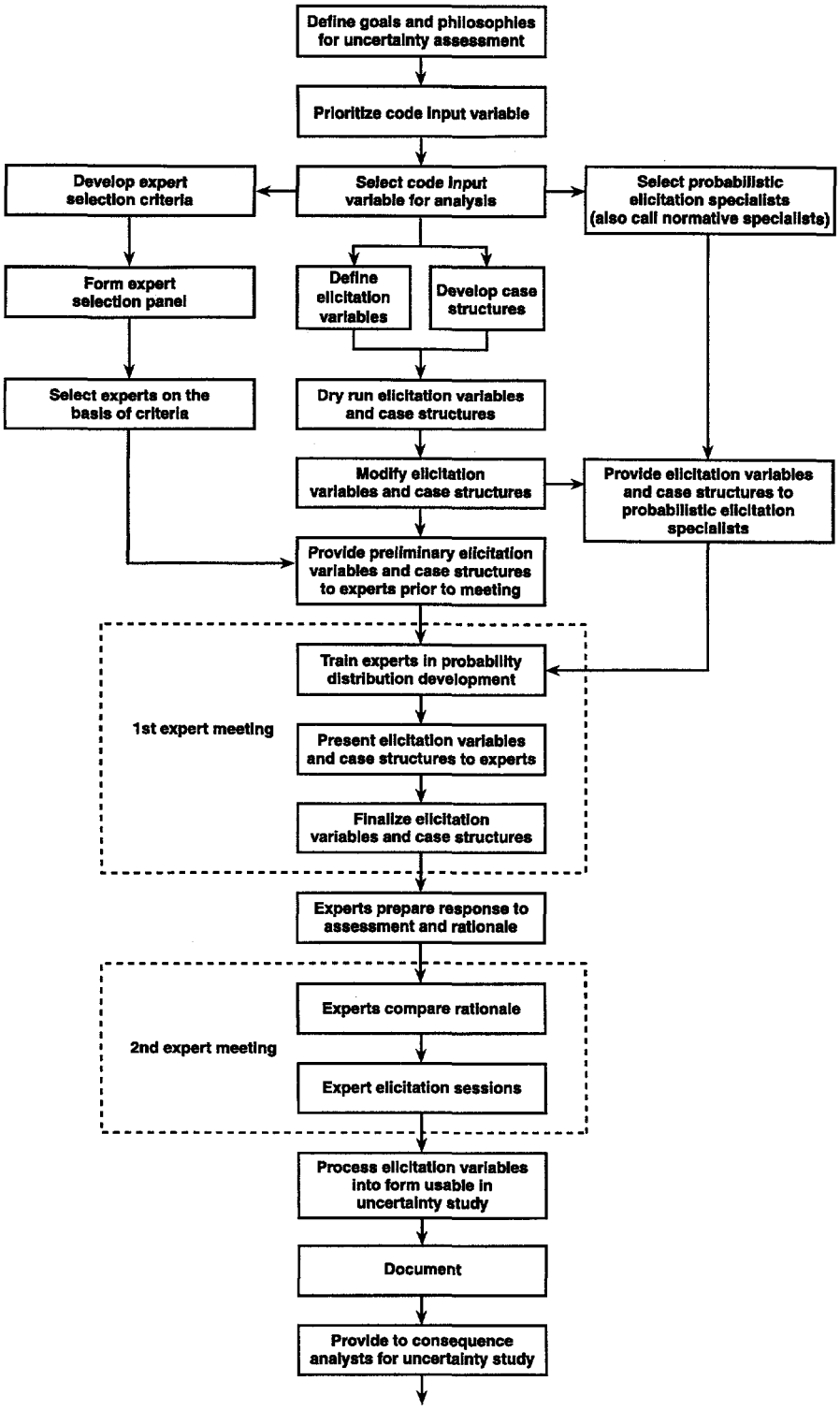

Figure 3.1 Sequence of methods used to develop the uncertainty distributions. Due to programmatic constraints, the EC and the US experts held separate first expert meetings; however, some project staff attended both European and American meetings. The EC and US groups communicated through a teleconference in a joint second meeting.

The main areas in which elicitation questions were framed were

1. Inhalation
2. Ingestion
3. Systemic distribution and retention
4. Organ dose coefficients

While the first three provide information from which dose coefficients can be calculated and are in principle measurable quantities, organ dose coefficients are the required input to ACA codes and are generally not directly measurable or observable quantities.

3.2.1 Inhalation

The questions covered important contributions to uncertainty in calculating doses from inhaled radionuclides, considering the behavior of materials in the respiratory tract.

The experts were asked to consider exposure to unit air concentration of radioactive aerosols (say, 1 Bq m^{-3}) for a short duration (say, 1 minute). The questions addressed parameters primarily for adults but with additional information sought for 5-year-old children. The parameters elicited were

- ventilation rates, assuming a normal daily mix of activities (combined male and female average);
- total initial deposition in the respiratory tract as percent inhaled, assuming a normal daily mix of activities, for particle sizes 0.1, 1, and 10 μm AMAD;
- distribution of deposited material, as percent deposited, 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 as percent of total initial deposition, assuming completely insoluble particles, at times from 10 minutes to 10 years after deposition;
- absorption by blood as percent of total initial deposition for Sr, I, Cs, Pu, Ru, Ce and Te, at times from 1 hour to 10 years after deposition, assuming 1 μm AMAD oxide particles apart from I in elemental form.

Questions on the distribution of particles deposited among the three regions were formulated to provide some information on correlations. Thus, the first question on distribution asked for deposition in the extrathoracic region, allowing total deposition in the lung (thoracic region) to be obtained from the total initial deposition. Distribution within the lung was then elicited by asking for deposition in the tracheobronchial region, allowing pulmonary deposition to be determined from total thoracic deposition.

In considering the mucociliary clearance of particles, complete insolubility was specified so that only this process would be addressed rather than the physiological situation of competing particle clearance and dissolution. Experimental data on particle clearance are from studies using insoluble particles.

In considering dissolution, it was particularly important to specify the chemical form of the intake. In the absence of this information, uncertainties in absorption by blood would be dominated by differences in chemical form. The usual assumption has been that elements would be inhaled in oxide form, apart from iodine, which is assumed to be in elemental form.

Factors omitted that might also contribute significantly to uncertainties are the location of sensitive cells in different regions, the relative radiosensitivity of the different regions, and tissue mass and geometric considerations.

3.2.2 Ingestion

Elicitation was limited to absorption to blood as a fraction of total ingested for Sr, I, Cs, and Pu, by 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. For Pu, separate questions were asked for intakes as a refractory oxide and Pu in biologically incorporated form in food. Experts were asked to consider a single intake involving ingestion of 1 Bq.

Factors omitted that might also contribute significantly to uncertainties were gut transit times, doses to sensitive cells from activity in gut contents, particularly for alpha emitters, retention in intestinal tissue, and tissue mass and geometric considerations.

3.2.3 Systemic Distribution and Retention

These questions covered important contributions to uncertainty in calculating doses from radionuclides reaching blood. The elements were grouped according to biokinetic similarities.

For strontium, plutonium, cerium, and tellurium, the questions were:

- total retention in the liver and skeleton, as percent of total reaching blood, at times from 1 day to 50 years after entry to blood;
- distribution between the liver and skeleton at times from 1 day to 50 years after entry into blood;

and for plutonium only:

- distribution within the skeleton, on endosteal and trabecular bone surfaces and in red bone marrow, at times between 1 day and 50 years after administration.

Questions on the distribution of elements between liver and skeleton and the distribution of plutonium within the skeleton were formulated to provide some information on correlations. Thus, retention in the skeleton was elicited as percent of total retention in liver + skeleton. For Pu distribution within the skeleton, the first question was retention on endosteal bone surfaces as percent of total skeletal retention, and the second was retention on trabecular surfaces as percent of total endosteal retention.

For ruthenium and cesium, the information elicited was whole-body retention, as percent of the total reaching blood, at times from 1 day to 5 years after entry into blood.

For iodine, retention in the thyroid was elicited, as percent reaching the blood, at times from 1 day to 3 months after entry into blood.

In considering the systemic distribution and retention of elements, factors omitted that might also contribute significantly to uncertainties were the location of sensitive cells in bone, absorbed fractions for alpha- and beta- emitting bone-seekers, and tissue mass and geometric considerations. In each case, experts were asked to consider the behavior of the elements and take no account of the radioactive half-lives of isotopes.

3.2.4 Dose Coefficients

Inhalation and ingestion dose coefficients represent ACA code inputs. Uncertainties will include dosimetric modeling considerations as well as the parameters considered above.

The information elicited was absorbed organ doses per unit intake, committed doses to 70 years of age (Gy Bq^{-1}). For inhalation, 1 μm AMAD particles were specified except in the case of ^{131}I and ^{132}Te, for which a mixture of 1 μm AMAD particles and vapor was specified, and experts were asked to determine the proportions. The radionuclides for which both inhalation and ingestion were considered were ^{90}Sr, ^{131}I, ^{137}Cs, and ^{239}Pu. Inhalation only was considered for ^{132}Te and ^{144}Ce. In each case, the most important organ or organs were specified.

3.3 Expertise Required for the Elicitation Process

The design for the probability elicitation sessions in this study was taken from the methodology developed for the NUREG-1150 study. This design includes an elicitation team composed of the phenomenological experts whose judgments are sought, a normative specialist who manages the session, and a substantive assistant from the project staff who aids communication between the expert and the specialist and helps answer questions about the assumptions and conditions of the study.

The normative specialist is an expert in probability elicitation whose role is to ensure that each expert's knowledge is properly encoded into probability distributions. To accomplish this, the specialist must be alert to the potential for biases in forming judgments. The specialist also tests the consistency of judgments by asking questions from various points of view and checking agreement among the answers. Another role is ensuring that the expert expresses rationales for the judgments and is able to substantiate any assumptions that are made. Along with the phenomenological expert, the normative specialist ensures that the distributions are properly recorded and annotated to curtail ambiguity in their meanings.

The substantive assistant brings knowledge of project assumptions and conditions to the study. The role of this participant is to promote a common understanding of the issues and to clarify and articulate how the data will be interpreted in the modeling activities.

This team member also assists the experts with documentation of rationales.

3.3.1 Selection of Phenomenological Experts

The project staff sought to engage the best experts available in the fields of radionuclide biokinetics and internal dosimetry who were willing to undertake the task. Experience in the NUREG-1150 study and elsewhere has shown that the selection of experts can be subjected to much scrutiny. Thus, it was necessary to construct a defensible selection procedure. The selection procedure for this study involved the following:

1. A large list of experts was compiled from the literature and by requesting nominations from organizations familiar with the areas.

2. The experts were contacted and curriculum vitae (CVs) were requested.

3. Two selection committees that included members both external and internal to the project, one in the EC and one within the US, were established and charged with expert selection based on a common set of criteria. These included:

   Reputation in the relevant fields,
   Number and quality of publications,
   Familiarity with the uncertainty concepts,
   Diversity in background,
   Balance of viewpoints,
   Interest in this study,
   Availability to undertake the task in the time prescribed.

The result was a panel of internationally recognized scientists, three of whom were from the US and six of whom were from Europe (see Table 3.2). Brief biographies are provided in Volume 2.

3.3.2 Selection of Normative Specialists

Normative specialists were responsible for managing the elicitation sessions. These specialists came from various fields such as psychology, decision analysis, statistics, or risk and safety analysis. The characteristic that distinguishes them is familiarity with the methods and literature for probability elicitation, and experience in applying these methods. Normative specialists must be able to manage the elicitation sessions by providing assistance in developing and expressing quantitative judgments.

Table 3.2 Internal dosimetry experts

Michael Bailey	UK
Keith Eckerman	US (jointly with Leggett)
Anthony James	US
Richard Leggett	US (jointly with Eckerman)
Ilya Likhtarev	Ukraine
Henri Métivier	France
Dietmar Nosske	Germany
Nick Priest	UK
David Taylor	UK

Four normative specialists were used in this study. Three of them (Dr. Goossens, Dr. Hora, and Mr. Kraan) were part of the project staff. They were supplemented by an additional specialist, Dr. Detlof von Winterfeldt, who was a participant in the NUREG-1150 study and is internationally known in the field of decision analysis. He has served as a consultant on many projects involving expert judgment elicitation. Drs. Goossens and Hora have extensive experience in probability elicitation. Dr. Goossens has managed a number of studies involving expert judgment for the safety institute at TU Delft and Dr. Hora was a key participant in the NUREG-1150 expert elicitation activities.[1] Mr. Bernd Kraan of TU Delft is experienced in probability elicitation (and processing) of expert judgments.

3.4 Expert Elicitation

The expert elicitation process consisted of the following activities:

1. Dry run elicitation. A dry run elicitation was conducted with an internal dosimetry expert recruited from the National Radiological Protection Board (NRPB) in the UK to test the methodologies to be used in the actual expert elicitation meetings and to evaluate the case structures.

2. First expert meetings. The purpose of these meetings was to train the experts in providing their judgments in terms of probability distributions and to present the technical problems to be assessed.

3. Expert prepares assessment. The expert prepared his or her assessment of the problems posed in the first meeting. The expert also prepared to provide the staff with the rationale behind his or her distributions in written form before leaving the second meeting. Requirements on the form of the written rationale were provided.

4. Second expert meeting. The second expert meeting was conducted approximately 2 months after the first expert meeting, to jointly share the rationale with all internal dosimetry panel experts and to elicit from each expert the required distributions of the elicitation variables.

3.4.1 Dry-Run Elicitation

The dry-run meeting was conducted in November 1995 with an internal dosimetry expert, Dr. Michael Bailey, from the NRPB. The meeting began with a short introduction to the training in probability elicitation. The training focused on the meaning of subjective probabilities, the structure of formal expert judgment processes, biases in probability formation, and practice in expressing judgments as probabilities. The draft case structure document and elicitation questionnaires were handed out prior to the dry-run meeting. The dry-run expert was not asked to prepare quantitative responses to the questions, but was requested to judge the merits of the questions, to detect possible ambiguities in the questionnaires, and to indicate the relevance of the questions in general, not related to the ACA codes in particular. The case structures and questionnaires to be presented to the experts in the first meeting were prepared according to the lessons learned in the dry run.

3.4.2 First Expert Meeting

At the first meeting, held December 11-13, 1995 in Annapolis, Maryland, a brief description of the process and the elicitation questions were provided to the experts. Reading this description was the only preparation necessary for this meeting. The experts were introduced to the purposes of the study, including how their judgments were to be used. They were given the case structures, a clear definition of the variables to be assessed, and a description of how the information they provided would eventually be used by the project staff. The experts were also introduced to background material on consequence codes and the science of probability elicitation. This required the distribution of materials explaining the consequence area, the relation of the questions posed to the parameters in the model, and the specific initial conditions and assumptions to be used in answering the elicitation questions.

Training was conducted to introduce the experts to psychological biases in judgment formation and to give them feedback on their performance in assessing probability distributions. In the NUREG-1150 study, feedback was provided to the experts by measuring their performance on the development of probabilistic distributions for training variables. In that study, the training variables were nontechnical, almanac-type questions for which the answers were known. In the current study, performance was measured by querying the experts about variables whose true values are uncertain for the experts but known to project staff from actual experiments. These training variables were chosen to resemble the variables of interest as closely as possible.

3.4.3 Preparation of the Distributions

Following the first meeting, the experts typically spent 1 to 2 weeks preparing responses to the elicitation questions and at the same time prepared a statement describing their information sources and presenting the rationale for the distributions. The experts were encouraged by project staff to use whatever modeling technique or experimental results they felt appropriate to assess the problems. The only constraints placed on them were that: (1) the initial conditions had to be defined at the same level of detail as the internal code model (i.e., uncertainty due to lack of detail in the initial conditions had to be included in the uncertainty distributions provided) and (2) the rationale behind the distributions had to be thoroughly documented.

3.4.4 Second Expert Meeting: Elicitation

A joint videoconferenced meeting was held on February 29, 1996, followed by individual elicitation sessions. During the videoconference, held in Brussels and Albuquerque, a common session was conducted at which the experts presented the technical approach and rationale behind their assessments. No distributions were provided in these sessions to avoid biasing the other experts. The elicitation of each expert took place privately with a normative specialist and a substantive assistant. In both cases, the experts were allowed to change their elicitation results at any point.

The interviews allowed for significant interaction between the assessment team and the expert in the encoding of probabilities.

3.5 Mathematical Processing of Elicited Distributions

At the end of the elicitation sessions, the project staff had from each expert the 5th, 50th, and 95th percentile values from the cumulative distribution of each elicited variable for each case structure. It was the responsibility of the project staff to aggregate the individual expert distributions (5th, 50th, and 95th percentile values) for each elicitation variable for each case structure into a single cumulative distribution for each elicitation variable for each case structure. For the questions on biokinetic parameters for the inhalation and ingestion of radionuclides and for systemic behavior, further mathematical processing is required to determine the resulting distributions on organ dose coefficients.

3.5.1 Aggregation of Elicited Distributions

The processing tool for combining expert assessments was the computer code EXCALIBR.[2] Inputs for EXCALIBR were percentile assessments from experts for query variables (elicitation variables). A cumulative distribution function (CDF) was associated with the assessments of each expert for each query variable in such a way that (1) the cumulative probabilities agreed with the expert's percentile assessments, and (2) the cumulative probabilities were minimally informative with respect to the background measure, given the percentile constraints. The background measures were either uniform or loguniform, depending on the magnitude of the range factor band for the variable as elicited from the experts. (Throughout this study, the term "range factor" is used to express the ratio between the 95th and 5th percentiles of the distribution, and is used as a measure of uncertainty.) For each variable, non-negative weights summing to one were assigned to the CDFs developed for the individual expert assessments, and the aggregation was accomplished by taking the weighted sums of the cumulative probabilities for each variable obtained through an equal-weighting aggregation scheme. EXCALIBR output the 5th, 50th, and 95th percentiles and percentiles from the combined CDF for each variable.

In an equal-weighting aggregation scheme, an equal weight is assigned to each expert. If N experts have assessed a given set of variables, the weights for each density are $1/N$; hence for variable i in this set the decision maker's CDF is given by:

$$F_{ewdm,i} = (1/N)\sum_{j=1}^{N} f_{j_i}$$

where f_{j_i} is the cumulative probability associated with expert j's assessment for variable i.

Investigating the different weighting schemes was not the objective of this joint effort. A decision was therefore made within the program to assign all experts equal weight (i.e., all experts on each panel were treated as being equally credible). One of the primary reasons the equal-weighting aggregation method was chosen for this study was to ensure the inclusion of different modeling perspectives in the aggregated uncertainty distributions. The implications of different weighting schemes are discussed elsewhere.[3]

3.5.2 Combining Dependencies

It has long been known that significant errors in uncertainty analysis can be caused by ignoring dependencies between uncertainties.[3] New techniques for estimating and analyzing dependencies in uncertainty analysis have been developed in the course of the joint EC/NRC accident consequence uncertainty analysis. The best source of information about dependencies is often the experts themselves. The most thorough approach would be to elicit directly the experts' joint distributions. The practical drawbacks to this approach have forced analysts to look for other dependency elicitation strategies. One obvious strategy is to ask experts to directly assess a (rank) correlation coefficient. However, even trained statisticians have difficulty with this type of assessment task.[4] Within the joint EC/NRC study, a new strategy[5] has been employed for eliciting dependencies from experts.

3.6 References

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4. Results and Analysis

4.1 Introduction

This section summarizes the experts' responses to the elicitation meetings and includes a selection of the elicited data and the aggregated elicited distributions.

4.2 Summary of Elicitation Meetings

Three different meetings were conducted relating to the actual elicitation exercise. This section reviews the responses of the experts to the project materials and the methods presented during the elicitation meetings.

4.2.1 Dry Run Elicitation Meeting

The robustness of the basic expert elicitation methodology developed for this project was validated by the dry-run exercise; however, several important issues were raised and subsequently evaluated as a result of the dry run. The main issue raised was the need to reduce the number of elicitation questions in the questionnaire by: (1) limiting the number of questions on different age groups and (2) significantly reducing the number of nuclides.

4.2.2 Summary of First Expert Meetings

A joint meeting was held for the European and US experts in Annapolis, Maryland, on December, 11-13, 1995. The meeting was held jointly with the experts for the late health effects panel and the early health effects panel. The initial reception of the project by the experts was excellent. The experts expressed their interest in the prospect of addressing uncertainty in their field of expertise. After the probabilistic training exercise, the elicitation variables and the case structure were presented and discussed.

In the training meeting, the issues regarding internal dosimetry were discussed and several changes to the definition of the elicitation variables and the case structure were agreed upon. Following the meeting, some of the questions were further rephrased to address the issues raised by the experts, and the experts were sent a final version of the case structure and elicitation variables shortly afterward.

A number of experts were unhappy with the amount of work that would be required to adequately address all of the questions posed in the case structure. The scope was reduced during the meeting mainly by reducing the number of elements and age groups considered, but also by removing questions on some of what were considered to be the least important parameters (e.g., gut transit times).

An issue identified as of particular importance was the chemical form of intake of radionuclides. Project staff undertook to provide additional information and guidance on this question.

4.2.3 Summary of Second Expert Meeting

All experts except two were present at the joint video-conference session. At this session, the experts presented the approach they had taken to answering the questions posed but did not discuss their probability assessments in order to avoid biasing the other experts. The issue of anonymity was discussed and it was agreed to preserve the anonymity of the experts. The remainder of the meeting consisted of individual expert elicitation sessions. The initial common session was videotaped.

All experts expressed the view that they would have preferred more time to undertake the considerable amount of work entailed. A number of experts chose to answer subsets of the questions with which they were more familiar; this applied to Michael Bailey, who concentrated on inhalation and the respiratory tract; and Nick Priest, who concentrated on systemic distribution and retention. Rich Leggett and Keith Eckerman chose to answer all questions, but as a joint response.

The basic approach of all experts was similar but their reliance on and adherence to ICRP values for central estimates varied. Access to basic data varied. The greatest difference in their handling of the data was in access to mathematical models with which to analyze the effect of varying parameter assumptions.

4.3 Summary of Individual Expert Assessments

Representative results are summarized and discussed in this section. The figures are presented at the end of the chapter so as not to interrupt the flow of the text. The complete set of expert rationales and the elicited distributions are published in Appendix C in Volume 2 of this report. In this section, the figures plot some of the elicited results along with the results of the equal-weighted aggregation of the elicited distributions. The figures use the numbers 1 to 8 to indicate the results of different experts while Appendix C uses the letters A through H. There is no correlation between the two systems. This section discusses individual assessments and aggregated results. Aggregation employed equal weighting of the individual elicited distributions. The performance-based method developed at Delft University of Technology[1,2] provides the means to evaluate the performance of the equal-weighted aggregated uncertainty distributions. Discussions on this issue and uncertainty distributions based on this weighting technique will be published separately.[3]

Throughout Section 4.3 and 4.4 the term "range factor" is used to express the ratio between the 95th and 5th percentiles of the distribution.

4.3.1 Inhalation

All experts were asked to assess average ventilation rates, the volume of air entering and leaving the lungs (liters min^{-1}), assuming a normal daily mix of activities (work, rest, exercise, etc.) for adults and 5-year-old children. For both age groups, the experts' medians and range factors (around 2 to 3) were quite similar (Figures 4.1 and 4.2). The aggregated medians were 13 liters min^{-1} for adults and 6 liters min^{-1} for children, with range factors of about 3 and 2, respectively.

The experts provided generally quite similar assessments for total deposition in the respiratory tract (percent inhaled), with the same trend of increasing total deposition with increasing particle size in adults (0.1, 1, and 10 μm AMAD) and greater deposition of 1-μm particles in 5-year-old children than adults (Figures 4.3 and 4.4). Medians differed by up to a factor of 2 for 0.1-μm particles to up to 10% for 10-μm particles. Similarly, range factors were greatest for deposition of 0.1-μm particles (1.3 to 6) and least for 10-μm particles (around 1 to 2.5). Aggregated medians for adults were 36, 47, and 75% for 0.1, 1, and 10-μm particles, respectively, with a value of 50% for 1-μm particles in children. Aggregated range factors were from 2 to 6 for deposition in adults and 4 for children. The initial deposition in the extrathoracic region (percent of total deposited in the respiratory tract) was similarly assessed by all but one expert, who provided lower medians. The aggregated medians were from 14 to 88%, depending on particle size, with range factors of 2 – 20. For initial deposition in the tracheobronchial region (percent of total deposition in the lung), the experts gave quite similar medians but differing ranges. The aggregated medians were from around 20 to 40%, with aggregated range factors of about 4 – 10.

The assessments of retention of particles (1 μm AMAD) in the tracheobronchial airways and pulmonary region of the lung (percent total initial deposition in the respiratory tract) in adults were reasonably consistent with regard to median values (Figures 4.5 and 4.7) but gave widely different ranges (Figures 4.6 and 4.8). For retention in the pulmonary region, ranges were typically less than 10 for times up to 1 year after deposition and up to 100 at 10 years. For retention in the tracheobronchial airways, ranges were generally less than 100 up to 1 year but up to 100,000 for the small proportion remaining at 10 years. Aggregated medians showed retention in the tracheobronchial airways falling from around 7% initially to 2% at 1 month and in the pulmonary region from 24 to 2% after 10 years. Median values for retention in 5-year-old children were assessed to be lower than in adults by factors ranging from 0.9 to 0.6.

Absorption to blood in adults (percent total initial deposition in the respiratory tract) was considered for Sr, I, Cs, Pu, Ru, Ce, and Te at times between 1 hour and 10 years after deposition. Figures are included here for Sr, Cs, Pu, and Ru (Figures 4.9 – 4.16). For Sr, experts differed considerably in their assessments of absorption, with median values for total absorption after 10 years varying from about 20 to 65%; the aggregated median was 40% (Figure 4.9). There was greater consistency in range factors, with values of less than 10 for all time points other than 1 hour after deposition (Figure 4.10). For Cs, there was greater consistency among experts in their estimates of medians, most values for total absorption being around 70%; two differing assessments gave an overall range of 40 – 95% (Figure 4.11). Range factors were gen-

erally less than 3 (Figure 4.12). For Pu, experts gave differing assessments of absorption, with a range in median values at 10 years after deposition of less than 2 to 15%; range factors at this time point varied from 3 to 300 (Figures 4.13 and 4.14). The aggregated median at 10 years was 7%, with an aggregated range factor of about 50. For Ru, there was again considerable variation in medians, with total absorption after 10 years of 2 to 50%; range factors varied from 3 to 50 (Figures 4.15 and 4.16). The aggregated median at 10 years was 13%, with an aggregated range factor of about 100. In general, it was clear that experts differed in their assessment of the expected solubility of the materials inhaled, particular individuals giving lower values for each element while others consistently gave higher values. It was also apparent in the answers to this question and others that experts varied in their assessment of uncertainty, with consistently smaller ranges predicted by some individuals.

4.3.2 Ingestion

Absorption to blood after ingestion was considered for Sr, I, Cs, and Pu as an oxide or in a biologically incorporated form. In each case, the experts provided values of fractional absorption for adults, 5-year-old children, and 3-month-old infants. Results for Sr, Cs, and Pu oxide are discussed here. For Sr, median values ranged from 0.15 to 0.35 for adults and 0.4 to 0.7 for infants, with intermediate values for children (Figure 4.17). Range factors were 3 – 7 for adults and 3 – 10 for infants (Figure 4.18). Aggregated medians were 0.24 for adults, 0.33 for children, and 0.55 for infants, with aggregated range factors of 6 – 14. For Cs, median values were greater and more consistent among experts than for Sr, ranging from 0.8 to 0.95 independent of age; the aggregated medians were about 0.9 in each case (Figure 4.19). Range factors were consistently low, from 1 to 2.5, with aggregated values of about 1.8 in each case (Figure 4.20). For Pu oxide, there were a number of identical estimates from experts, with 10^{-5} being the favored median value for adults and children and 10^{-4} for infants; corresponding aggregated values were 1×10^{-5} and 9×10^{-5}, respectively (Figure 4.21). Range factors were around 100 in adults and up to about 10,000 in infants, with aggregated values of 2000 – 4000 (Figure 4.22).

4.3.3 Systemic Distribution and Retention

Retention in the liver and skeleton in adults and 5-year-old children (percent of total reaching blood) was elicited for Sr, Pu, Ce, and Te for times from 1 day to 50 years after entry to blood. Figures 4.23 to 4.28 show the results for Sr in adults and children and Pu in adults. For Sr in adults, median values of retention were very similar, with the greatest at 1 day at 30 – 35% and falling to 1 – 4% after 50 years (Figure 4.23). Estimated ranges were more disparate but still reasonably consistent; the maximum range factors at 50 years were about 20 to 25, with an aggregated value of 80 (Figure 4.24). For Sr retention in children, median values ranged from 40 to 70% at 1 day, falling to 5% and less at 50 years (Figure 4.25). Range factors were generally greater than for adults but were nevertheless mostly less than 10 (there was one estimate of 800 at 50 years) (Figure 4.26). For Pu retention in adults, median values were similar after 1 day, reaching a peak of about 80% at 1 month (there was one estimate of 90%) and falling to 50% after 50 years; range factors were generally between 1 and 3, with aggregated ranges of 2 – 4 (Figures 4.27 and 4.28).

A further question elicited the partition of Sr, Pu, Ce, and Te between the liver and skeleton in adults and 5-year-old children at times from 1 day to 50 years after entry into blood, by asking for estimates of the proportion retained by the skeleton. For Sr, median values from each expert were near 100%, although there was less agreement on 5% values. For Pu, there was reasonable agreement among experts.

Distribution within the skeleton was elicited for Pu only: the important isotopes are alpha emitters, and their distribution within bone determines dose to sensitive cells and consequent risks of osteosarcoma and leukemia. Figure 4.29 shows estimated median values for retention on endosteal bone surfaces (percent of total skeletal retention) in adults at times from 1 day to 50 years after deposition. Agreement among experts was high, particularly for early times, with values of retention falling from about 95 to 100% initially to about 55 to 70% after 50 years. One expert predicted significantly more rapid removal from endosteal surfaces, to about 10% after 50 years. Aggregated medians were about 98% at 1 day, falling to 62% after 50 years. Estimated range factors were also generally very similar and low, with the highest values at 50 years being less than 5 except for one

estimate of 10; the aggregated range at 50 years was 25 (Figure 4.30). Median values for retention of plutonium in red bone marrow (percent of total skeletal retention) were also generally quite consistent among experts, with the highest values about 3 – 4% after 1 year (Figure 4.31). One expert predicted a median value for retention at 1 day after deposition of about 7%, while others predicted very low initial values. Range factors were high and variable, from about 10 to 100 at early times and about 5 to 1000 at 50 years (Figure 4.32).

Whole-body retention (percent of total reaching blood) was elicited for Cs and Ru in adults and 5-year-old children at times from 1 day to 5 years after entry into blood. The results for adults are presented here (Figures 4.33 to 4.36). For Cs and Ru, there was a high degree of consistency among experts in estimated median values for each time point (Figures 4.33 and 4.35). For Cs, range factors were very low for early time points: 10 to 100 for retention at 1 year (medians of about 5 – 10%) and 10^3 to 10^8 for the very small fraction remaining at 5 years (Figure 4.34). For Ru, range factors were more variable but were generally less than 10 for times up to 1 month; they were up to about 100 at 1 year and up to 2000 at 5 years (Figure 4.36).

Retention of I in the thyroid (percent of total reaching blood) was elicited for adults and 5-year-old children at times from 1 day to 3 months after entry into blood. The results for adults are presented here and show a high degree of consistency in estimated median values (Figure 4.37) and range factors (Figure 4.38), with aggregated medians of 29% at 1 day falling to 15% after 3 months, and aggregated range factors of from 5 to 9.

4.3.4 Dose Coefficients

Organ dose coefficients (Gy Bq^{-1}) were elicited for ingestion and inhalation (1 μm AMAD particles + vapor for I and Te) of ^{90}Sr, ^{131}I, ^{137}Cs, and ^{239}Pu by adults and 5-year-old children; for ^{132}Te and ^{144}Ce, only inhalation was considered. Selected results for ^{131}I, ^{90}Sr, ^{137}Cs, ^{144}Ce, and ^{239}Pu are presented here (Figures 4.39 to 4.48), for the examples of thyroid dose from ^{131}I and doses to red bone marrow from the other nuclides.

For ^{131}I, estimated median values for the dose to the thyroid showed a high degree of consistency among experts, the greatest difference of a factor of about 3 being for doses to children after ingestion of ^{131}I; other estimates for this dose coefficient were virtually identical (Figure 4.39). Range factors varied, with very low values for each dose coefficient from particular experts (values of 2 – 3) and values of up to 10 – 18 from others (Figure 4.40). Aggregated median values were 2.3×10^{-7} Gy Bq^{-1} and 1.1×10^{-6} Gy Bq^{-1} for inhalation by adults and children, respectively, and 4.4×10^{-7} Gy Bq^{-1} and 2.1×10^{-6} Gy Bq^{-1} for ingestion by adults and children, respectively. Aggregated range factors were from 9 to 14.

For ^{90}Sr dose to red bone marrow, median values varied by up to factors of 60 for ingestion by adults and 25 for ingestion by children, with smaller differences for inhalation by adults and children (Figure 4.41). Range factors varied, with low values from some experts and high values up to around 100 from others (Figure 4.42). Aggregated median values were about 1×10^{-7} Gy Bq^{-1} in each case, with aggregated range factors of 35 to 240.

For ^{137}Cs, median estimates of dose to red bone marrow showed a high degree of consistency among experts (Figure 4.43). Range factors were from around 2 to 3 to 10 to 15 (Figure 4.44). Aggregated median values were 3.9×10^{-9} Gy Bq^{-1} and 2.8×10^{-9} Gy Bq^{-1} for inhalation by adults and children, respectively, and 1.3×10^{-8} Gy Bq^{-1} and 7.0×10^{-9} Gy Bq^{-1} for ingestion by adults and children, respectively. Aggregated range factors were from 4 to 20.

For inhalation of ^{144}Ce, median estimates of bone marrow dose varied by up to a factor of 1000 although some estimates were similar (Figure 4.45). Range factors varied from less than 10 to up to 1000 (Figure 4.46). Aggregated median values were 2.1×10^{-8} Gy Bq^{-1} for adults and 1.4×10^{-7} Gy Bq^{-1} for children, with aggregated range factors of 9000 and 6000, respectively.

For ^{239}Pu, median estimates of bone marrow dose varied by two orders of magnitude although again there was good agreement between some individuals (Figure 4.47). Range factors varied from around 10 to 2000 (Figure 4.48). Aggregated median values were 1.4×10^{-6} Gy Bq^{-1} and 1.9×10^{-6} Gy Bq^{-1} for inhalation by adults and children, respectively, and 2.7×10^{-8} Gy Bq^{-1} for ingestion by adults and children. Aggregated range factors were from 1000 to 30,000.

4.4 Processing of Aggregated Distributions into Distributions of Code Input Parameters

The aggregated distributions on biokinetic parameters are being used to calculate distributions on dose coefficients, the required input to the MACCS and COSYMA codes. The distributions will be compared with those provided by the experts. These post-processing procedures and data comparisons will be reported separately.[4-6]

Table 4-1 compares aggregated median values for dose coefficients with corresponding ICRP values[7,8] used in the MACCS and COSYMA codes. In all the examples given, the aggregated medians from the expert assessments are within a factor of 3 of ICRP values. The table also shows the associated aggregated range factors, as discussed in Section 4.3.4. Ranges are generally lower for ^{131}I and ^{137}Cs and higher for ^{90}Sr, ^{144}Ce, and ^{239}Pu. Particularly high ranges were obtained for doses to bone marrow and bone surfaces from inhalation of ^{144}Ce (5000 – 9000) and ingestion of ^{239}Pu (4000 – 34,000). The larger ranges are partly attributable to uncertainties over the chemical forms likely to be inhaled or ingested after an accident as well as uncertainties in the biokinetic parameters involved.

4.5 References

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Table 4.1. Committed dose coefficients for adults and 5-year-old children, Gy Bq^{-1} intake

			Adults		Children	
Nuclide	**Intake**	**Organ**	**50%/ICRP**	**95%/5%**	**50%/ICRP**	**95%/5%**
^{131}I	Ingestion	Thyroid	1	9	1	12
^{137}Cs	Ingestion	Colon	1	4	1	8
		RBM[a]	1	4	1	20
	Inhalation	Lungs	2(F)[c]	50	3(F)	150
		RBM	1(F)	8	1(F)	10
^{90}Sr	Ingestion	Colon	1	600	1	730
		RBM	0.6	240	0.4	120
		B. Surf.[b]	0.5	390	0.4	100
	Inhalation	Lungs	0.7(M)	5300	0.7(M)	1200
		RBM	1.6(M)	35	1.4(M)	100
		B. Surf.	1.4(M)	28	1.6(M)	120
^{144}Ce	Inhalation	Lungs	0.5(M)	520	0.8(M)	370
		RMB	0.8(M)	8500	0.8(M)	5600
		B. Surf.	2(M)	6300	1(M)	5800
^{239}Pu	Ingestion	Colon	1	250	0.4	400
		RBM	1	4300	1	34,000
		B. Surf.	0.8	20000	0.7	12,500
		Liver	0.8	700	0.7	7200
	Inhalation	Lungs	2(S)	400	0.7(S)	1500
		RBM	3(S)	1300	0.3(S)	2900
		B. Surf.	3(S)	770	0.3(S)	1600
		Liver	3(S)	800	0.3(S)	1300

[a] RBM = red bone marrow.
[b] B. surf. = bone surface.
[c] F,M,S refer to ICRP respiratory tract absorption types—fast, medium, slow.

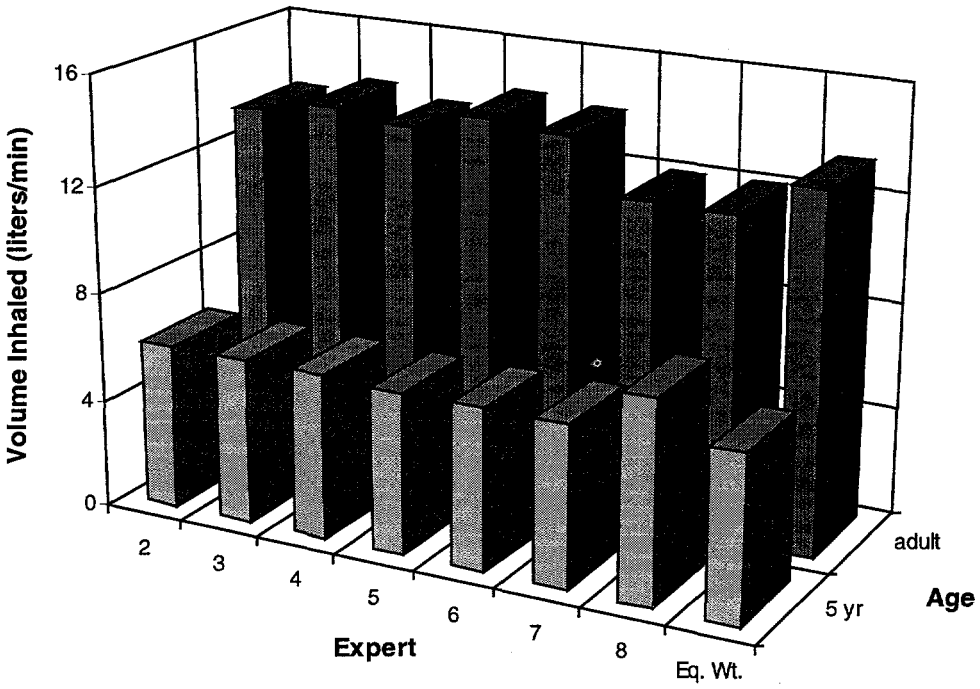

Figure 4.1 Median values for average ventilation rates, assuming a normal daily mix of activities.

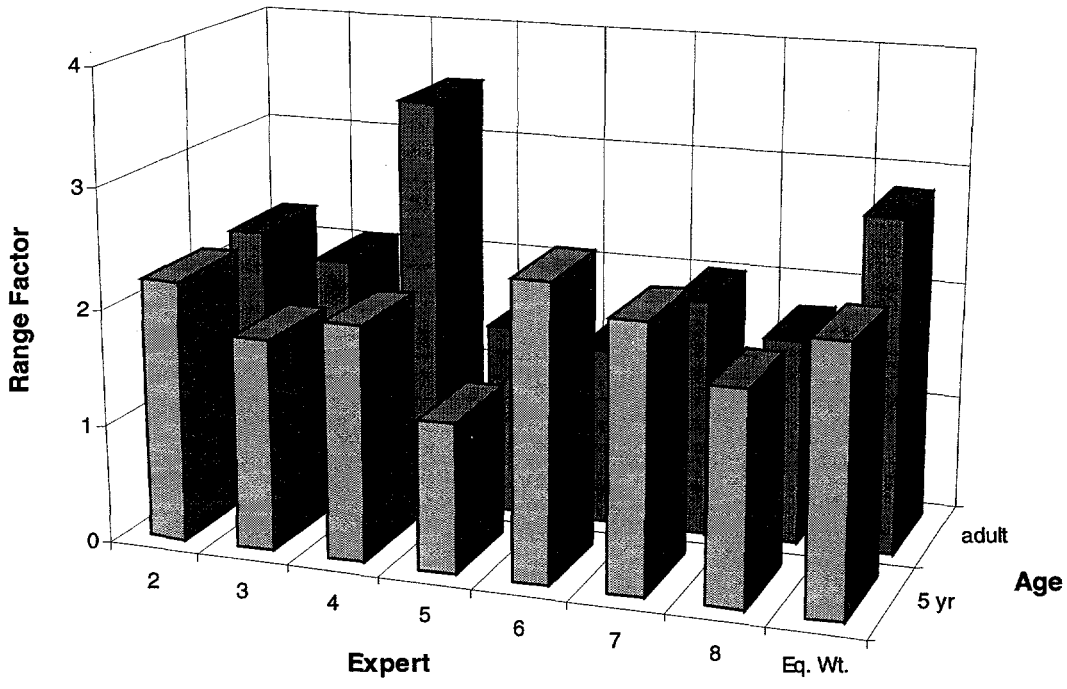

Figure 4.2 Range factors (ratio of 95th/5th percentile) for average ventilation rates.

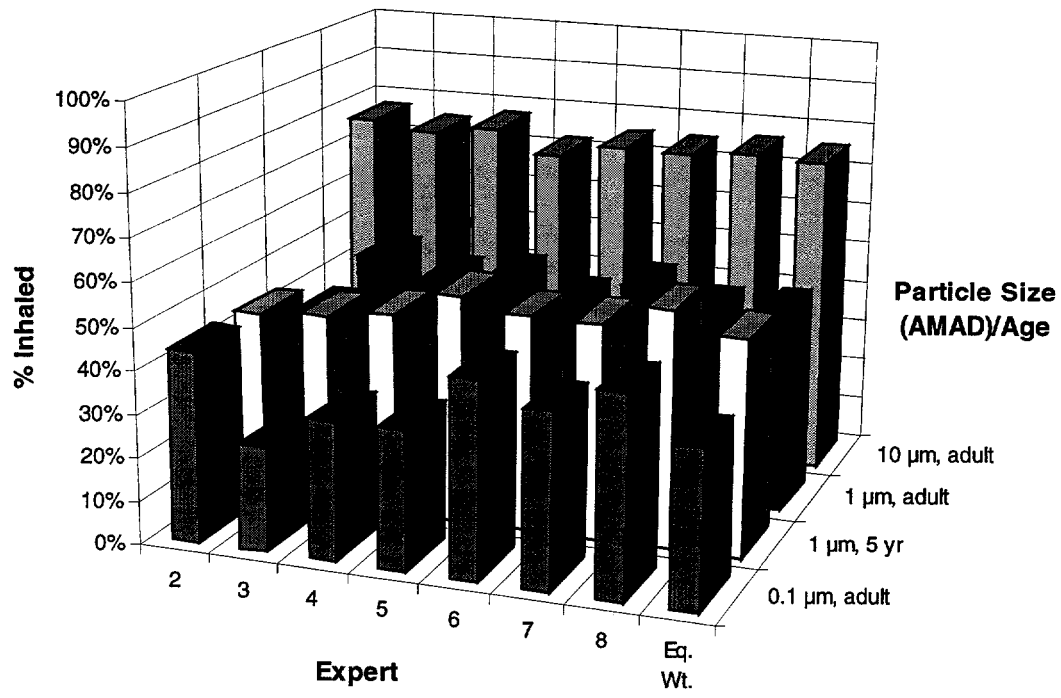

Figure 4.3 **Median values for total initial deposition in the respiratory tract for a normal daily mix of activities.**

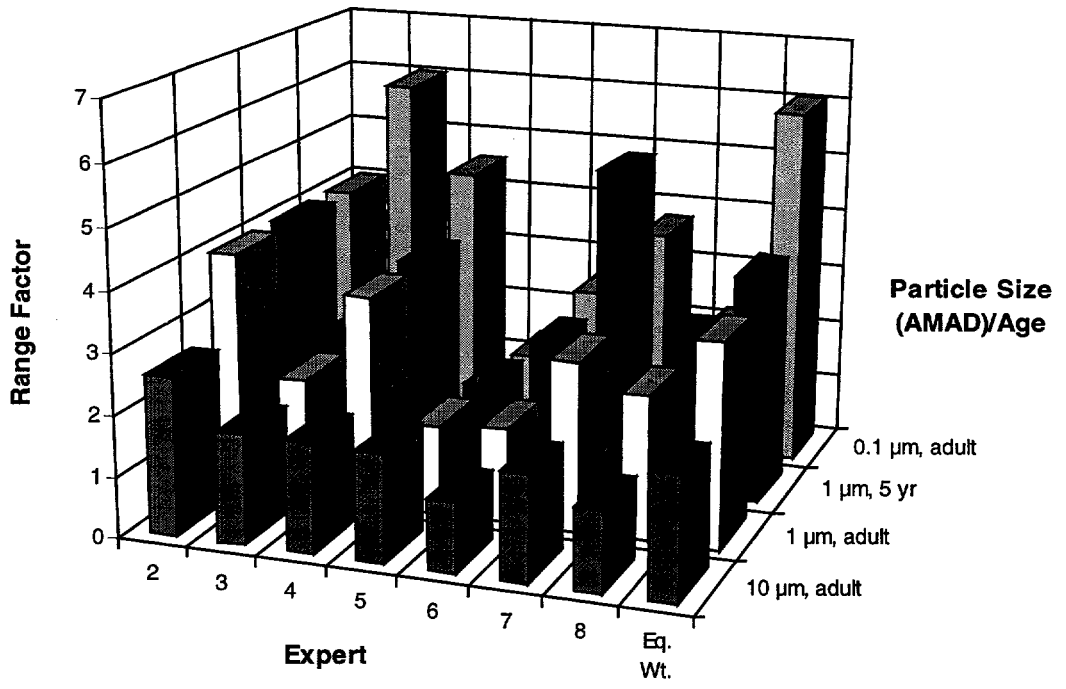

Figure 4.4 **Range factors (ratio of 95th/5th percentile) for total initial deposition in the respiratory tract.**

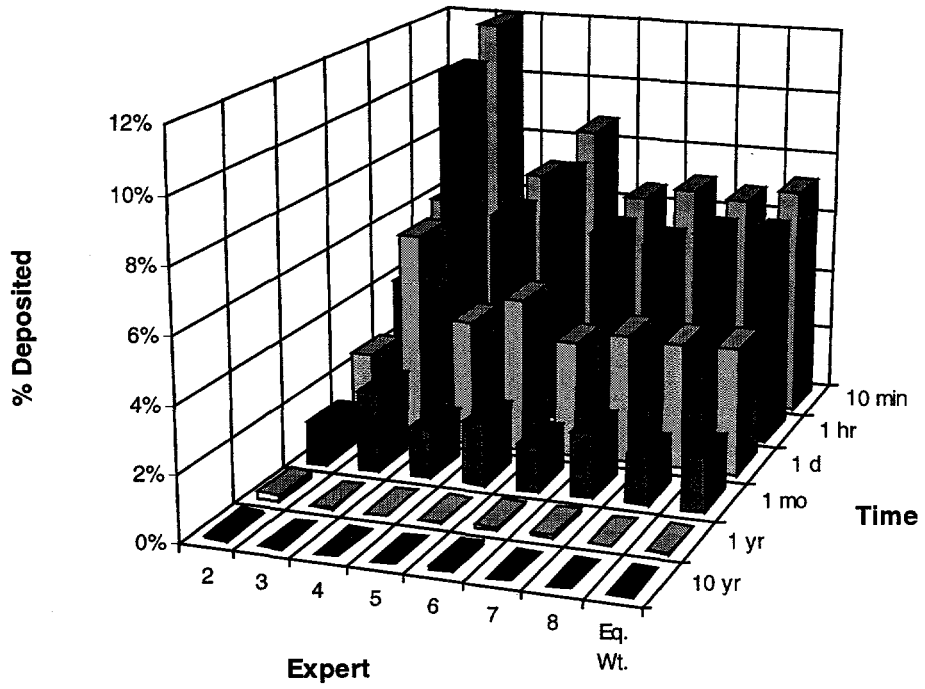

Figure 4.5 **Median values for retention in the tracheobronchial airways in adults, assuming completely insoluble particles (1 μm AMAD) as percent of total initial deposition in the respiratory tract.**

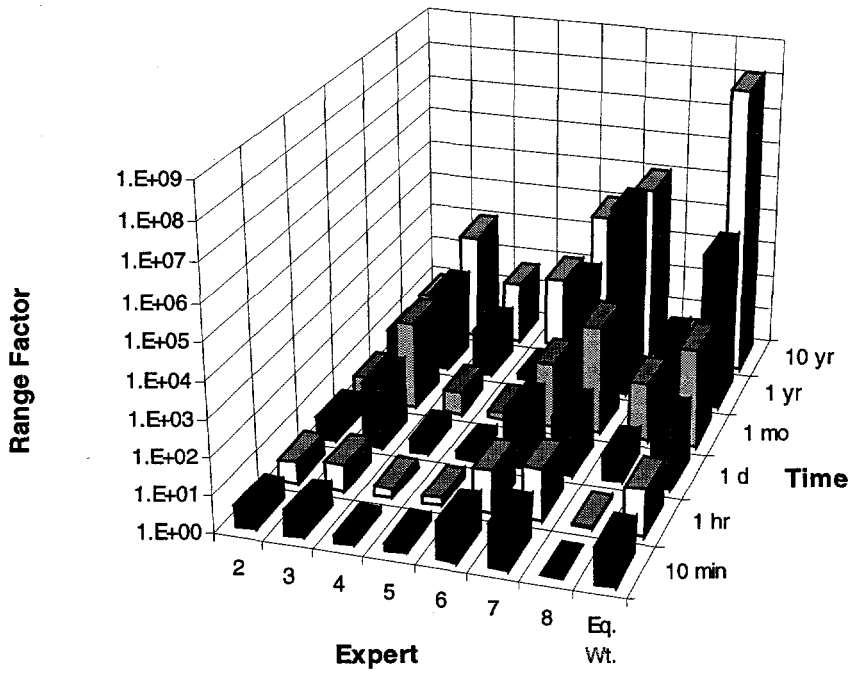

Figure 4.6 **Range factors (ratio of 95th/5th percentile) for retention of insoluble particles (1 μm AMAD) in the tracheobronchial airways in adults.**

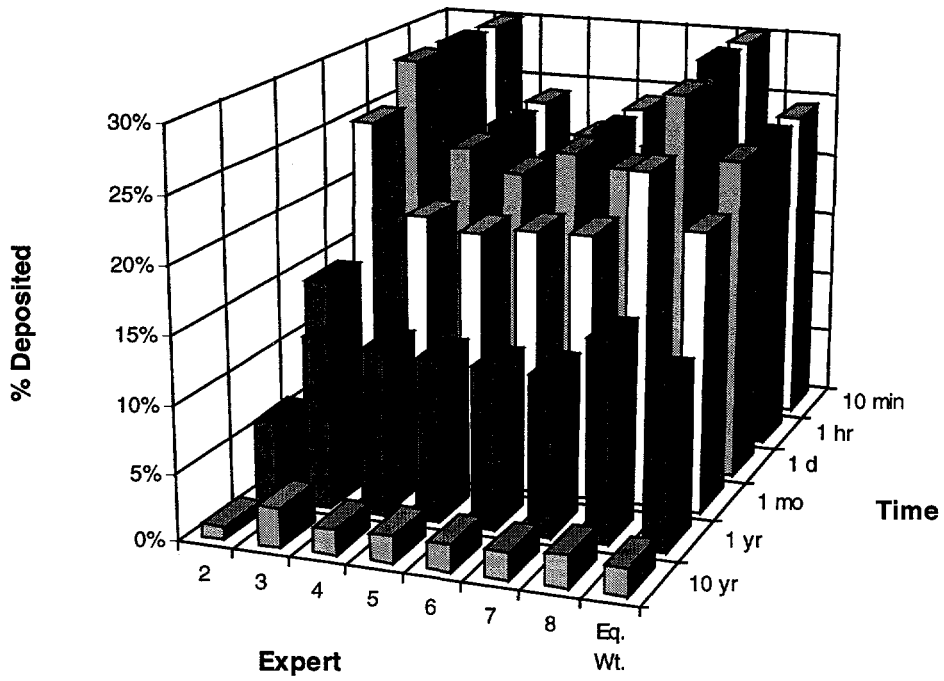

Figure 4.7 **Median values for retention in the pulmonary region of the lungs in adults, assuming completely insoluble particles (1 μm AMAD) as percent of total initial deposition in the respiratory tract.**

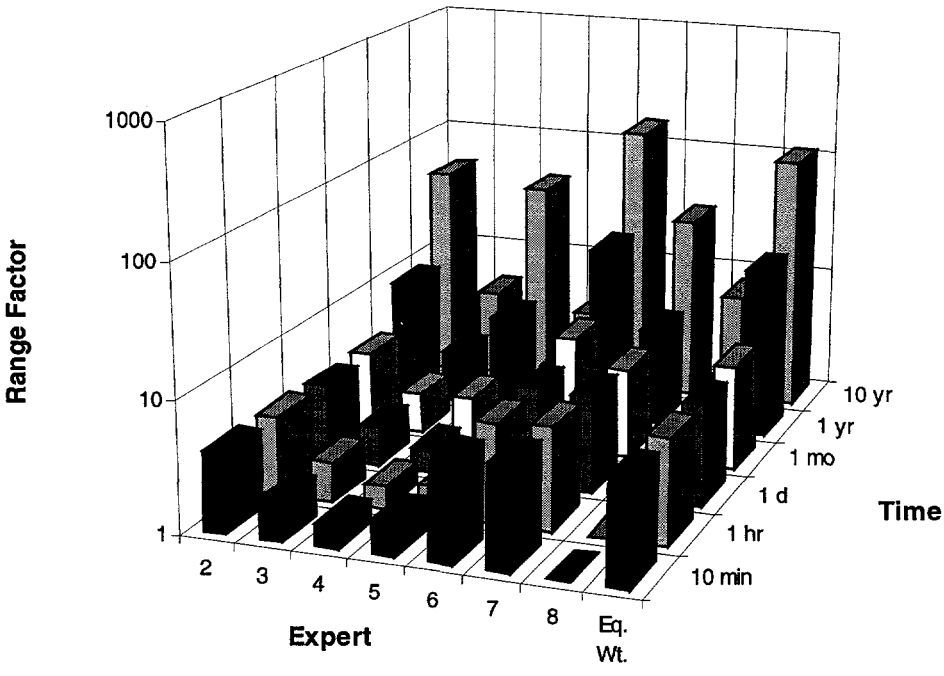

Figure 4.8 **Range factors (ratio of 95th/5th percentile) for retention of insoluble particles (1 μm AMAD) in the pulmonary region of the lungs in adults.**

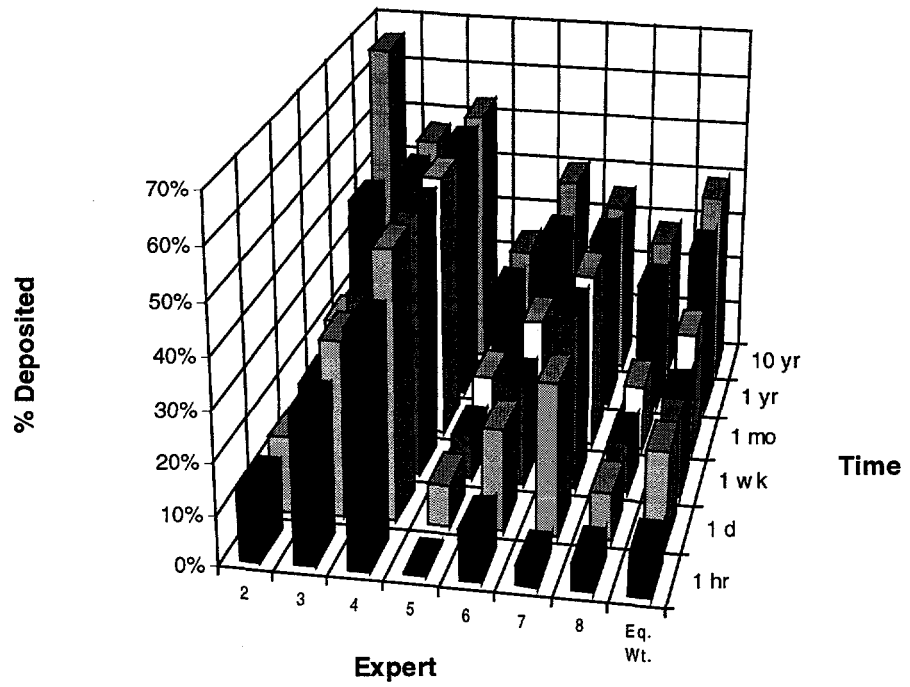

Figure 4.9 **Median values for absorption of strontium to blood in adults, as percent of total initial deposition in the respiratory tract (1 μm AMAD particles), for chemical forms likely to be inhaled after an accident (usually oxides).**

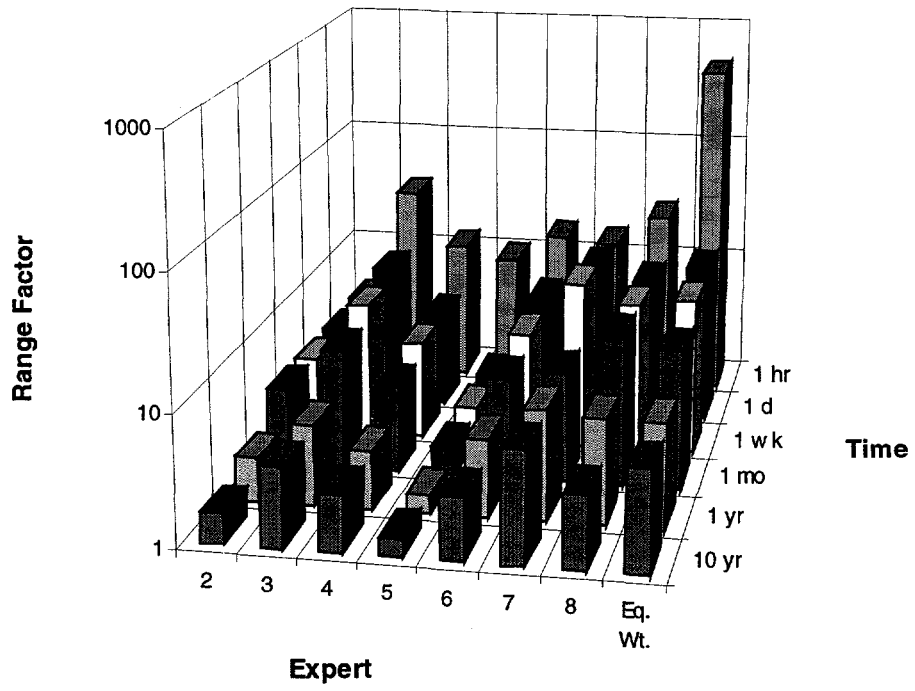

Figure 4.10 **Range factors (ratio of 95th/5th percentile) for absorption of strontium to blood from the respiratory tract in adults.**

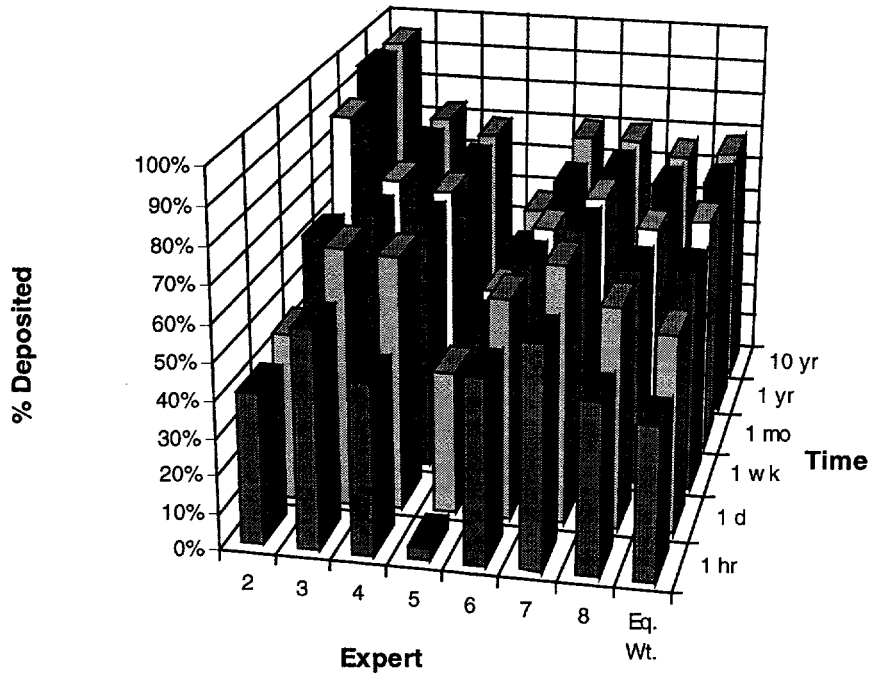

Figure 4.11 Median values for absorption of cesium to blood in adults, as percent of total initial deposition in the respiratory tract (1 μm AMAD particles), for chemical forms likely to be inhaled after an accident (usually oxides).

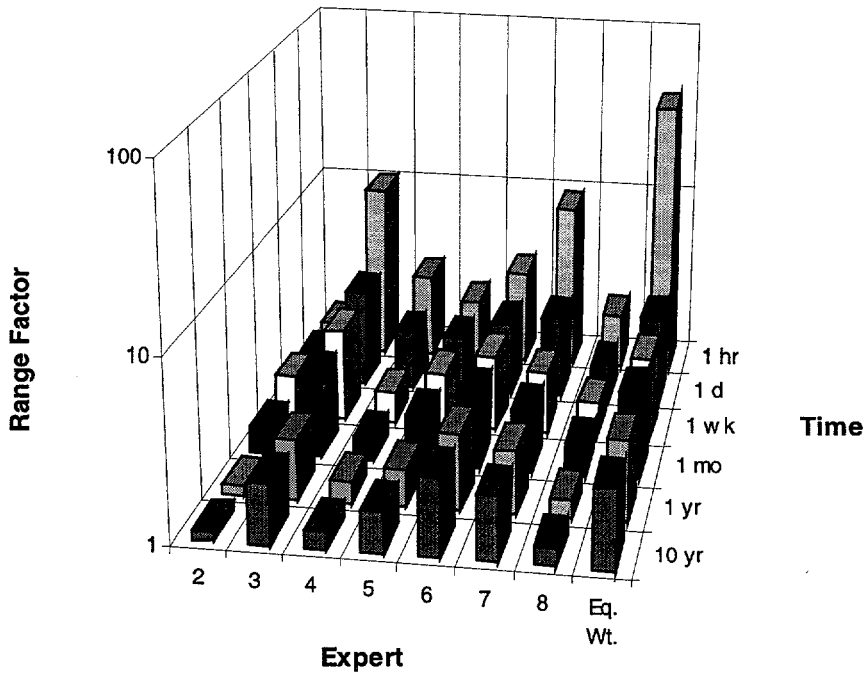

Figure 4.12 Range factors (ratio of 95th/5th percentile) for absorption of cesium to blood from the respiratory tract in adults.

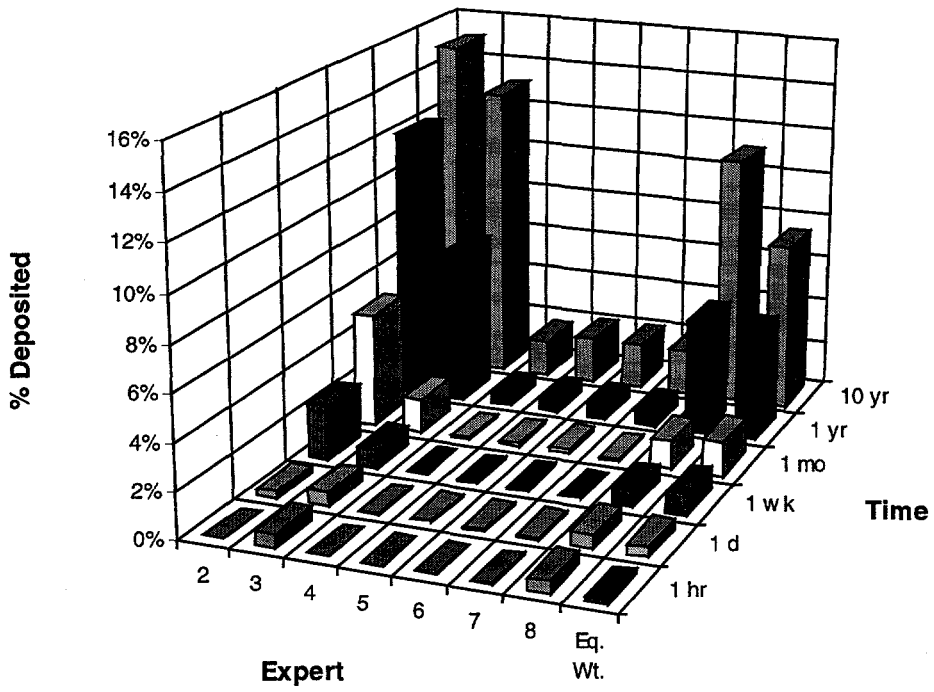

Figure 4.13 **Median values for absorption of plutonium to blood in adults, as percent of total initial deposition in the respiratory tract (1 μm AMAD particles), for chemical forms likely to be inhaled after an accident (usually oxides).**

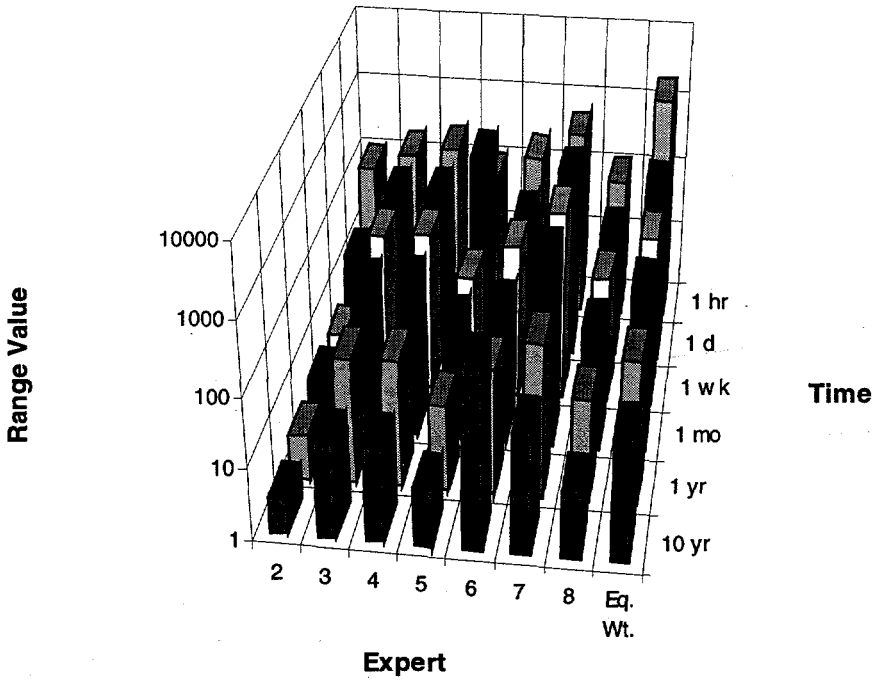

Figure 4.14 **Range factors (ratio of 95th/5th percentile) for absorption of plutonium to blood from the respiratory tract in adults.**

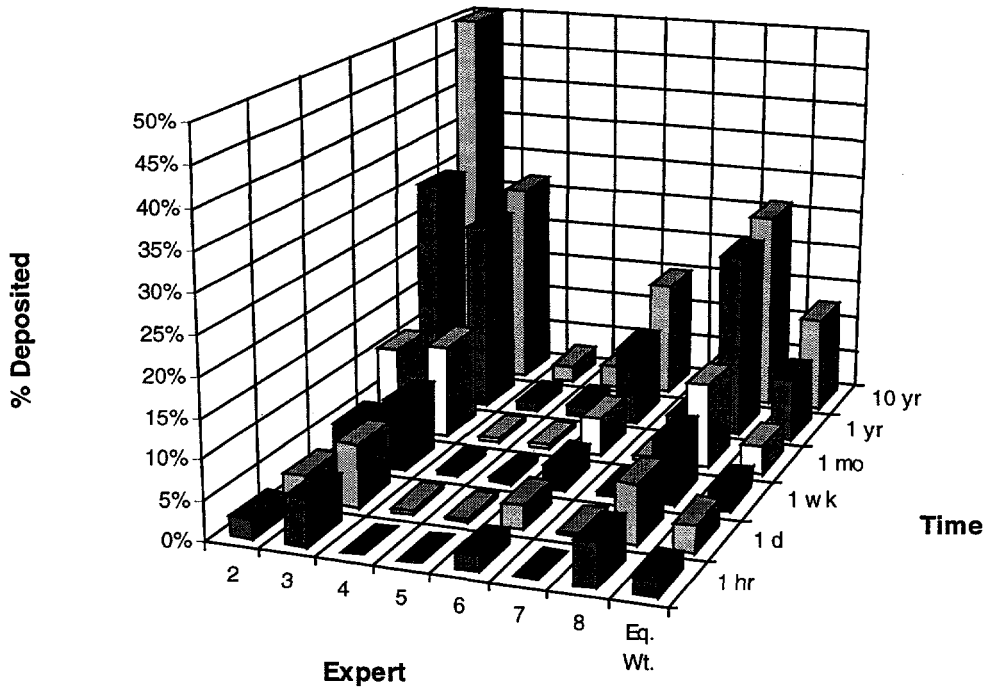

Figure 4.15 **Median values for absorption of ruthenium to blood in adults, as percent of total initial deposition in the respiratory tract (1 μm AMAD particles), for chemical forms likely to be inhaled after an accident (usually oxides).**

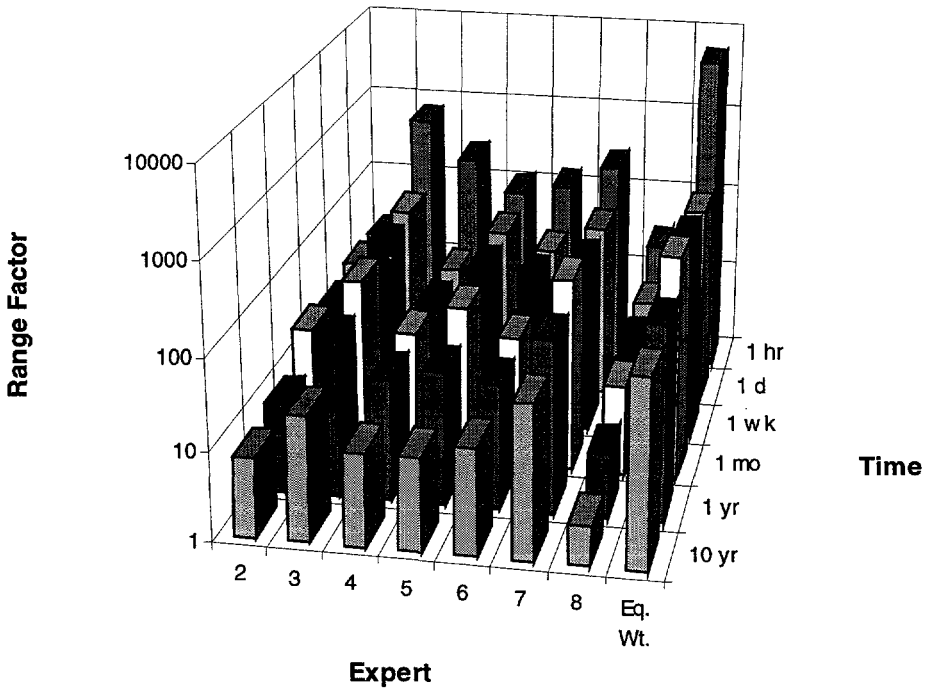

Figure 4.16 **Range factors (ratio of 95th/5th percentile) for absorption of ruthenium to blood from the respiratory tract in adults.**

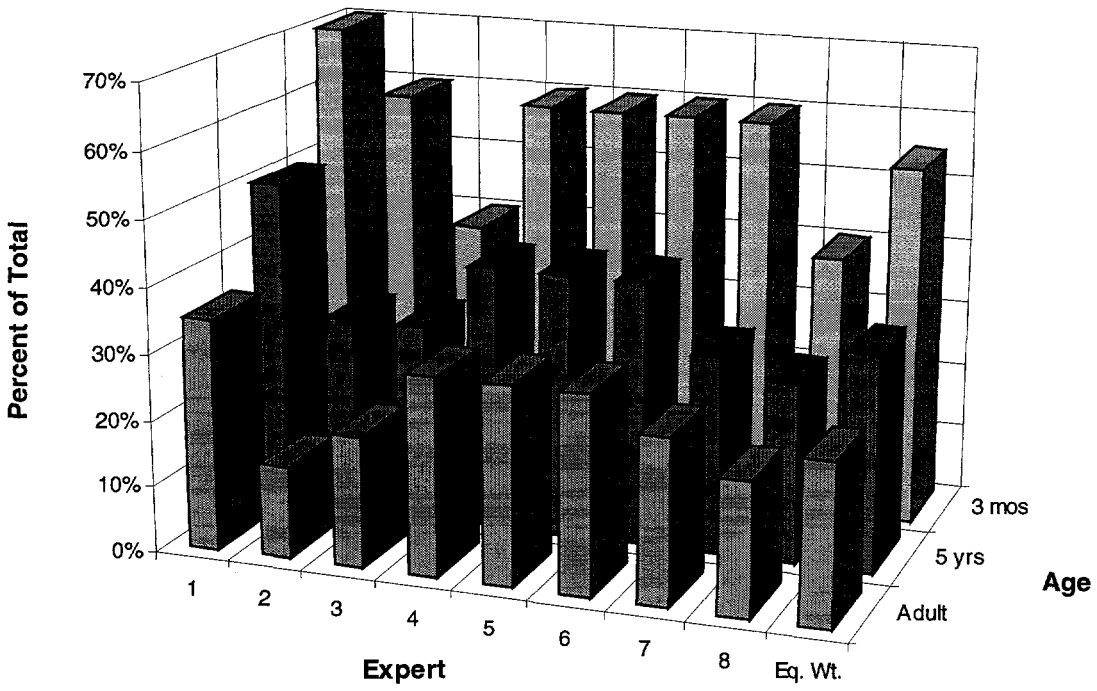

Figure 4.17 Median values for absorption of strontium to blood from the gastrointestinal tract, as a percent (f_1) of total ingested, for chemical forms likely to be encountered after an accident.

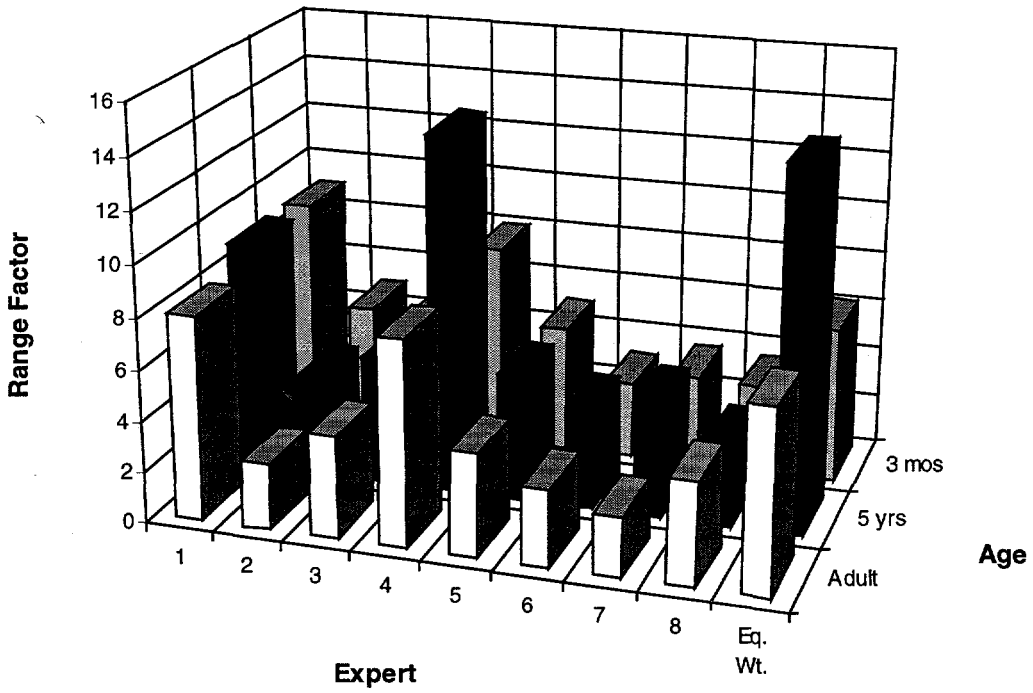

Figure 4.18 Range factors (ratio of 95th/5th percentile) for absorption of strontium to blood from the gastrointestinal tract.

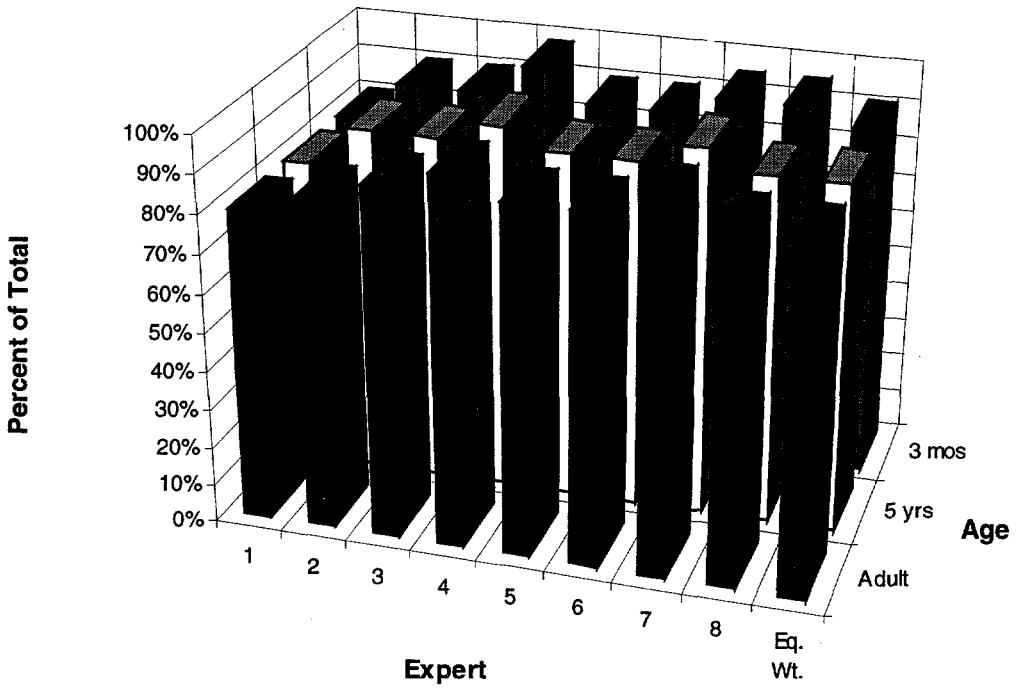

Figure 4.19 Median values for absorption of cesium to blood from the gastrointestinal tract, as a percent (f_1) of total ingested, for chemical forms likely to be encountered after an accident.

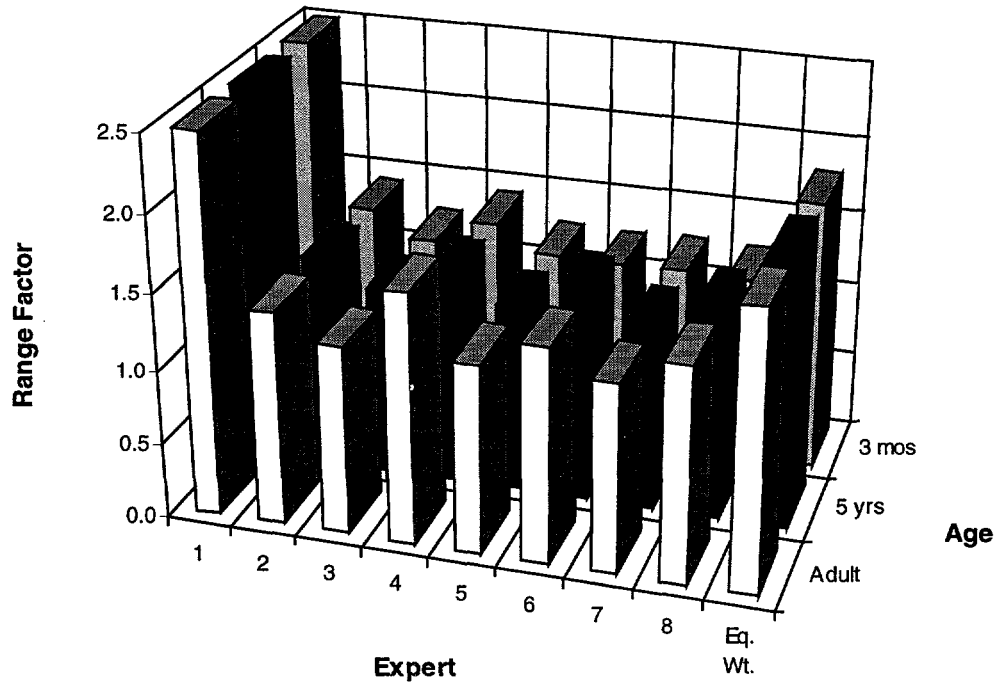

Figure 4.20 Range factors (ratio of 95th/5th percentile) for absorption of cesium to blood from the gastrointestinal tract.

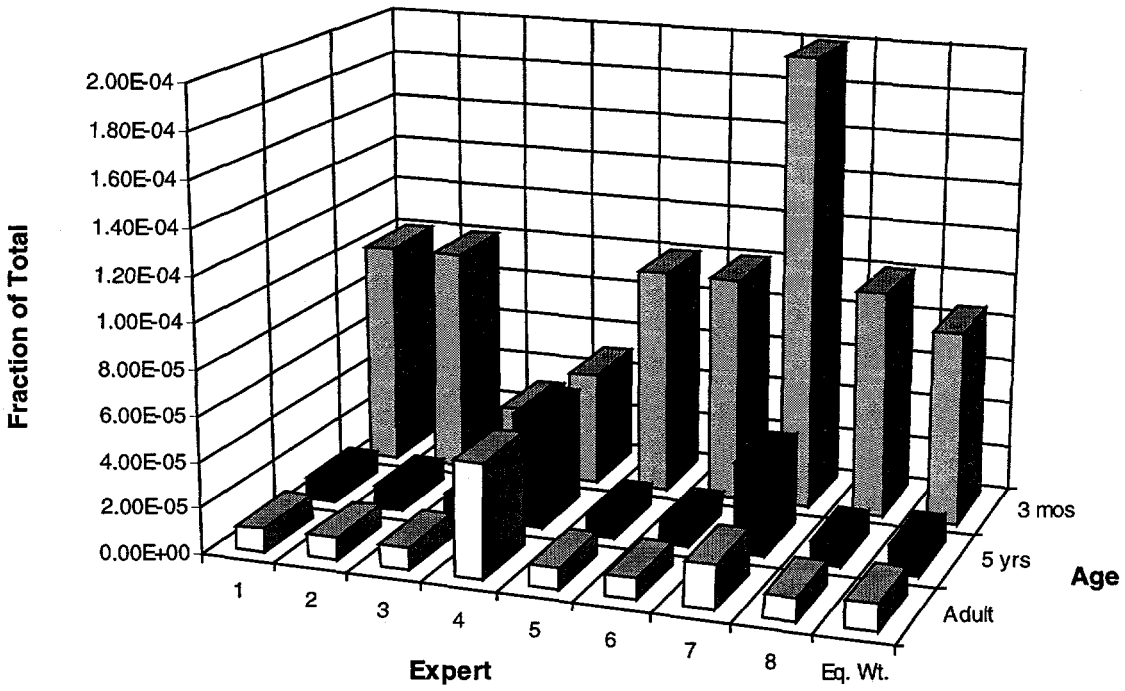

Figure 4.21 Median values for absorption of plutonium to blood from the gastrointestinal tract, as a fraction (f_1) of total ingested as oxides.

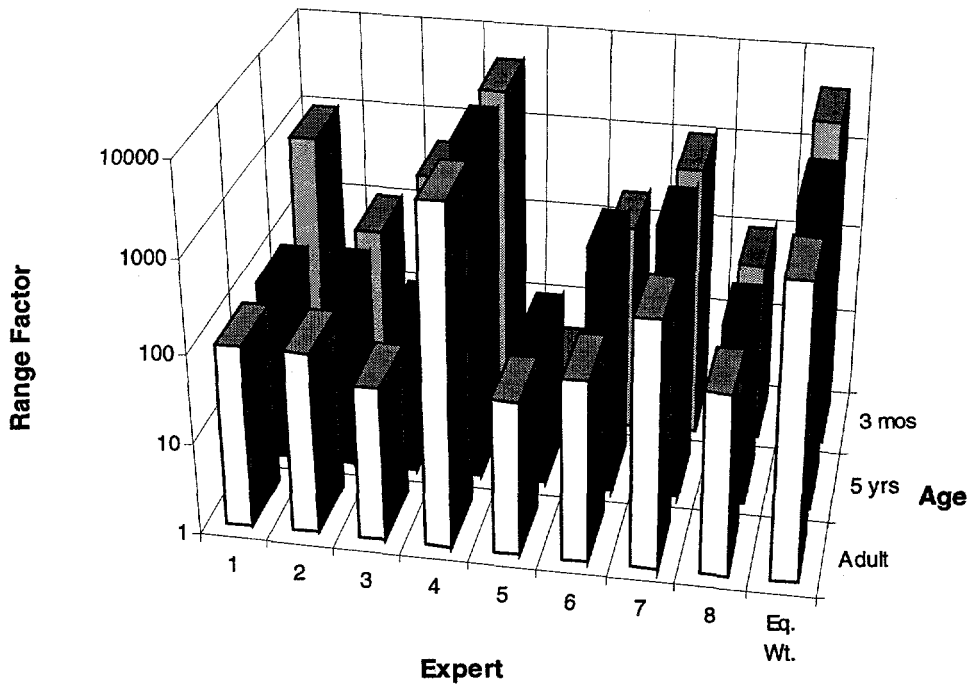

Figure 4.22 Range factors (ratio of 95th/5th percentile) for absorption of plutonium to blood from the gastrointestinal tract after ingestion as oxides.

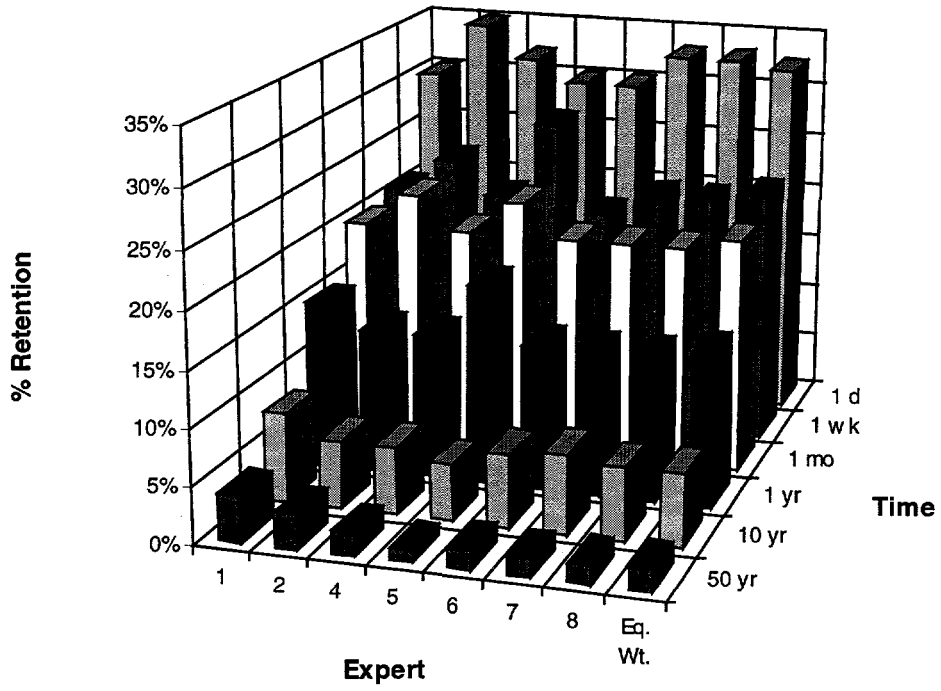

Figure 4.23 **Median values for the retention of strontium in liver + skeleton in adults, as percent of total reaching blood.**

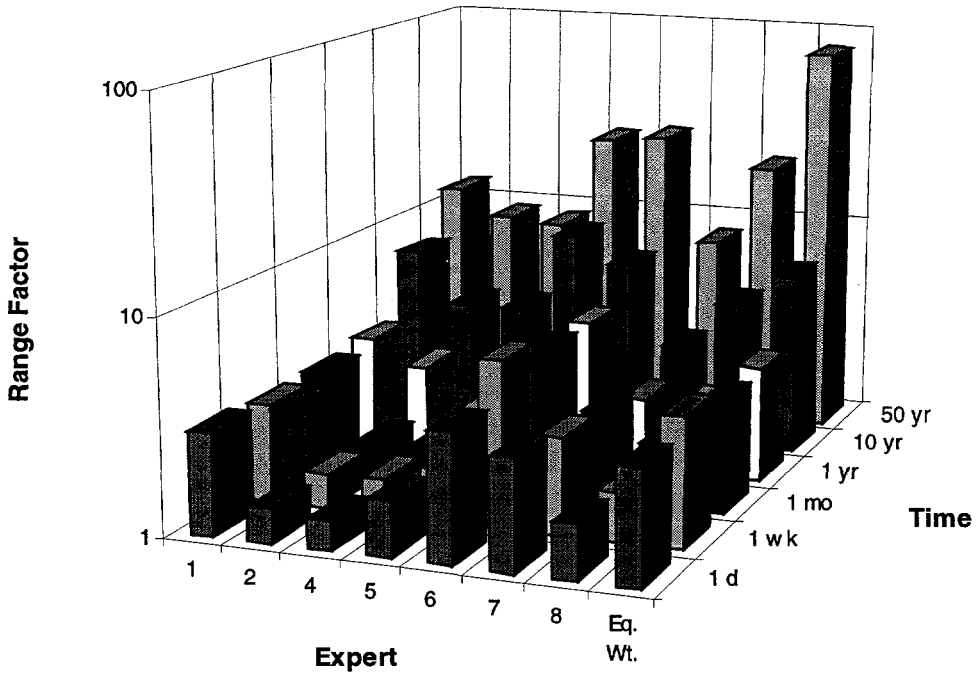

Figure 4.24 **Range factors (ratio of 95th/5th percentile) for the retention of strontium in liver + skeleton in adults, as percent of total reaching blood.**

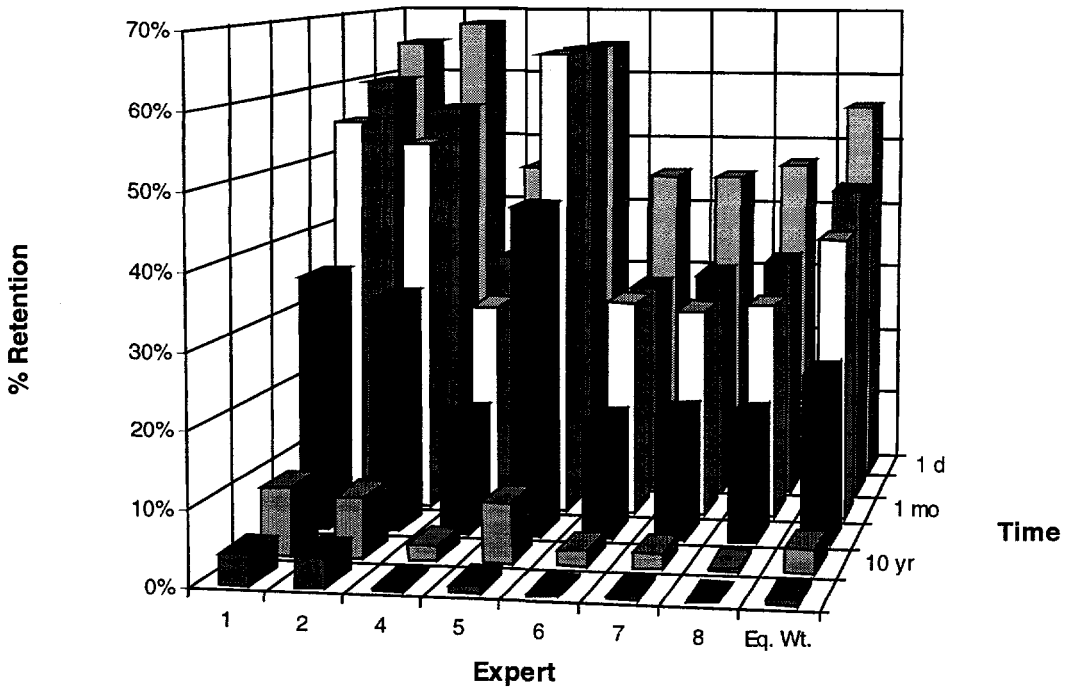

Figure 4.25 Median values for the retention of strontium in liver + skeleton in 5-year-old children, as percent of total reaching blood.

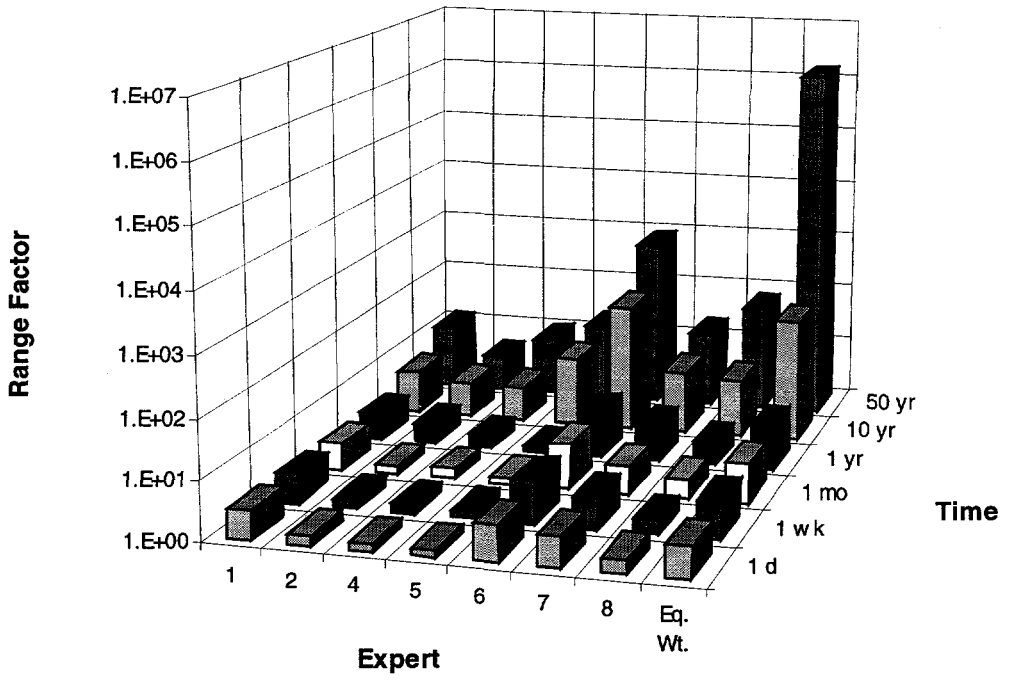

Figure 4.26 Range factors (ratio of 95th/5th percentile) for the retention of strontium in liver + skeleton in 5-year-old children, as percent of total reaching blood.

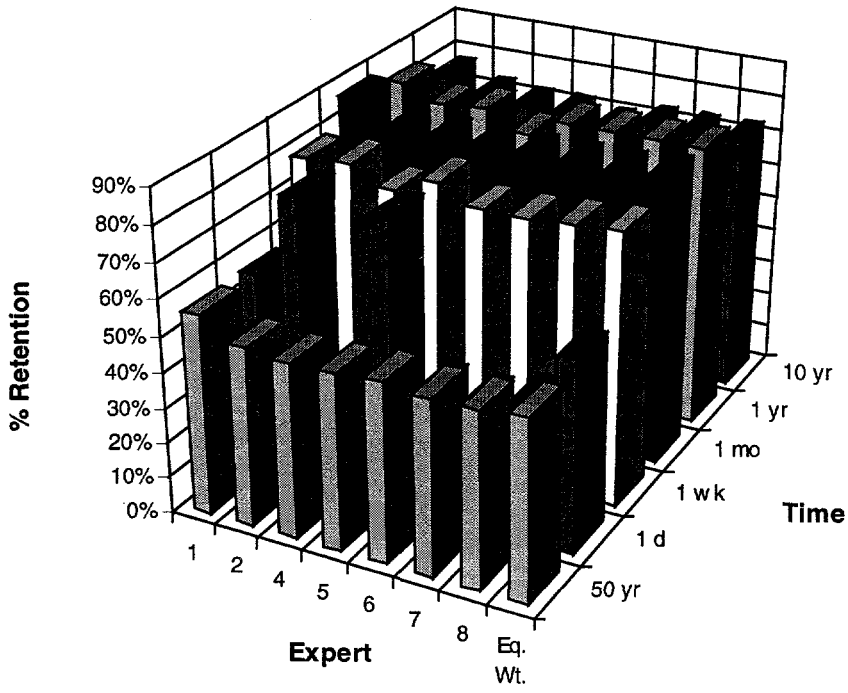

Figure 4.27 **Median values for the retention of plutonium in liver + skeleton in adults, as percent of total reaching blood.**

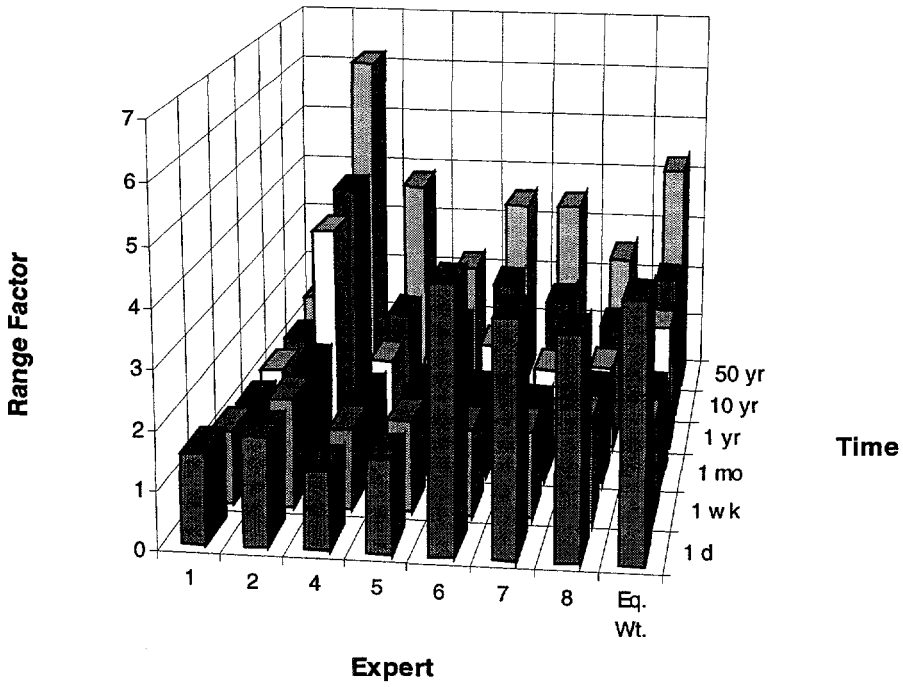

Figure 4.28 **Range factors (ratio of 95th/5th percentile) for the retention of plutonium in liver + skeleton in adults, as percent of total reaching blood.**

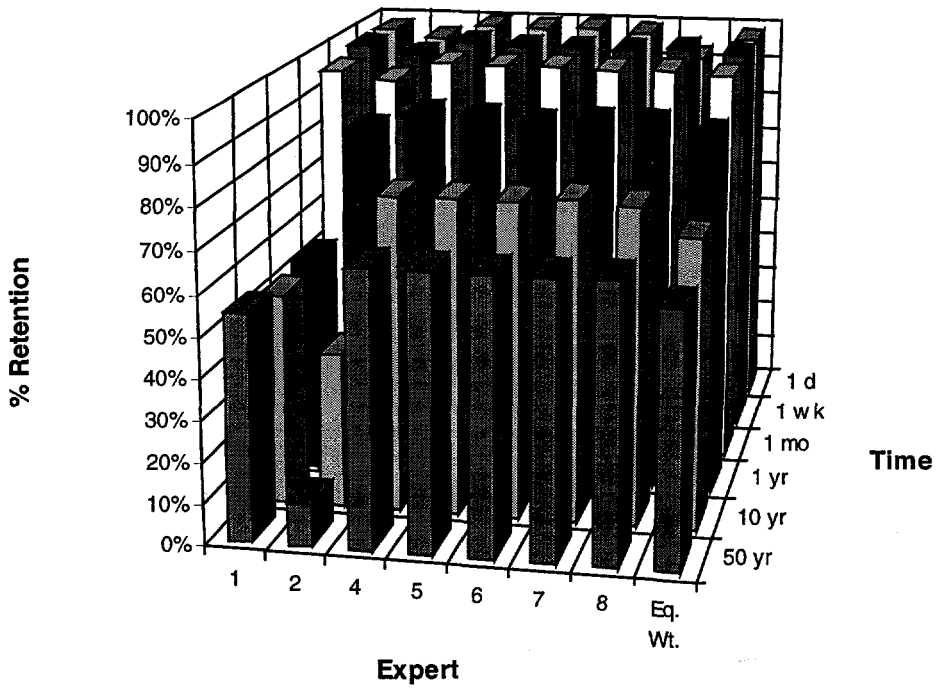

Figure 4.29 Median values for the retention of plutonium on endosteal bone surfaces in adults, as percent of *total* skeletal retention.

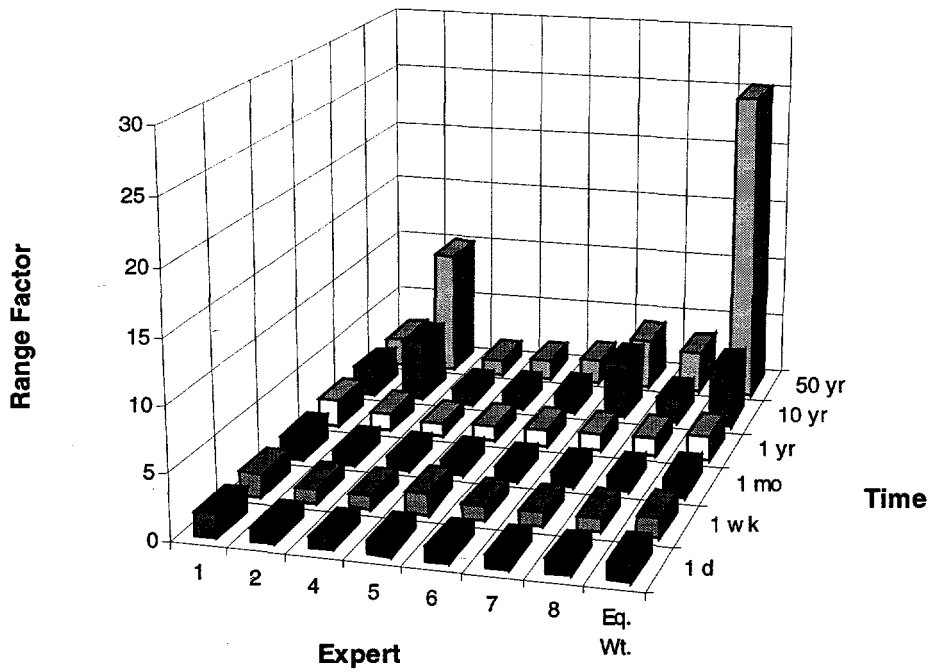

Figure 4.30 Range factors (ratio of 95th/5th percentile) for the retention of plutonium on endosteal bone surfaces in adults.

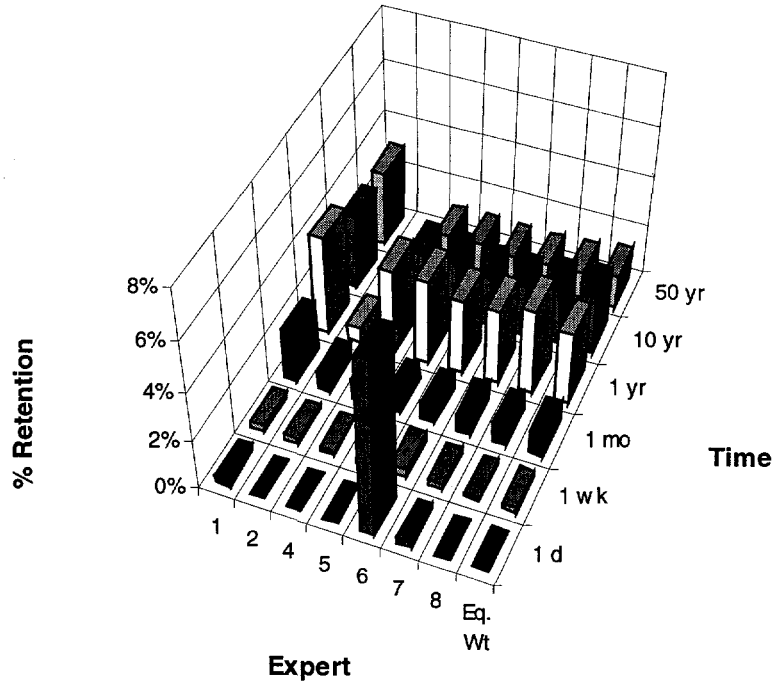

Figure 4.31 Median values for the retention of plutonium in red bone marrow in adults, as percent of total skeletal retention.

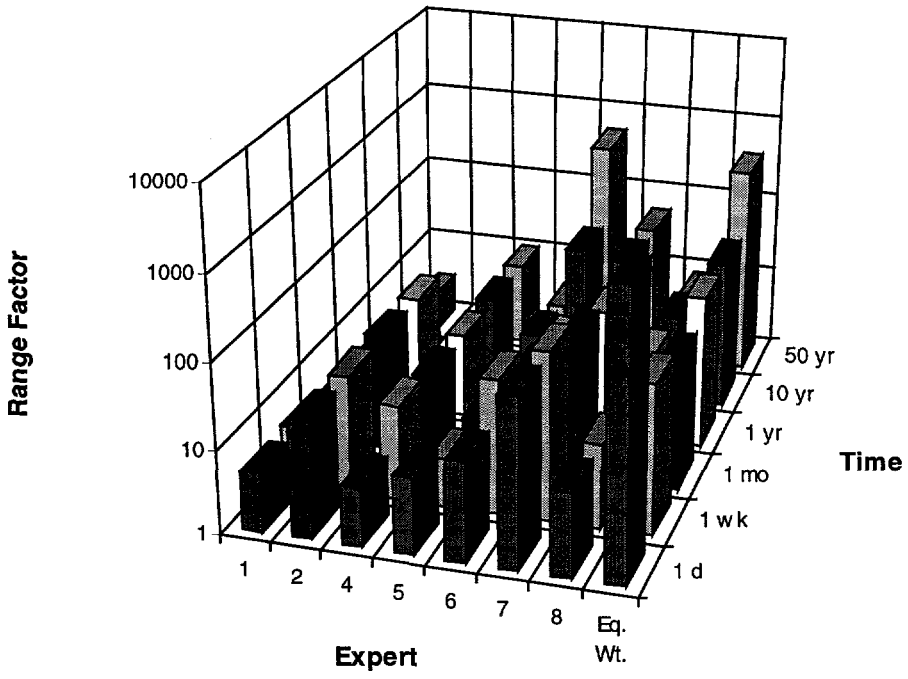

Figure 4.32 Range factors (ratio of 95th/5th percentile) for the retention of plutonium in red bone marrow in adults.

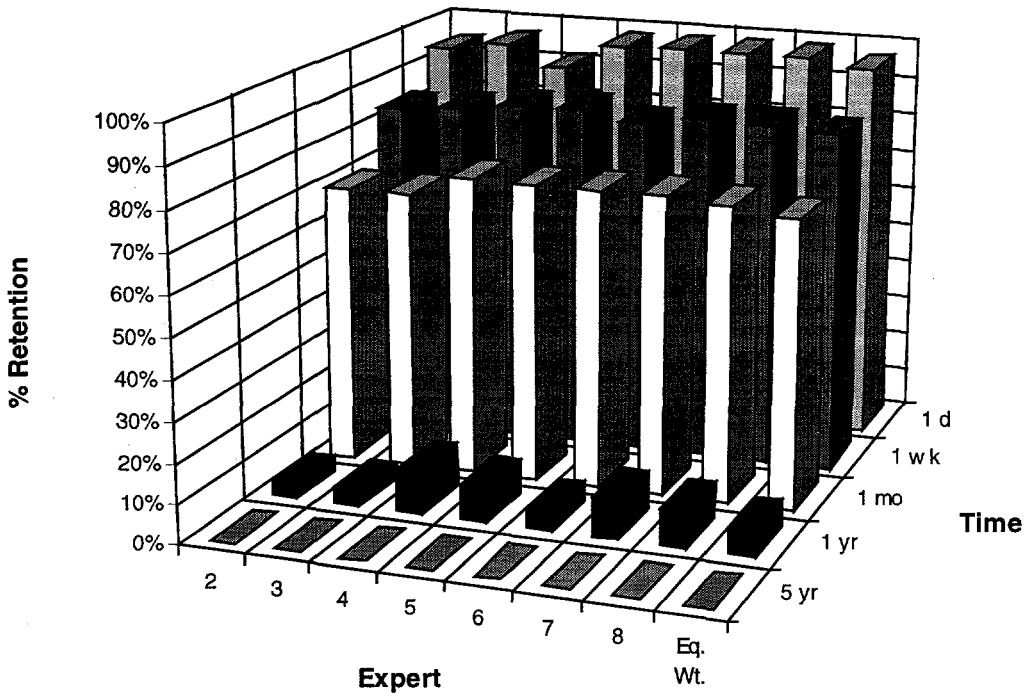

Figure 4.33 Median values for the whole-body retention of cesium in adults, as percent of total reaching blood.

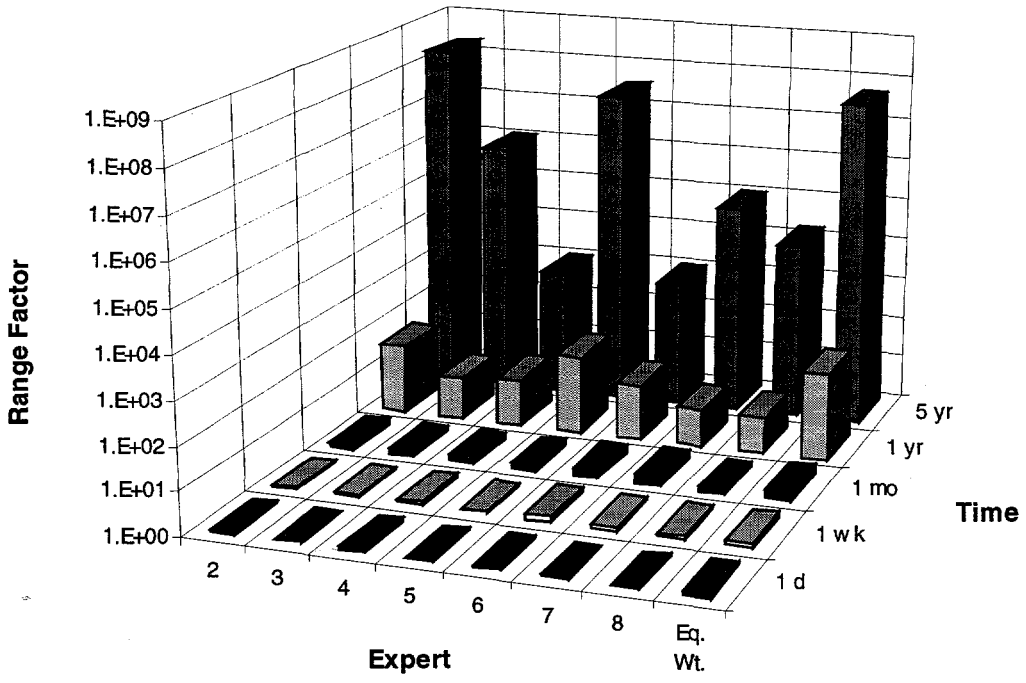

Figure 4.34 Range factors (ratio of 95th/5th percentile) for the for the whole-body retention of cesium in adults.

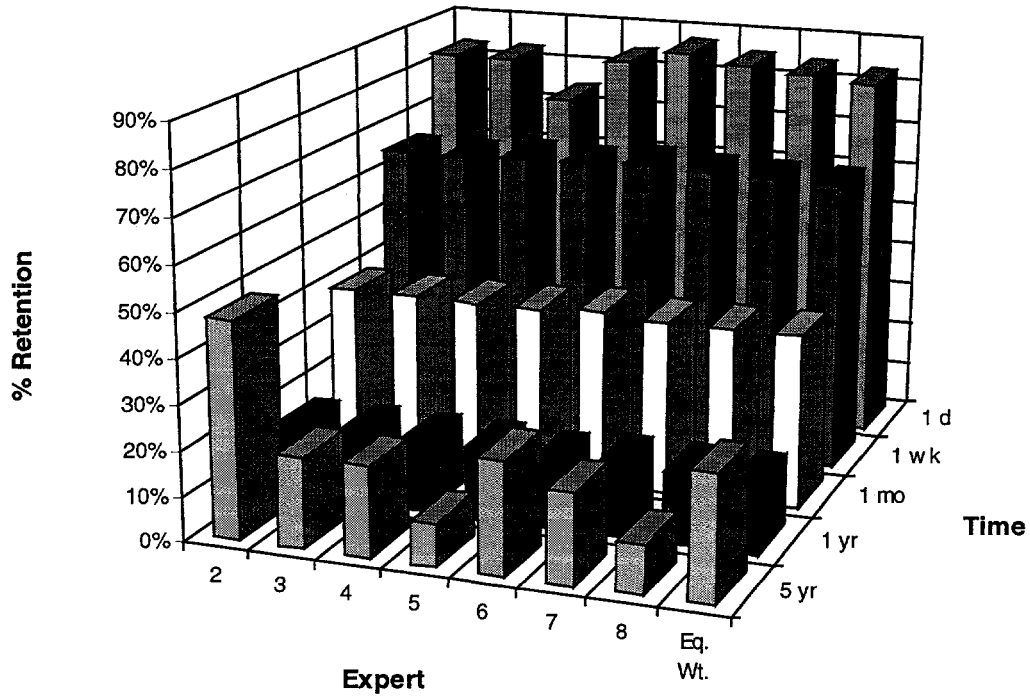

Figure 4.35 Median values for the whole-body retention of ruthenium in adults, as percent of total reaching blood.

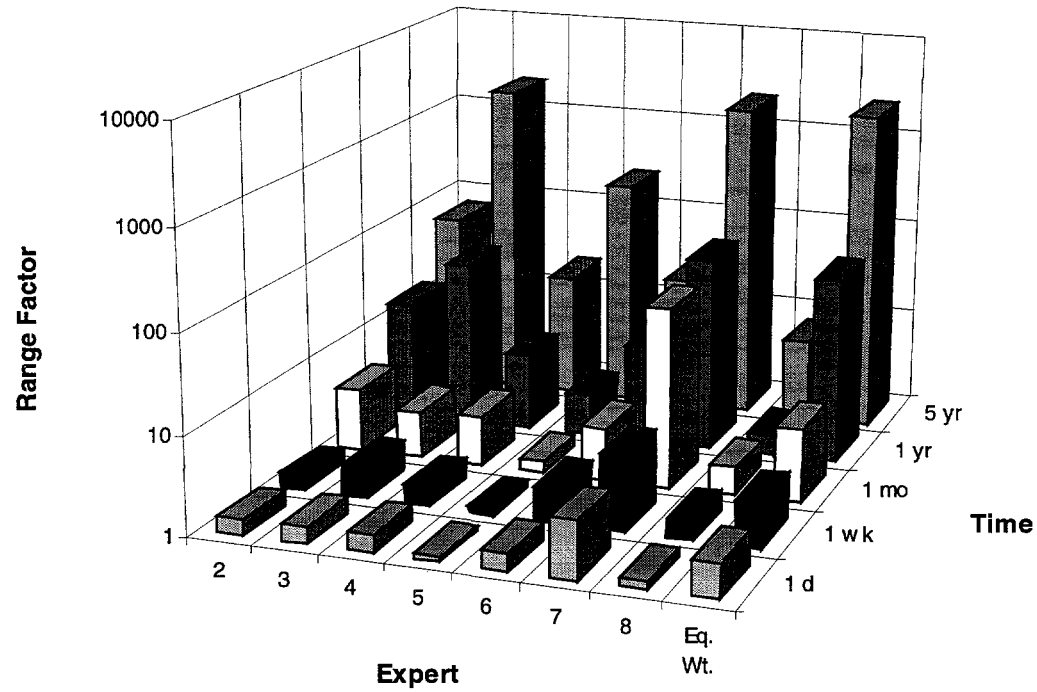

Figure 4.36 Range factors (ratio of 95th/5th percentile) for the for the whole-body retention of ruthenium in adults.

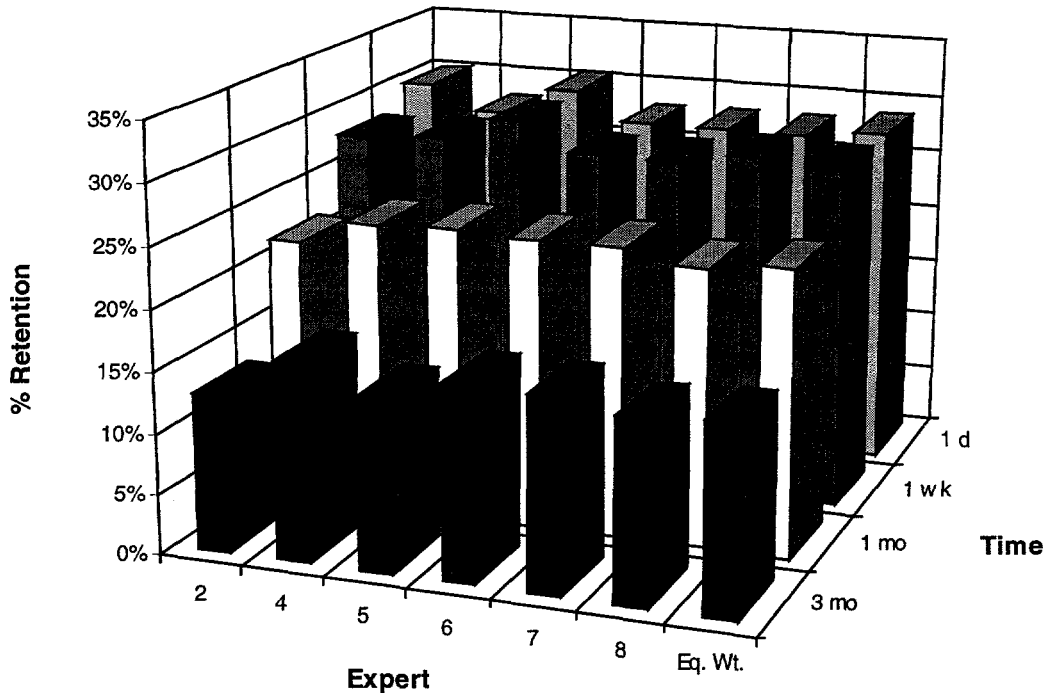

Figure 4.37 Median values for the retention of iodine in the thyroid in adults, as percent of total reaching blood.

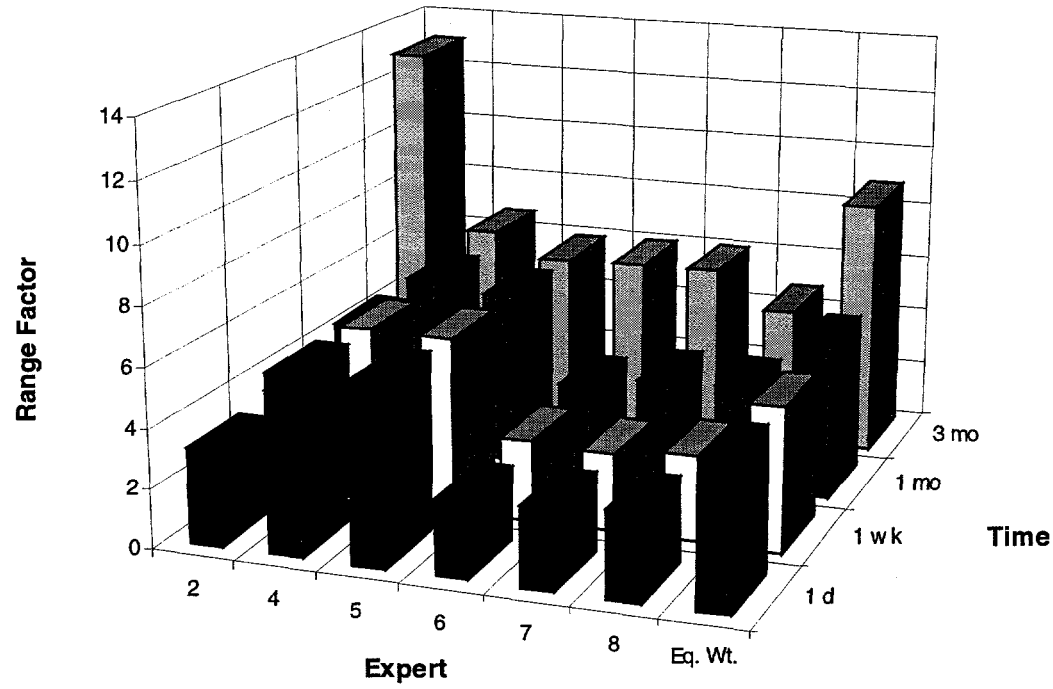

Figure 4.38 Range factors (ratio of 95th/5th percentile) for the retention of iodine in the thyroid in adults.

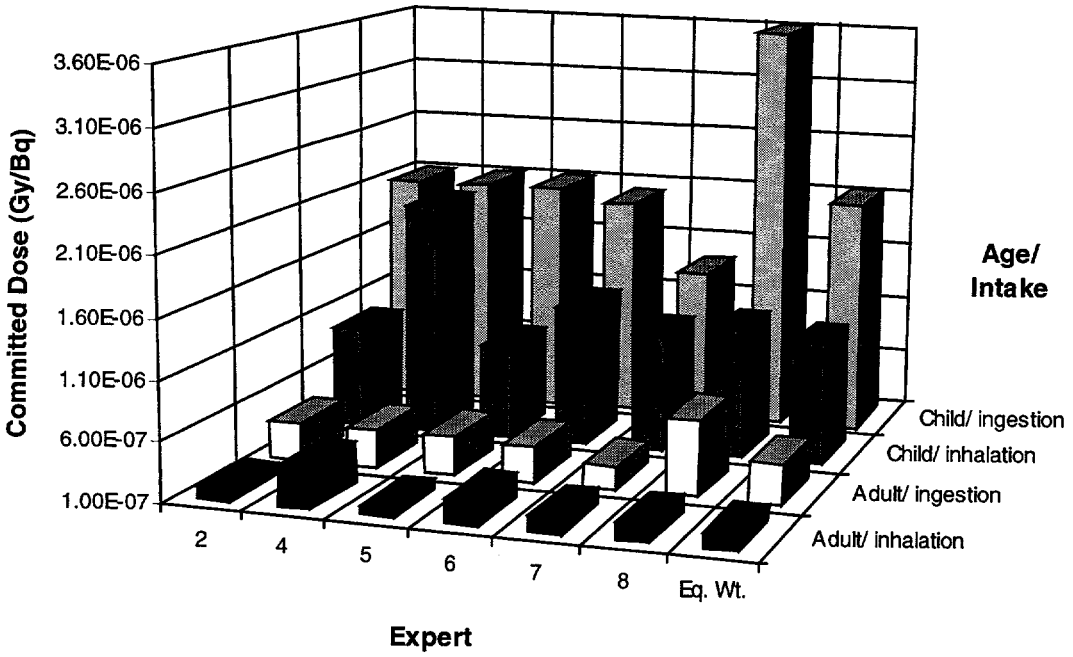

Figure 4.39 Median values for committed dose to the thyroid following intakes of ^{131}I by ingestion or inhalation (1 μm AMAD particles + vapor).

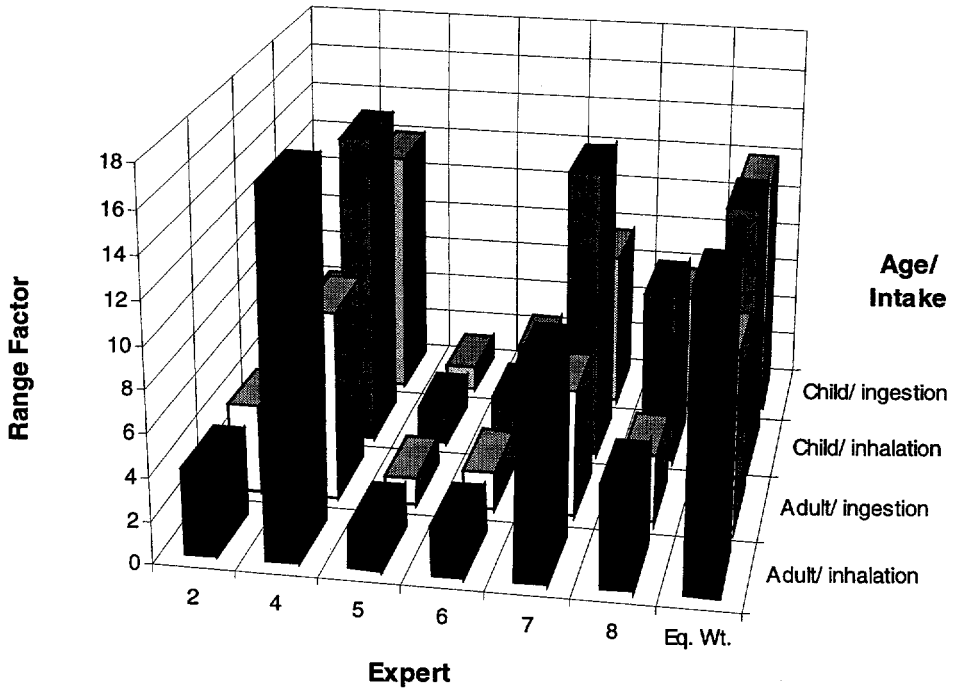

Figure 4.40 Range factors (ratio of 95th/5th percentile) for committed dose to the thyroid following intakes of ^{131}I by ingestion or inhalation (1 μm AMAD particles + vapor).

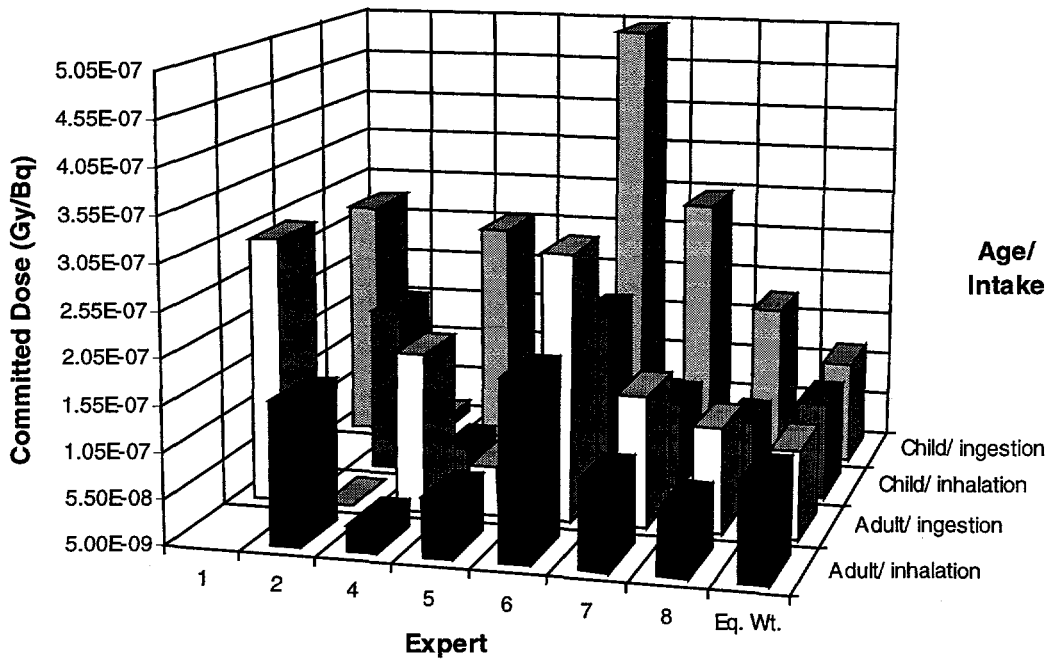

Figure 4.41 Median values for committed dose to red bone marrow following intakes of ^{90}Sr by ingestion or inhalation (1 μm AMAD particles).

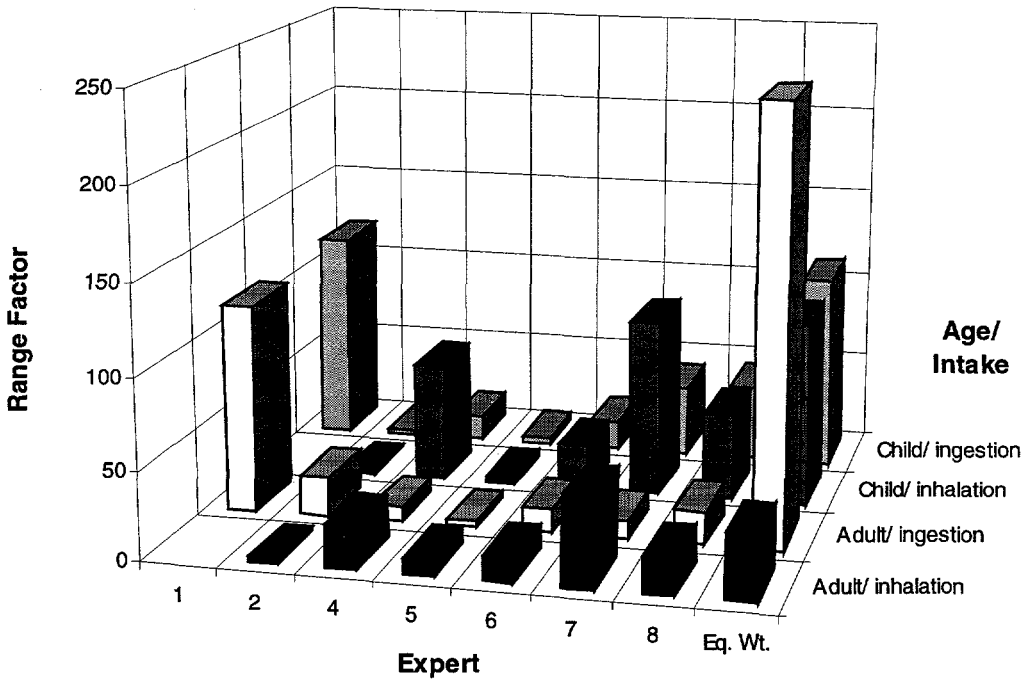

Figure 4.42 Range factors (ratio of 95th/5th percentile) for committed dose to red bone marrow following intakes of ^{90}Sr by ingestion or inhalation.

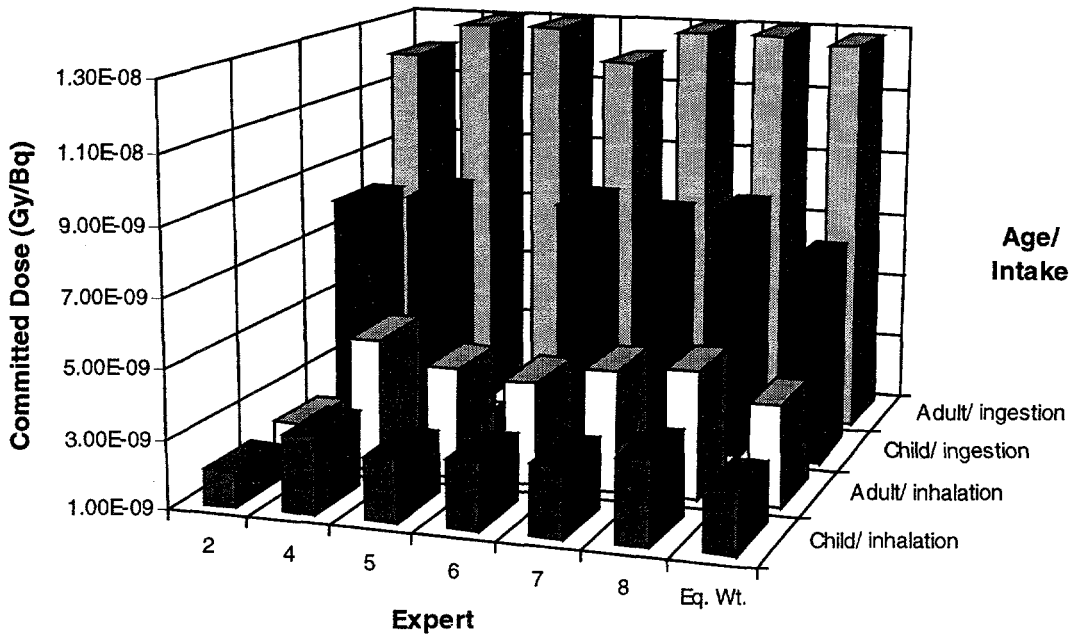

Figure 4.43 Median values for committed dose to red bone marrow following intakes of ^{137}Cs by ingestion or inhalation (1 μm AMAD particles).

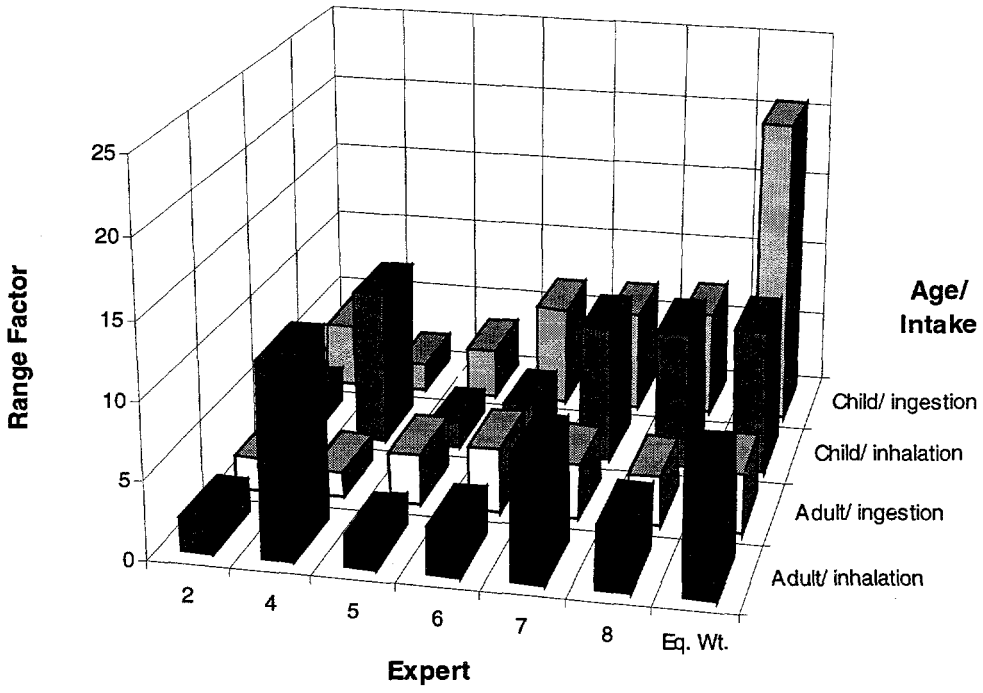

Figure 4.44 Range factors (ratio of 95th/5th percentile) for committed dose to red bone marrow following intakes of ^{137}Cs by ingestion or inhalation.

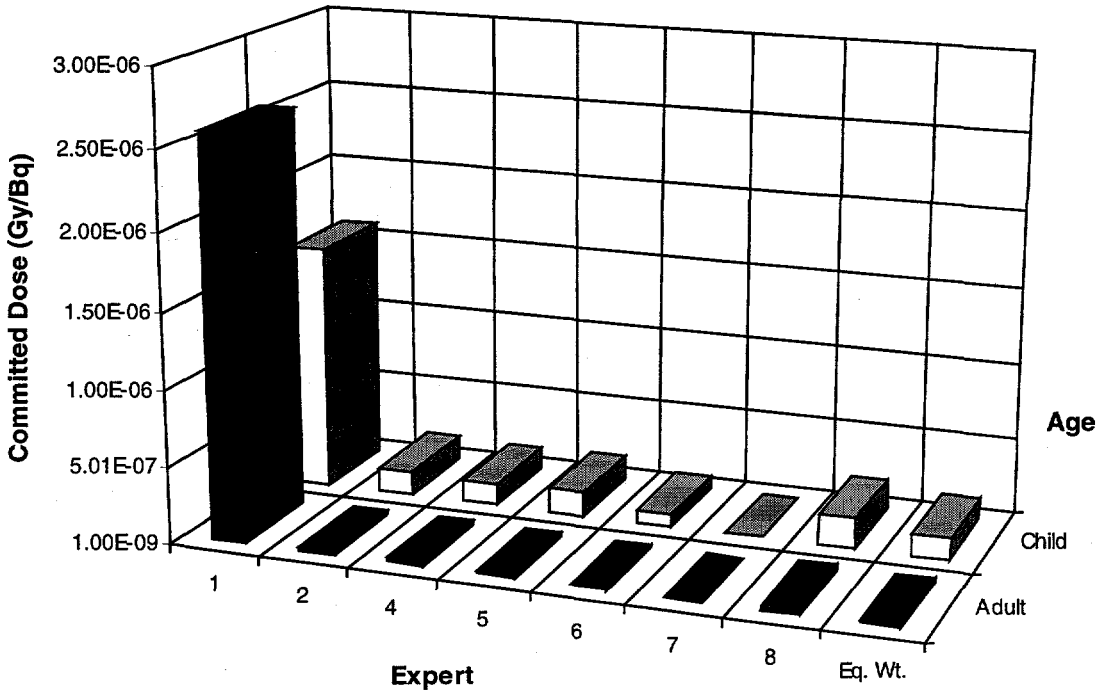

Figure 4.45 Median values for committed dose to red bone marrow following intakes of ^{144}Ce by inhalation (1 μm AMAD particles).

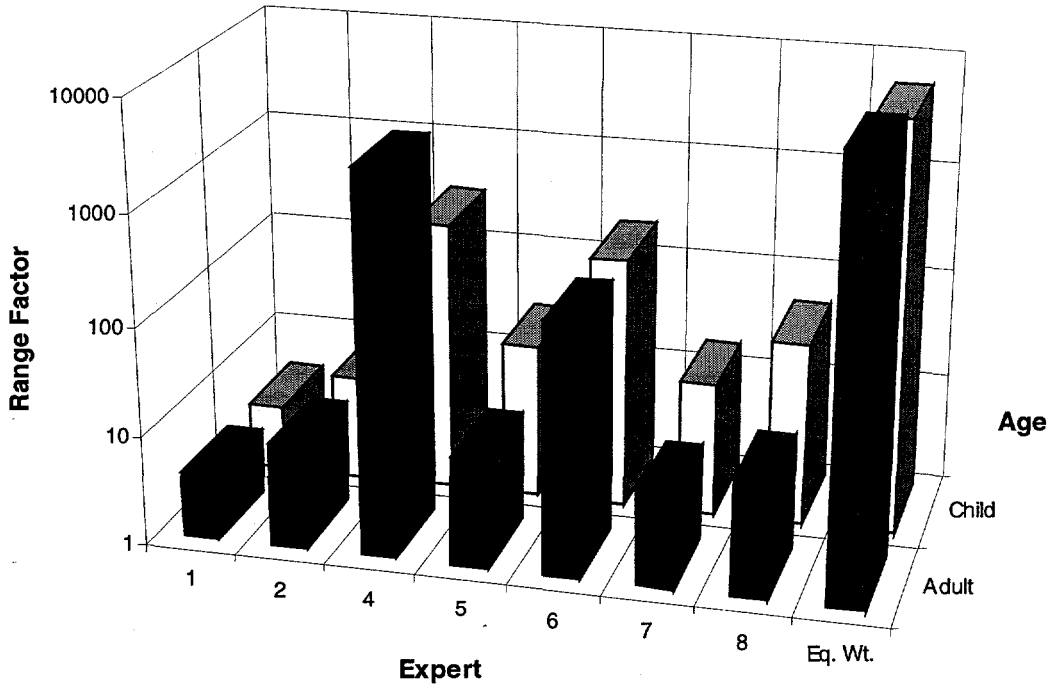

Figure 4.46 Range factors (ratio of 95th/5th percentile) for committed dose to red bone marrow following intakes of ^{144}Ce by inhalation.

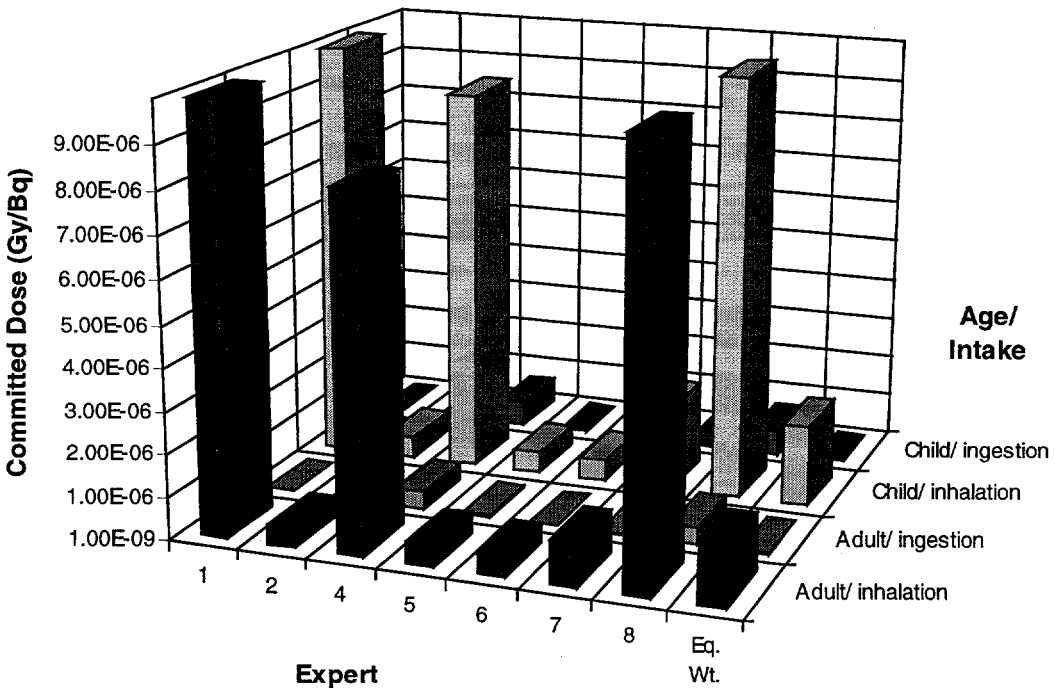

Figure 4.47 Median values for committed dose to red bone marrow following intakes of ^{239}Pu by ingestion or inhalation (1 μm AMAD particles).

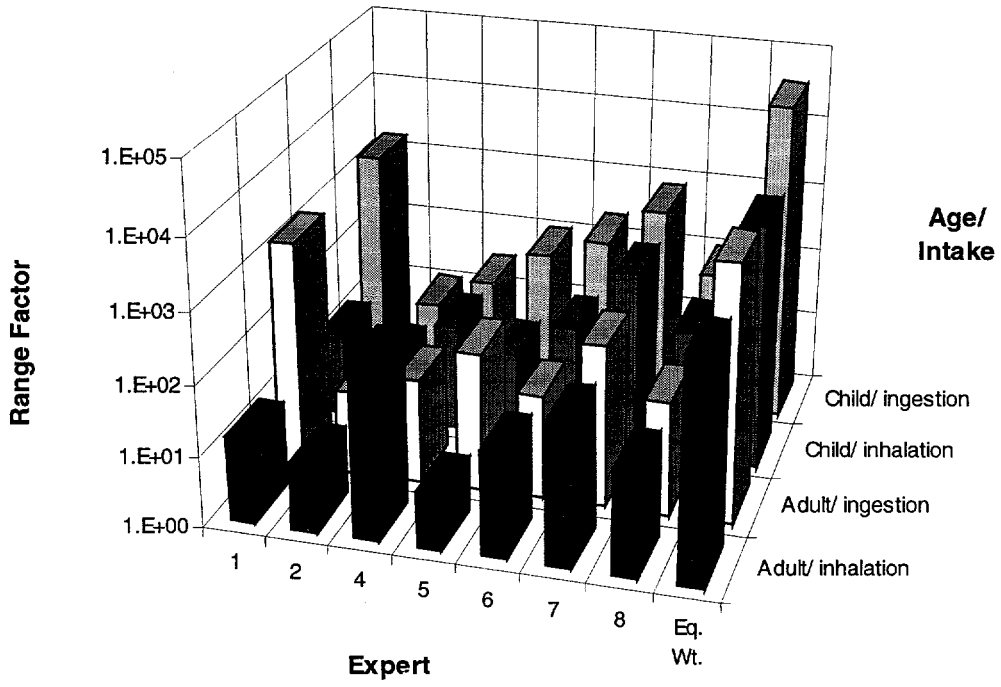

Figure 4.48 Range factors (ratio of 95th/5th percentile) for committed dose to red bone marrow following intakes of ^{239}Pu by ingestion or inhalation.

5. Summary and Conclusions

5.1 Project Accomplishments

In this project, teams supported by the NRC and EC were able to work together successfully on a process for developing and implementing uncertainty distributions on consequence code input variables. Staff on both teams with diverse experience and expertise were responsible for a creative and synergistic interplay of ideas that would not have been possible in isolation. Potential deficiencies in processes and methodologies that might not have received sufficient attention in independent studies were addressed. The final product of this study, therefore, was enhanced by this cooperation.

Distributions on parameters important for internal dose calculations were successfully elicited from distinguished experts. To fulfill the requirement that parameters should in principle be measurable, elicitation parameters were selected that represent input data for the calculation or organ dose coefficients. Thus, uncertainty in biokinetic parameters for selected radionuclides was addressed, considering inhalation, ingestion, and distribution and retention in body tissues. Aggregated distributions, developed by combining the individual elicited distributions, represent state-of-the-art knowledge in the area of radionuclide biokinetics. Experts also provided distributions on organ dose coefficients for inhalation and ingestion of selected radionuclides that represent ACA code inputs. The distributions for the biokinetics parameters and dose coefficients are available on computer media and can be obtained from the project staff.

5.2 Uncertainty Included in Distributions

The distributions elicited from the experts concern physically measurable quantities, conditional on the case structures provided to the experts. The individual distributions contain uncertainty that includes the coarseness of the initial conditions of the case structure and natural variability. The experts were not directed to use any particular modeling approach but were allowed to use whatever models, tools, and perspectives they considered appropriate for the problem. The elicited distributions obtained were developed by the experts from a variety of information sources. The aggregated internal dosimetry parameter distributions capture the uncertainty in the inhalation, ingestion, and systemic processes to be expected after induction of radiation in the body.

Mathematical processing of the aggregated distributions on biokinetic parameters will be necessary to produce distributions on the dose coefficients used in the MACCS and COSYMA codes. The results of this work will be published separately. The calculated distribution on dose coefficients will be compared with those provided directly by the experts.

5.3 Uncertainty Assessment with Fixed Models

The results of this project will allow the internal dosimetry components of consequence uncertainty analyses to be performed in a manner consistent with the NUREG-1150 methodology. The risk integration step in the NUREG-1150 methodology (the step in which the uncertainty in all modules of the analyses was assessed) relied on Latin hypercube sampling (LHS) techniques. The dose coefficient distributions will be available in a form compatible with LHS and other sampling techniques. The distributions obtained will, in principle, allow the uncertainty analyst to perform consequence uncertainty studies on any inhalation and ingestion model available. In addition, the experts provided numerical data on dependencies between the elicited kinetics parameters and between the assessed dose coefficients for inhalation and ingestion.

The methods of this project were also consistent with the NUREG-1150 philosophy because all modeling perspectives are included and consensus among the experts was not required. Although this project focused on the development of distributions for MACCS and COSYMA input parameters, the elicited information is not specific to a model and consequently can used in other approaches. In addition, the development of distributions over physically measurable parameters means that the distributions will have applications beyond the scope of consequence code uncertainty analysis (e.g., emergency response planning). The library of uncertainty distributions on biokinetic parameters and dose coefficients should provide a valuable resource for applications outside

the project. The distributions may provide additional insights regarding areas where current consequence codes are deficient, and they can be a useful guide for directing future research.

5.4 Conclusions

Valuable information has been obtained from this exercise. The goal of creating a library of uncertainty distributions for biokinetic parameters was fulfilled. In addition, uncertainty distributions on dose coefficients were obtained from the experts and will be compared with values calculated from the biokinetic data in a separate publication. In this exercise, formal expert judgment elicitation has proven to be a valuable vehicle for synthesizing the best available information by a highly qualified group.

With a thoughtfully designed elicitation approach that addresses such issues as selection of elicitation variables, development of case structure, probability training, communication between the experts and project staff, and documentation of the results and rationale—followed by an appropriate application of the elicited information—expert judgment elicitation can play an important role. Indeed, it possibly will become the only alternative for assembling the information required to make a decision at a particular time when it is impractical to perform experiments or when the available experimental results do not lead to unambiguous and a noncontroversial conclusions.