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Probabilistic Accident Consequence Uncertainty Analysis

Food Chain Uncertainty Assessment

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 parameters. This report refers only to the food chain part of the study. The work relating to external doses is described in a companion report. The goal again was to develop a library of uncertainty distributions for the selected consequence parameters. Sixteen experts from eight countries were selected and two expert panels were set up—one to evaluate soil/plant transfer processes and one on food intake and radionuclide transport processes in animals. Their results were processed with an equal-weighting aggregation method, and the aggregated distributions will be processed into the code input variables of the food chain models in use for COSYMA (called FARMLAND) and for MACCS (called COMIDA).

Further expert judgment studies are being undertaken to examine the uncertainty in other aspects of probabilistic accident consequence codes. Finally, the uncertainties will be propagated through the codes and the uncertainties in the code predictions will be quantified.

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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 sixteen experts was formed to compile credible and traceable uncertainty distributions for food chain variables that affect calculations of offsite consequences. 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. Volume 2 contains appendices that include (1) a summary of the MACCS and COSYMA consequence codes, (2) the elicitation questionnaires and case structures for both panels, (3) the rationales and results for the panels on soil and plant transfer and animal transfer, (4) short biographies of the experts, and (5) the aggregated results of their responses.

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List of Acronyms

ACA	accident consequence analysis
ACC	accident consequence codes
CDF	cumulative distribution function
COSYMA	code system from MARIA (method for assessing the radiological impact of accidents)
EC	European Commission
LHS	Latin hypercube sampling
MACCS	MELCOR accident consequence code system
NRC	Nuclear Regulatory Commission
NSA	normalized specific activity
NRPB	National Radiological Protection Board
PRA	probabilistic risk assessment

Executive Summary

Introduction

The US Nuclear Regulatory Commission (NRC) and the European Commission (EC) have co-sponsored an uncertainty analysis of their respective probabilistic 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 by the experts involved in the numerous phenomenological areas of a consequence analysis. In addition, both organizations were aware of the importance of using uncertainty analysis in making decisions on prioritizing 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 respective code input variables using a formal expert judgment elicitation process.

The specific goals of this study are to: (1) develop a library of uncertainty distributions for the processes of radionuclide distribution in the food chain by using a formal expert judgment elicitation process, and (2) further determine whether the technology is appropriate for the development of credible uncertainty distributions on the input variables of the food chain models used in MACCS (COMIDA) and COSYMA (FARMLAND). This report focuses on the methods used in the food chain study and its results.

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. 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 US.

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 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 variable definitions; more important, the physical quantities elicited are not tied to any particular model and thus have a much wider potential application. The actual 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

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 in accordance with the sophistication of the respective code models 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 phenomenological experts internal to the project and refined.

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

Food chain experts

Soil and Plant Processes		Animal Processes	
Expert	**Country**	**Expert**	**Country**
Martin Frissel	Netherlands	Peter Coughtrey	UK
John Garland	UK	François Daburon	France
René Kirchmann	Belgium	Owen Hoffman[a]	US
Gerhard Pröhl	Germany	Brenda Howard	UK
George Shaw	UK	Jack Pearce	UK
Ward Whicker[a]	US	Per Strand	Norway
Lynn Anspaugh[b]	US	Christian Vandecasteele	Belgium
		Gaby Voigt	Germany
		Gerry Ward	US

[a] Drs. Whicker and Hoffman also provided support to both panels.
[b] Dr. Anspaugh provided some limited information.

part.) The committees were charged with selecting experts based on 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. Two panels were formed: one on soil and plant transfer processes and one on food intake and radionuclide transfer processes in animals. Brief biographies are provided in Volume 2. A brief 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

Separate training meetings were 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 both fields of the food chain (food intake and radionuclide transfer processes in animals and soil and plant transfer processes). The training meetings were 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 questions.) 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 questionnaire on case structure for food intake and radionuclide transfer in animals was modified for the American meeting from the original given to the European experts due to very different farming practices. In both meetings, a method to extract quantitative information on knowledge dependencies between the elicitation variables was developed.

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

All of the European experts were elicited individually in separate sessions. During the elicitation for the soil and plant panel, the majority of the experts felt strongly that additional elicitation variables on the interception factor should be considered, that is, interception by plants during wet and dry deposition events as well as the generic value required. All European experts provided these additional data.

The American experts were elicited individually, after a common session during which the experts presented the approach they had taken in answering the questions posed but did not reveal their probability assessments in order to avoid biasing the other experts.

In both European and American elicitation sessions, an attempt was made to use the method developed to extract quantitative information on knowledge dependencies. 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 with-in the program to assign all experts equal weight, that is, all experts on each panel would be treated as being equally credible. One of the primary reasons 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 results. These results will be reported separately. The following aggregation scheme was used to combine unique distributions from individual experts for all weighting schemes:

1. A continuous distribution was constructed from the information that each expert gave.

2. This continuous distribution was then averaged with the continuous distributions provided by the other experts. This was done by averaging the different probabilities given by the experts for each unique value of the elicitation variable (in this way, extreme values of a parameter are not averaged away, but are assigned appropriate aggregate probabilities).

Additional processing may be required in order to use the elicited distributions in an uncertainty study. This processing is documented elsewhere.

Results and Conclusions

Input from a group of highly qualified experts was used to develop uncertainty distributions. 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 were developed 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 variables and code input variables are available on computer media and can be obtained from the project staff.

The aggregated estimates of soil and plant distributions capture the uncertainty in soil migration, the fixation in soil of the relevant radionuclides, and root uptake concentration factors for generic and specified soils. They cover interception factors, resuspension factors, and retention times of radionuclides. Furthermore, they capture the uncertainty for concentrations of radionuclides in grain at harvest, in root crops, and in green vegetables.

The aggregated elicited distributions for animal processes capture the uncertainty in consumption rates, and reflect different feeding and grazing practices in Europe and America. They cover transfer processes in animals, such as transfer to meat, milk, and eggs. Finally, they capture the uncertainty in biological half-lives of the relevant radionuclides in animals.

The experts were also asked to provide quantitative data on dependencies among the elicited variables. The results show areas where high dependency or no dependency was identified.

This exercise provided valuable information. Thus, the goal of creating a library of food chain uncertainty distributions that 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 for consequence code input variables. Staff with diverse experience and expertise 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 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. 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 risk and the appropriate use of the results of risk assessments in regulatory activities.

This document describes an ongoing project designed to assess the uncertainty in the MACCS and COSYMA calculations for offsite consequences of radionuclide releases in hypothetical nuclear power plant accidents. The first exercise performed 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 for important parameters in the food chain calculations of the codes. Other reports describe the elicitation of uncertainty distributions on variables in other code areas. The elicited distributions will be used in consequence uncertainty analyses using the MACCS and COSYMA consequence 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 as well. 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. The 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 utilize 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 the 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 joint 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 obtain 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 a consequence calculation, 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 not be subjected to a joint expert elicitation.

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, food chain pathways, dosimetry, etc.).

This report provides the results of the expert judgment exercise on the food chain parameters. The exercise

Table 1.1 Phenomenological areas for joint NRC/EC study

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

had as its goal developing a library of uncertainty distributions in food chain areas (both soil/plant transfer and food intake and transfer in animals) that could be used in many different consequence uncertainty studies employing the MACCS and COSYMA consequence codes.

The information in this report also has potential uses outside the reactor safety community (e.g., aerospace safety, chemical ingestion safety, general pathology sciences, etc.).

The state-of-the-art 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 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.

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 or associated food chain software programs like FARMLAND or COMIDA, 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

July 1991	First meeting between the EC and the NRC held in the US. Possibility of a joint consequence uncertainty project discussed.
October 1991	Second meeting between the NRC and the EC held in Europe. Further programmatic and technical details discussed.
January 1992	Outlined specifications of the project submitted to NRC and EC management.
April 1992	Agreement between EC and NRC management to proceed with the implementation planning stage of the joint effort.
May 1992	General planning meeting in Brussels. Possibility of proceeding with one panel to demonstrate the efficacy and feasibility of the joint effort before continuing with the remainder of the study discussed.
September 1992	Decision to proceed with one panel on atmospheric dispersion and deposition parameters.
November 1992	Kickoff meeting for atmospheric dispersion and deposition expert panels.
December 1993	Draft report on the results of the atmospheric dispersion and deposition expert panels published for review by NRC and EC.

January 1994	Kickoff meeting in the UK to proceed with three more panels in the EC: two food chain panels and one panel on deposited material and the calculation of related doses.
April 1994	Joint EC/NRC planning meeting held in Brussels for the panels on the food chain and deposited material/related doses.
September 1994	Decision by NRC management to join the panels on the food chain and deposited material/related doses.
December 1994	Dry run meetings held in Europe for experts to review the case structure documents.
January 1995	Publication of Vol. 1 of dispersion and deposition uncertainty assessment.
	Training meeting for the European experts on the food chain and deposited material/related doses.
February/ March 1995	Elicitation meetings for the European experts on the food chain and deposited material/related doses.
April 1995	Training meeting for the US experts on the food chain and deposited material/related doses.
July 1995	Elicitation meeting for the US experts on the food chain and deposited material/related doses.
November 1995	Processing meeting.
February 1996	Draft reports.
1996	Final reports.

1.6 Structure of Document

Section 2 contains a discussion of the technical issues that were considered before the actual elicitation process. It provides a short characterization of consequence uncertainty studies, briefly describes why uncertainty information is necessary for decision making, briefly describes the MACCS and COSYMA models, describes the process used to select 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 conclusions are presented in Section 5.

Volume 2 of this report contains the technical appendices. Appendix A contains information on the principles of probability assessment, equal- and performance-based weighting, and a summary of MACCS and COSYMA consequence codes. The case structures are contained in Appendices B and D. The rationale provided by the experts and a summary of results are provided in Appendices C and E. Appendix F has short biographies of the food chain experts and Appendix G 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 when 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 analysis 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 value 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. Uncertainty in variables 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. Mathematical 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 involved in the process.

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 in the main report on atmospheric dispersion and deposition[3] briefly describes the history of consequence uncertainty analyses. The US and European developments are also 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;
- 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 statistical 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 Food Chain Models Used with MACCS and COSYMA

The descriptions of COSYMA and MACCS are presented solely to familiarize the readers with the models. The expert elicitations are not constrained by these models.

ACA codes produce a number of results (endpoints) that require information on the contamination of the food chain and the subsequent ingestion of contaminated foodstuffs. To calculate these endpoints, these codes require input from a terrestrial food chain model. The COSYMA code does not contain such a model, while the MACCS code contains only a simplistic food chain model. The latest MACCS model, COMIDA, is external to the code. Thus information from data libraries provided by a food chain model must be input to the codes.

2.4.1 Food Chain Models Used with COSYMA

The food chain models currently linked with COSYMA to produce the required data libraries are the FARMLAND model[4] of the National Radiological Protection Board (NRPB) and the ECOSYS model[5] of the GSF-Research Center for Environment and Health (GSF). The relationship between the models and COSYMA is shown schematically in Figure 2.1. To produce the inventories and integrals needed by COSYMA, the food chain models require a considerable input of basic food chain data, for example, the interception factor for pasture grass, the root uptake concentration factors for all radionuclides of interest, and transfer factors from animal feed to animal products. The major processes included in such food chain

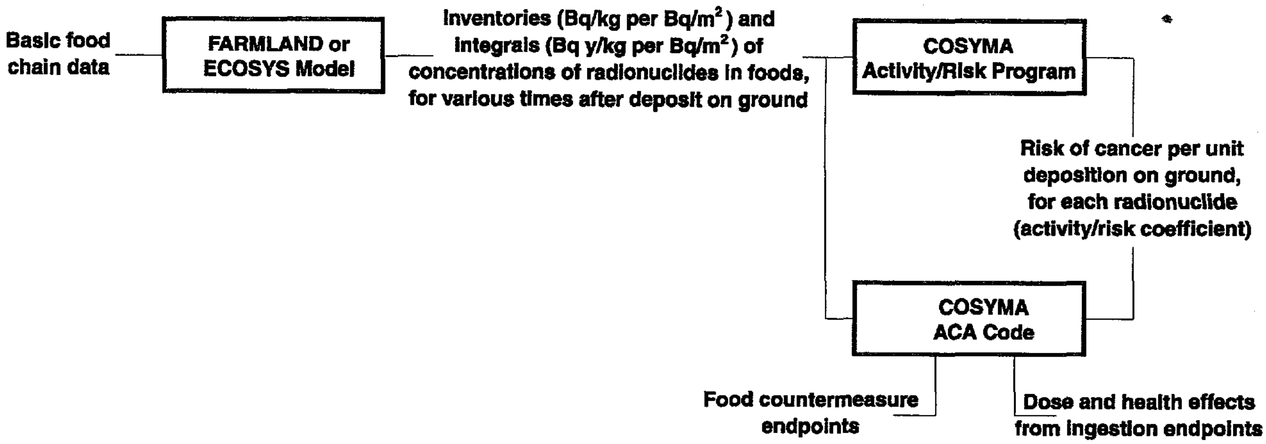

Figure 2.1 Link between FARMLAND or ECOSYS and COSYMA ingestion calculations.

models and the data required are discussed in more detail in Section 3.

The input to COSYMA from the terrestrial food chain models is in the form of instantaneous and integrated activity concentrations in a number of foods as a function of time after deposition, for a number of radionuclides. The units of this input are thus Bq kg^{-1} (instantaneous concentrations) and Bq y kg^{-1} (integrals of concentration). Nine food types are considered in COSYMA and are shown in Table 2.1. These data libraries are provided for deposition occurring on January 1 and July 1, to represent accidents occurring in winter and summer. Depending on the time of year, one or the other of these files is used. Where important, the in-growth of daughters (e.g., americium-241 ingrowth from plutonium-241) is considered in the data library.

Table 2.1 Foodstuffs considered in COSYMA

Milk/milk products	Grain products
Beef and offal[a]	Leafy vegetables
Sheep meat[a] and offal[a]	Root vegetables
Pork	Nonleafy vegetables[b]
	Potatoes

[a] Not considered in ECOSYS.
[b] Not modeled explicitly in FARMLAND.

Ingestion doses in COSYMA are calculated from the amount of radioactivity deposited, the concentration of activity in foods for a unit deposition, the consumption rate or amount of food produced, and the dose per unit of radioactivity ingested. The calculation of the risk of late health effects, allowing for the time variation of the dose, the age distribution of the population, and the delay between exposure and occurrence of the effect, requires the evaluation of complex multiple integrals. These integrals have been precalculated for use in COSYMA, for the risk of each cancer type for a unit concentration in air and unit deposition of each nuclide. The integrals relating the probability of health effects to air concentration or to deposition are referred to as "activity risk coefficients."

The discussion here is limited to the FARMLAND model because this model is used to derive uncertainty distributions on the input to the COSYMA code in the later parts of this study. However, it should be noted that this study has been designed so that the resulting library of uncertainty distributions can be used for many different uncertainty studies in the future. The main physical processes modeled in consequence assessment codes, such as MACCS and COSYMA, and in the underlying food chain models, are the same even though the models representing the processes may be different.

The FARMLAND model[4] is a general, dynamic model with a modular structure. Separate submodels have been developed for each of the major crop types and animals considered, and these can be linked to represent the situation of radiological interest. The movement of radionuclides within each module is represented by transfers between interconnected compartments, and within each module it is assumed that first-order kinetics apply (i.e., the transfer of material between compartments is proportional to the inventory in the source compartment). The main advantage of a compartmental approach is that it provides a flexible system that can accommodate large differences in the amount of detail included in various parts of the system. Radioactive decay is taken into account in the model by a loss term from each compartment. The compartmental models are solved using a matrix technique for solving coupled linear first-order differential equations.

Where data are available, the models are dynamic, and changes with time in the physical system are modeled. In particular, element-specific modules have been developed for animals so that the important biological and metabolic processes for those elements whose transfer through terrestrial food chains is significant can be taken into account. For some parts of the food chain, however, there are few data on the short-term time dependence of transfer (for example, root uptake into plants) and for these parts of the model, quasi-equilibrium is assumed.

For any food chain model, a set of default variable values is specified for a given application. These variables form the basic input to the model and are used to determine the rate constants that describe the transfer between compartments in the model. ECOSYS requires some different variables than FARMLAND, although the important variables describing the movement of radioactivity through the food chain are common to both models.

The food chain models used in COSYMA take into account agricultural practices in their modeling of the transfer of radionuclides to food. This is of particular importance for accidental releases when the time of year has a marked influence on the transfer of radionuclides through the food chain. The extremes are a release in winter, when relatively few crops are grown and livestock is generally housed indoors, and a release in the summer at the height of the growing season, when cattle and sheep are grazing. The influence of the time of year of the release depends on the agricultural practices of an area. For use in COSYMA, FARMLAND contains assumptions on agricultural practices that are appropriate for the EC; these are based on a review of information on farming practices across Europe. The default agricultural practices assumed in COSYMA for the EC are listed in Table 2.2 for information.

Table 2.2 Agricultural practices for the EC assumed in COSYMA

Product	Agricultural practice
Green vegetables	Continuous harvesting throughout the year
Winter wheat	Sown: October 1 Harvested: August 5
Spring wheat	Sown: April 15 Harvested: August 15
Root vegetables	Planted: May 1 Harvested: August 1 to October 31
Potatoes	Planted: May 15 Harvested: August 1 to September 25
Cattle - dairy and beef	Graze pasture: April 15 to October 31 Eat hay/silage: November 1 to April 15
Pigs	Eat winter wheat grown and harvested as described above
Sheep	Graze pasture: April 15 to October 31 Eat hay/silage: November 1 to April 15

2.4.2 Food Chain Model Used with MACCS (COMIDA)

The most recent version of the MACCS analysis package, MACCS2, includes the dynamic food chain model, COMIDA.[6] The major differences between COMIDA and the steady-state models previously used are COMIDA's ability to: (1) dynamically simulate important vegetation and soil transport processes; (2) account for seasonal changes in these transport processes using a single set of input variables; (3) evaluate discrete deposition dates and agricultural events (e.g., tillage, multiple hay harvests); (4) provide concentrations in individual food products and contributions from specific feed sources (e.g., grazing vs. stored grain); and (5) provide output for any year following a deposition event.

The COMIDA code provides estimates of radionuclide concentrations in crops for human consumption at yearly harvest intervals (Bq kg^{-1} crop per Bq m^{-2} deposition) and integrated concentrations in animal products (Bq d kg^{-1} animal product per Bq m^{-2}) for a unit of acute deposition. COMIDA2 is an interface shell between MACCS2 and COMIDA that creates a MACCS2 input file containing data on dose per unit of deposition for up to nine different accident dates and calculates projected and accumulated doses per unit of deposition based on the data calculated by COMIDA. COMIDA2 calculates projected and accumulated doses based on food consumption rates, agricultural productivity, and processing losses.

The conceptual model for the COMIDA food chain model is provided in Figure 2.2. COMIDA models five types of crops: leafy vegetables, root vegetables, grain, fruit, and legumes. For animal products, COMIDA calculates integrated concentrations in milk, beef, poultry, and a user-defined "other animal" (e.g., pork and lamb). Four animal feed sources are evaluated: pasture grass, hay, grain, and legumes (soybeans), in addition to ingestion of soil.

Time-variable concentrations are dynamically modeled for five compartments: (1) vegetation surface (Qvs), (2) vegetation internal tissues (Qvi), (3) surface soil (Qss), (4) labile (active root zone) soil (Qrs), (5) and fixed soil (Qfs). To explicitly treat the ingrowth and differential transport of radioactive progeny, an additional set of modeling compartments is defined for each decay chain member (four members, including parent, maximum). Each decay chain model is identical to that shown in Figure 2.2 with the addition of transport (ingrowth) from each parent compartment to the same progeny compartment. The model therefore evaluates up to 20 compartments—five compartments for each of the four decay chain members.

The vegetation/soil model is used to calculate: (1) human crop inventories at harvest; (2) integrated pasture grass inventories while animals are grazing; (3) harvested animal feed storage inventories; and (4) integrated surface soil inventories for soil ingestion by animals. The model simulates both continuous and discrete transport processes in order to move radioactivity between modeling compartments. The continuous processes are assumed to be first-order where the rate of transfer of radioactivity from a compartment is proportional to the amount remaining in that compartment. As such, they may be described mathematically by a rate constant that is the fraction of radioactivity removed from a compartment per unit of time. Except for the root uptake process, the rate of transfer of radioactivity between compartments (Bq m^{-2} d^{-1}) is the product of the current activity in the source compartment (Bq m^{-2}) and the rate constant (d^{-1}). The root uptake rate (Rup) is assumed to be a function of the plant growth rate (dB/dt), which is calculated in COMIDA using a logistic biomass growth model. The current plant biomass at the deposition date is used to calculate the fraction of fallout allocated between vegetation and soil compartments.

Calculations of animal product concentrations are based on the assumption that they are in equilibrium with the time-variable concentrations in vegetation and soil being consumed by the animal. Because animal slaughter and milk production occur on a somewhat continuous basis (as opposed to a discrete crop harvest), COMIDA calculates integrated animal product concentrations for consecutive 365-day "accident years" after the date of deposition.

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 mentioned previously:

1. The current code models and submodels cannot be modified to facilitate the uncertainty studies, and

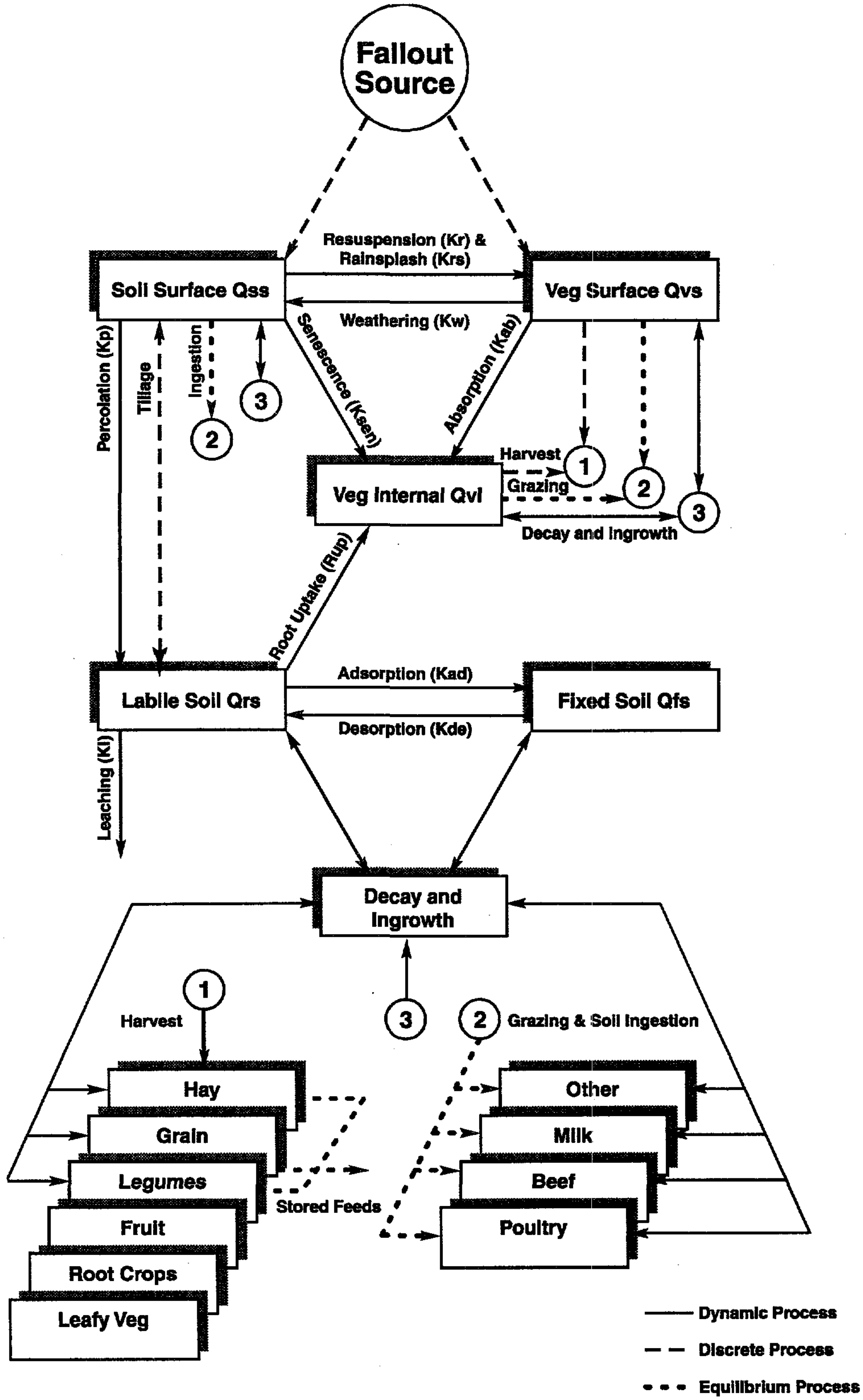

Figure 2.2 Conceptual model for the COMIDA food chain model.

2. In principle, the experts will be asked to assess only physical quantities that could be measured in experiments.

Because the food chain models exist outside of the accident consequence analysis codes, it was necessary to decide whether to select variables that are:

1. The basic input data to the food chain model, or

2. The input to the ACA code (the activity concentrations in foods that are the output of the food chain model).

It was decided to select elicitation variables that would provide the basic input data to the food chain models for the following reasons:

First, asking questions related only to the activity concentrations in foods would limit the usefulness of the study because judgments on the uncertainty in the variables describing the transfer of radioactivity through food at a process level would be lost.

Second, a number of basic food chain variables that are input to food chain models may well be correlated. Table 2.3 shows some groups of FARMLAND input variables that an earlier study considered to be strongly correlated.[7,8] It is important to consider these correlations and their effects on the concentrations in food by including a food chain model in the full uncertainty analysis.

Third, in addition to the correlations between input variables in a food chain model, there are a considerable number of correlations between the activity concentrations in food calculated using the food chain model. For example, the concentration in milk at 7 days will be strongly correlated with the concentration in milk at 30 days, and the concentration in milk will be correlated with the concentration in the animal's body. These correlations arise because a single variable input to the food chain model can influence a range of output quantities (for example, the residence time of radioactivity in a cow's gut will influence the concentration in milk at all times, and will also influence the concentration in its meat at all times). Such correlations can be estimated only by use of a food chain model—another reason for the starting point of the analysis to be the variable input to the food chain model.

It is therefore the uncertainty in these variables describing the transfer processes within the food chain, and the influence of these uncertainties on the predictions of the ACA system, rather than the uncertainty ranges in the activity concentrations in foods, that need to be considered. The latter uncertainty ranges will be produced during the analysis using the appropriate food chain model but will not be used as the basic input to the study, as may be the case in other areas.

The experts therefore were not expected to answer questions on the mathematical models as such since they might have had difficulty relating to the models, particularly when the models have been derived empirically. The advantage of this approach is that many programs may use the information derived from the elicitation questions posed to the experts, since the experts are somewhat divorced from the basic modeling. The disadvantage, however, is that the uncertainty distributions suggested by the experts have to be processed in order to derive the distributions for the model variables used within a particular program.

The transfer of radioactive material through terrestrial food chains involves interactions among soil, plants, and animals; they are processes that require diverse understanding and modeling. Because of the diversity of the subject, there were two expert panels for the food chain. One panel considered issues relating to the uncertainties in estimating the transfer of radioactive material through soil and plant systems. The other panel considered this transfer into and through animals. Even within these subject areas, particularly for the panel considering soil and plant systems, a large number of transfer processes were considered and there were experts whose knowledge did not extend to all the other areas under consideration. Collectively the elicited judgment adequately covered all the processing under consideration.

The list of input variables required by the food chain models used in COSYMA and MACCS is long. It was not considered practical to obtain ranges for all these variables from expert judgment. This technique has been used only for those variables for which the uncertainty is likely to affect the overall uncertainty; where alternative sources of information, such as experimental or observational data or even validated mathematical models, are unavailable; or where multiple sources of information provide conflicting or incomplete evidence of the uncertainties.

Table 2.3 Subsets of FARMLAND input variables assumed to be strongly correlated

1.	Root uptake concentration factor for strontium for pasture (lower than 1 cm)
	Root uptake concentration factor for strontium for pasture (top 1 cm)
	Root uptake concentration factor for strontium for grain
	Root uptake concentration factor for strontium for green vegetables
	Soil migration rate for strontium
2.	Root uptake concentration factor for cesium for pasture
	Root uptake concentration factor for cesium for grain
	Root uptake concentration factor for cesium for green vegetables
	Soil migration rate for cesium
3.	Root uptake concentration factor for iodine for pasture
	Root uptake concentration factor for iodine for grain
	Root uptake concentration factor for iodine for green vegetables
	Soil migration rate for iodine
4.	Root uptake concentration factor for ruthenium for pasture
	Root uptake concentration factor for ruthenium for grain
	Root uptake concentration factor for ruthenium for green vegetables
	Soil migration rate for ruthenium
5.	GI tract residence time for strontium in cow
	GI tract residence time for stronium in sheep
6.	GI tract residence time for cesium in cow
	GI tract residence time for cesium in sheep
7.	GI tract residence time for iodine in cow
	GI tract residence time for iodine in sheep
8.	GI tract residence time for ruthenium in cow
	GI tract residence time for ruthenium in sheep
9.	Transfer of cesium to milk
	Transfer of cesium to meat (cow)
	Transfer of cesium to meat (sheep)
10.	Transfer of strontium to meat (cow)
	Transfer of strontium to meat (sheep)
11.	Transfer of iodine to meat (cow)
	Transfer of iodine to meat (sheep)
12.	Transfer of ruthenium to meat (cow)
	Transfer of ruthenium to meat (sheep)
13.	Biological half-life of strontium in cow
	Biological half-life of strontium in sheep
14.	Biological half-life of cesium in cow
	Biological half-life of cesium in sheep
15.	Biological half-life of iodine in cow
	Biological half-life of iodine in sheep
16.	Biological half-life of ruthenium in cow
	Biological half-life of ruthenium in sheep

The overall parameter list has been reduced primarily on the basis of experience obtained through uncertainty analyses of the MARC ACA code and the FOODMARC module of MARC, which also contains the FARMLAND model.[4,7,8] These studies show that the most important uncertainties are those relating to strontium, cesium, and iodine; these are the only elements considered in this study. The important food chain parameters are listed in Table 2.4. A study of the uncertainty associated with the German ECOSYS model[9] has indicated significant uncertainties in the ECOSYS parameters that are consistent with this list, with a few minor differences due to differences in modeling structure between ECOSYS and FARMLAND. The subset of parameters chosen for this study is discussed in Section 3.2. There is enough similarity between FARMLAND and COMIDA that the results from the elicitation of these parameters will be useful for COMIDA also. The evaluation of ranges for parameters not considered in this study (such as the uncertainty in the time between harvesting a food and its consumption) will be based on current data.

Table 2.4 Important food chain variables identified in uncertainty analyses of FOODMARC for a range of endpoints

Crop area lost	Concentration of cesium in flour
	Root uptake of cesium
Milk volume lost	Initial resuspension factor
Meat production lost	Transfer factor to meat for cesium
	Initial resuspension factor
Collective dose	Root uptake of cesium

2.6 Formal Expert Judgment Methods

The food chain panels 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

As a result of the variety of agricultural areas and agricultural practices, and the difference in siting practices for reactors within Europe and the US, the distributions for food chain variables cannot be universally applied to all nuclear power plants. Therefore, the project's management decided to elicit only those distributions that would be representative of the majority of commercial reactors within Europe and the US. Regions studied in this report are warm temperate climates such as northwestern Europe, and the northeastern and southeastern US. Mediterranean countries, arid areas of the US, and areas subject to arctic conditions are not included. The experts' uncertainty estimates should be applicable to the main agricultural production areas in the regions studied. Unique food-producing areas such as seminatural environments* should only be considered insofar as they contribute to food production for the regions of interest in this study.

In general, the questions were asked for the generic case and the expert was asked to define the assumptions he or she made in determining a generic value. In some cases, more detailed information was asked for, such as a parameter value as a function of soil type.

It was critical that the scope of the problem to be assessed be explicitly defined for the experts in order to receive consistent responses. During the expert meetings, guidelines were established for (1) the phenomena to be considered in defining initial conditions for the distribution, (2) the phenomena to be considered as part of the uncertainty distributions, and (3) the phenomena outside the scope of the project. In general, the uncertainty distributions should include the uncertainty resulting from all conditions not specified in either the initial conditions or not specified as outside of the program's scope. For each elicitation variable, an example list of phenomena that were not specified in the case structure was given. These phenomena, and those considered outside the scope of the project, are given in Table 2.5. This list is not exhaustive and did not preclude the experts taking into account other factors that they considered important to the uncertainty.

*These are areas that are not managed, but are used for grazing. In the US they would be publicly owned lands, such as national forest lands, that are used by ranchers to graze their cattle

Table 2.5 Examples of phenomena considered in defining uncertainty distribution

Type of question	Phenomena contributing to uncertainty included in distributions provided by experts	Phenomena not contributing to uncertainty in distributions provided by experts (specified as out of scope)
General		Variability across different agricultural areas. Mediterranean countries, arid areas of the US and areas subject to arctic conditions.
Soil and soil/plant processes	Composition of generic soil. Different rainfall patterns. Physical form of deposited material.	
Direct deposition onto plant and subsequent process	Physical form of material deposited. Definition of average weather conditions and rainfall intensities. Soil type. Crop type. Time dependence of resuspension. Agricultural practices. Crop yield and variety and species of crop.	Effect of plant growth
Intake by animals	Animal age and weight. Milk yield and stage of lactation. Quality of feed. Fattening period. Grass consumption rate. Weather conditions. Time of year. Stocking density. Quality of pasture.	
Transfer processes within animals	Animal species. Soil type. Physical form of deposited material. Animal age and weight. Milk yield and stage of lactation. Egg production rate.	

2.8 References

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3. Summary of Expert Elicitation Methods for Food Chain Panels

3.1 Introduction

This section summarizes the joint methodology used to develop uncertainty distributions for the consequence calculations in this project, and the use of this methodology in developing the distributions for food chain code input variables. The joint methodology is shown graphically in Figure 3.1. 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.

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 for a question 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 physics of the problem). 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.

It was not feasible for the experts to provide information over all possible agricultural conditions. It was therefore necessary to design a case structure that would cover the scope of the study and the requirements of ACA codes. Subsections 3.2.1 and 3.2.2 describe the case structures for the elicitation questions concerning soil and plant processes and animal processes. The case structures have been developed in such a way that the resulting data library of uncertainty distributions can be used for many different uncertainty studies in the future. The main physical processes modeled in consequence assessment codes, such as MACCS and COSYMA, are the same even though the models representing the processes may be different.

The input variables from the food chain model are, in general, based on physically measurable parameters. There are two important areas in the FARMLAND and COMIDA models where physically measurable parameters are preprocessed to provide input to the model; these are identified in the description of the elicitation variables and the case structure described in Sections 3.2.1 and 3.2.2.

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	

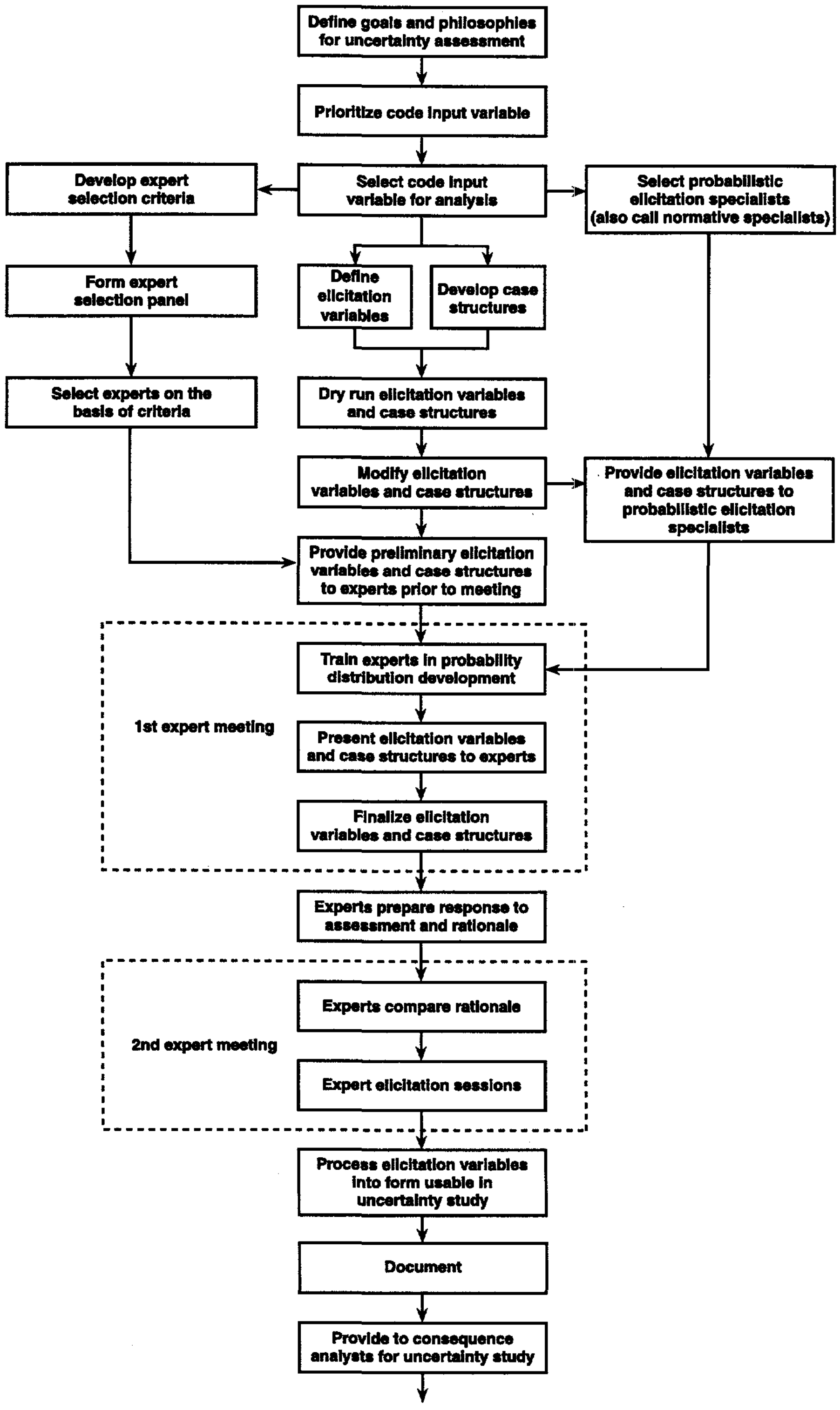

Figure 3.1 Sequence of methods used to develop the uncertainty distributions. Due to programmatic constraints, the EC and the US experts held separate first expert meetings; however, some project staff attended both European and American meetings. The EC did not hold a common second expert meeting, but held individual expert elicitations at sites convenient for the experts. The US did hold a common second expert meeting as depicted in the figure.

Some of the cases refer to transfer from generic soils to crops. In these cases, the experts were asked to consider which types of soil are likely to support the crop under consideration in the defined region and take into account their relative amounts in deriving the generic value. The quantity requested for each elicitation variable was the uncertainty on the average value for the defined region. Unless otherwise stated, the effect of radioactive decay was not to be taken into account.

For the crops considered in COSYMA and MACCS, the generic terms green vegetables, grain and root vegetables are used. Green vegetables include all leafy green vegetables and brassicas (e.g., cauliflower and cabbages). Grain represents cereals grown for human consumption, which are dominated by wheat. Root vegetables include potatoes and other vegetables such as carrots and onions. The consumption of root vegetables is typically dominated by potatoes and this needed to be taken into account in estimating uncertainty relating to root vegetables.

3.2.1 Case Structure for Soil and Plant Processes

The detailed case structure is provided in Volume 2 of this report and is summarized here.

The main transfer mechanisms included in a food chain model are:

- Migration of radionuclides in soil,
- Root absorption into plants from soil,
- Surface contamination of plants,
- Loss from the surface and subsequent translocation to the edible part of the plant.

For illustration, the main features of a model developed to describe the transfer of radionuclides to plants are illustrated in Figure 3.2. The compartment marked "soil" represents the model for migration in soil appropriate to the plant species and agricultural conditions considered. All plants consumed directly by man are assumed to be derived from land that is frequently cultivated, and the FARMLAND migration model for well-mixed soil is most appropriate in these circumstances. Grass, however, is usually assumed to be produced only on undisturbed pasture (i.e., permanent pasture used to graze animals—a common practice in Europe), in which case the migration model for undisturbed soil is applicable. For crops, COMIDA evaluates a discrete tillage process that mines contaminants between a surface and a root zone layer. Contamination of both internal and external parts of the plant is considered: transfer to the external plant surfaces may occur by interception of deposition or by resuspension of radioactivity from soil and redeposition on the plant. Transfer to the internal plant occurs via root uptake and absorption from the external surfaces and subsequent translocation. A case structure was developed to address the important transfer processes.

3.2.1.1 Soil Migration and Fixation

Data on migration in soil were elicited for a generic soil within the regions of interest in Europe and the US and for sandy and highly organic soil types. The elements for which data were elicited were strontium and cesium. The initial condition was a single deposition of 1 Bq m^{-2} onto an area of soil used for growing pasture and which is not affected by plowing or other mechanical disturbances.

For the majority of soil types, a fraction of radioactive material is bound to the clay component of the soil and is unavailable for uptake into plants. The effect of this process on the uptake of radionuclides from the soil via plants' roots is included in the models. Data on the fraction of strontium and cesium that becomes unavailable for uptake by plants (as a function of time) following deposition to the soil surface were elicited for the soil categories given above.

3.2.1.2 Root Uptake

Data on root uptake concentration factors were elicited for a generic soil within the region of interest in Europe and the US and for sandy and highly organic soil types. The elements for which data were elicited were strontium and cesium. Crops considered were green vegetables, grain, root vegetables, potatoes, and pasture grass. The initial condition was that the soil contained 1 Bq kg^{-1} of the element which was well mixed throughout the soil volume in the root zone of the crops following a single deposit. The subsequent concentrations in the crop were elicited as a function of time to enable the process of fixation to be taken into account.

3.2.1.3 Interception

When radioactive material is deposited onto agricultural land from the atmosphere, only part of the material is intercepted by the foliage of the plant; the rest lands on the surrounding soil. In general, radioactive

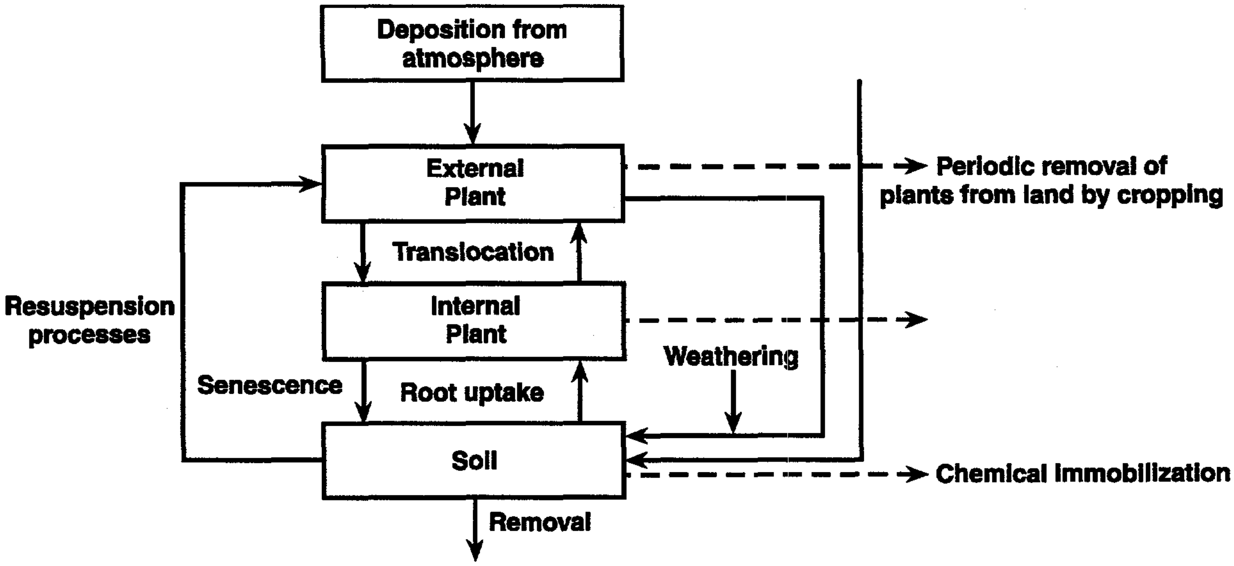

Figure 3.2 Schematic representation of the principal mechanisms for the transfer of radionuclides to plants.

material is removed from the surfaces of the plant by natural processes such as erosion of fragments of wax from the leaf surface and weathering caused by wind and rain. Part of the surface deposits to plants may be absorbed and transferred to other parts of the plant through translocation. The three processes—interception, retention, and translocation—are interrelated and govern the contamination of plants by direct deposition onto the plant surface.[1]

The amount of radioactive material intercepted by the foliage of the plant is dependent on a number of factors, including whether the material is deposited under wet or dry conditions, the particle size, chemical form of the contaminant, etc. For some ACA codes, a single interception factor is used that is applicable for annual average conditions (i.e., there is no distinction between wet and dry deposited material), and the total deposition is used as the input to the food chain model. COMIDA uses a plant growth model to calculate a time-dependent interception factor These approaches are appropriate for use with probabilistic accident consequence codes that consider a range of meteorological conditions and estimate the consequences of postulated accidental releases over large areas.

Data on interception factors were elicited for a generic deposition (i.e., where the weather conditions are unknown and for wet and dry deposition conditions). Crops considered were green vegetables, grain, root vegetables, grass for hay and silage, and pasture. The initial elicitation question was worded as follows: Given a deposition of some radioactive material on a unit area of the ground, what fraction of this material is deposited onto the plant surface at maturity? The yields of the mature crops were given.

3.2.1.4 Retention

The removal of activity from the external plant surface was modeled using a retention half-life. This half-life represents the loss due to weathering from rain and wind and that due to flaking off of fragments of wax from the leaf surface to which radioactivity has been attached.

Data on retention times were elicited for green vegetables, grass for hay and silage, and pasture. The initial condition was that deposition of some radioactive material onto the crop had occurred and pasture grass was grazed by animals. The effect of plant growth on retention was considered to be outside the scope of the study.

3.2.1.5 Translocation

Part of the surface deposits to plants may be absorbed and transferred to other parts of the plant; this translocation is significant for elements that are mobile within the plant, such as cesium, and is unimportant for immobile elements such as the actinides. For root vegetables, translocation is the only mechanism by which radionuclides are transferred from the surface of the plant to the edible root underground.

Data on translocation were elicited for grain and root vegetables. The elements were strontium and cesium, and the fraction translocated to the edible part of the crop at harvest was elicited as a function of time before harvest. The initial condition was a single deposition to ground for grain and a single deposition to the plant for root vegetables.

3.2.1.6 Resuspension

The resuspension of radioactivity from the soil surface and deposition on the external parts of crops will occur through the action of wind and rain. Considerable variation might be expected in the importance of this route of contamination, depending on the plant type, the conditions under which crops are grown, and the method of their preparation before consumption. The resuspension of the radioactive material in the period soon after deposition by wind-driven processes is typically modeled using a single mean resuspension factor.

Data on resuspension factors were elicited for surface crops and pasture grass. The initial conditions were that a resuspension factor should be derived over the entire growing period of a surface crop and a mean value should be derived for pasture grass. The resuspension factors requested excluded any contribution from soil contamination at the time of harvest.

3.2.2 Case Structure for Animal Processes

The transfer of radionuclides to animals can be considered in two stages: (1) the intake of radionuclides by ingestion or inhalation and (2) the subsequent metabolism of these radionuclides and in particular their transfer to animal tissues and animal products that are consumed by man. This case structure deals with cattle (dairy and beef), sheep, pigs, poultry, and goats. It should be noted that, since COMIDA uses an equilibrium animal transfer process, this second stage applies to FARMLAND only.

The principal mechanisms involved in the transfer of radionuclides to grazing animals are illustrated schematically in Figure 3.3. Ingestion is the most important route of intake by the animal; inhalation is, in general, not important although it may be significant for those radionuclides whose transfer across the gut of the animal is small. In this study, inhalation by animals was not considered for expert elicitation.

Various feeding regimes for cattle and sheep are implemented depending on the country, region, availability of fodder, etc. Typically, dairy cows and sheep graze on pasture grass during part of the year and eat stored feed such as cereals and hay during winter months. Beef cattle can be raised on diets of cereals or pasture with other additional minor feedstuffs. Pigs and poultry are typically raised on cereals although pigs can be fed a wide variety of other feedstuffs, including milk products. The inadvertent consumption of soil associated with grass by grazing animals can also be an important contributor to the intake of grazing animals. For radionuclides that have a low transfer from soil to grass by root uptake, the ingestion of soil may be the most important source of intake.

The rate of intake for ingestion is an important parameter in a food chain model because it governs the intake of radioactivity into the animal. Ingestion rates depend on the grazing habits of the animal and these are difficult to assess, particularly for free-grazing animals and those that are selective eaters (e.g., sheep). Ingestion rates also depend on the body weight of the animal.

Data were elicited on the daily consumption rates of feedstuffs for the animal species considered in the study. The feedstuffs were pasture grass, silage and hay, cereals, and any other significant feedstuff consumed both indoors and outdoors. The initial conditions were that animals consumed 100% of the feedstuff. The experts were given the opportunity to use diets consisting of a combination of these feedstuffs if they felt this was more representative.

Data were also elicited on the daily consumption of soil for cattle, sheep, pigs, and poultry. The initial condition was that the animals were outdoors on an inland site and the feeding practices were continuous grazing of pasture for cattle and sheep and consumption of cereals for pigs and poultry.

The metabolism of the animals considered in this study can be represented by three physiological mechanisms: (1) the absorption of the nuclide into the bloodstream and body fluids from the gastrointestinal tract; (2) the distribution and recycling of the nuclide between the circulating fluids and the body organs and tissues; and (3) the excretion of the nuclide from the body, including secretion into milk and, for chickens, transfer to eggs.

Animal metabolism is modeled at different levels of complexity, depending on the radiological importance of the element of concern and the radiological application. A simple model is used for studies on the uncertainties of transfer in animals.

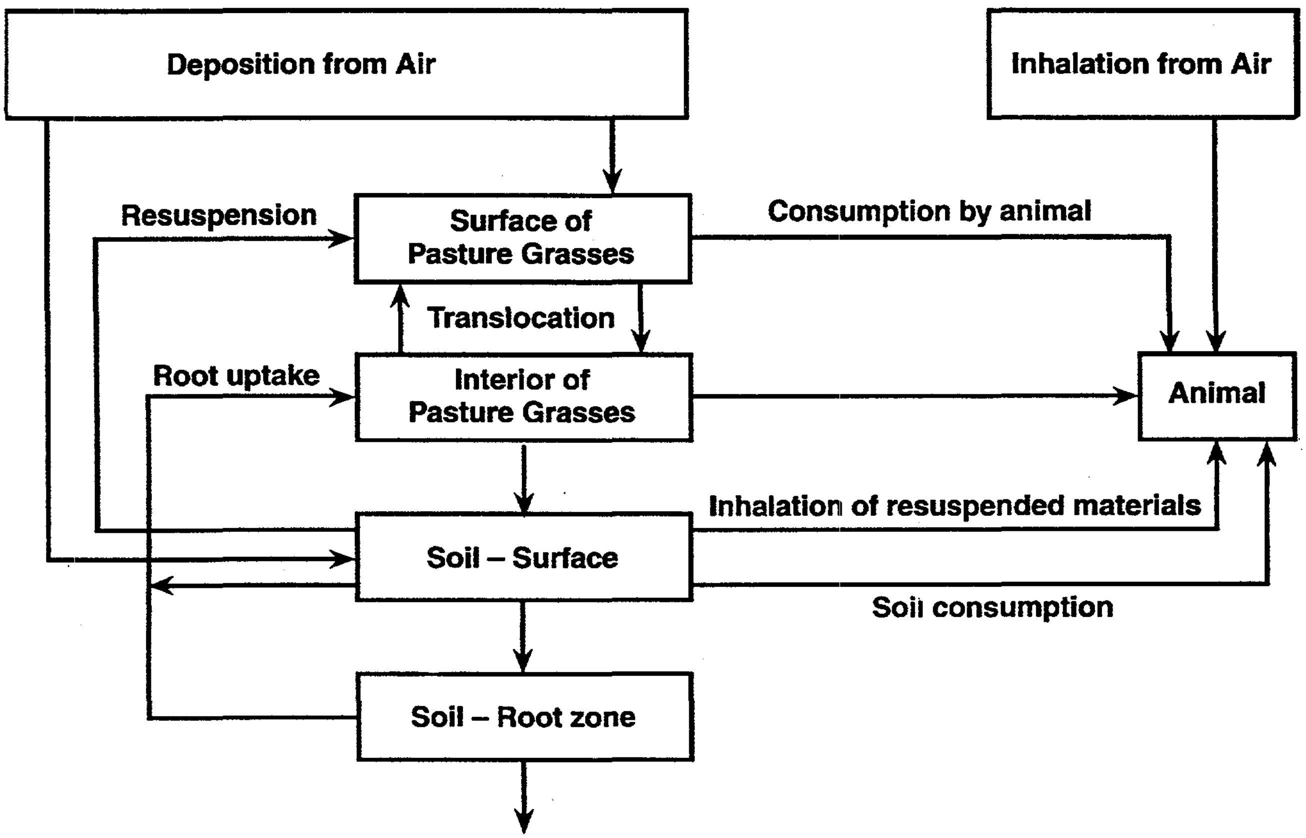

Figure 3.3 Schematic representation of the principal mechanisms for the transfer of radionuclides to grazing animals.

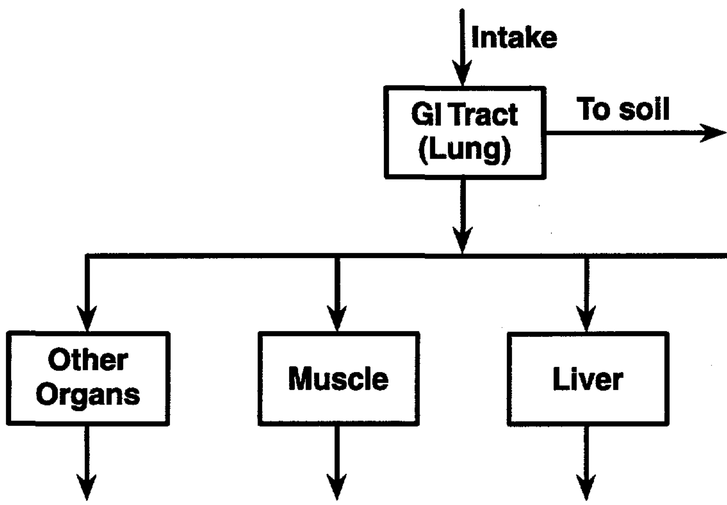

Figure 3.4 Schematic representation of the simpler metabolism model for animals.

An example of a simple model used in FARMLAND is illustrated in Figure 3.4. The approach taken is to model the retention in the gut, the fractional transfer of ingested or inhaled radioactivity to particular organs and tissues of the animal, and the half-lives of radioactivity in these tissues. The amount of radioactivity that enters both meat and milk is usually expressed in terms of an equilibrium transfer factor. The data are in the form of the fraction of the daily intake that is transferred to a unit mass (1 kg) of the product at equilibrium and has the units d kg^{-1}. The model also uses biological half-lives in the animal to allow activity concentrations to be evaluated as a function of time.

Data were elicited on the transfer of radioactive material to meat, milk, and eggs for the appropriate animals. The parameter used was the fraction of the daily intake that is transferred to a unit mass (1 kg) of the product at equilibrium. Data were elicited for strontium and cesium for meat; and strontium, cesium, and iodine for milk and eggs. The initial condition was that the animals were fed continuously at a constant daily rate under field conditions and that values for meat should be for animals at slaughtering age.

Additional data were elicited on the availability of radioactivity associated with ingested feed for transfer across the gut. Availability is implicitly included in the transfer addressed above. However, the project team considered it useful to obtain the views of the experts on this subject. For radioactivity freshly deposited onto grass, biologically incorporated into grass and associated with soil, data were elicited on the fraction of this activity that would be available for transfer across the gut of an animal.

Data were elicited on the biological half-life in dairy cows, beef cattle, sheep, pigs, and poultry for strontium, cesium, and iodine. The initial condition was that the animal had been fed at a constant daily rate for some period of time under field conditions so that equilibrium within the animal's body had been reached. The variable elicited was the weighted average half-life of retention in the meat of the animal.

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 various answers. Another role is ensuring that each 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 has responsibility for assisting the expert 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 the food chain processes. 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 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 external committees, one in the US and one within the EC 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 two panels of internationally recognized scientists, four of whom were from the US and twelve 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 are responsible for managing the elicitation sessions. These specialists come 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.

Four normative specialists were used in this study. Three of them (Dr. Goossens, Dr. Hora, and 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 Delft University of Technology (TU) and Dr. Hora was a key participant in the NUREG-1150 expert elicitation activities. Mr. Bernd Kraan of TU Delft is experienced in the 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 food chain experts recruited by the National Radiological Protection Board 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. No requirements on the form of the written rationale were imposed.

4. Second expert meeting. Different approaches were taken by the EC and the US. In the US, the

Table 3.2 Food chain experts

Soil and Plant Processes		Animal Processes	
Expert	**Country**	**Expert**	**Country**
Martin Frissel	Netherlands	Peter Coughtrey	UK
John Garland	UK	François Daburon	France
René Kirchmann	Belgium	Owen Hoffman[a]	US
Gerhard Pröhl	Germany	Brenda Howard	UK
George Shaw	UK	Jack Pearce	UK
Ward Whicker[a]	US	Per Strand	Norway
Lynn Anspaugh[b]	US	Christian Vandecasteele	Belgium
		Gaby Voigt	Germany
		Gerry Ward	US

[a] Drs. Whicker and Hoffman contributed to both panels.
[b] Dr. Anspaugh provided some limited information.

second expert meeting was conducted approximately 6 weeks after the first expert meeting, although the time varied because of the commitments of the experts. The second meeting was held to elicit the percentile values from the cumulative distributions of the elicitation variables. In Europe, no formal second meeting was held. The EC elicitors traveled to each expert to elicit the required information.

3.4.1 Dry Run Meeting to Finalize Case Structure

The dry run meeting was conducted in December 1994 with two food chain experts: Dr. B. Wilkins from the NRPB and Dr. P. Cawse (a food chain specialist). The meeting began with training in probability elicitation, which 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 before the dry run meeting. The dry run experts were not asked to prepare quantitative responses to the questions, but were 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. The case structures and questionnaires to be presented to the experts in the first meeting were finalized according to the lessons learned in the dry run.

3.4.2 First Expert Meeting

Before the first meeting, 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 variables 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. Two separate training meetings were held: one in Europe (January 1995) and one in the US (April 1995).

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 the experts by the project were that: (1) the initial conditions had to be defined at the same level of detail as the code input (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

The elicitations were carried out differently in Europe and the US. In Europe there was no joint meeting for each food chain panel. All experts were elicited individually at their own institutes, during February and March 1995. A normative specialist and a substantive assistant were present at all elicitation sessions.

In the US a joint meeting was held on July 20 and 21, 1995. On the first day of the elicitation meeting, the experts presented the technical approach and rationale behind their assessments in a common session. 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 into a single cumulative distribution for each elicitation variable for each case structure.

No further mathematical processing was required for the questions on animal processes. The same is true for some of the questions on soil and plant processes: the root uptake concentration factor, the interception factor, the resuspension factor, and the retention times. In all these questions, the elicitation variable was the important code input variable. For soil migration, fixation in soil, and activity concentrations in root crops and grain at harvest, the elicitation variables were not consequence code input parameters of FARMLAND or COMIDA. Additional processing is required in order to use the information in our uncertainty study. The following section discusses the mathematical processing of the elicited distributions.

Mathematical processing techniques for soil/plant processes (soil migration and fixation, root crops and grain) were developed for FARMLAND at Delft University of Technology and for COMIDA at the University of New Mexico and INEL. It was decided to publish the results of the mathematical processing in two separate reports: one for FARMLAND for the EC and one for COMIDA for the NRC.

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 log uniform, depending on the magnitude of the range factor for the variable as elicited from the experts. (Throughout this study, the term "range factor" is used to express the rate between the 95th and 5th percentiles of the distribution, and is used as a measure of uncertainty.) For each variable, nonnegative 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 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:

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

where fj,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 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 was to ensure the inclusion of different modeling perspectives in the aggregated uncertainty distributions. However, additional information was elicited to allow the application of performance-based weighting schemes to the elicited 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.[4] 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.[5] Within the joint EC/NRC study, a new strategy[6] has been employed for eliciting dependencies from experts. The detailed procedure is given in Volume 2.

3.6 References

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4. Results and Analysis

4.1 Introduction

This section contains the experts' responses to the elicitation meetings and includes the elicited data, the aggregated elicited distributions, and the distributions to be used in uncertainty analyses for the food chain models.

4.2 Summary of Elicitation Meetings

Three different meetings were conducted and this section summarizes the outcome of those meetings.

4.2.1 Dry Run Elicitation Meeting

The robustness of the basic expert elicitation methodology developed for this project was validated by a dry run exercise. Several important issues were raised and subsequently evaluated as a result: (1) there was a need to clarify the underlying conditions for some questions; (2) the consumption of soil by animals and any differences between indoor (nongrazing) and outdoor (grazing) consumption rates were considered important to evaluating animal intakes (this was added as part of the animal case structure); and (3) strong references to particular models in the case structure that might bias the thinking of the expert should be removed.

4.2.2 Summary of First Expert Meetings (Training Meetings)

Separate meetings were held for the European and US experts. Both the European and American meetings were videotaped for historical records. The US meeting was held after agreement had been reached on the elicitation variables and case structure for the European experts. The initial reception of the project by the experts was excellent. The experts expressed a deep 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 European training meeting, several changes to the definition of the elicitation variables and the case structure were proposed for both food chain panels. Following the meeting, some of the questions were rephrased to address the issues raised. The experts were sent a final version of the case structure and elicitation variables shortly after the meeting.

The experts on both panels were initially uncomfortable with the use of the uncertainty on average values rather than the range across all possible conditions. However, as the experts became more familiar with the scope of the study and the use of the data within PRA codes, this issue was clarified. The geographic areas that should be encompassed in answering the questions were also defined in the case structure.

In the soil and plant panel, the following major change to the elicitation variables was made: the elicitation question on root uptake concentration factors was rephrased to enable the effect of time on the availability of elements to plants to be addressed in the most appropriate way given the observed data available.

In the US training meeting, the questions and case structure presented were those used in the elicitation of the European experts with the following exception. Soil and plant experts had been queried on elicitation variables for a generic European soil. The US experts were asked for a generic US soil. Differences between soils in Europe and the US were discussed and all experts were asked to assess them if their views differed.

In the US soil and plant panel, the following major changes to the elicitation variables were made: additional separate elicitation variables for interception of wet and dry deposits were added to the case structure for the question on the interception factor. This information had been elicited from the European experts following the second expert meeting (see Section 4.2.3). It was proposed that several questions be changed to provide additional information for the US, which was useful for the COMIDA model; these changes did not change the elicitation variables considered by the European experts. Details of the additional elicitation variables are given in Volume 2.

In the animal panel, the following major changes to the elicitation variables were made as a result of the first European expert meeting: pigs, poultry, and goats were added to the questions at the request of the experts. The question on animal consumption rates was rephrased to consider feeding regimes both indoors and outdoors. For the elicitation variable on the availability of ingested feed for transfer across the gut, the experts felt strongly that the form of the intake should be considered and it was agreed that the question would be rephrased to ask the elicitation variable as a function of the form of the intake (i.e., recently deposited onto pasture, biologically incorporated into the pasture, or associated with soil). The experts questioned the importance of considering the residence time of feed within the gut of the animal and, following discussion, the question was removed.

The questions for the US animal panel were changed to make them more relevant to farming practices in the US and to incorporate the preferred format of the questions by the US experts. Husbandry practices for animals in the US are markedly different from those in Europe: animals in Europe are typically not kept outdoors or allowed to graze free. Additional feedstuffs were added to the question on animal consumption rates, and the elicitation questions requested information on grazing and nongrazing animals rather than on animals kept indoors or outdoors. The US experts had a problem with separating the availability of ingested feed for transfer across the gut from the feed-to-product transfer parameters (Ff and Fm). The two questions were combined and a single question on the transfer to meat, milk, and eggs as a function of the form of intake (i.e., recently deposited onto pasture, biologically incorporated into the pasture, or associated with soil) was asked.

The experts decided to keep the elicitation results and the written rationales anonymous. The work that they performed for this study is published in Volume 2, but their names are not associated with their specific work.

4.2.3 Summary of Second Expert Meeting

All of the European experts were elicited individually without a common session. The majority of the experts on the soil and plant panel felt strongly that additional elicitation variables on the interception factor should be considered (i.e., interception by plants during wet and dry deposition events as well as generic values). All European experts subsequently provided these additional data.

The US experts were elicited individually, following a common session during which they presented the approach they had taken to developing their distributions. The experts did not reveal their probability assessments in order to avoid biasing the other experts. The issue of anonymity was discussed and it was agreed to preserve anonymity. The remainder of the meeting consisted of individual expert elicitation sessions. Once again, the initial common session was videotaped, and the individual sessions were audiotaped.

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 section so as not to interrupt the flow of the text. The complete set of expert rationales and the elicited distributions are published in Volume 2 of this report. In this section, Figures 4.1 through 4.36 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 through 7 to indicate the results from soil and plant experts and the numbers 1 through 10 for experts on animal processes. The appendices use A through G for soil and plant experts, and H through Q for experts in animal processes. There is no correlation between the two systems. This section discusses only the individual assessments; Subsection 4.4 contains the results of the equal aggregation of the distributions.

4.3.1 Summary of Individual Soil and Plant Assessments

4.3.1.1 Soil Migration and Fixation in Soil

All experts were asked to consider generic European and US soils separately. One expert thought that there was a significant difference between the two generic soils and did not want to provide an assessment because of lack of knowledge of the differences. Based on the experts' views, data are presented for a generic soil that is appropriate for the areas under consideration in the US and Europe. Figures 4.1 and 4.3 show the 50th percentile values of cesium and strontium for a generic soil as a function of soil depth, and Figures 4.2 and 4.4 show the range factors. The range factors for cesium tend to be smaller than for strontium. For both radionuclides, one expert has wider range factors with high values (for both median and 95th percentile). For sandy soils, the picture is comparable, albeit the range factors tend to be larger (see Figures 4.5 and 4.6). For cesium, one expert has a wider band with high values. For highly organic soils, there appears to be more scatter among the individual assessments.

The experts provided assessments for fixation in soil similar to those for soil migration. Figures 4.7 through 4.10 show examples of the experts' assessments for a generic soil. As for soil migration, large differences among experts are occasionally shown (for example, see Figures 4.11 and 4.12).

4.3.1.2 Root Uptake Concentration Factors

Experts were again asked to consider differences between generic European and US soils in the root uptake concentration factors. As for the soil migration question, one expert thought that there was a significant difference but did not provide a separate assessment. Data are presented for a generic soil appropriate for the US and Europe. Figures 4.13 and 4.14 show the assessments for cesium on root uptake concentration factors with time for green vegetables grown on a generic soil. The observations made for green vegetables are representative of those seen for the other crops. The 50th percentiles are mainly within a narrow range of values. The range factors in Figure 4.14 show large differences among the individual experts, with some experts assessing very large range factors due to the large range in absolute values. The range factors do not suggest any significant trend in increased or decreased confidence by the experts in assessing root uptake as a function of time. The results from two experts are outliers. Similar observations were made for strontium.

4.3.1.3 Interception Factor

The results for the interception factor are shown in Figures 4.15 and 4.16 for all five crops. The individual expert assessments of the interception factor show large differences in the 50th percentiles for some crops: values range from less than 0.1 to 0.9 on a scale of zero to unity. The range factors are typically less than 10 across experts. In some cases, the experts provided assessments for wet and dry weather conditions separately and not for a generic case where the deposition type was unknown. In these cases, the experts were asked to provide a weighting factor for wet and dry weather conditions, so that the project staff were able to calculate a combined uncertainty distribution appropriate for the generic case.

4.3.1.4 Resuspension Factor

The resuspension assessments are shown in Figures 4.17 and 4.18 for the two crop types specified. The individual expert assessments of the resuspension factor show reasonable agreement in the 50th percentiles given the broad scope of the question: in general, the assessed medians lie closer to the 5th percentiles. Large differences in the range factors are seen among experts due to the large uncertainty some experts associated with a generic resuspension factor.

4.3.1.5 Retention Times

The retention assessments are shown in Figures 4.19 and 4.20 for green vegetables, pasture grass, and grass grown for silage or hay. The individual expert assessments of the retention times show good agreement for the 50th percentiles. Large differences are seen in the range factors across experts; some experts provided small range factors, others much larger ones.

4.3.1.6 Concentration in Grain and Root Crops at Harvest

The assessments for grain concentrations at harvest from external contamination of the crop at different times before harvest are shown in Figures 4.21 and 4.22 for cesium. The individual expert assessments of the concentrations in grain with time show reasonable agreement on the 50th percentiles except at contamination 90 days before harvest, where differences among experts are larger. This is also seen for strontium. Larger differences are seen in the range factors: some experts assessed large 95th percentiles, resulting in wide range factors. Similar observations were made for strontium.

As for grain, the 50th percentiles assessed by most experts for the concentrations in root crops at harvest as a function of time are in reasonable agreement, particularly for cesium. The range factors assessed varied greatly among experts, ranging from less than an order of magnitude to several orders of magnitude (see Figures 4.23 and 4.24).

4.3.2 Summary of Individual Assessments of Animal Processes

4.3.2.1 Animals' Consumption Rates

As mentioned earlier, the husbandry practices in Europe and the US are, in general, significantly different. Therefore, where appropriate, the European and US experts were given different questions. The experts were asked to assume that the animals were fed 100% on each feedstuff separately, rather than on combinations of feedstuffs, and to consider those feedstuffs appropriate for each animal. This assumption was expected to facilitate the use of data within the food chain models. All of the European experts expressed strong views that this was an unrealistic assumption in some cases, particularly for beef cattle and animals fed indoors. The assumption of feeding a single feedstuff was most appropriate for sheep outdoors and for pigs and poultry. Most of the experts did, however, provide the assessments for this case, with caveats given in their rationales. Several experts also provided an assessment for combination diets that in their view were more realistic. Some experts stated that their assessment of consumption rates was appropriate for animals in the area defined in the project, and other experts gave values for their own country. Data were not assessed for all feedstuffs for each animal if the feedstuffs were not consumed; for example, pigs and poultry do not, in general, consume pasture grass and silage or hay.

Detailed results from the assessment of animal intakes are given in Volume 2 for the US and European questions. Data are presented here for a selection of animals and feedstuffs that are major contributors to each animal's diet. Figure 4.25 shows the 50th percentiles, and Figure 4.26 the range factors for the following feeding regimes: dairy cows grazing on outdoor pasture, beef cattle eating silage indoors, and pigs eating cereals indoors.

For the dairy and beef cattle, there is good agreement among the 50th percentiles assessed by the experts. However, for cereal consumption by pigs, two experts give a much higher daily intake rate than the others. The range factors assessed are typically very small for the selection of results shown in Figure 4.26. For other feedstuffs consumed by dairy and beef cattle, however, some experts assessed very large range factors with very low 5th percentiles, reflecting a very large uncertainty in the consumption of a particular feedstuff. Most of the range factors are less than a factor of 7.

Figures 4.27 and 4.28 show the assessments of soil consumption by cattle, sheep, pigs, and poultry. A large scatter in the 50th percentiles can be observed, particularly for pigs and poultry. The range factors show large differences among the individual experts, with range factors ranging between a factor of a few to two orders of magnitude.

4.3.2.2 Transfer to Meat, Eggs, and Milk

Different underlying conditions were used by the European and US experts in assessing transfer to animal products (as discussed in Section 4.2), the main difference being the assumption made by the experts, and hence data used, on the form of intake for which the estimates of transfer variables (Fm and Ff) were valid. The US experts provided values as a function of the form of intake, taking availability into account, which was directly consistent with the question they were asked. The European experts were asked for a single generic value. From information provided at the elicitation sessions and the experts' rationales, the values provided are valid for all forms of intake, and the uncertainty distributions reflect the uncertainty in the availability of an unknown intake. One US expert also provided generic data valid for all forms of intake and these data are presented with the European experts' data.

Figures 4.29 and 4.30 show the assessments for the transfer of cesium to the meat of dairy cows, beef cattle, sheep, pigs, and poultry. For transfer to meat (Ff), the individual expert assessments show reasonable agreement for the 50th percentiles for cesium (see Figure 4.29); more scatter in the assessments is observed for strontium. The range factors estimated by individual experts are typically greater than a factor of 10 for cesium (see Figure 4.30) and larger for strontium. In particular, large uncertainties are assessed for sheep and pigs.

Similar results are seen for the transfer to eggs. The experts assessments for cesium, strontium, and iodine are given in Figures 4.31 and 4.32. The experts' 50th percentiles are in good agreement and in general are within a very small range (Figure 4.31). The range factors assessed by the experts varied, with some experts providing large uncertainties, particularly for iodine and strontium (Figure 4.32).

Similar observations can be made on the assessments of the transfer to milk (Fm), as illustrated in Figures 4.33 and 4.34, which show the experts assessments of iodine transfer to the milk of dairy cows, sheep, and goats. In general, the 50th percentiles assessed for each animal are in reasonable agreement; values for strontium show a wider spread for all animals. In general, range factors of greater than 10 are provided by all experts for sheep and goats milk; the range factors for cows milk are smaller than those for goats and sheep milk for cesium and strontium although this is not seen for iodine.

4.3.2.3 Biological Half-Life in Animals

Figures 4.35 and 4.36 summarize the estimates of biological half-life in meat for strontium as a function of animal species. The highest level of agreement between the experts is seen for cesium for all animals.

The agreement on the 50th percentile values is, in general good, and the range factors assessed by most of the experts are reasonably narrow. For strontium and iodine, more scatter is seen among the experts' assessments, as illustrated in Figure 4.35, and large differences are seen in the range factors among individual experts (see Figure 4.36).

4.4 Summary of Aggregated Results

This section presents the results of the equal-weighted aggregation of the individual elicited distributions into single distributions over each elicited variable. The performance-based method developed at Delft University of Technology[1,2] provides a means to evaluate the performance of the equal-weighted aggregated uncertainty distributions. Discussions on this issue and uncertainty distributions based on this performance-based weighting technique will be published separately.[3]

4.4.1 Summary of Aggregated Soil and Plant Assessments

The 50th percentile and range factors for the equal-weighted aggregated distributions are presented along with the individual assessments illustrated in Figures 4.1 through 4.24. The figures for the range factors show that in some cases the aggregation results in distributions that have a wider range factor than any of the individual elicited distributions. Except where indicated, the data from European and US experts have been aggregated.

For soil migration, the aggregated range factors are generally smaller for cesium than for strontium. For generic soils, the range factors are typically within a factor of two larger for strontium than for cesium, in general equal for sandy soils, and up to a factor of two larger for highly organic soils. For fixation in soil, the range factors for cesium and strontium are similar. Range factors range from 3 to 60, being larger for the highly organic soil, but are typically less than 10 for times greater than 1 year following deposition. The 95th percentile values of the fraction of cesium that becomes fixed as a function of time are all close to unity; at 1 year following deposition the 5th percentile values are a few percent. With increasing time (up to 10 years), the 5th percentile increases to about 0.3. For strontium the 95th percentile is observed to increase with time by about a factor of 2; the 5th percentile value is less than 0.1 for all times following deposition.

Range factors for cesium and strontium root uptake concentrations factors for all crops are similar and typically in the range of 50–200. The exceptions are those for cesium uptake by root vegetables, which are between 400 and 4000. The overall trend is that the range factors for strontium are smaller than those for cesium for all crops, typically by a factor of two. Range factors for root uptake from sandy soils are smaller than those observed for the generic soils; those for highly organic soils are typically larger than both generic and sandy soils, particularly for cesium.

The aggregation of data for interception factors results in range factors of about a factor of 10 to 40 for most crops. In all cases, the aggregated 95th percentile is close to unity, the 50th percentile values are around 0.4, and the 5th percentile values less than 0.06. The aggregated resuspension factors give rise to large range factors that are about 10,000, with the 50th percentile relatively close to the 5th percentile. For the retention times, range factors on the order of 20 are found for all crops.

The aggregated range factors for the concentrations of grain at harvest in general are similar for both strontium and cesium, with range factors ranging from 90 to 500. The smaller uncertainty ranges are seen for deposition at 30 and 60 days before harvest for cesium and at 15 and 30 days before harvest for strontium. For concentrations in root crops at harvest, the range factors are much larger than those seen for grain for cesium and strontium. Range factors for strontium are noticeably smaller than those observed for cesium. For root vegetables, the range factors are smallest for deposition occurring 60 and 90 days before harvest for both elements.

4.4.2 Summary of Aggregated Assessments of Animal Processes

Figures 4.25 through 4.36 plot the central measure and the uncertainty measure of the aggregated distributions for the assessments of animal processes. As with the plant/soil results, the width of the aggregated range factor is typically greater than for the individual elicited distributions.

As discussed in Section 4.3.2, there were significant differences in the elicitation variables assessed by the European and US experts. Aggregation of the European and US data is, therefore, limited.

For the animals' consumption rates, aggregated distributions are presented in Figures 4.25 and 4.26 for selected animals and feedstuffs. In Volume 2 aggregated distributions for all animals and feedstuffs are compiled for European and US husbandry practices separately using the European and US experts' data. Although some of the European experts provided assessments for their own countries, aggregation of all the European data is considered appropriate in most cases to give generic values for European conditions. In some cases large range factors are found, reflecting the uncertainty some experts associated with the consumption rate of a particular feedstuff.

For the transfer to meat, milk, and eggs, the assessment of only one US expert could be aggregated with the European data due to the different questions asked (see Section 4.3.2). In all the assessments on transfer to meat, milk, and eggs, the experts are least uncertain for cesium, with range factors ranging from 20 to 80. The range factors for strontium are larger, particularly for meat, where range factors vary from 200 for dairy cows to 2000 for poultry. The largest range factors were observed for transfer to lamb, pork, and chicken. The transfer of iodine to eggs and sheep and goats' milk is also very uncertain, with range factors of about 1100 and 600, respectively.

For the biological half-lives in meat for the animal species considered, the aggregated range factors are smallest for cesium, ranging from 10 to 30 and 200 to 500 for iodine; they are highest for strontium, ranging from 500 to 800.

4.5 Comparison of Results from Current Study with Code-Calculated Values and Past Uncertainty Studies

This section compares the food chain results obtained by the present study with the variable values currently in use in COSYMA and with variable distributions used in past uncertainty studies carried out with the COSYMA foodchain models, FARMLAND and ECOSYS.

Table 4.1 compares the 5th, 50th and 95th percentile values for transfer to milk, Fm from the aggregated expert distributions with the values used as default in the FARMLAND and ECOSYS models and those given in a compilation of literature values prepared by the International Atomic Energy Agency (IAEA)[6] for strontium, cesium, and iodine. The values used by FARMLAND and ECOSYS lie between the 5th and 50th percentile values from the aggregated distributions and are in good agreement with the 50th percentile value. The 50th percentiles from the expert distributions are lower than the "typical" values reported in the literature and the range factors from the aggregated distributions are wider than the reported range in literature values.

Table 4.2 shows equivalent data for the transfer to beef, Ff. Experts provided distributions for both dairy cows and beef cattle; these data are compared with the values used in ECOSYS and generic values for beef used in FARMLAND and reported in the literature.[6] In general, observations can be made that are similar to those for the transfer to milk. The default FARMLAND and ECOSYS values for strontium are, however, significantly lower than the 50% percentile from the aggregated expert distributions.

Tables 4.3 and 4.4 compare the aggregated expert distributions with distributions used in two past uncertainty studies for Fm and Ff respectively.[7,8] The values for the ECOSYS study are the maximum and minimum values of the distribution; values for the MARC study, which used the FARMLAND model, are the 0.1th, 50th and 99.9th percentiles of the distribution. As the percentiles of the distributions used in the three studies are different, it is only possible to make general observations about the differences between them. In general, in both of the past studies the range factors are smaller than those observed from the aggregated expert distributions, particularly in the ECOSYS study, even though the minimum and maximum values of the distribution are considered. For strontium transfer to beef (Tables 4.2 and 4.4), as well as the default values of the models lying between the 5th and 50th percentiles of the aggregated expert data, the maximum value and 99.9th percentile value for the ECOSYS and MARC studies, respectively, also both fall below the 50th percentile of the aggregated expert distribution (Table 4.4). For cesium, the MARC distribution for Ff is broadly comparable to the aggregated expert distribution.

Table 4.5 compares the 5th, 50th and 95th percentile values for soil-plant concentration ratios for cereals for strontium and cesium. In the literature, data are presented as a function of soil type, and values for both clay/loam and sandy soils are presented for comparison with the aggregated distributions and the FARMLAND and ECOSYS values for a generic soil. There is good agreement between the 50th percentile values, the model defaults, and the "typical" values for sand and clay/loam soils. The 5th and 95th percentile values are also comparable with those from the literature if both soil types are taken into account. Table 4.6 compares the aggregated expert distributions with those used in the two uncertainty studies. In both studies the observed range factors are again narrower than those observed from the aggregated distributions. The distributions from ECOSYS and MARC both lie within the 5th and 95th percentiles of those from the study.

4.6 References

1. Cooke, R.M. *Experts in Uncertainty: Opinion and Subjective Probability in Science*. New York, Oxford University Press, 1991.

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6. IAEA, Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments, Technical Report Series No. 364, International Atomic Energy Agency, Vienna, 1994.

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Table 4.1 Comparison of values for Fm for dairy cows from aggregated expert distributions with those used in COSYMA and from the literature

Element	**Fm dairy cows, d L^{-1}**					
	Aggregate expert distribution					
	5%	50%	95%	**ECOSYS default**[a]	**FARMLAND default**[a]	**IAEA**[b]
Sr	4.3E-4	2.3E-3	4.8E-3	2E-3	2E-3	2.8E-3[c] (1E-3 – 3E-3)[d]
Cs	1.0E-3	5.7E-3	2.4E-2	3E-3	5E-3	7.9E-3[c] (1E-3 – 2.7E-2)[d]
I	5.3E-4	7.6E-3	3.7E-2	3E-3	5E-3	1E-2[c] (1E-3 – 3.5E-2)[d]

[a] Default value used in model.
[b] IAEA, Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments, Technical Report Series No. 364, IAEA, Vienna, 1994.
[c] Expected value, i.e., value that is considered "typical" or most likely to occur.
[d] Range is minimum to maximum value reported in the literature.

Table 4.2 Comparison of values for Ff for beef cattle and dairy cows from aggregated expert distributions with those used in COSYMA and from the literature

Element	Ff, d kg^{-1}					
	Aggregate expert distribution			ECOSYS default[a]	FARMLAND default[a]	IAEA[b]
	5%	50%	95%			
Sr: dairy cows	3.8E-5	2.4E-3	9.1E-3	3E-4	3E-4	8E-3[c] (3E-4 – 8E-3)[d]
Sr: beef cattle	1.6E-4	4.8E-3	6.2E-2	3E-4		
Cs: dairy cows	1.1E-3	2.1E-2	7.6E-2	1E-2	3E-2	5E-2[c] (1E-2 – 6E-2)[d]
Cs: beef cattle	3.1E-3	4.0E-2	9.1E-2	4E-2		

[a] Default value used in model.
[b] IAEA, Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments, Technical Report Series No. 364, IAEA, Vienna, 1994.
[c] Expected value, i.e., value that is considered "typical" or most likely to occur.
[d] Range is minimum to maximum value reported in the literature.

Table 4.3 Comparison of values for Fm for dairy cows from aggregated expert distributions with those used in other uncertainty studies

Element	Fm dairy cows, d L^{-1}				
	Aggregate expert distribution			ECOSYS[a]	MARC[b]
	5%	50%	95%		
Sr	4.3E-4	2.3E-3	4.8E-3	1E-3 – 2.5E-3	4.5E-4 – 1.3E-3 – 3.5E-3
Cs	1.0E-3	5.7E-3	2.4E-2	2E-3 – 9E-3	2.5E-3 – 7.9E-3 – 2.5E-2
I	5.3E-4	7.6E-3	3.7E-2	2E-3 – 9E-3	3E-3 – 1E-2 – 3.5E-2

[a] Minimum and maximum values of uniform distribution.
[b] 0.1–50–99.9 percentiles of log-normal distribution.

Table 4.4 Comparison of values for Ff for beef cattle and dairy cows from aggregated expert distributions with those used in other uncertainty studies

Element	Ff, d kg^{-1}				
	Aggregate expert distribution			ECOSYS[a]	MARC[b]
	5%	50%	95%		
Sr: dairy cows	3.8E-5	2.4E-3	9.1E-3	1E-4 – 5E-4	6E-5 – 1.9E-4 – 6E-4
Sr: beef cattle	1.6E-4	4.8E-3	6.2E-2	1E-4 – 5E-4	
Cs: dairy cows	1.1E-3	2.1E-2	7.6E-2	5E-3 – 5E-2	7E-3 – 2.5E-2 – 9E-2
Cs: beef cattle	3.1E-3	4.0E-2	9.1E-2	2E-2 – 6E-2	

[a] Minimum and maximum values of uniform distribution.
[b] 0.1–50–99.9 percentiles of log-normal distribution.

Table 4.5 Comparison of values for soil/plant concentration ratio for cereals from aggregated expert distributions with those used in COSYMA and from the literature

Element	Concentration ratio, Bq kg^{-1} fresh mass plant / Bq kg^{-1} dry mass soil					
	Aggregate expert distribution					
	5%[a]	50%[a]	95%[a]	ECOSYS default[b]	FARMLAND default[b]	IAEA[c,d]
Sr	1.1E-2	1.4E-1	1.2	2E-1	2E-1	clay, loam: 1.2E-1[e] (2.2E-2 – 6.6E-1)[f]
						sand: 2.1E-1[e] (3.2E-2 – 1.4)[f]
Cs	7.5E-4	1.6E-2	1.8E-1	2E-2	1E-2	clay, loam: 1E-2[e] (1E-3 – 1E-1)[f]
						sand: 2.6E-2[e] (2.6E-3 – 2.6E-1)[f]

[a] Value for a generic soil, 3 years following deposition.
[b] Default value for a generic soil used in model.
[c] IAEA, Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments, Technical Report Series No. 364, IAEA, Vienna, 1994.
[d] Data for dry mass of plant. Conversion to fresh mass assumed insignificant (about 10-15% reduction).
[e] Expected value, i.e., a value that is considered "typical" or most likely to occur.
[f] 95% confidence interval.

Table 4.6 Comparison of values for soil/plant concentration ratio for cereals from aggregated expert distributions with those used in other uncertainty studies

Element	Concentration ratio, Bq kg^{-1} fresh mass plant / Bq kg^{-1} dry mass soil				
	Aggregate expert distribution				
	5%[a]	50%[a]	95%[a]	ECOSYS[b]	MARC[c]
Sr	1.1E-2	1.4E-1	1.2	6E-2 – 6E-1	2E-2 – 6.3E-2 – 2E-1
Cs	7.5E-4	1.6E-2	1.8E-1	8E-3 – 5E-2	3E-3 – 1.2E-2 – 5E-2

[a] Value for a generic soil, 3 years following deposition.
[b] Minimum and maximum values of log-uniform distribution.
[c] 0.1–50–99.9 percentiles of log-normal distribution.

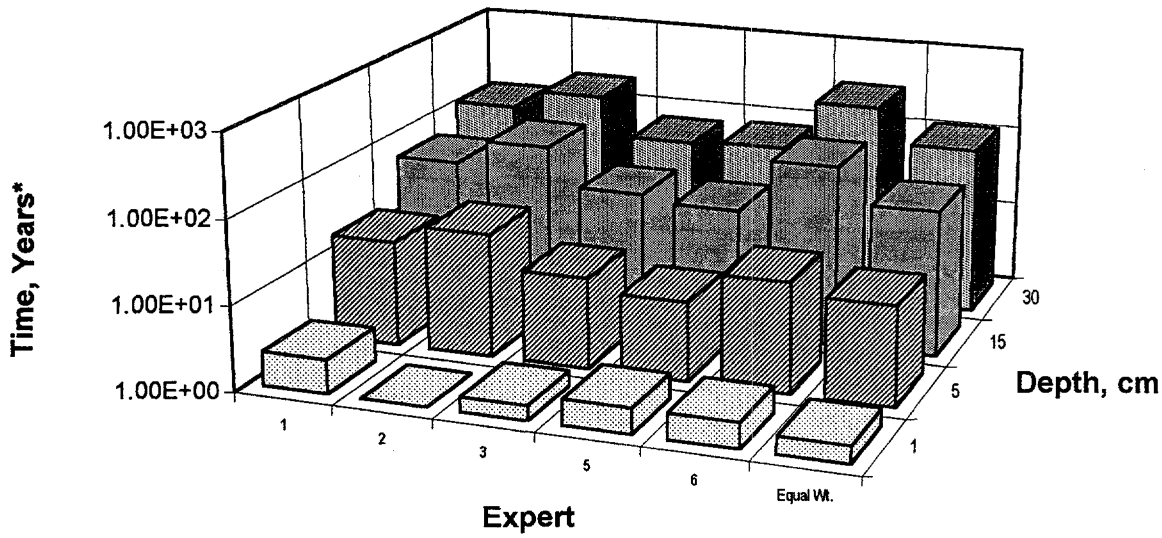

Figure 4.1 Median values for migration of cesium in a generic soil as a function of soil depth.
*** The variable representing soil migration is expressed as the time taken for 50% of the initial deposit to migrate to below the specified depth in the soil.**

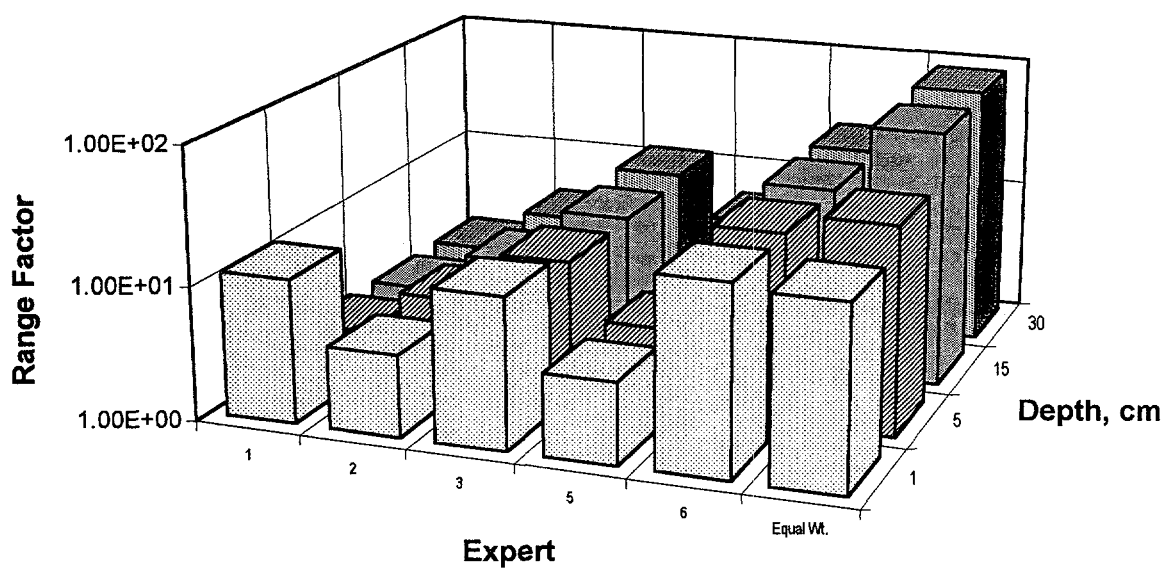

Figure 4.2 Range factors (ratio of 95th/5th percentile) for migration of cesium in a generic soil.

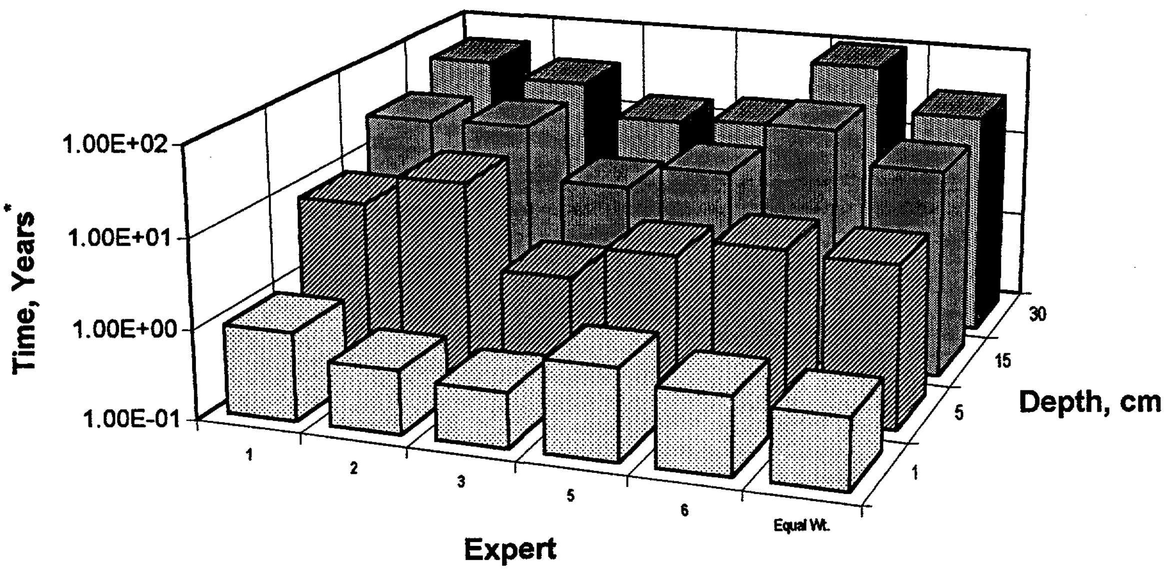

Figure 4.3 Median values for migration of strontium in a generic soil as a function of soil depth.
*** The variable representing soil migration is expressed as the time taken for 50% of the initial deposit to migrate to below the specified depth in soil.**

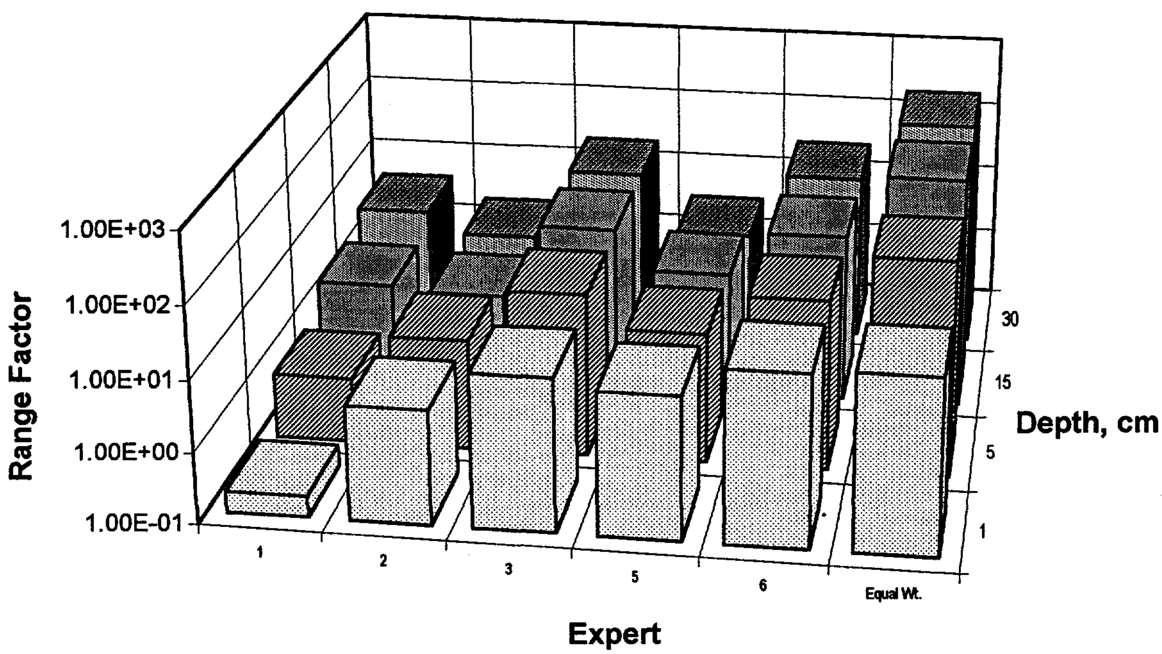

Figure 4.4 Range factors (ratio of 95th/5th percentile) for migration of strontium in a generic soil as a function of soil depth.

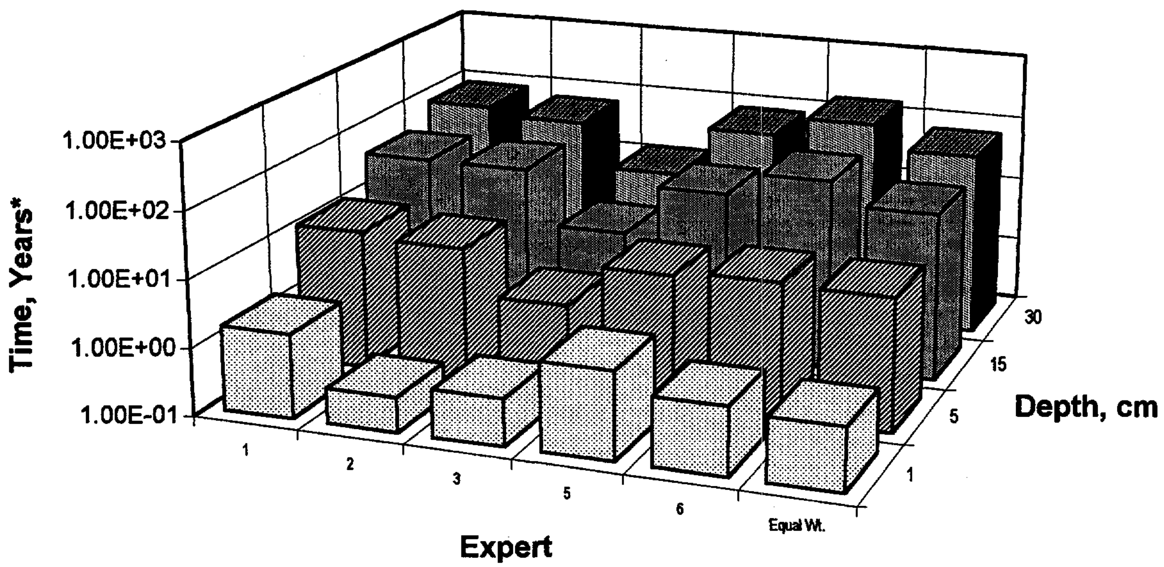

Figure 4.5 Median values for soil migration for sandy soil with depth for cesium.
*** The variable representing soil migration is expressed as the time taken for 50% of the initial deposit to migrate to below the specified depth in soil.**

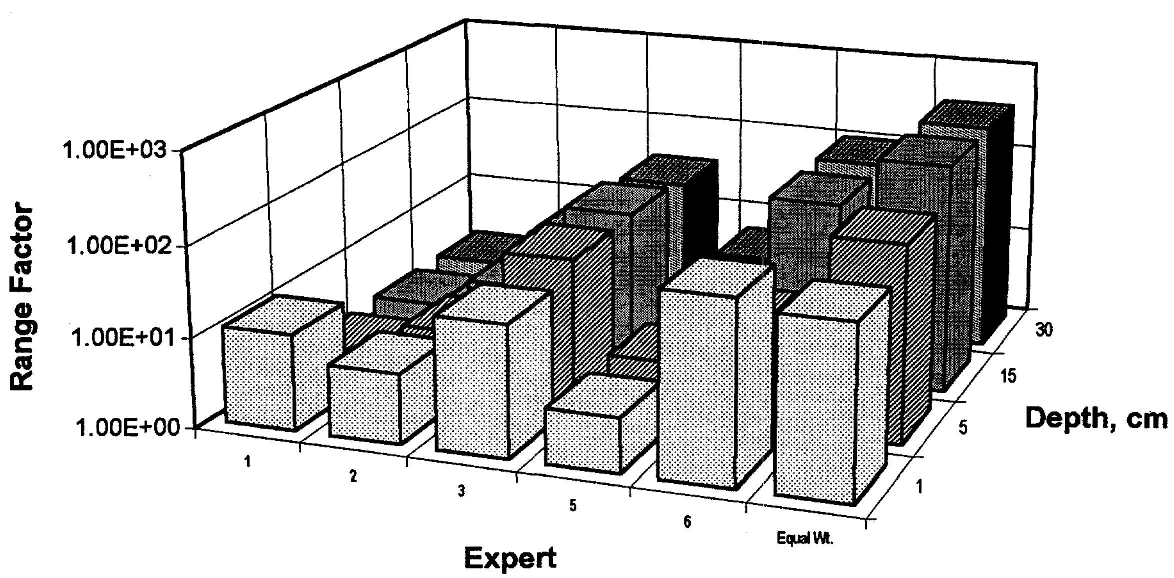

Figure 4.6 Range factors (ratio of 95th/5th percentile) for soil migration for sandy soil with depth for cesium.

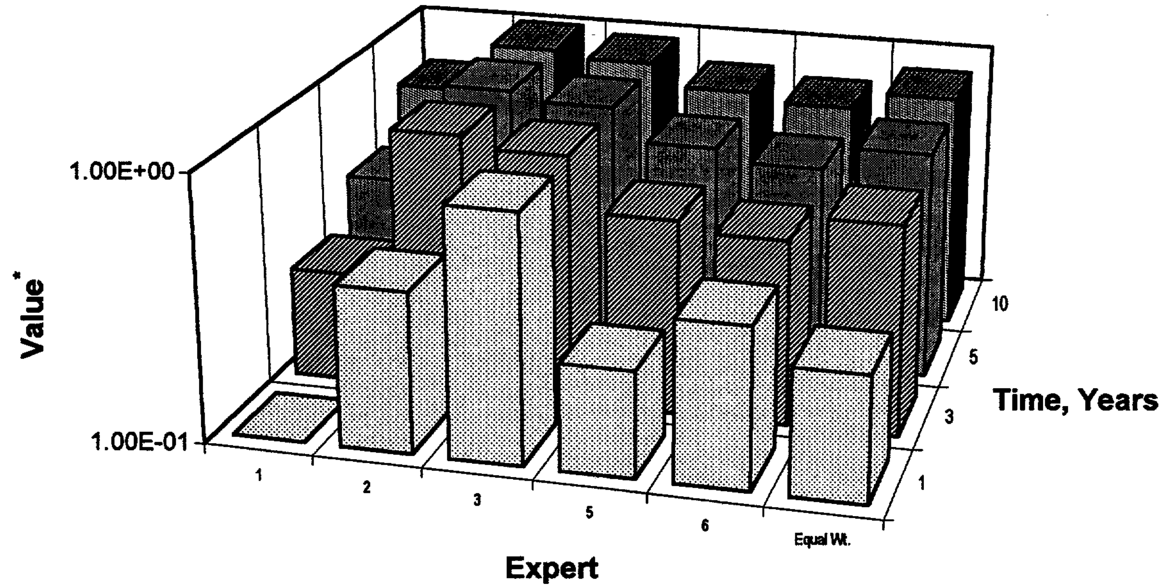

Figure 4.7 Median values for fixation of cesium in a generic soil as a function of time.
*** The variable representing fixation in soil is expressed as the fraction of the element that is unavailable for uptake by plant roots at the specified time following deposition.**

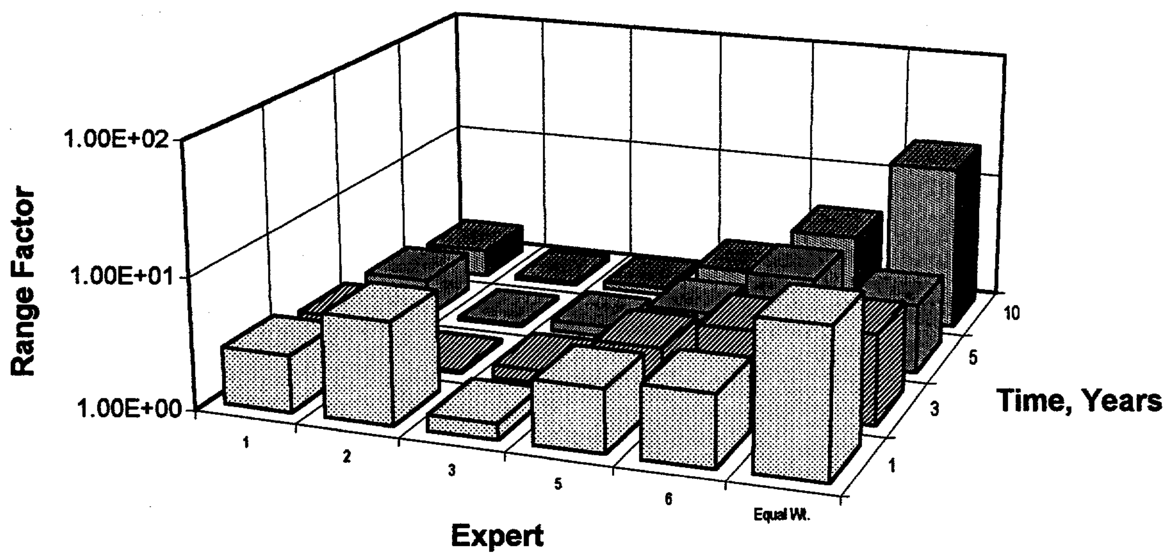

Figure 4.8 Range factors (ratio of 95th/5th percentile) for fixation of cesium in a generic soil as a function of time.

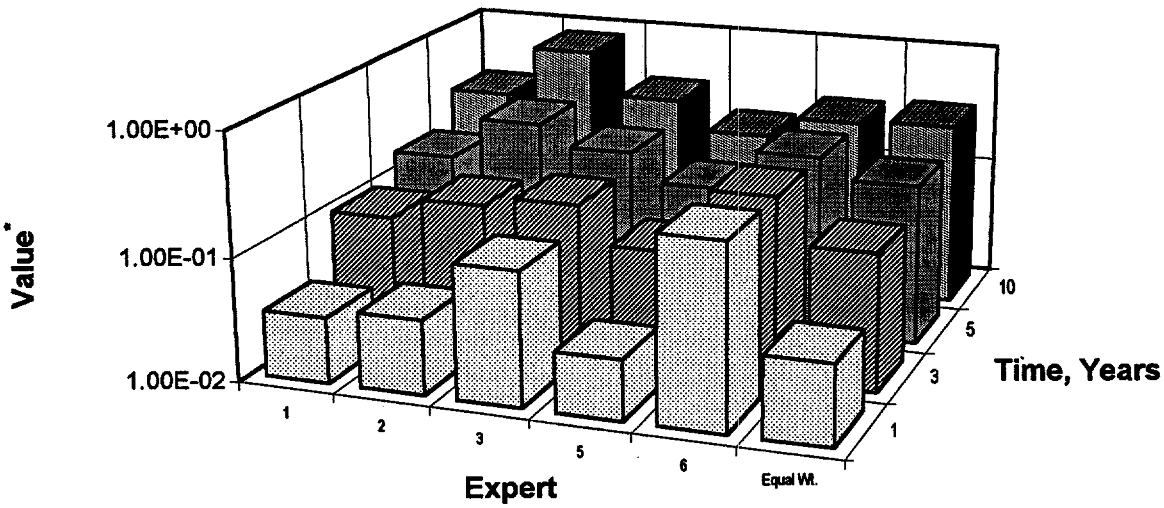

Figure 4.9 Median values for fixation of strontium in a generic soil as a function of time.

*** The variable representing fixation in soil is expressed as a fraction of the element that is unavailable for uptake by plant roots at the specified time following deposition.**

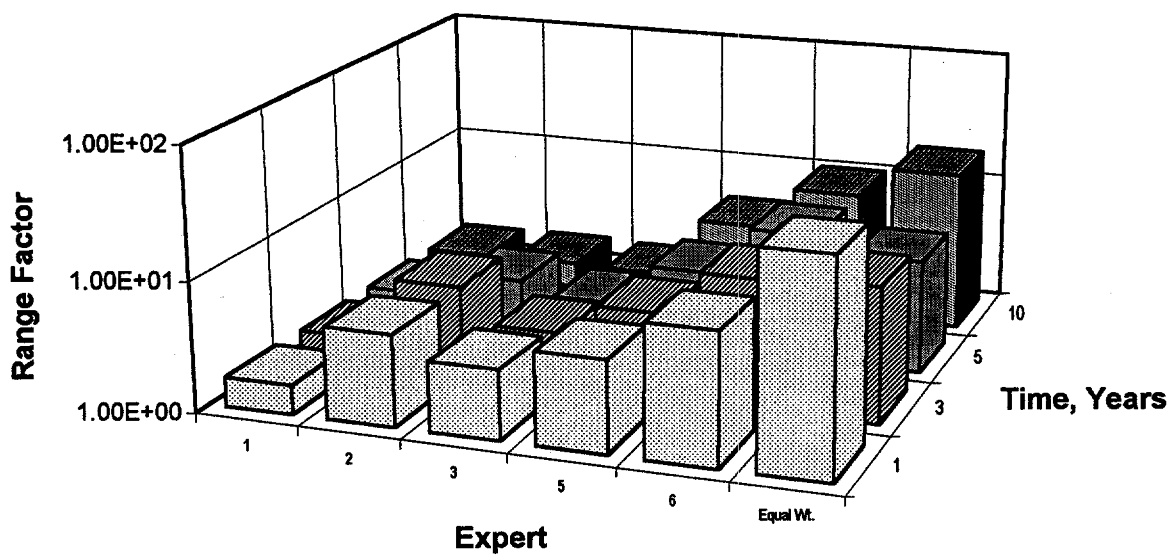

Figure 4.10 Range factors (ratio of 95th/5th percentile) for fixation of strontium in a generic soil as a function of time.

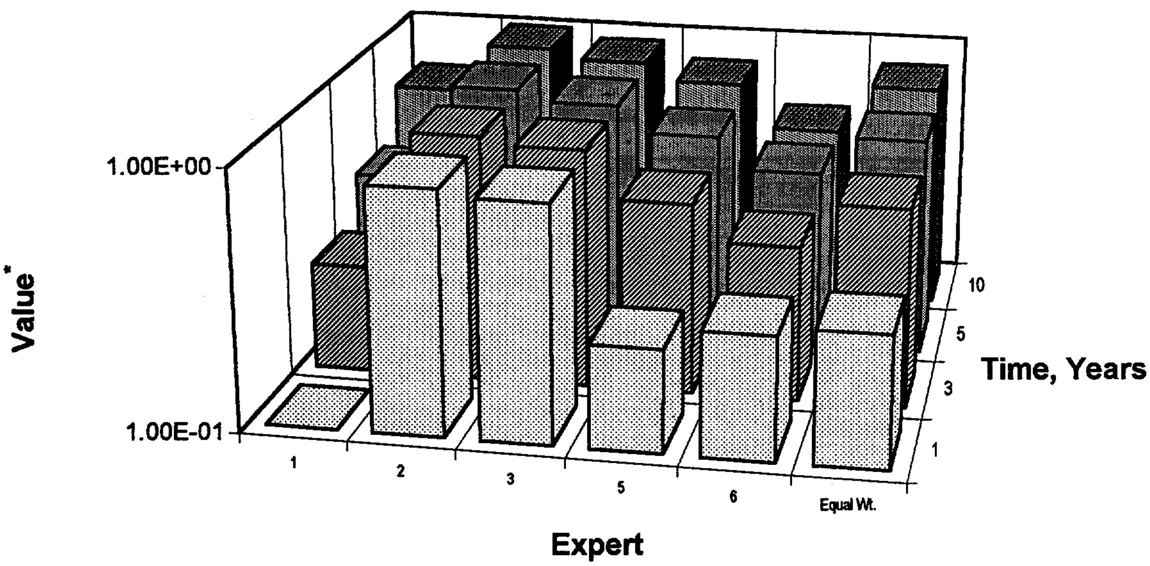

Figure 4.11 Median values for fixation of cesium in sandy soil as a function of time.
*** The variable representing fixation in soil is expressed as a fraction of the element that is unavailable for uptake by plant roots at the specified time following deposition.**

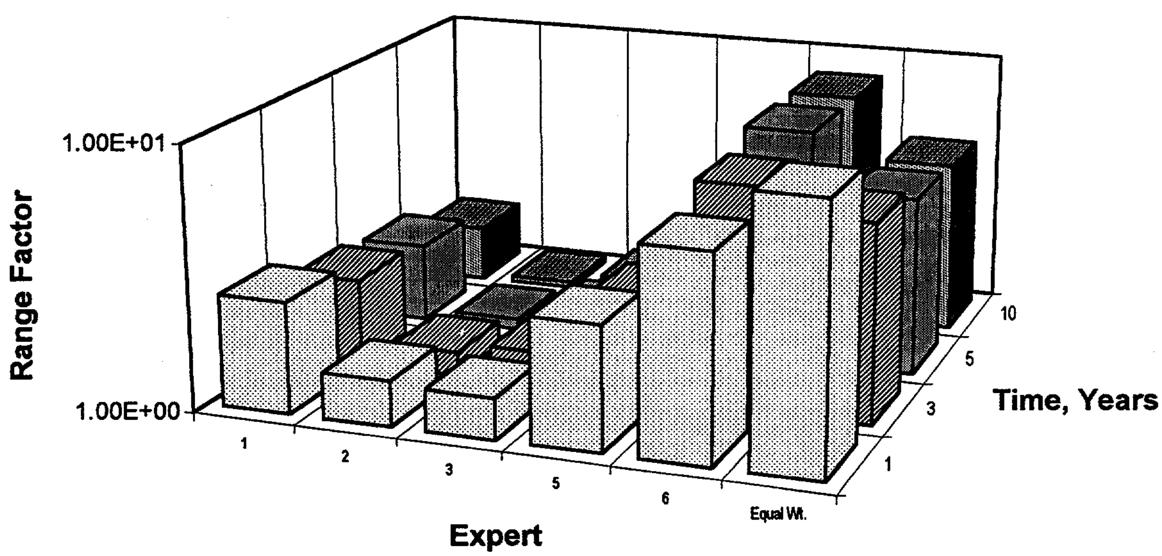

Figure 4.12 Range factors (ratio of 95th/5th percentile) for fixation of cesium in sandy soil as a function of time.

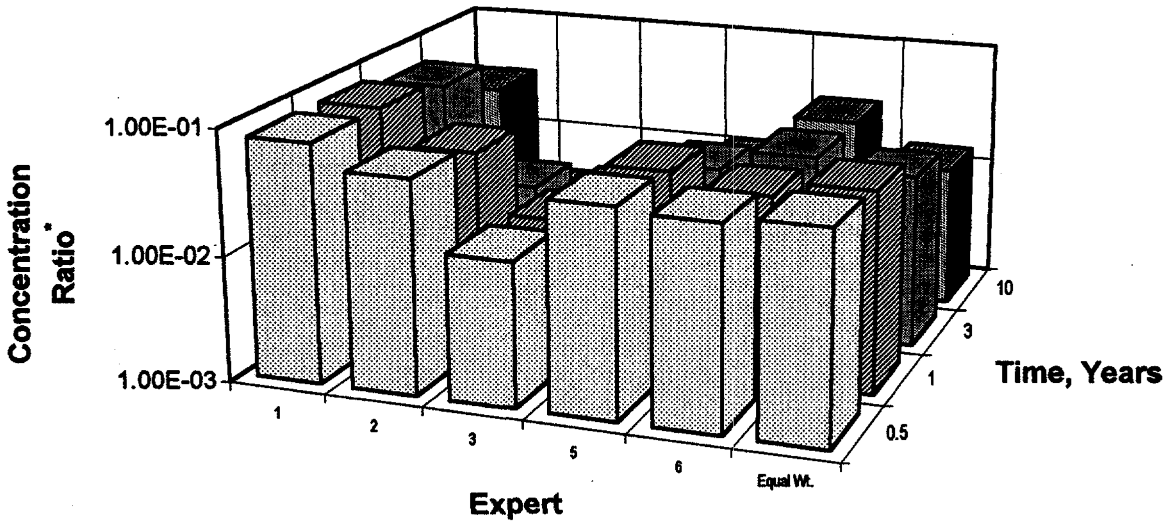

Figure 4.13 Median values for soil to plant uptake of cesium in green vegetables for a generic soil as a function of time. * Concentration ratio is expressed as Bq kg^{-1} fresh plant mass per Bq kg^{-1} dry soil mass.

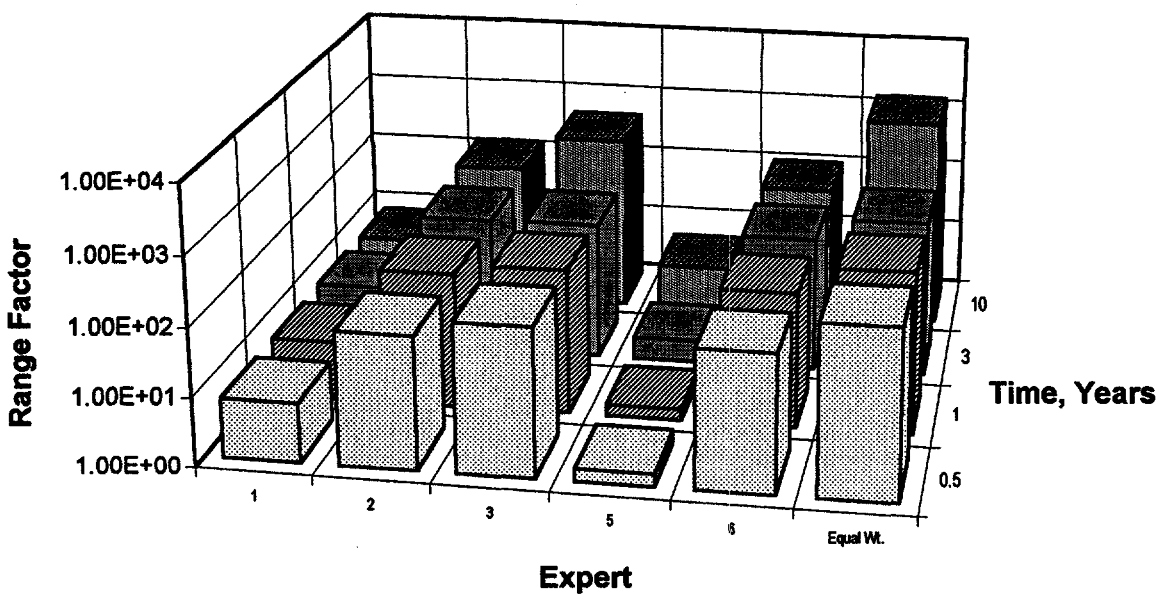

Figure 4.14 Range factors (ratio of 95th/5th percentile) for soil to plant uptake of cesium in green vegetables for a generic soil as a function of time.

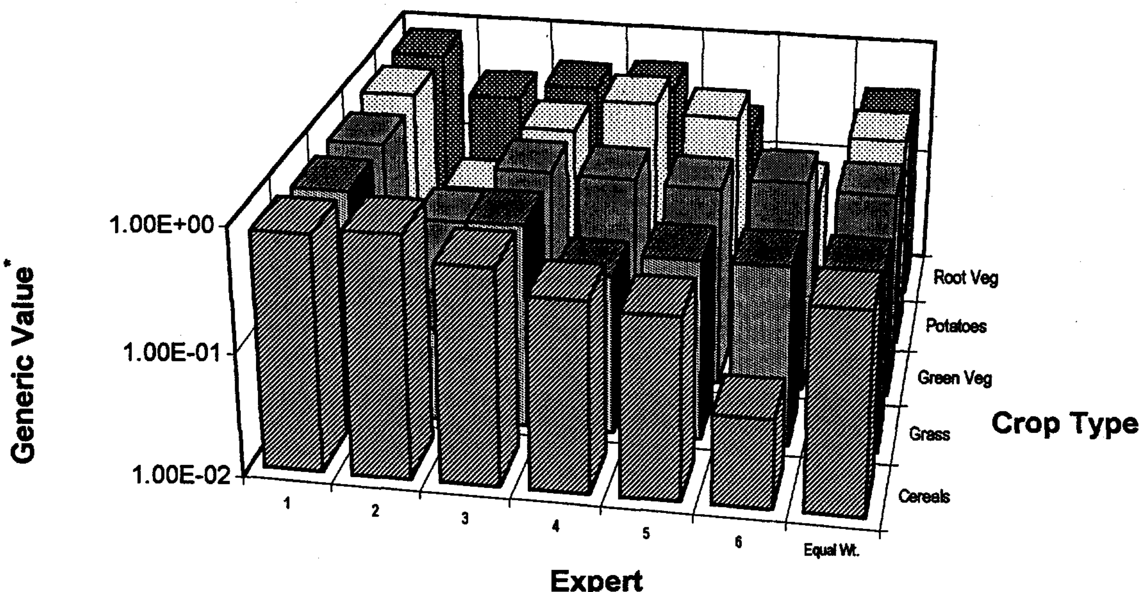

Figure 4.15 Median values for element-independent interception factors for five crops.
*** The interception factor is the fraction of the ground deposit that is intercepted by the plant at maturity.**

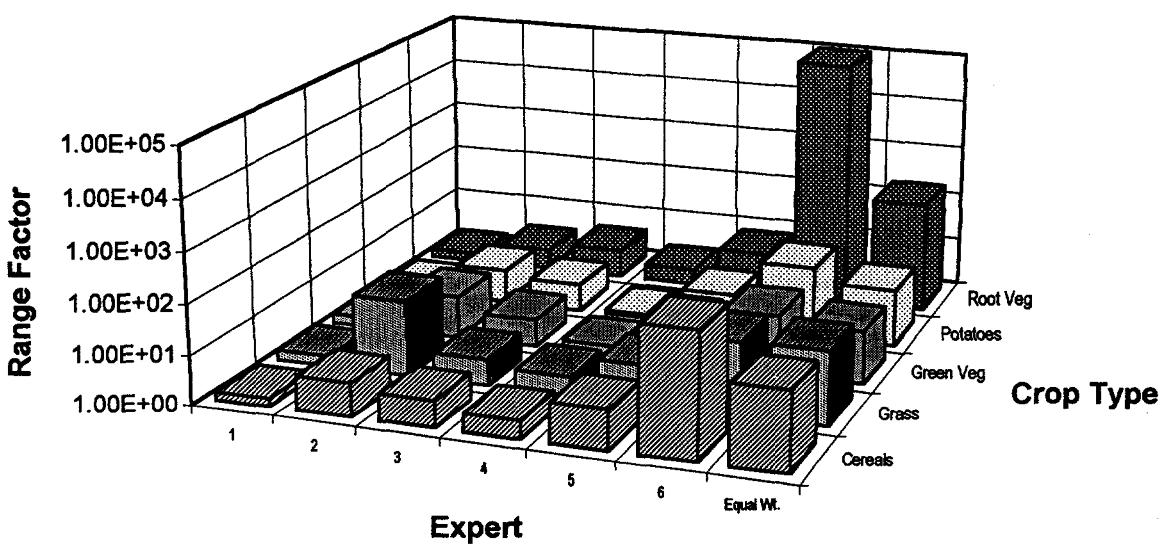

Figure 4.16 Range factors (ratio of 95th/5th percentile) for element-independent interception factors for five crops.

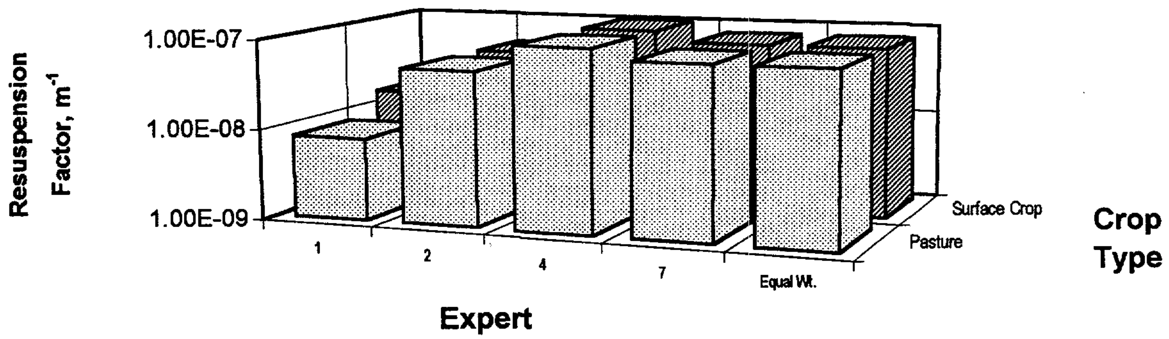

Figure 4.17 Median values for resuspension factors for surface crops and pasture.

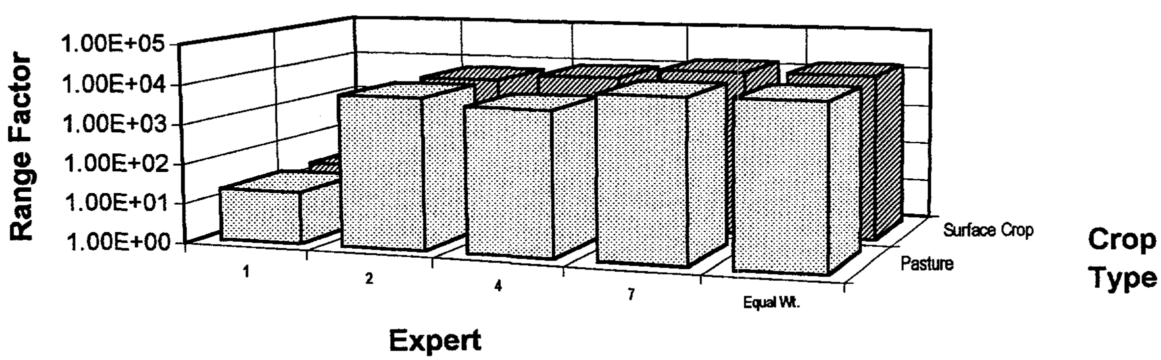

Figure 4.18 Range factors (ratio of 95th/5th percentile) for resuspension factors for surface crops and pasture.

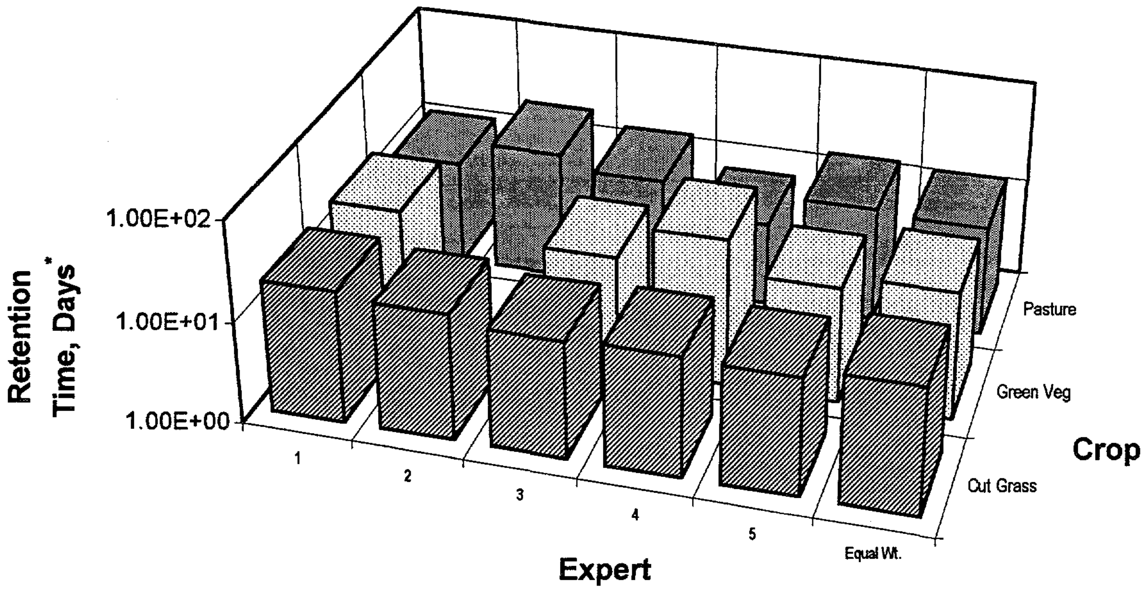

Figure 4.19 Median values for element-dependent retention times on three crops.
*** Time taken for the activity on the surface of the plant to be reduced to half of its original value.**

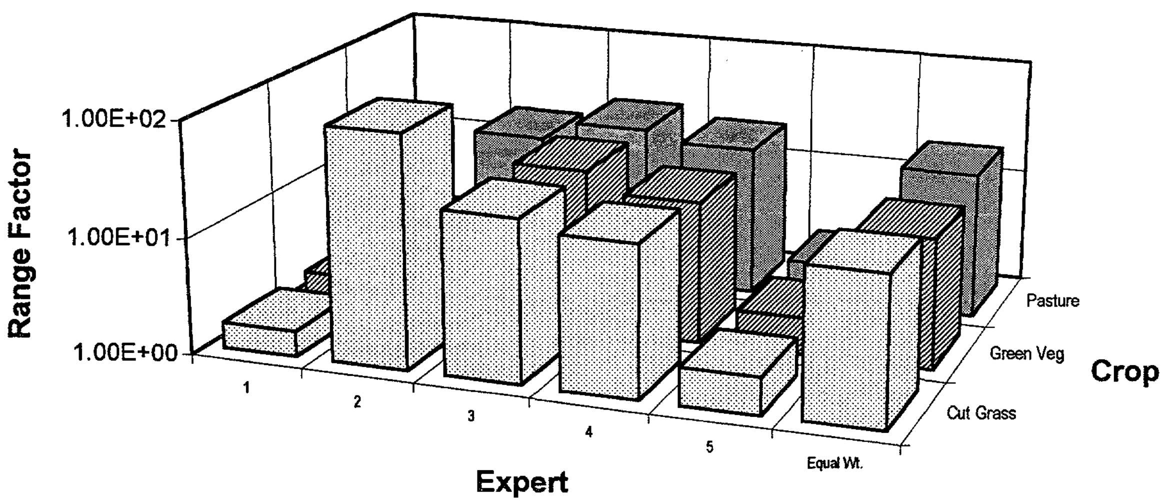

Figure 4.20 Range factors (ratio of 95th/5th percentile) for element-dependent retention times on three crops.

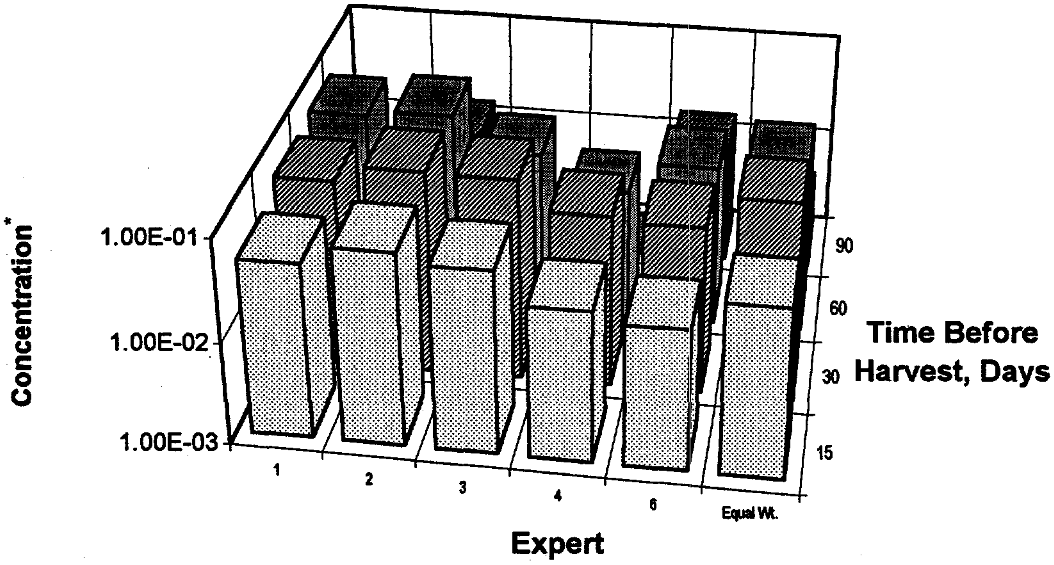

Figure 4.21 Median values for the concentration of cesium in grain at harvest from direct contamination of the crop at specified times before harvest. * Bq kg^{-1} fresh mass of edible grain at harvest per Bq m^{-2} deposited on the ground.

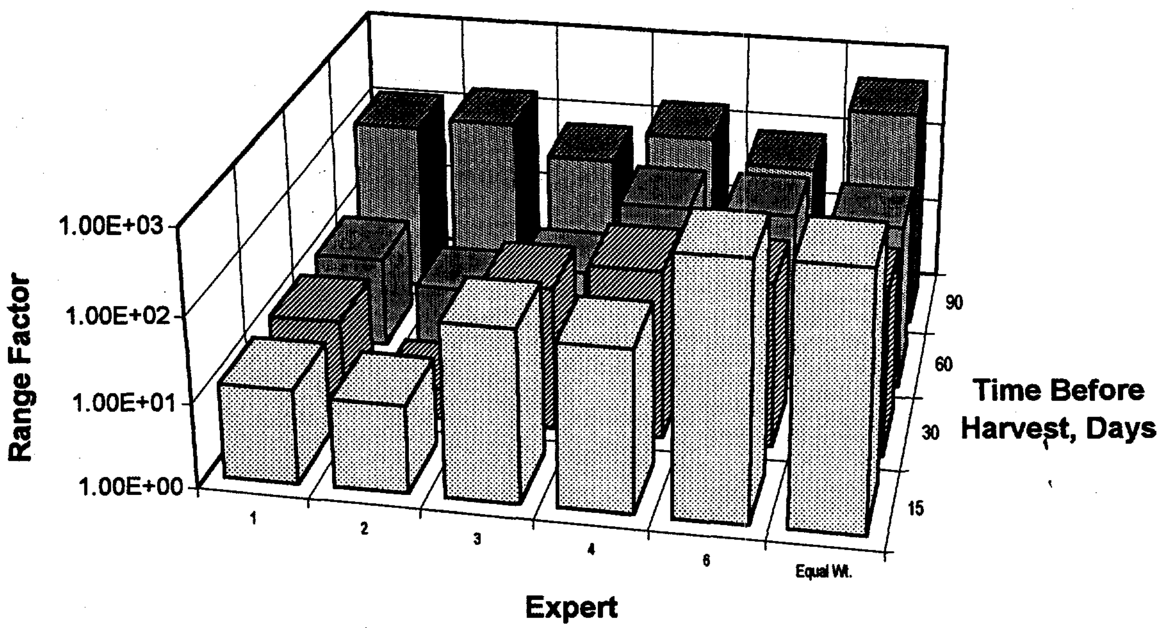

Figure 4.22 Range factors (ratio of 95th/5th percentile) for the concentration of cesium in grain at harvest from direct contamination of the crop at specified times before harvest.

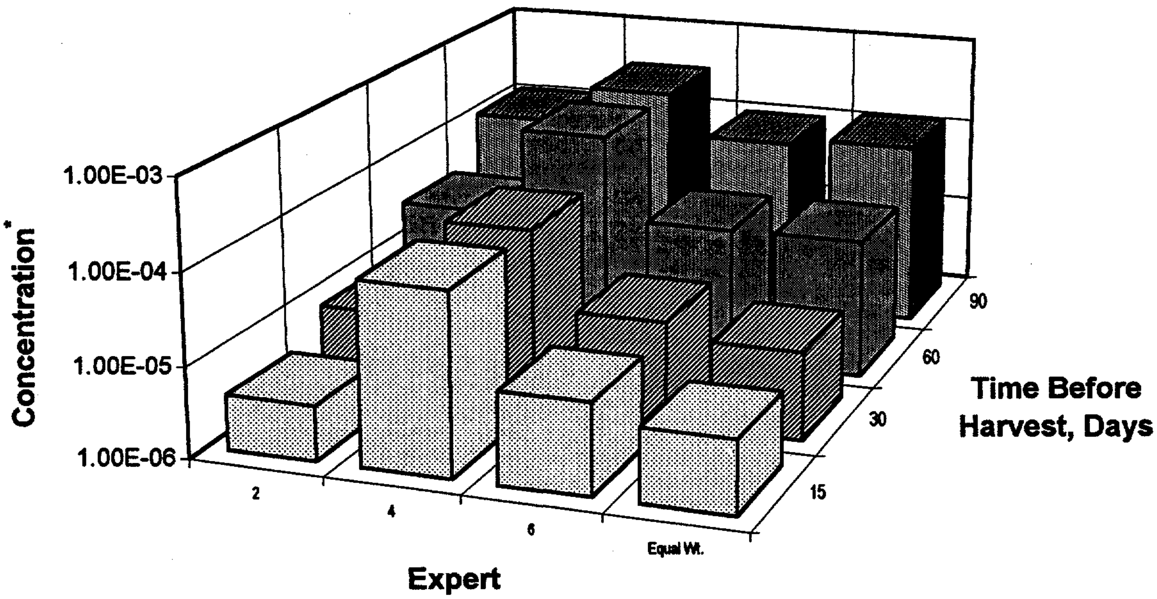

Figure 4.23 Median values for the concentration of strontium in root vegetables at harvest from direct contamination of the crop at specified times before harvest. * Bq kg^{-1} fresh mass of edible root vegetables at harvest per Bq m^{-2} deposited on the plant.

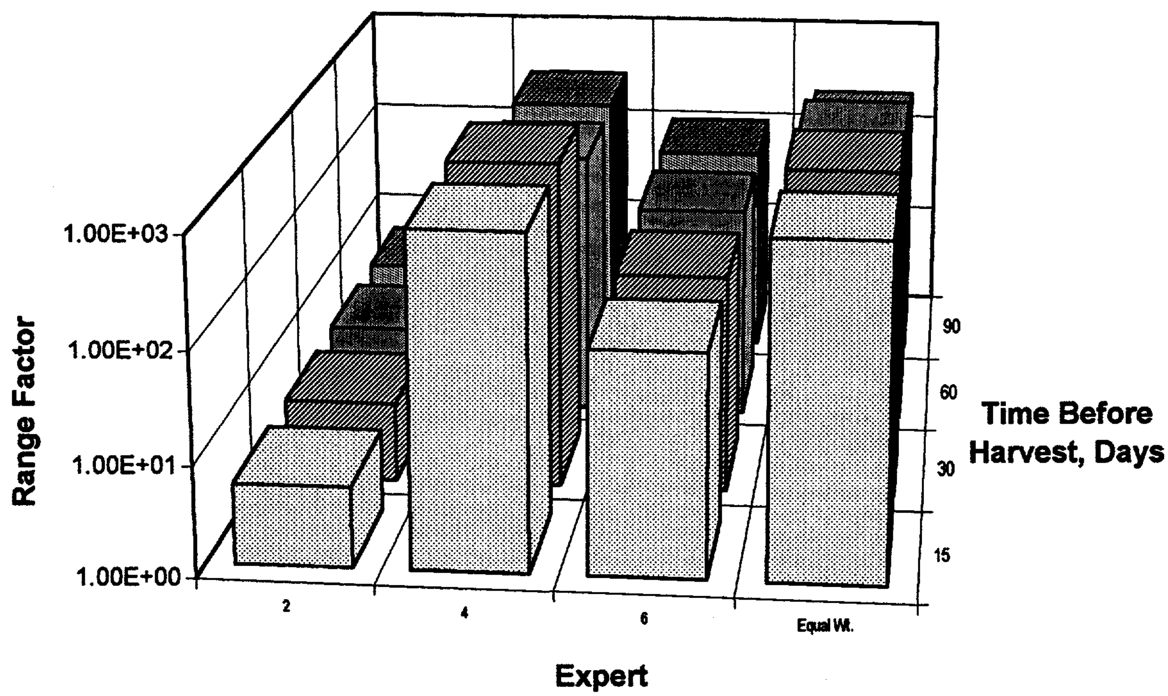

Figure 4.24 Range factors (ratio of 95th/5th percentile) for the concentration of strontium in root vegetables at harvest from direct contamination of the crop at specified times before harvest.

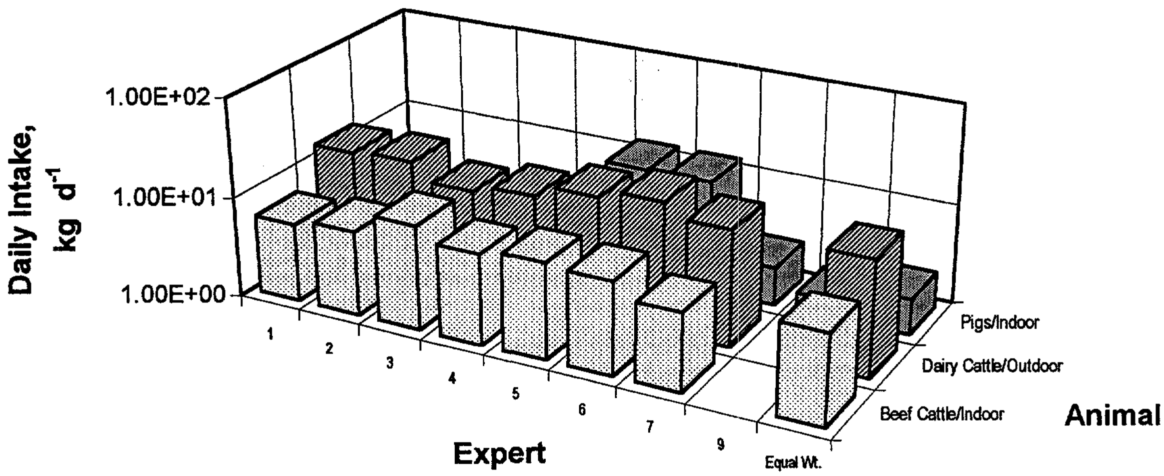

Figure 4.25 Median values for some selected daily animal intakes.

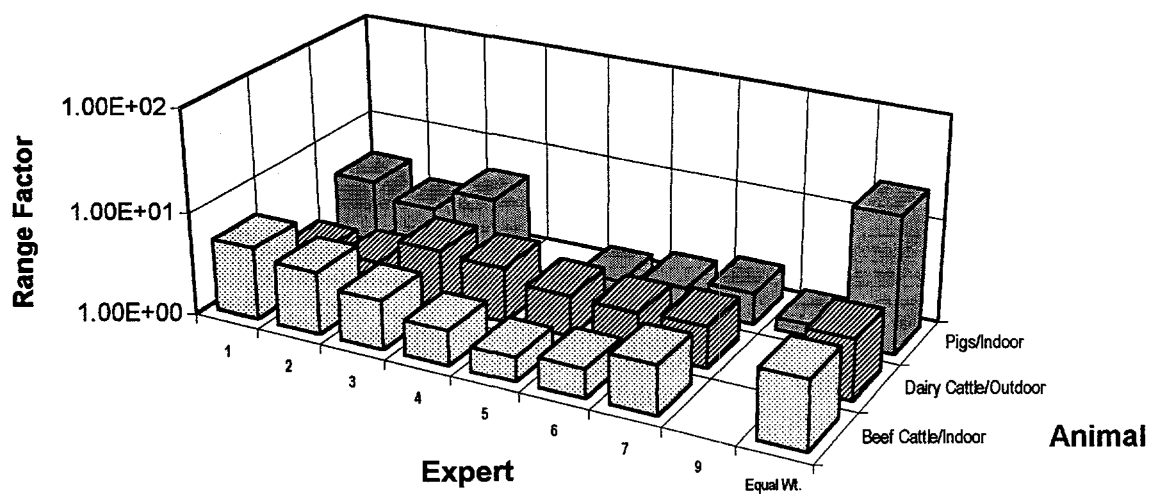

Figure 4.26 Range factors (ratio of 95th/5th percentile) for some selected daily animal intakes.

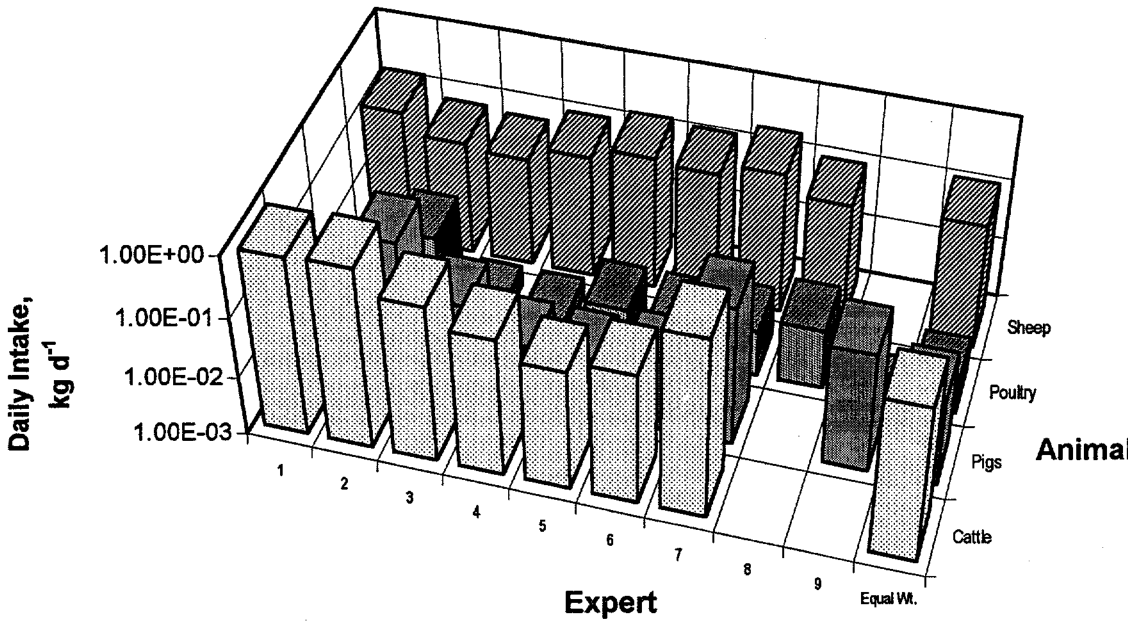

Figure 4.27 Median values for daily soil consumption for different animals.

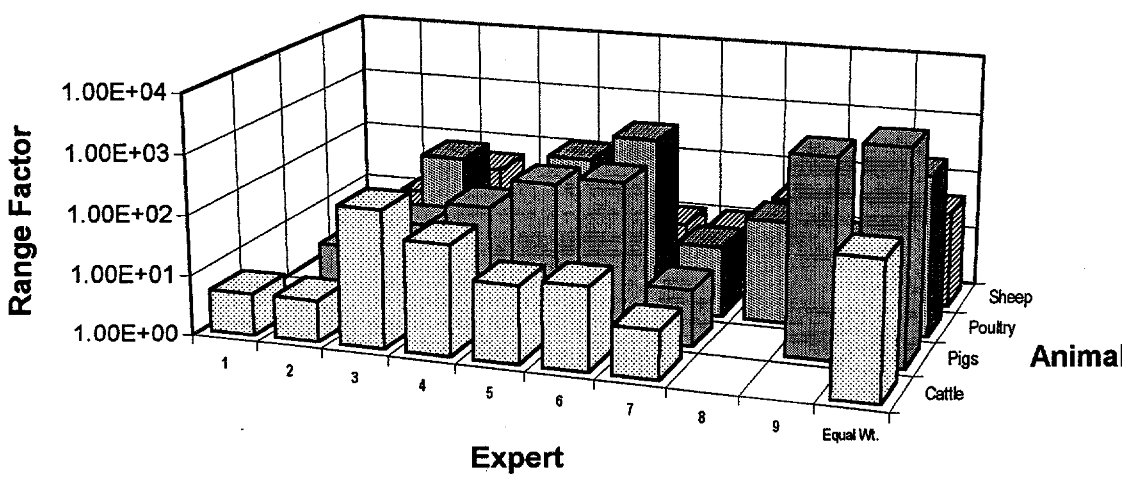

Figure 4.28 Range factors (ratio of 95th/5th percentile) for daily soil consumption for different animals.

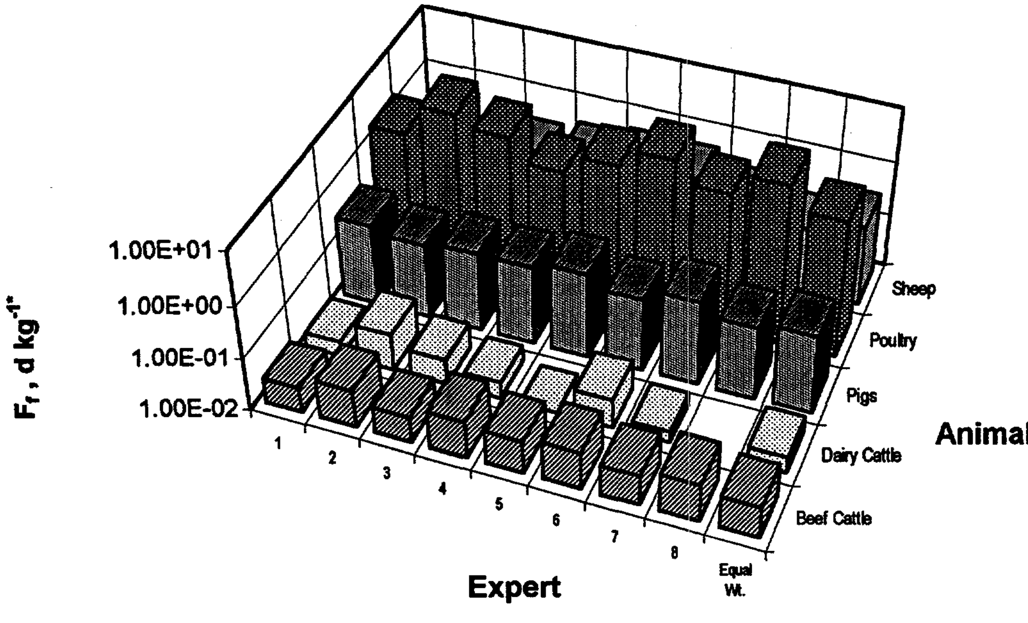

Figure 4.29 Median values for the equilibrium transfer to meat (Ff) for cesium for different animals.
*** Ff is the fraction of the daily intake that is transferred to 1 kg of meat at equilibrium.**

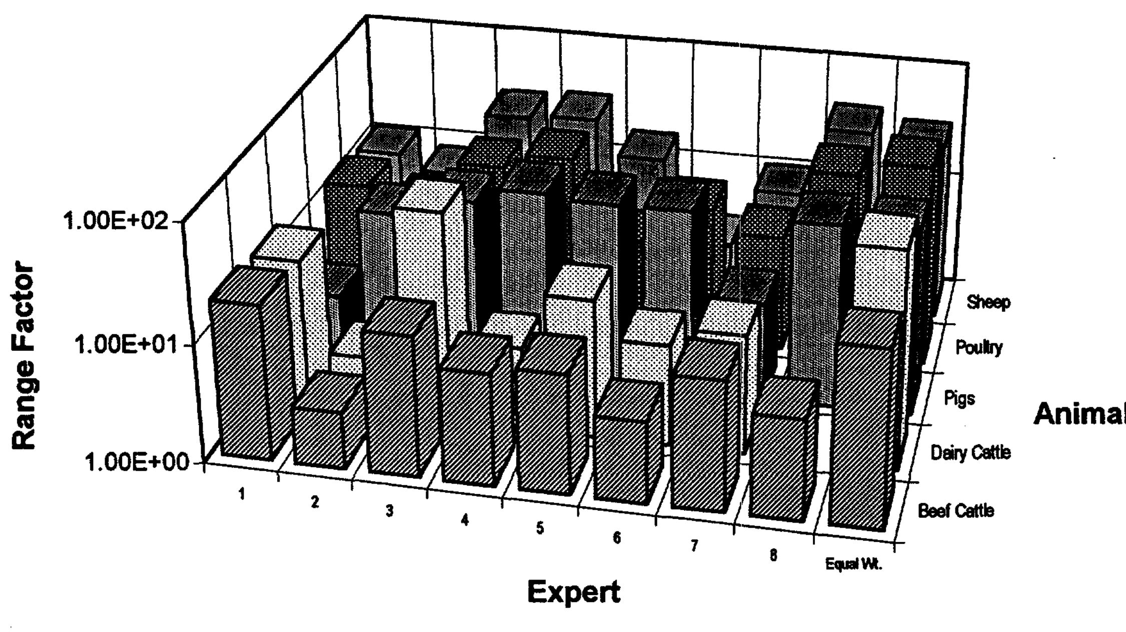

Figure 4.30 Range factors (ratio of 95th/5th percentile) for the equilibrium transfer to meat (Ff) for cesium for different animals.

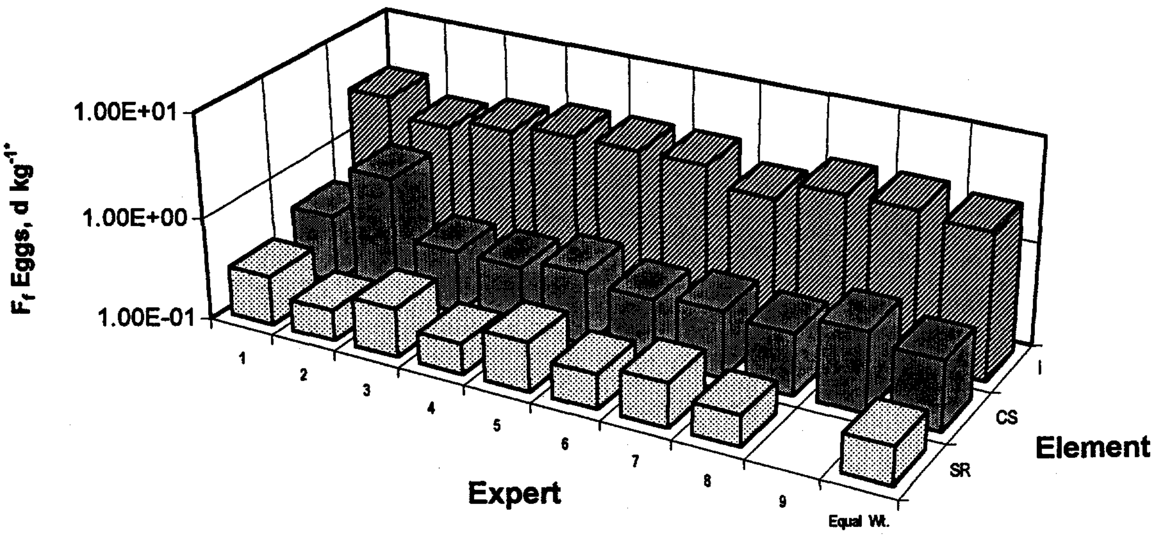

Figure 4.31 Median values for the equilibrium transfer to eggs as a function of element.
*** Ff is the fraction of the daily intake that is transferred to 1 kg of egg at equilibrium.**

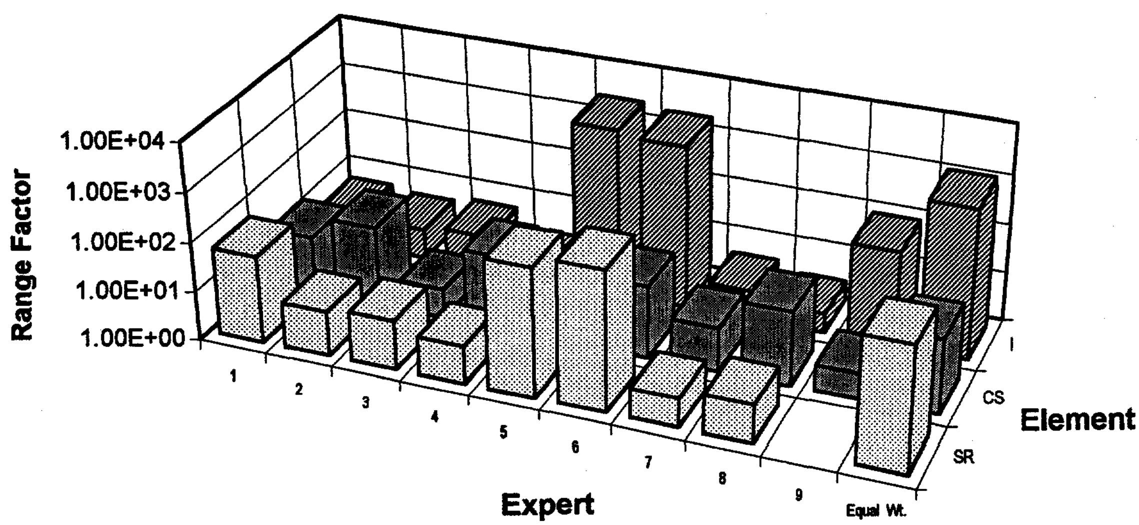

Figure 4.32 Range factors (ratio of 95th/5th percentile) for the equilibrium transfer to eggs as a function of element.

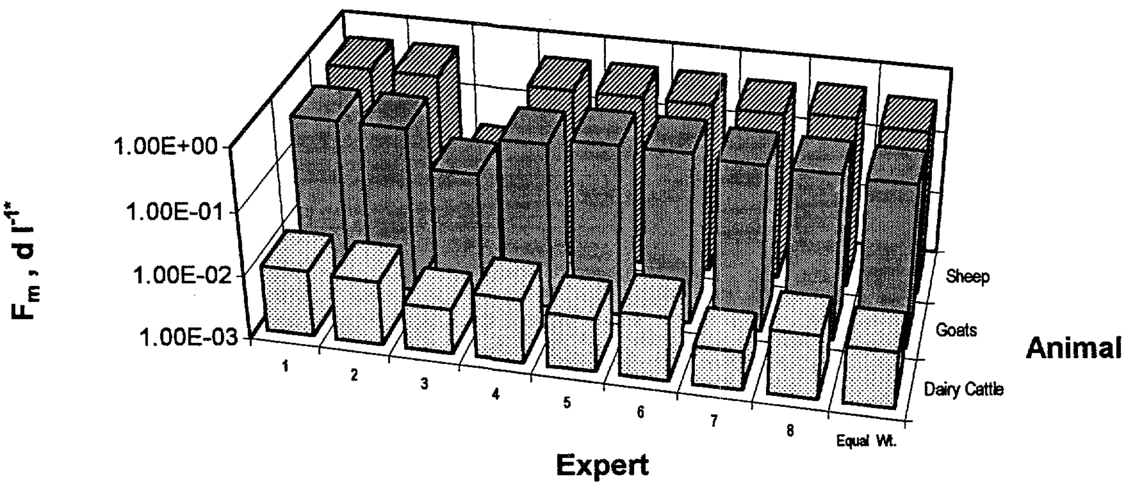

Figure 4.33 Median values for the equilibrium transfer to milk (Fm) for iodine for different animals.
*** Fm is the fraction of the daily intake that is transferred to 1 liter of milk at equilibrium.**

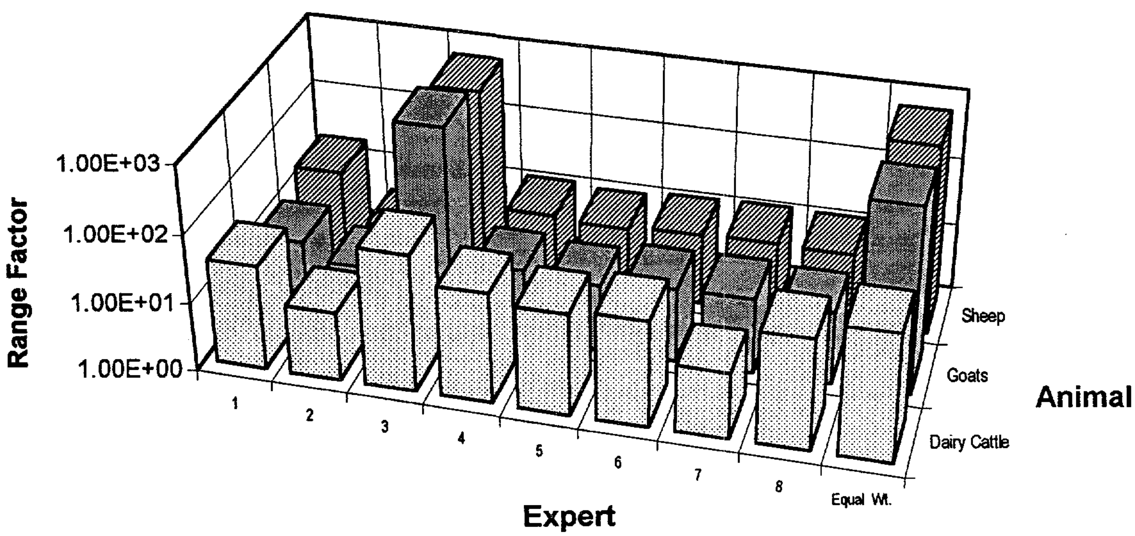

Figure 4.34 Range factors (ratio of 95th/5th percentile) for the equilibrium transfer to milk (Fm) for iodine for different animals.

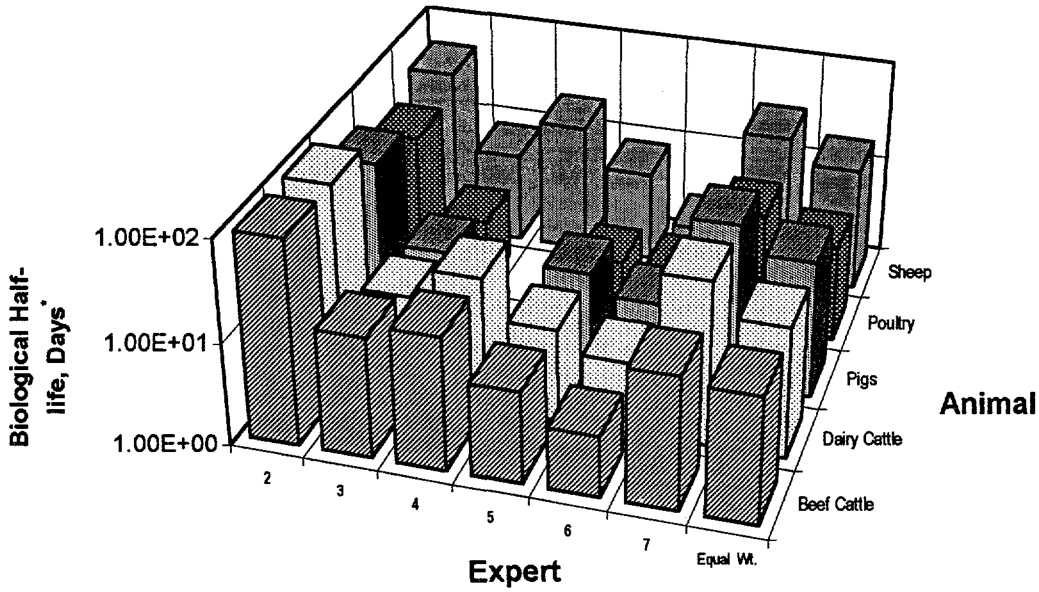

Figure 4.35 Median values for the biological half-life of strontium in the meat of different animals.
*** Biological half-life is the weighted average residence time of the activity in the meat of the animal.**

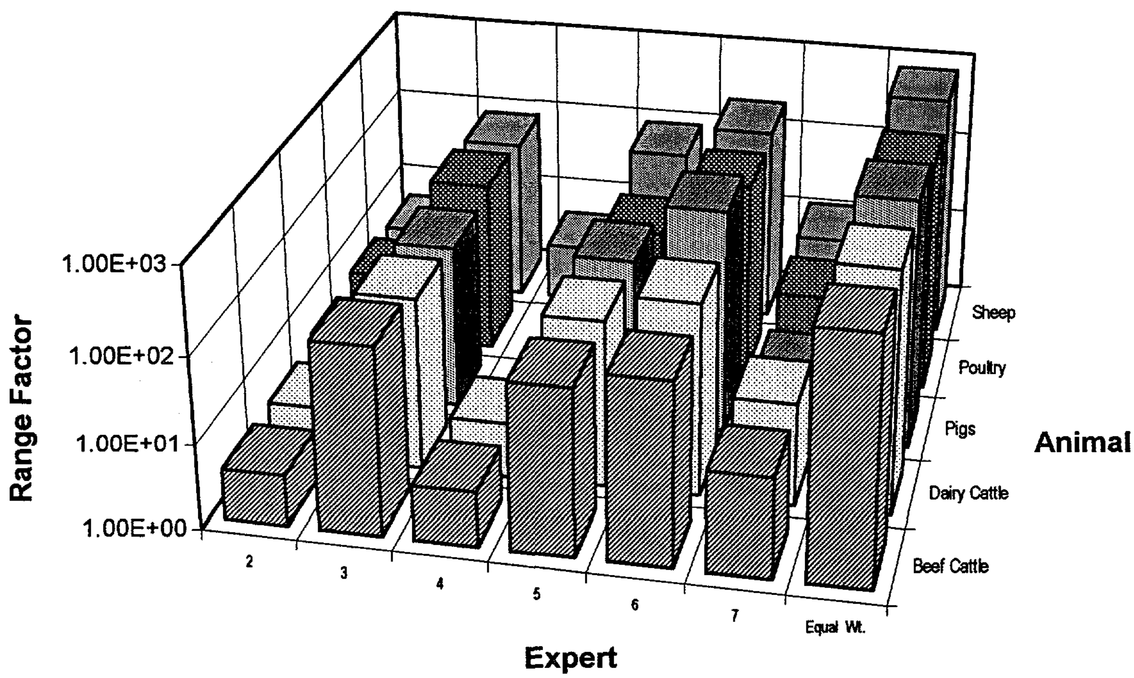

Figure 4.36 Range factors (ratio of 95th percentile) for the biological half-life of strontium in the meat of different animals.

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 identified and addressed. The final product of this study, therefore, was enhanced by this cooperation.

Distributions on measurable food chain parameters were successfully elicited from distinguished experts. Aggregated distributions, developed by combining the individual elicited distributions, are now available for measurable food chain parameters. The aggregated elicited uncertainty distributions represent state-of-the-art knowledge in the areas of food chain modeling. Uncertainty distributions on food chain code input variables are also now available for use in performing consequence uncertainty analyses using the MACCS and COSYMA codes. The distributions for the elicitation and code input variables 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 elicited distributions, therefore, include variations that result from different modeling approaches and perspectives.

The aggregated elicited food chain distributions for soil/plant transfer processes capture the uncertainty in migration and fixation of radionuclides in soil; root uptake into plants; in interception, retention, and translocation in plants; and in resuspension and deposition onto plants. The aggregated elicited food chain distributions for animal food intake and radionuclide transport in animals capture the uncertainty in transfer from feedstuffs to milk and meat, retention in the gut of the animals, the biological half-life of the nuclide in the meat of animals, and in animal diets.

Mathematical processing of the aggregated elicited data was not necessary for the distributions of animal food intake and transport processes because the elicited quantities and the code input variables were observable quantities. For soil/plant transfer processes, most of the elicited quantities must be mathematically processed for use in the current food chain models FARMLAND and COMIDA. Since the food chain models are different, the mathematical processing will be performed for COSYMA and MACCS applications separately.

5.3 Application of Distributions

The results of this project will allow the distribution representing uncertainty in food chain parameters to be determined 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 food chain distributions are 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 food chain model available. However, different processing techniques may be required to modify the elicited distributions into distributions that are compatible with different models.

The distributions obtained here will be processed for both COSYMA and MACCS uncertainty studies. In many cases, different distributions will be needed for MACCS than for COSYMA. This occurs for two reasons: (1) some of the code input variables for

MACCS differ from the COSYMA code input variables that are related to a common elicitation variable, and (2) agricultural practices and husbandry practices differ between Europe and the US, requiring separate distributions for the same elicitation variable. In addition, the experts provided numerical data on dependencies between the food chain model parameters (for the animal and soil/plant items separately).

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 variables, the elicited information is not specific to a model and can be used by many other analytical models. 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 food chain uncertainty distributions will have many applications outside this project. The distributions also 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, despite the modifications of questions for the animal food intake and radionuclide transfer variables. The goal of creating a library of uncertainty distributions for food chain variables was fulfilled. Furthermore, 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 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 unambiguous and noncontroversial conclusions.

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J. Randall, NRC Project Manager

11. ABSTRACT *(200 words or less)*

The development of two new probabilistic accident consequence codes, MACCS and COSYMA, was completed in 1990. These codes estimate the consequence from the accidental releases of radiological material from hypothesized accidents at nuclear installations. In 1991, the U.S. Nuclear Regulatory Commission and the Commission of the European Communities began cosponsoring a joint uncertainty analysis of the two codes. The ultimate objective of this joint effort was to systematically develop credible and traceable uncertainty distributions for the respective code input variables. A formal expert judgment elicitation and evaluation process was identified as the best technology available for developing a library of uncertainty distributions for these consequence parameters. This report focuses on the results of the study to develop distribution for variables related to the MACCS and COSYMA food chain models. Both soil/plant transfer processes and radionuclide transport in animals were assessed.

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