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Probabilistic Accident Consequence Uncertainty Analysis

Late Health Effects 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, further expert judgment exercises were carried out. This report is on the late health effects part of the study. The goal again was to develop a library of uncertainty distributions for the selected consequence parameters. Ten experts from five countries were selected for the late health effects panel. Their results were processed with an equal-weighting aggregation method, and the aggregated distributions will be processed into the code input variables for the late health effects models in COSYMA and MACCS.

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 the results of one phase of 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 radionuclide releases from hypothetical nuclear power plant accidents, based on postulated frequencies and magnitudes of potential accidents. A panel of ten experts was formed to compile credible and traceable uncertainty distributions for late health effects variables that affect calculations of offsite consequences. The expert judgment elicitation procedure and its outcomes are described in this volume and its appendix. 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) their rationales and results, (4) short biographies of the experts, and (5) the aggregated results of their responses.

Acknowledgments

The authors would like to acknowledge all the participants in the expert judgment elicitation process, in particular the expert panel on late health effects. While we organized the process, processed the results, and wrote and edited the report, the experts provided the technical context that is the foundation of this report. Dr. Steve Hora and Dr. Detlof von Winterfeldt are acknowledged for their contributions as elicitors. The authors would also like to express their thanks for the support and fruitful remarks of Dr. G.N. Kelly (EC/DG XII).

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List of Acronyms

ACA	accident consequence analysis
CDF	cumulative distribution function
COSYMA	code system from MARIA (method for assessing the radiological impact of accidents)
EC	European Commission
LHS	Latin hypercube sampling
MACCS	MELCOR accident consequence code system
NRC	Nuclear Regulatory Commission
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 goal of this study is to develop a library of uncertainty distributions by using a formal expert judgment elicitation process on the input variables of the risk coefficients used in MACCS and COSYMA. This report focuses on the methods used in the study on late health effects 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. These results were used to screen 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 internal phenomenological experts and refined.

Originally all late health effects were to be considered in this panel. The decision was made to consider hereditary health effects, if at all in this exercise, by a separate panel (yet to be assembled). The uncertainties in the category of multifactorial disorders are large, and these disorders make up potentially the largest class of radiation-induced hereditary disease. At the moment there is no very adequate way to assess the

likely magnitude of this component of hereditary disease.

Two external expert selection committees were established: one in the US and one in the EC, respectively. (The selection committees consisted of external and internal members of the project.) 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 of late health effects issues. 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.

Late health effects experts

Expert	Country
M. Blettner (jointly with K. Kreienbrock)	Germany
M.W. Charles	UK
F. de Vathaire	France
E.S. Gilbert	US
L. Kreienbrock (jointly with Blettner)	Germany
I.A. Likhtarev*	Ukraine
H. Metivier*	France
J.S. Puskin	US
W.K. Sinclair	US
B. Ullrich	US
M. Vaeth	Denmark
R. Wakeford	UK

* These experts from the internal dosimetry panel were used on some questions.

Expert Training Meetings

A joint training meeting was held for 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. The training meeting was held in Annapolis, Maryland, and was attended by the early health effects expert panel, the late health effects panel, and the internal dosimetry panel. A probability training session was conducted to familiarize the experts with the concept of uncertainty and the potential pitfalls in preparing subjective assessments; practice exercises followed. Material for the training exercise was drawn directly from the late health effects field. 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 both meetings, a method to extract quantitative information on knowledge dependencies between the elicitation variables was developed. At the experts' request, the number of questions was reduced by simplifying the age groups and ignoring gender differences.

Preparation of the Assessments and Written Rationale

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

Expert Elicitation Sessions

A joint video-conferenced meeting was held on February 27, 1996, followed by individual elicitation sessions. During the video-conference, held between Brussels and Albuquerque, a common session was conducted in which the experts presented the technical approach and rationale behind their assessments. No distributions were provided in 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 elicitation interviews allowed for significant interaction between the

assessment team and the expert. The issue of anonymity was discussed and it was agreed to preserve anonymity.

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 within 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 risk coefficients assessed were the code input variables. It is therefore not necessary to process the aggregated distributions into distributions over high dose-rate code input variables of the COSYMA and MACCS codes. Additional processing must, however, be performed when the required risk coefficients relate to low dose rates.

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 aggregated cancer risk coefficient distributions capture the uncertainty in the stochastic processes expected by the expert after induction by radiation. The distributions for the elicitation and code input variables are available on computer media and can be obtained from the project staff.

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 uncertainty distributions for cancer risk 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 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 credible 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 well-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 late health effects 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.

Originally all late health effects were to be considered by this panel. The decision was made to not consider hereditary health effects and, if it were done at all in this exercise, it would be by a separate panel (yet to be assembled). The uncertainties in the category of multifactorial disorders are large, and these disorders make up potentially the largest class of radiation-induced hereditary disease. At the moment there is no very adequate way to assess the likely magnitude of this component of hereditary disease.

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 benefits 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 (hereafter cited simply as NUREG-1150). 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 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. 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 late health effects parameters. The exercise had as its goal developing a library of uncertainty distributions for late health effects, both for cancer mortality and cancer incidence as a result of exposure to radiation, that could be used in many different consequence uncertainty studies employing the MACCS and COSYMA consequence codes.

Table 1.1 Phenomenological areas for the 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 (deterministic) health effects
Late (stochastic) health effects

The information in this report also has potential uses outside the reactor safety community (e.g., nonreactor nuclear facilities, radioisotope power and irradiation sources, and other radiation sources).

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 MACCS and COSYMA could not be modified, 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 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 discussed of proceeding with one panel to demonstrate the efficacy and feasibility of the joint effort before continuing with the remainder of the study.

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 EU: 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.
May 1995	Kickoff meeting in the UK for three more panels: internal dosimetry, early health effects, and late health effects.
July 1995	Elicitation meeting for the US experts on the food chain and deposited material/related doses.
November 1995	Dry run meetings for the internal dosimetry and late health effects panel case structure documents in Europe and for the early health effects panel document in the US.
December 1995	Joint training meeting for US and EC experts on early health effects, late health effects, and internal dosimetry parameters
February 1996	Elicitation meeting for late health effects and internal dosimetry experts (common session included EU and US experts using video conferencing)
March 1996	Elicitation meeting for early health effects experts (common session included EU and US experts using video conferencing)

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 the conclusions are presented in Section 5.

Volume 2 of this report contains the technical appendices. Appendix A contains a summary of MACCS and COSYMA consequence codes. The case structures are contained in Appendix B. The rationale provided by the experts and a summary of results are provided in Appendix C. Appendix D has short biographies of the experts and Appendix E contains their aggregated results.

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2. Technical Issues Considered Relevant

2.1 Introduction

Uncertainty analysis with respect to potential public risks from nuclear power installations was introduced into a broad decision-making context with the Reactor Safety Study (WASH-1400).[1] Although the technique has undergone considerable development since this study, the essentials have remained unchanged. The intent of uncertainty analysis is to estimate the uncertainty in the output of quantitative decision support modeling in order to provide the decision maker with a measure of the robustness or accuracy of the conclusions based on the model. To accomplish this, a joint distribution is 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 modeling 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 number of susceptible stem cells. Parameter value uncertainty arises because we rarely know with certainty the correct values of the code input variables. Moreover, this lack of knowledge contributes also to modeling uncertainty. 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.

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 benefits and costs 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 of 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 Late Health Effects Models Used in MACCS and COSYMA

2.4.1 Models Used in MACCS

MACCS evaluates cancer risk due to acute and chronic exposure from the pathways associated with cloudshine, groundshine, inhalation and ingestion. MACCS calculates risk to individuals from direct exposures as well as collective risk from ingestion and decontamination exposures.

Mortality and morbidity resulting from radiation-induced cancers are evaluated based on the equivalent doses received by specific organs or on the effective dose to the whole body, which are obtained by applying dose conversion factors (DCFs) for the various exposure pathways. DCFs relate the calculated environmental contamination levels or intakes to resultant doses and are calculated for individual nuclides. The DCFs applied in MACCS are obtained from one of a set of three databases chosen by the user for the specific calculational application. The dose commitments from inhalation and ingestion exposures that are implemented in MACCS through the DCFs are 50-year commitments, because an average exposed individual will be about 30 years old and at this age will have a life expectancy of about 50 years.

The cancer risk model implemented in MACCS for emergency phase exposures utilizes a two-equation piecewise linear dose-response function that is discontinuous at a dose level dividing low and high exposures:

$$R(D) = \alpha \times \frac{D}{DDREF} \qquad D < DDTHRE$$

$$R(D) = \alpha \times D \qquad D \geq DDTHRE$$

where: D is the calculated equivalent or effective dose, α is the linear lifetime risk factor (either for mortality or morbidity), DDREF is the dose-dependent reduction factor, and DDTHRE is the threshold dose for applying DDREF.

The user defines the specific cancer being evaluated, supplies the associated values for α and DDREF, and inputs DDTHRE for a selected critical organ. An additional user-supplied factor is the fraction of the population that is susceptible to the latent cancer being evaluated. For the long-term exposure calculations, MACCS implements only the first equation, in which the dose-dependent reduction factor is applied because exposures are expected to be below the threshold value for dose and dose rate (typically 0.2 Sv or 0.1 Sv/hr).

MACCS contains an alternative cancer risk model that is considered to be obsolete and is no longer recommended for the calculation of cancer induction risk. The alternative model utilizes a linear-quadratic dose-response function for the emergency phase exposures. The quadratic response function is applied at higher dose levels, whereas the linear function is applied at lower dose levels. The linear model is applied for long-term exposure calculations. When the piecewise linear dose-response function described above is implemented, the alternative model is deactivated.

2.4.2 Models Used in COSYMA

The inputs to the calculation routines for late health effects in COSYMA are the exposures from various pathways (e.g., cloudshine, groundshine, inhalation, ingestion) of specified radionuclides in various time periods. The output from the late health effects routines consists of numbers of radiation-induced cancer deaths and incident cases by cancer site, possibly disaggregated by time after exposure. Also provided are the numbers of days of life lost as a result of death from each cancer type.

In order to derive the numbers of radiation-induced cancers, COSYMA uses linear dose-response models. In COSYMA the numbers of radiation-induced cancers are calculated by performing integrations over time and age for the concentration of each nuclide received multiplied by various factors (e.g., to account for differential ingestion of various foodstuffs by age). To simplify the calculations, the intermediate integrations (over time between exposure to the radionuclide and the time at which the organ receives radiation, time from radiation to observation, age at exposure, etc.) are precalculated as an activity risk coefficient (ARC) matrix. This gives for each organ the excess fatal cancer risk, possibly as a function of time since exposure if this variable has not been incorporated into the ARC as an additional variable of integration. Calculation of years of life lost is achieved by multiplying the exposure by a similar ARC matrix. The numbers of incident cancers are calculated by multiplying the number of fatal cancers by the reciprocal of the proportion of incident cancers that are fatal. The ARC matrices used in COSYMA were calculated by Forschungszentrum Karlsruhe (FZK) using data provided by the GSF (National Center for Environment and Health) for a German population, using either time-constant additive (leukemia, bone cancer) or relative risk (all other sites) projection models.[4] The COSYMA risk coefficient library can be easily modified by introducing (distributions on) modification factors for the GSF data. Although the GSF data are derived for a German population, COSYMA uses these data for all possible calculations.

2.5 Selection of Variables for Presentation to Formal Expert Elicitation Panels

2.5.1 Early and Late Health Effects Variables

Because the resources required to develop distributions for elicitation variables using a formal elicitation process are relatively large, it is critical to select those variables for elicitation that are most important to consequence uncertainty. Exclusion of some variables from the list of those to be formally elicited does not mean that they are to be excluded from the analysis. The uncertainty in these variables will be evaluated by less resource-intensive methods (e.g., literature searches and consequence analyst judgment). Thus the prioritization procedure, while important in terms of ensuring effective utilization of resources, is not critical in terms of excluding the contributions of potentially important variables.

The variables to be elicited were chosen systematically using the method outlined below.

1. Sensitivity studies using MACCS in the US and UFOMOD in the EC were performed. Lists of code input variables that were shown to be important to the different consequence measures

were generated independently by the US and EC. Lists of important code input variables were generated for both early (prompt) and late (latent) consequences. As an example, the US list is summarized in Table 2.1. Sensitivity studies from the US relied on traditional regression techniques and additional parametric importance assessment techniques developed at Los Alamos National Laboratories specifically for this program to prioritize code input variables.[5]

2. A team of US and EC consequence experts developed a joint list of important code input variables from a review of the lists generated from the sensitivity studies performed in the US and the EC. This list is presented in Table 2.2.

   It was not considered feasible to jointly assess code input variables that are highly specific to conditions in the EC or in the US. For this reason, any variables related to policy or economics were eliminated from consideration by the joint study (evacuation policy, food interdiction criteria, and costs of countermeasures are all examples of these variables). For the purposes of the uncertainty calculations, these variables will be assessed independently by the EC and NRC using the methods developed in the joint project.

3. If there were any analytical or experimental alternatives to obtaining defensible distributions for any of the code input variables, the variable in question was dropped from the list of assessed elicitation variables using expert judgment techniques. The selected variables represent only parameters for which insufficient experimental data are available for developing uncertainty distributions. Some of the reasons for lack of sufficient experimental evidence could be unacceptable costs and lack of technology.

4. From the final list of code input variables, elicitation variables that were experimentally observable were selected or developed. The experimentally observable constraint was inserted for two reasons (a) to avoid ambiguity when presenting the definition of the elicitation variables (if the experts assess poorly defined variables, the potential for incompatible assessments is high) and (b) to ensure that the elicited distributions are applicable beyond the context of the present study.

In many cases, the experimentally observable constraint results in elicitation variables that are the output of specific submodels rather than the code input variable in the submodels. The distributions obtained by eliciting only on experimentally observable parameters have the potential of containing uncertainty due to the fundamental limitations in model physics, data uncertainties, and random or stochastic uncertainties in observational data.

2.5.2 Late Health Effects Variables

Originally all late health effects were to be considered by this panel. However, for reasons of economy, it was decided that hereditary health effects were to be considered, if at all, by a separate panel (yet to be assembled). The uncertainties in the category of multifactorial disorders, that is to say, those diseases in which there are both genetic and environmental modifiers of the disease process, are large, and these disorders make up potentially the largest class of radiation-induced genetic disease. At the moment there is no adequate way to assess the likely magnitude of this component of genetic disease, although information being considered by an ICRP Committee 1 Task Group, which is due to report in the next couple of years, may provide some useful reduction in uncertainties in this area.

The main requirement of COSYMA and MACCS is for cancer risks to be evaluable following moderate to low dose-rate exposure, since this characterizes the overwhelming majority of exposures following a typical nuclear accident. It was decided, for example, as a result of preliminary discussions among various experts, that one would expect linearity of risk at low dose-rate exposure, so that eliciting risks for one value of administered dose would suffice. Linearity would not, however, be expected to apply in general, e.g., in extrapolating from high dose-rate exposure (e.g., 1 Gy over 1 minute) to low dose-rate exposure (e.g., 1 Gy over 1 year). For that reason, assessments were required for at least one additional low dose-rate case. Dose-dependent reduction factor (DDREF) values were not elicited because these variables are not observable, but could be deduced from the high and low dose rate assessments. Cancer risks for both codes were included in the list of target tissues given in Table 2.3. (The present versions of both codes use a subset of this list.) If a disaggregation of cancer risk by time after exposure for these tissues is required in COSYMA (and MACCS), then in principle information would

Table 2.1 Code input variables for prompt and latent consequences

Important code input variable	Proposed expert panel	Important for early or chronic consequence measures	Factors that should be considered in elicitation design	Comment
Power law parameters that define the standard deviation of the plume in the cross-wind direction	Dispersion	Dominant for early consequences; important for chronic consequences	X, Y, Z coordinates Wind speed Stability Surface roughness (in conjunction with deposition velocity)	Contribute more to high values of early fatalities in stable weather (when standard deviation of plume is small)
			Discrete rain intensity (in conjunction with wet deposition velocity)	Contribute more to high values of chronic cancers in unstable weather (more dilution, less interdiction, wider spread, more cancers)
Power law parameters that define the standard deviation of the plume in the vertical (z) direction	Dispersion	Important (not dominant) for both early and chronic consequences	Same as above	
Dry deposition velocity	Deposition	Dominant for both early and chronic consequences	Surface roughness for meadow, city, and forest aerosol particle size	
Linear term in washout model (exponential term should be assessed also)	Deposition	Important (not dominant) for chronic consequences	Rain intensity, aerosol particle size	
Critical wind speed scale factor (plume rise occurs only if wind speed is less than critical wind speed—if speed is greater, plume is caught in wake)	Plume rise	Important (not dominant) for early consequences; dominant for safety goal fatality risk (dose at boundary)	Plume energy Wind speed Stability class Building scale length Ambient temperature	
Lethal dose (variable for bone marrow)	Health effects	Important (not dominant) for early consequences	Specify period of exposure and period of manifestation	
Groundshine shielding factor for nonevacuees	Behavior of deposited material and calculation of related doses	Important (not dominant) for both early and chronic consequences	Experts must provide values for population in different types of shelters	

Table 2.1 Code input variables for prompt and latent consequences (continued)

Important code input variable	Proposed expert panel	Important for early or chronic consequence measures	Factors that should be considered in elicitation design	Comment
Inhalation protection factor for nonevacuees	Behavior of deposited material and calculation of related doses	Important (not dominant) for early consequences		
Dose/dose reduction factors (for 7 organs)	Late health effects	Important (not dominant) for chronic consequences		
Transfer factor food to beef—cesium (for cesium)	Food chain	Important (not dominant) for chronic consequences		The ingestion pathway models are different in MACCS and COSYMA.
Transfer factor to milk for I, Cs, Sr	Food chain	Did not show up as important in sensitivity calculation, but the interdiction criteria may have masked the effect of this variable		Consistency between MACCS and COSYMA could be a problem

Table 2.2 Combined list of code input variables shown to be important

Phenomenological area	Code input variable requiring
Dispersion	Plume spread parameters
Dispersion	Dry deposition velocity Wet deposition parameters
Behavior of deposited material and calculation of related doses	Decontamination Resuspension parameters Weathering parameters Shielding factors Penetration factors
Plume rise	Amount of plume rise Critical wind speed for liftoff
Internal dosimetry	Breathing rate Dose conversion factors
Early health effects	Lethal dose thresholds
Late health effects	Dose rate effectiveness factors Risk coefficients (cancer)
Food chain	All food chain parameters

Table 2.3 Key to primary cancer sites considered in the late health effects elicitations, with the relevant codes from the 9th revision of the International Classification of Diseases (ICD9)

Abbreviated Title	ICD9 Code	Full Description
Bone	170	Bone
Colon	153	Colon
Breast	174	Female breast
Leukemia	204-208	Leukemia
Liver	155.0, 155.1	Liver and intrahepatic bile ducts
Lung	162	Lung
Pancreas	157	Pancreas
Skin	173	Nonmelanoma skin
Stomach	151	Stomach
Thyroid	193	Thyroid
All other cancers	140-208 excluding above	All cancers other than those listed
All cancers	140-208	All cancers

have to be elicited on organ-specific risks by 5-year intervals of follow-up. Eliciting such information was deemed a poor use of the expert resources, so that information was only elicited on (at most) cancer risks over the intervals 0-20, 0-40, and 0-∞ years after exposure. Variations in cancer risk by sex were also thought to not contribute substantially to overall uncertainties and so were not considered in the elicitations.

Equally, it was decided that although not strictly required by the initial consequence uncertainty exercise, it would be desirable to obtain expert judgment on the variation of cancer risk by age at exposure (including *in utero* exposure), as a function of dose and dose rate (including the possibility of threshold effects), and for certain sorts of high linear energy transfer (LET) and low LET radiation. The experts quite strongly asked to take questions on those late health effects into consideration, because they considered the endpoints to be critical and they expected to get useful information for future applications from them.

2.6 Formal Expert Judgment Methods

The health effects panels used the same formal expert judgment method as the food chain 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

Because of the nature of the stochastic processes involved in late health effects, the only restriction for applying the data worldwide is the population data used for the assessments. The population data set was composed by averaging mortality and cancer incidence rates for America[6,7] and England and Wales.[8,9] The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)[10,11] uses mostly Japanese and sometimes British population data. The US National Academy of Sciences' Committee on the Biological Effects of Ionizing Radiations (BEIR)[12] uses US population data.

The International Commission on Radiological Protection (ICRP)[13] uses five different sets of population data. Parkin et al.[7] examined cancer risks on five continents and found significant differences in cancer incidence rates among countries, although the differences between the US and Western Europe were less marked.

It was critical that the scope of the problems to be assessed be explicitly defined for the experts in order to receive consistent responses. During the expert meetings, guidelines were established for the phenomena to be considered in the definition of initial conditions for the distributions, the phenomena to be considered as

part of the uncertainty, and the phenomena to be considered outside the scope of the project. Table 2.4 provides the scope, which was not restricted to short exposure periods (high dose rate). For *in utero* exposure only, uniform exposure over all three trimesters was considered. See the explanation of the case structures in Section 3.2.2.

2.8 References

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3. Harper, F. T. et al., Probabilistic Accident Consequence Uncertainty Analysis, NUREG/CR-6244, EUR-15855EN, SAND94-1453, Vol. 1, Sandia National Laboratories, Albuquerque, NM, 1995.
4. Ehrhardt, J., I. Hasemann, C. Matzerath, J. Raicevic, and C. Steinhauer, "COSYMA: Health Effects Models," Report FZKA 5567, Forschungszentrum Karlsruhe, 1995.
5. Helton, J.C., et al., "An Exploratory Sensitivity Study with the MACCS Reactor Accident Consequence Model," *Reliability Engineering and System Safety*, 36:137-164, 1992.

Table 2.4 Scope of the late health effects panel

Parameters for which uncertainty is handled through specification of initial conditions (case structure) **This uncertainty is not addressed in the distributions**	**Parameters for which uncertainty is addressed in distributions**	**Factors that are out of scope and not to be considered in uncertainty distribution or in case structure**
Uniform whole-body dose or uniform tissue radiation	Average population with varying health states of members of population	No deterministic effects Tumors other than ICD9 140-208
Given population distribution (= constant), constant mortality - incidence rates	Modeling of cancer risk (relative vs. absolute, etc.)	
Equal doses during 3 trimesters *in utero*	Sampling variation in risk coefficients in Japanese and other datasets, dosimetric errors	
Other environmental exposures are constant	Relative biological effectiveness (RBEs)	
Medical surveillance/treatment constant	DDREFs	
Population subject to normal diet etc. after accident	Transport of risks across populations	
	Time/age variation in risk	
	Ascertainment biases/data quality	
	Limited data on synergistic effects	

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9. Office of Population Censuses and Surveys, *Cancer Statistics Registrations*. Series MB1, No. 22, HMSO, London, 1994.

10. United Nations Scientific Committee on the Effects of Atomic Radiation, *Sources, Effects, and Risks of Ionizing Radiation*, United Nations, New York, 1988.

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3. Summary of Expert Elicitation Methods for the Health Effects Panel

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 late health effects 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.

3.2.1 Definition of Elicitation Variables

It was the responsibility of the probability elicitation team to develop elicitation variables that relate directly to observable biological and epidemiological quantities. The physical "processes" modeled in ACA codes, such as COSYMA and MACCS, are identical, even though the models representing the processes in the codes may be different. One of the guiding principles of this expert elicitation exercise is that the experts should be asked to respond only to questions about physically observable or measurable quantities, even though the actual measurement of these quantities may be impracticable due to resource constraints. Therefore, the experts were not expected to answer questions on the mathematical models themselves, to which they may not be able to easily relate, particularly when the models have been derived empirically. The advantages of this approach are that all ACA codes may make use of the information derived from the elicitation questions posed to the experts, since they are somewhat divorced from the basic modeling. The disadvantage, however, is that the uncertainty distributions suggested by the experts will have to be processed in order to derive the distributions for those model parameters used within a particular program.

The joint study was limited to those issues where alternative sources of information, such as experimental or observational data or even validated computer models, were not available to directly calculate the risks of late health effects, or where multiple sources of information provided conflicting or incomplete evidence of the uncertainties.

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 postprocessing
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

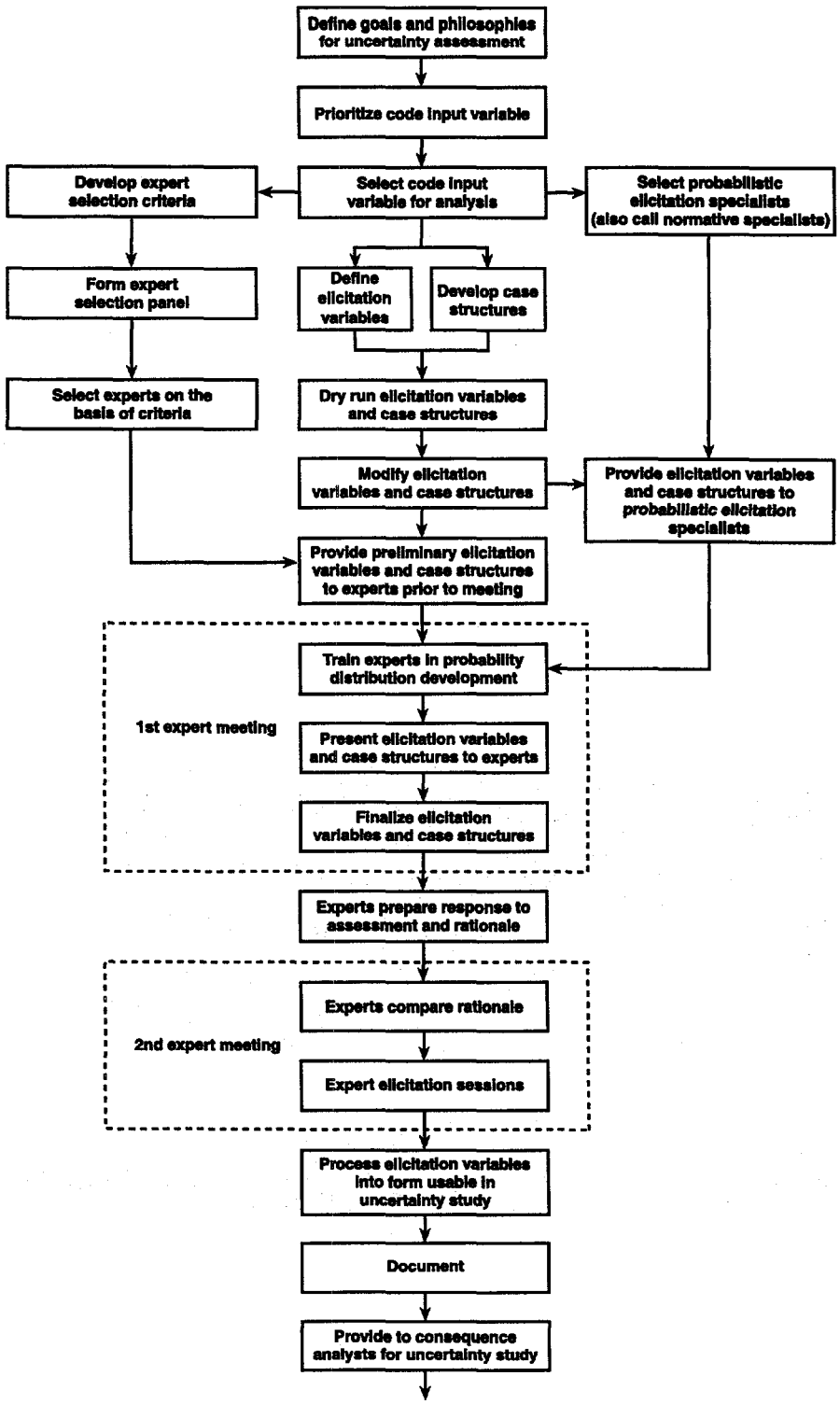

Figure 3.1 Sequence of methods used to develop the uncertainty distributions. Due to programmatic constraints, the EC and the US experts held separate first expert meetings; however, some project staff attended both European and American meetings. The EC and US groups communicated through a teleconference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

3.2.2 Development of Case Structure

It was impossible for the experts to provide information over the complete variable space needed to perform a comprehensive consequence uncertainty study. It was therefore necessary to design a case structure that would cover the variable space so that the project could interpolate and extrapolate to all areas necessary to perform consequence uncertainty studies.

As stated in Section 2.5, the main requirement of COSYMA and MACCS is for cancer risks to be evaluable following moderate to low dose-rate exposure. It was decided that the set of cancer sites for which information should be elicited would be as given in Table 2.3. If a disaggregation of cancer risk by time after exposure for these tissues is required in COSYMA (and MACCS), then in principle, information would have to be elicited on organ-specific risks by 5-year follow-up intervals. Eliciting such information was deemed a poor use of the expert resources, so that information was only elicited on (at most) cancer risks for the sites given in Table 2.3 over the intervals 0-20, 0-40 and 0-∞ years after exposure. DDREF values were not elicited because these variables are not observable, but can be deduced from the high dose rate and low dose rate assessments.

After a dry run with two European experts (not used in the final panel), and discussions among project staff in Europe and the US as well as discussions at the experts' first meeting in Annapolis, the case structure was finalized. It is shown in condensed form in Table 3.2.

Table 3.2 Outline of case structure document for late health effects

1	General population, 12 cancer sites in Table 2.3, high dose, high dose-rate low LET radiation, cancer deaths 0–20, 0–40, 0–∞ years after exposure
2	Children (ages 0–14 at exposure), 4 cancer sites (breast, leukemia, thyroid, all cancers), high dose, high dose-rate low LET radiation, cancer deaths 0–40, 0–∞ years after exposure
3	*In utero* exposure, 2 cancer sites (leukemia, all cancers), high dose, low dose-rate low LET radiation, cancer deaths 0–20, 0–∞ years after exposure
4	General population, 12 cancer sites in Table 2.3, high dose, high dose-rate low LET radiation, cancer cases 0–40 years after exposure
5	General population, 12 cancer sites in Table 2.3, high dose, low dose-rate low LET radiation, cancer deaths 0–40 years after exposure
6	General population, nonmelanoma skin cancer cases for low dose, low dose-rate high LET radiation 0–40 years after exposure
7	General population, 5 cancer sites (lung, bone, liver, leukemia, all cancers) cancer deaths for high dose, low dose-rate ^{239}Pu inhalation 0–40 years after exposure
8	General population, 4 cancer sites (lung, bone, leukemia, all cancers) cancer deaths for high dose, low dose-rate ^{90}Sr inhalation 0–40 years after exposure
9	General population, 12 cancer sites in Table 2.3, years of life lost due to radiation-induced cancer death 0–∞ years after exposure
10	General population, 12 cancer sites in Table 2.3, dose threshold for high dose-rate radiation.

In all, the experts were asked about 114 variables. For each variable, degrees of belief were elicited in the form of 5, 50, and 95% quantiles of subjective probability distributions. The 5% quantile of the distribution for an uncertain quantity X is the number $x(0.05)$ such that

$$\text{Prob}[X \leq x(0.05)] = 0.05$$

and similarly for the other quantiles.

Assessment of the risks of radiation-induced cancer depends upon a number of factors, such as the incidence of and mortality from cancers in the unexposed population, the effects of dose and dose rate, and the temporal patterns of risk among the various cancer types. The expert panel on late health effects quantified the degree of uncertainty in estimates of radiation-induced cancer risk for a number of cancer sites, taking account of the correlations introduced by the above variables.

With the exception of one question relating to ingestion of ^{90}Sr and ^{239}Pu, the population was assumed to be exposed to uniform whole-body doses of external ionizing radiation or uniform doses to specific organs from internal exposure. Deterministic effects arising from high radiation doses to the whole body were not assumed to take place. For that part of the population that was assumed to be exposed *in utero*, doses were assumed to be delivered uniformly to all tissues of the embryo and fetus, and dose was administered uniformly in time over all three trimesters of gestation. All mortality and incidence rates were assumed to be stable over time. The population was assumed to be in equilibrium, so that the numbers of persons in each age interval were constant over time.

Tumors other than those corresponding to the Ninth International Classification of Diseases (ICD9) codes 140-208 were not considered. Nonmalignant diseases (e.g., cardiovascular disease) were also not included. Medical treatment and surveillance was assumed to be constant, and in particular was not assumed to change after the accident. The population was assumed to be subject to its normal diet after the accident and nonradiological environmental conditions were assumed to be constant. The basis for the elicitations was exposure of a hypothetical "average" EU/US population of all ages and both sexes (the age- and sex-specific mortality and cancer incidence rates for this were given); see the tables in the appendix at the end of this volume. The mortality rates were calculated from the rates for the 1992 England and Wales population[1] and for the 1987 US population.[2] The cancer incidence rates were derived from the rates for the 1989 England and Wales population[3] and for the 1983–1987 US Surveillance, Epidemiology and End Results (SEER) registry data.[4]

The measure of cancer risk used in most of the questions was risk of exposure-induced death (REID)[5] and the analogous measure for cancer incidence, as used by UNSCEAR,[6] rather than the measure of excess cancer deaths employed by the BEIR IV[7] and BEIR V[8] committees.

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 late health effects. 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 were requested;

3. Two selection committees that included members both external and internal to the project, 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 a panel of internationally recognized scientists (see Table 3.3). Brief biographies are provided in Volume 2.

Table 3.3 Late health effects experts

Expert	Country
M. Blettner (jointly with K. Kreienbrock)	Germany
M.W. Charles	UK
F. de Vathaire	France
E.S. Gilbert	US
L. Kreienbrock (jointly with Blettner)	Germany
J.S. Puskin	US
W.K. Sinclair	US
B. Ullrich	US
M. Vaeth	Denmark
R. Wakeford	UK

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 Ir. 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. Dr. Goossens, Dr. Hora, and Ir. Kraan have 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 primary developer of the NUREG-1150 expert elicitation technique. Mr. Kraan of TU Delft is also 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 two late health effects experts recruited from the National Radiological Protection Board (NRPB) and the ICRP in the UK. The purpose was 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 the first expert meeting 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 provided the project staff with the distributions of the elicitation variables and the rationale behind

the distributions in written form before leaving the second meeting.

3.4.1 Dry Run Elicitation

The dry run meeting was conducted in November 1995 with two late health effects experts, Dr. H. Smith from the ICRP main commission and Dr. J.W. Stather from the NRPB. The meeting began with a short introduction to the training in probability elicitation. The training focused on the meaning of subjective probabilities, the structure of formal expert judgment processes, biases in probability formation, and practice in expressing judgments as probabilities. The draft case structure document and elicitation questionnaires were handed out prior to the dry run meeting. The dry run 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, not related to the ACA codes in particular. The case structures and questionnaires to be presented to the experts in the first meeting were prepared according to the lessons learned in the dry run.

3.4.2 First Expert Meeting

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

Training was conducted to introduce the experts to psychological biases in judgment formation and to give them feedback on their performance in assessing probability distributions. In the NUREG-1150 study, feedback was provided to the experts by measuring their performance on the development of probabilistic distributions for training variables. In that study, the training variables were nontechnical, almanac-type questions for which the answers were known. In the current study, performance was measured by querying the experts about variables whose true values are uncertain for the experts but known to project staff from unpublished data. These training variables were chosen to resemble the variables of interest as closely as possible. A subset of the Japanese atomic bomb survivor cancer mortality data was used.[9]

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

A joint video-conferenced meeting was held on February 27, 1996, followed by individual elicitation sessions. During the video conference, held between Brussels and Albuquerque, a common session was conducted at which the experts presented the technical approach and rationale behind their assessments. No distributions were provided in these sessions to avoid biasing the other experts. The elicitation of each expert took place privately with a normative specialist and a substantive assistant. In both cases, the experts were allowed to change their elicitation results at any point. The interviews allowed for significant interaction between the assessment team and the expert.

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 the case structure. It was the re-

sponsibility 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 late health effects coefficients. In all cases, the elicitation variables could be directly used as coefficients in the late health effects calculations performed with both codes.

3.5.1 Aggregation of Elicited Distributions

The processing tool for combining expert assessments was the computer code EXCALIBR.[10] 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 ratio between the 95th and 5th percentiles of the distribution, and is used as measure of uncertainty.) For each variable, non-negative weights summing to one were assigned to the CDFs developed for the individual expert assessments, and the aggregation was accomplished by taking the weighted sums of the cumulative probabilities for each variable obtained through an equal-weighting aggregation scheme. EXCALIBR output the 5th, 50th, and 95th percentiles from the combined CDF for each variable.

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

$$F_{ewdm,i} = (1/N)\sum_{j=1}^{N} F_{ji}$$ where F_{ji} is the cumulative probability associated with expert j's assessment for variable i.

Investigating the different weighting schemes was not the objective of this joint effort. A decision was therefore made within the program to assign all experts equal weight (i.e., all experts on each panel were treated as being equally credible). One of the primary reasons the equal-weighting aggregation method was chosen 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 distributions. The implications of different weighting schemes are discussed elsewhere.[11]

3.5.2 Combining Dependencies

It has long been known that significant errors in uncertainty analysis can be caused by ignoring dependencies between uncertainties.[12] 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. Because the experts were already convened to respond to the formal elicitation questions, the project took advantage of their availability to test a new methodology[11] in which dependency information was elicited from the experts. The methodology and results obtained from this activity will be reported in a separate publication.

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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 late health effects models.

4.2 Summary of Elicitation Meetings

As discussed in Chapter 3, three meetings were conducted relating to the actual elicitation exercise. This section reviews the responses of the experts to the project materials and the methods presented during the elicitation meetings.

4.2.1 Dry Run Elicitation Meeting

The robustness of the basic expert elicitation methodology developed for this project was validated by the dry run exercise. However, several important issues were raised and subsequently evaluated as a result of the dry run. The issues raised were (1) the need to reduce the number of elicitation questions in the questionnaire; (2) to limit the number of questions with various age groups; (3) to limit most assessments to high-dose, uniform irradiation of organs; from this the question arose of whether the internal dosimetry panel would address nonuniform radiation to organs; (4) genetic health effects will not be subjected to expert judgment for the reasons set out in Section 2.5.2; (5) *in utero* radiation could be very important to consider; (6) the table on mortality rates and incidence rates should be carefully explained to the experts as they must use the tables. All questions were reviewed and appropriate comments were taken into account in the draft for the expert training meeting.

4.2.2 Summary of First Expert Meetings (Training Meetings)

The agenda for the first expert meeting is presented in Volume 2. A joint meeting was held for the European and US experts in Annapolis, Maryland on December 11-13, 1995. The meeting was jointly held with the experts for the internal dosimetry panel and the early health effects panel. The initial reception of the project by the experts was excellent. They expressed an interest in the prospect of addressing uncertainty in their field of expertise. After the probabilistic training exercise, the elicitation variables and the case structure were presented and discussed.

In the training meeting, the issues regarding late health effects were discussed and several changes to the definition of the elicitation variables and the case structure were agreed upon. Following the meeting, some of the questions were further reformulated to address the issues raised by experts, and the experts were sent a final version of the case structure and elicitation variables shortly after the meeting.

The experts were initially uncomfortable with the large number of questions to be assesssed. They proposed to reduce the number of age groups because they did not expect large differences in uncertainties there. Because sex differences in cancer risk were not expected to be large, it was also decided to omit elicitation by sex. Lack of information on certain cancer types led to a reduction in the number of cancer sites for some questions.

The experts proposed a few additional questions on health effects following *in utero* exposure. They also suggested a few extra questions on nonuniform radiation exposure, for which joint arrangements were made with selected experts forom the internal dosimetry panel. The joint training meeting was videotaped to retain a record.

4.2.3 Summary of Second Expert Meeting

All experts except four were present at the joint video-conference session at which the experts presented the approach they had taken to answering the questions posed, but 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. The initial common session was videotaped.

4.3 Summary of Individual Expert Assessments

Representative results are summarized and discussed in this section. Figures are included at the end of the chapter so as not to interrupt the flow of the text.

The complete set of expert rationales and the elicited distributions are published in Volume 2. In this chapter, Figures 4.1 – 4.20 plot some of the elicited results, along with the results of the equal-weighted aggregation of the elicited distributions. The figures designate experts 1 through 9. (Experts 10 and 11, who appear in Figures 4.18 and 4.19, were drawn from the internal dosimetry panel.)

Throughout, the term "range factor" is used to express the ratio of the 95th and 5th percentiles of the distribution, i.e., × (0.95)/× (0.05), and is used as a measure of uncertainty.

There is a large measure of concordance in the datasets used by the experts. All experts make extensive use of the latest Japanese atomic bomb survivor mortality and cancer incidence datasets.[1-5] In particular, at least for the purposes of estimating the median (50% quantile) cancer risks for each organ, almost all experts make considerable use of the scoping population risks document provided to each of the experts and reproduced in Vol. 2. The cancer risks given in the scoping document are calculated from various models fitted to the Japanese atomic bomb survivor cancer incidence datasets.[2,4]

For certain organs (e.g., bone and breast), the experts used various other datasets, generally referred to in the latest UNSCEAR[6] and BEIR[7] reports. In contrast to the similarity of data and methods used to obtain the 50% quantiles, there is much more variation among the experts in the methods used to obtain the 5 and 95% quantiles of cancer risk.

Figures 4.1– 4.12 display the 5, 50, and 95% quantiles of lifetime high dose (1 Gy) high dose-rate (1 Gy/minute) cancer risks for a general population, for each of the 12 sites listed in Table 2.3. While for some sites (e.g., leukemia; Figure 4.4) there is only slight interexpert variation in the median cancer risk ($0.66 - 1.1 \times 10^{-2}$ Sv^{-1}), for other sites (e.g., liver; Figure 4.5) there is substantial variation, so that, for example, expert 7 indicates a risk (1.3×10^{-2} Sv^{-1}) that is about 20 times higher than the risks given by experts 2 and 8 (5.5×10^{-4} Sv^{-1}).

One possible reason for the much higher liver cancer risks calculated by expert 7 is that he used an absolute risk model to calculate liver cancer risks from the Japanese mortality data, in contrast to experts 2 and 8, who employed cancer risks based on the relative risk models utilized in the scoping document. Japanese liver cancer mortality[8] and incidence[9] rates are much higher than those in the UK and US. Therefore, transporting the absolute rather than the relative liver cancer excess from the Japanese bomb survivor population to the general EU/US population considered here, as expert 7 implicitly did, is bound to result in much higher cancer risks for this organ.

As might be expected, there is relatively little variation in the aggregate cancer risk (Figure 4.12) ($7.3 - 13.3 \times 10^{-2}$ Sv^{-1}). The range factor for all cancers is somewhat less than 10, while for the specific cancer sites the range factors are on the order of 100 to 250, except for the cases where the 5th percentile is assessed as close to zero. It is noteworthy that for some sites (e.g., pancreas; Figure 4.7), some of the experts assessed the 5th percentile as zero. Even for the cancer risks of radiation-exposed children (Figures 4.13 - 4.16), in which group the uncertainties might be expected to be largest, the interexpert variation in the 50% quantiles is no more than a factor of 4, even for specific cancer sites.

The range factors for all cancers given by the experts (see Figure 4.12) are reasonably similar, so that generally the 5th percentile for the lifetime REID for a general population falls in the range $3 \times 10^{-2} - 7 \times 10^{-2}$ Sv^{-1}, while the 95th percentile for the lifetime REID generally falls in the range $15 \times 10^{-2} - 35 \times 10^{-2}$ Sv^{-1}

Since the case structures required assessments on individual cancer sites and on all cancer sites, a consistency check could be performed for each expert's assessment, including correlation data from the experts. The results indicate consistent assessments.

The individual assessments of *in utero* radiation exposure for leukemia show a pattern similar to that for leukemia following exposure of a general population (Figures 4.4 and 4.14).

The individual assessments for radiation-induced cancer cases (including fatal and nonfatal cancers) also show a similar pattern, and the range factors are in general lower than for fatal cancers only. The number of radiation-induced skin cancer cases after

administration of a uniform skin dose of 1 mGy high LET from plutonium alpha particles has a larger spread in median assessments with relatively high range factors (Figure 4.17). It should be noted that experts 7 and 9 indicated no skin cancers arising from plutonium alpha particle exposure (even the 95% quantiles are 0). Both experts thought alpha particles would not penetrate to the basal layer, the relevant target tissue.

The so-called joint dosimetry/late health effects question in which nonuniform radiation exposure to specific organs was evaluated has been assessed by four experts (two from the late health effects panel and two from the internal dosimetry panel). Large differences in median assessments were found because expert 10 assumed the number of potential cancers following inhalation of 10 kBq of ^{239}Pu to be much lower (100 per 10^8 persons exposed) than the risks predicted by experts 7, 9, and 11 (0.15–1.0 × 10^6 per 10^8 persons exposed). The reason for this is that expert 10 states in his rationale that risk assessment for an accident involving release of plutonium dioxide cannot be performed with the risk estimates recommended by ICRP for radiation protection purposes; it is important to use the specific information for each case. The other three experts assumed much larger cancer risks. The results are given in Figures 4.18 (for ^{239}Pu) and 4.19 (for ^{90}Sr).

Only five experts assessed the average expected length of life lost given that radiation-induced cancer death has occurred (Figure 4.20). Among these five experts there was a large measure of agreement, both overall (range of median values 13.0–16.0 years) and for particular cancer sites.

The case structure questionnaires were organized so that both high dose rate (1 Gy/minute) and low dose rate (1 Gy/year) risks were elicited, allowing for the possibility of deriving distributions of DDREF values. Dividing the high dose-rate risk by the low dose-rate risk for all cancers indicates that all but one of the experts used DDREFs in the range 2.2–5.3; one expert (8) indicated a much higher value of DDREF, 17.1. Interestingly, expert 8 indicated some degree of belief in a dose threshold (see discussion below).

Finally, six experts assumed that there is no threshold in cancer induction; for all cancer sites, all percentiles of the threshold parameter distribution were assumed to be zero by these experts. Expert 8 indicated low values (0.01–1.0 Sv) for the 95th percentiles for all cancer sites; this expert gave nonzero 50th percentile values for two sites, pancreas (0.3 Sv) and all other cancers (0.1 Sv), and zero values for all the 5th percentile values, thereby indicating some degree of belief in a threshold for cancer induction. Expert 4 indicated very low values for all cancer sites (10^{-8}, 10^{-7}, 10^{-6} Sv for the 5th, 50th, 95th percentiles, respectively).

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 parameter. The performance-based method developed at Delft University of Technology[10,11] provides the 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[12] separately.

The results are depicted graphically in the final columns of Figures 4.1 – 4.20. The 50% quantiles of the aggregated distribution appear to be consistent with most individual assessments; the uncertainty distributions are in almost all cases substantially wider than the individual uncertainty intervals for each cancer site. This, of course, is a consequence of handling the individual assessments with a procedure in which the expert's contributions have equal weights in the aggregated distributions.

4.5 Processing of Aggregated Distributions into Distributions on Code Input Parameters

Since all cancer risk coefficients in COSYMA and MACCS relate directly to the observable quantities being elicited, no further postprocessing of code input parameters is required.

4.6 Comparison of Results from Current Study with Code-Calculated Values and Other Estimates of Cancer Risk

This section compares the cancer risk estimates obtained by the present study with the parameter esti-

mates employed in COSYMA, and with those derived by various scientific committees. Table 4.1 displays the elicited high dose and high dose-rate risks (calculated using equal weighting) with those estimated by various scientific committees and as used in the current version of COSYMA. As can be seen, when account is taken of the uncertainties in the elicited cancer risks, they are generally compatible with those derived by other bodies, and with the values previously used in COSYMA. In all cases these other cancer risk estimates lie within the 90% uncertainty intervals from the elicitation. The data derived from the other sources are comparable to those provided by the current exercise on high dose and high dose rate exposure (1 Gy low LET radiation delivered over 1 minute).

Table 4.1 Comparison of elicited high dose and high dose-rate lifetime low LET cancer risks for a general EU/US population with those derived from other sources (10^{-2} Gy^{-1})

	Elicited Risks[a] (+90% CI)	BEIR V[b]	ICRP 60[c]	UNSCEAR[d]	COSYMA[e]
Bone	0.035 (<10^{-3}, 0.88)	-	-	-	0.01
Colon	0.98 (0.011, 3.35)	-	3.24	0.6	2.24
Breast	0.78 (0.11, 3.78)	0.35	0.97	1.0	0.80
Leukemia	0.91 (0.026, 2.33)	0.95	0.95	1.1	0.52
Liver	0.086 (<10^{-3}, 2.02)	-	-	1.2	-
Lung	2.76 (0.59, 8.77)	1.70	2.92	2.5	0.90
Pancreas	0.17 (<10^{-3}, 1.26)	-	-	-	-
Skin	0.039 (<10^{-3}, 0.37)	-	0.03	-	0.01
Stomach	0.30 (<10^{-3}, 4.01)	-	0.51	1.4	-
Thyroid	0.059 (<10^{-3}, 0.71)	-	-	-	0.17
All other	2.60 (<10^{-3}, 10.8)	-	-	-	-
All cancers	10.2 (3.47\8, 28.5)	7.90	12.05	12.0	5.02

[a]Radiation exposure-induced deaths (REID) for the joint current EU/US population (as given in Appendix A of this volume).
[b]BEIR V[7] calculates excess cancer deaths for current US population.
[c]ICRP[13] calculates REID, average of risks for current UK and US populations, using relative risk projection model.
[d]UNSCEAR[6] calculates REID for current Japanese population, using various models.
[e]Radiation exposure-induced deaths, taken from Ehrhardt et al.[14]

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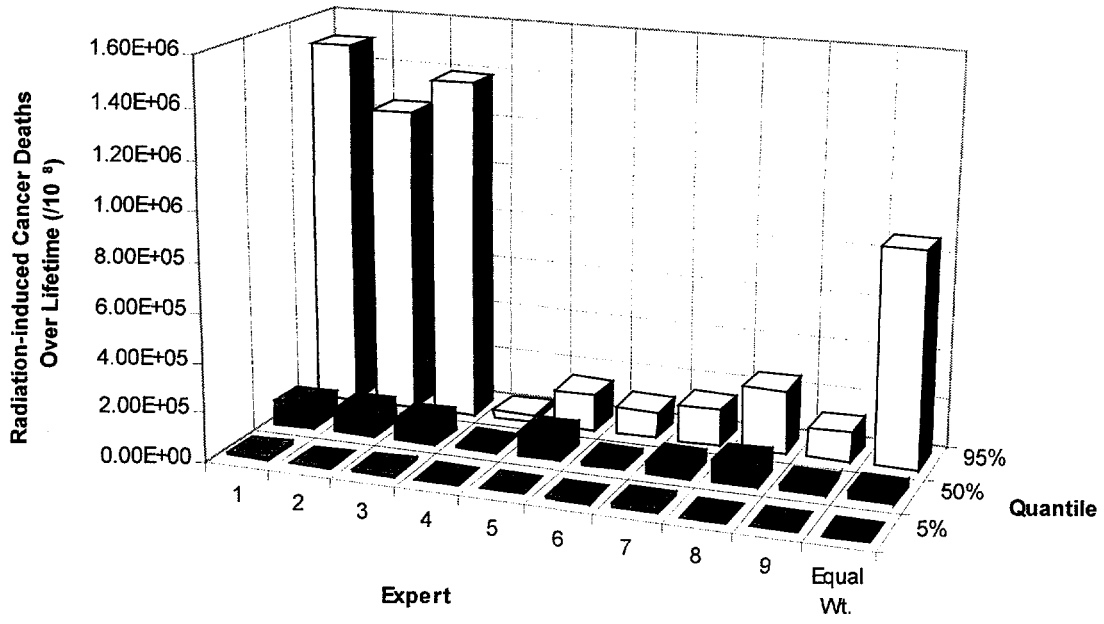

Figure 4.1 **Bone cancer, radiation exposure-induced deaths (REID) per 10^8 persons, 1 Gy low LET over 1 minute.**

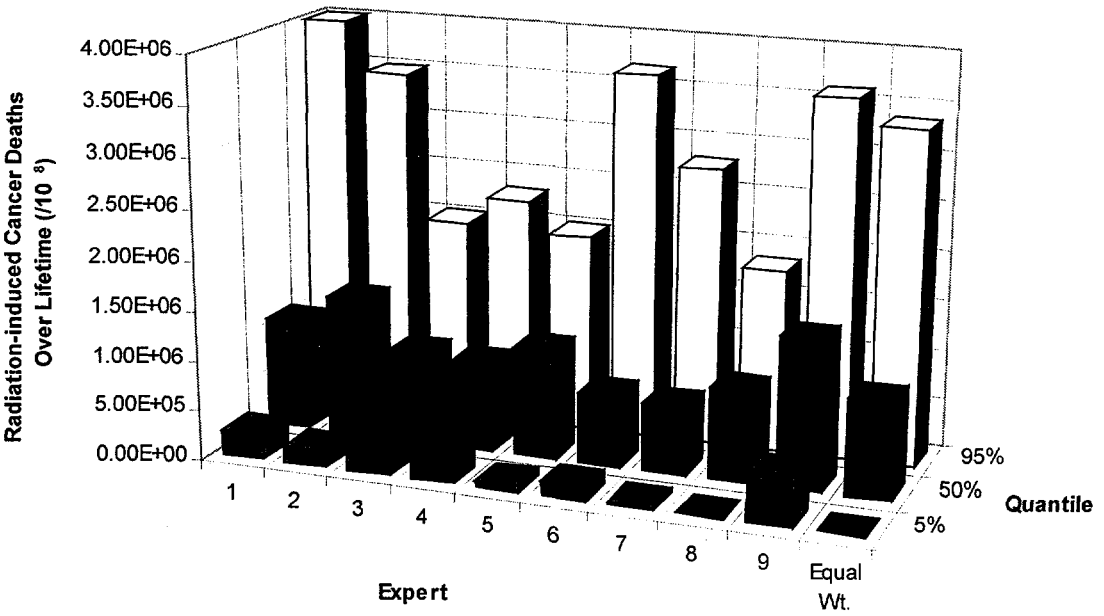

Figure 4.2 **Colon cancer, radiation exposure-induced deaths (REID) per 10^8 persons, 1 Gy low LET over 1 minute.**

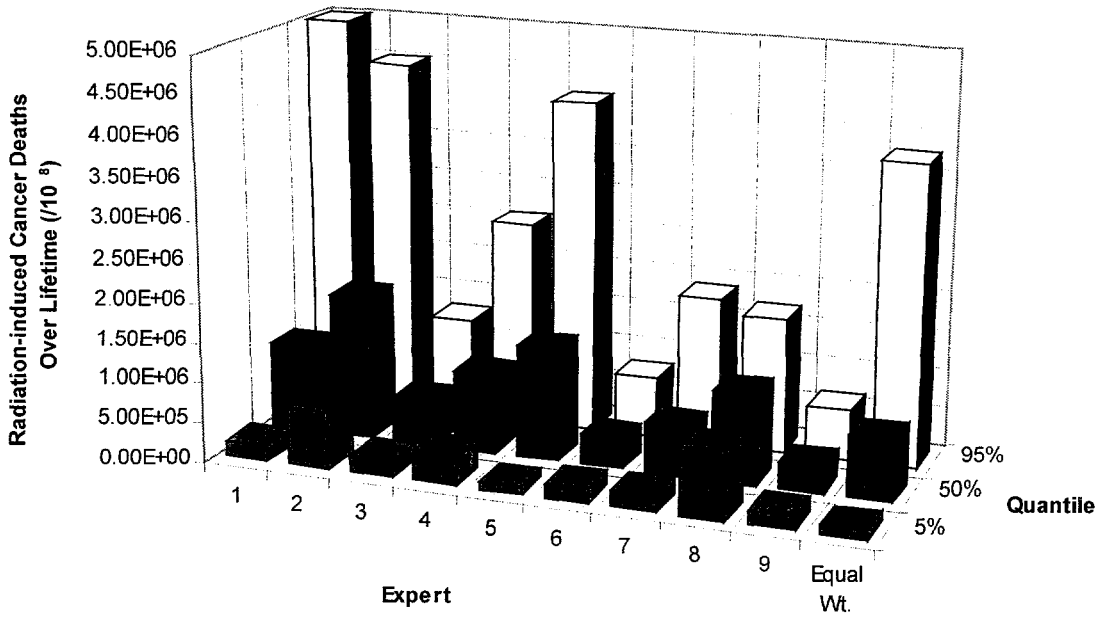

Figure 4.3 **Breast cancer, radiation exposure-induced deaths (REID) per 10^8 persons, 1 Gy low LET over 1 minute.**

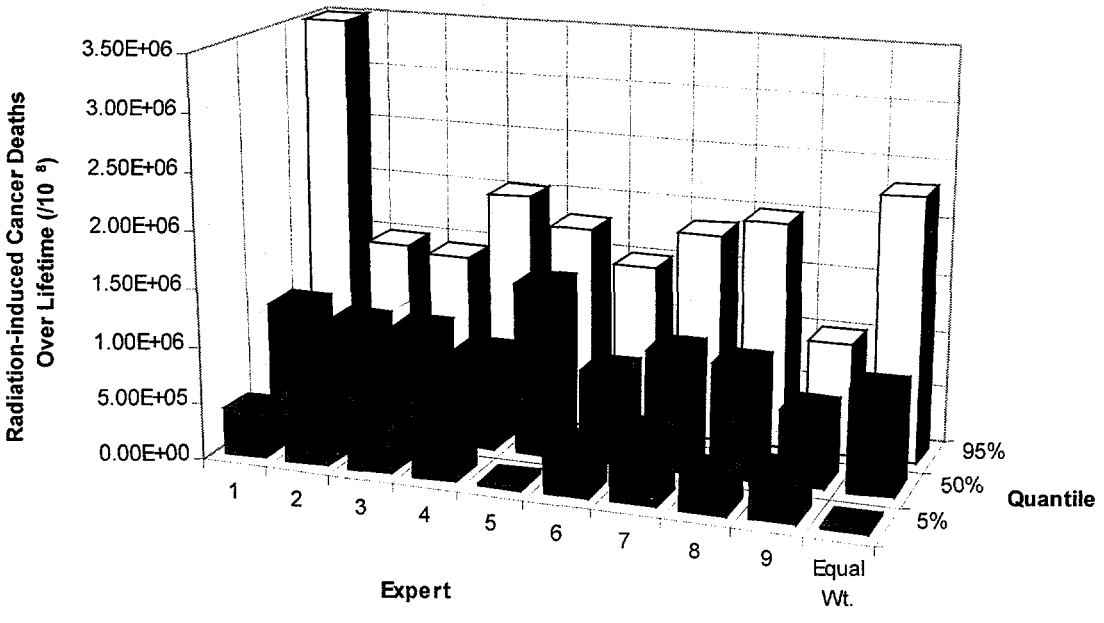

Figure 4.4 **Leukemia, radiation exposure-induced deaths (REID) per 10^8 persons, 1 Gy low LET over 1 minute.**

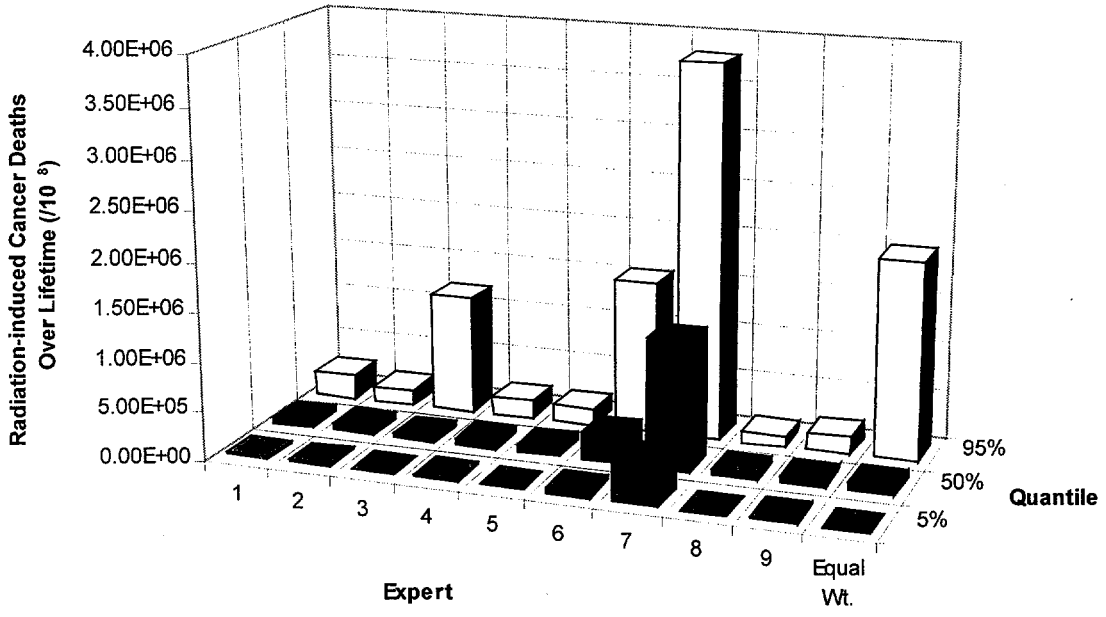

Figure 4.5 **Liver cancer, radiation exposure-induced deaths (REID) per 10^8 persons, 1 Gy low LET over 1 minute.**

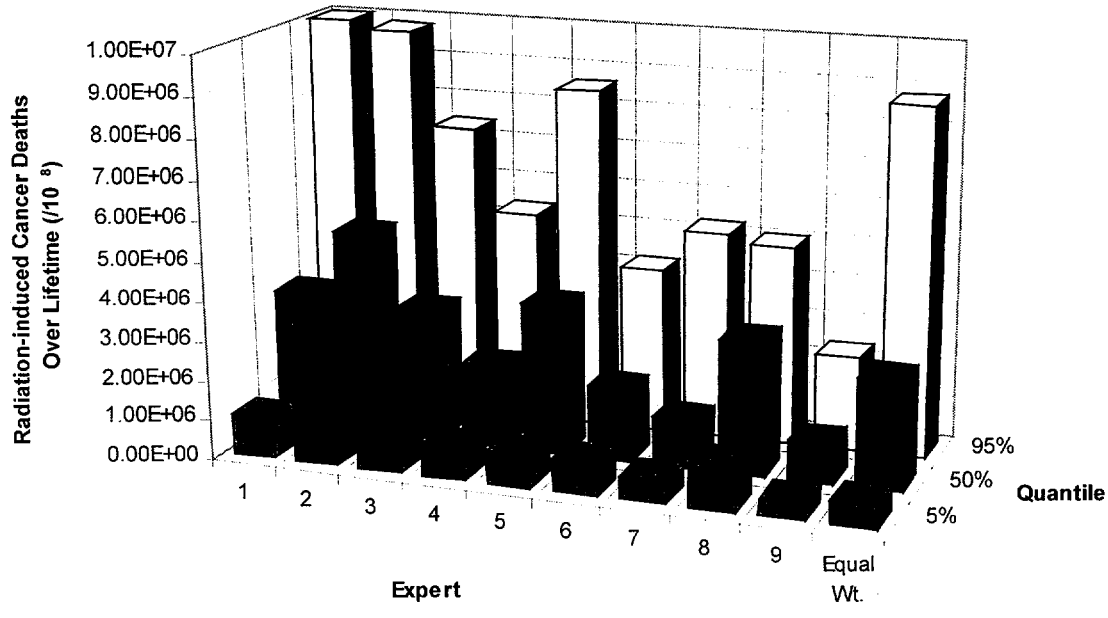

Figure 4.6 **Lung cancer, radiation exposure-induced deaths (REID) per 10^8 persons, 1 Gy low LET over 1 minute.**

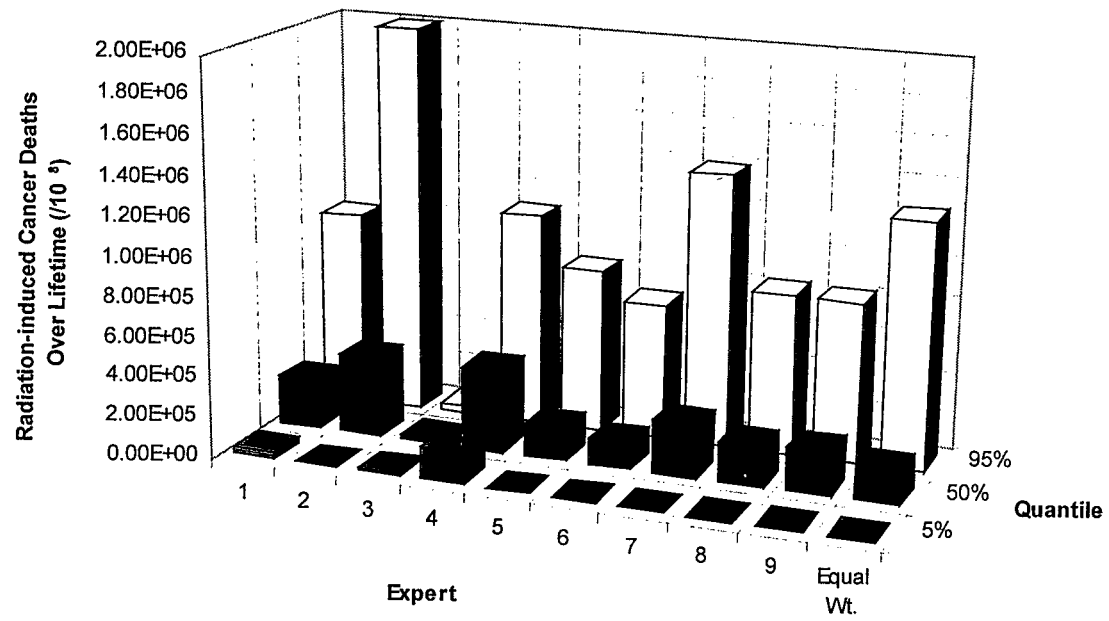

Figure 4.7 **Pancreatic cancer, radiation exposure-induced deaths (REID) per 10^8 persons, 1 Gy low LET over 1 minute.**

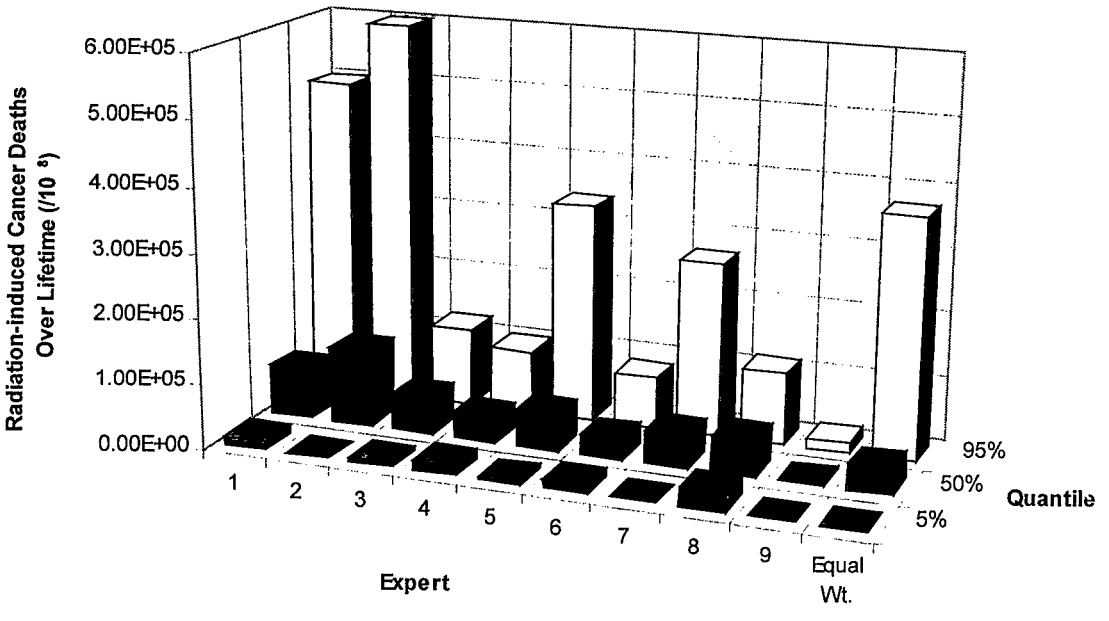

Figure 4.8 **Nonmelanoma skin cancer, radiation exposure-induced deaths (REID) per 10^8 persons, 1 Gy low LET over 1 minute.**

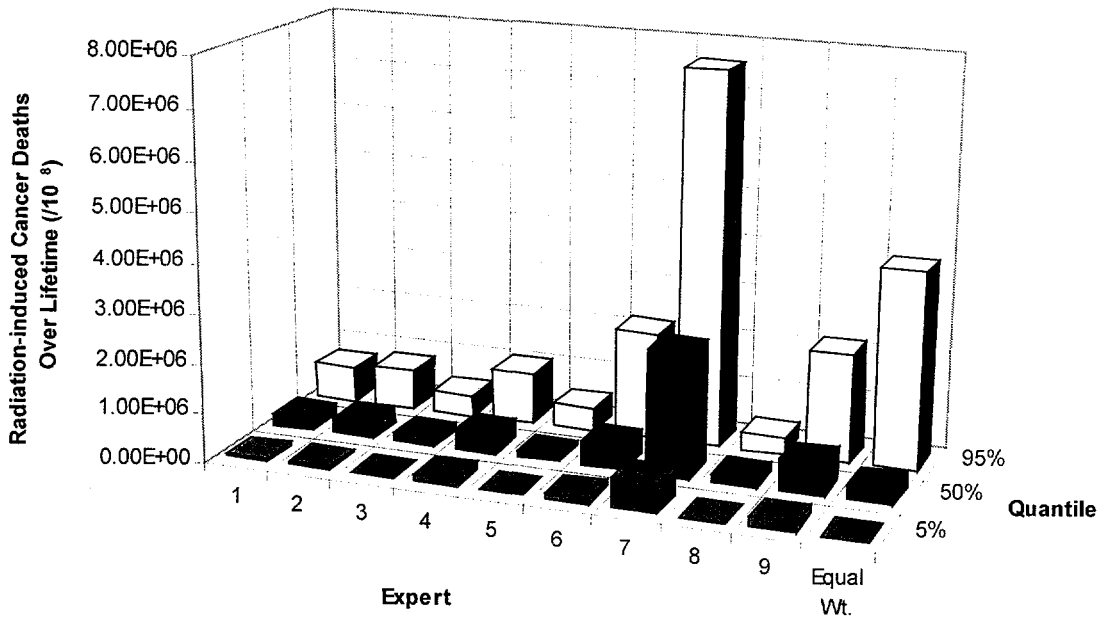

Figure 4.9 **Stomach cancer, radiation exposure-induced deaths (REID) per 10^8 persons, 1 Gy low LET over 1 minute.**

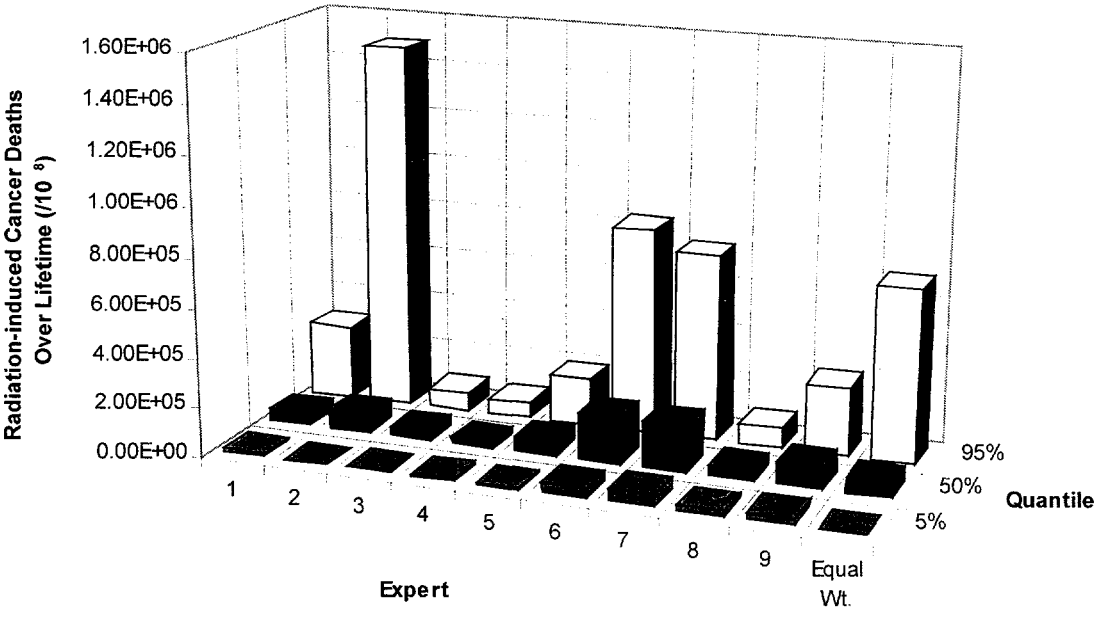

Figure 4.10 **Thyroid cancer, radiation exposure-induced deaths (REID) per 10^8 persons, 1 Gy low LET over 1 minute.**

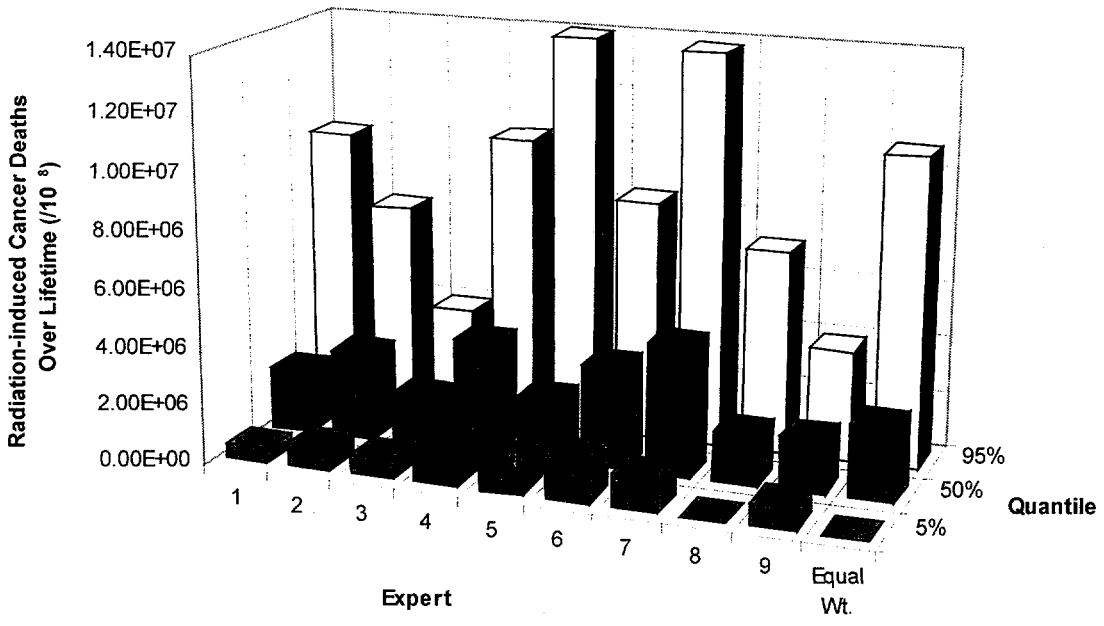

Figure 4.11 All other cancers, radiation exposure-induced deaths (REID) per 10^8 persons, 1 Gy low LET over 1 minute.

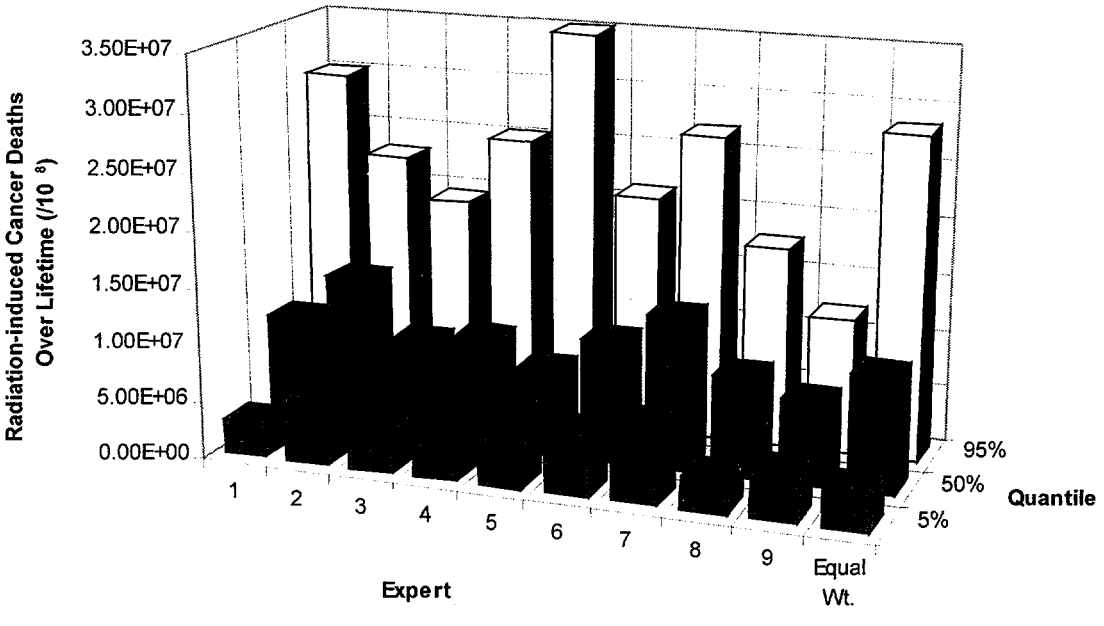

Figure 4.12 All cancers, radiation exposure-induced deaths (REID) per 10^8 persons, 1 Gy low LET over 1 minute.

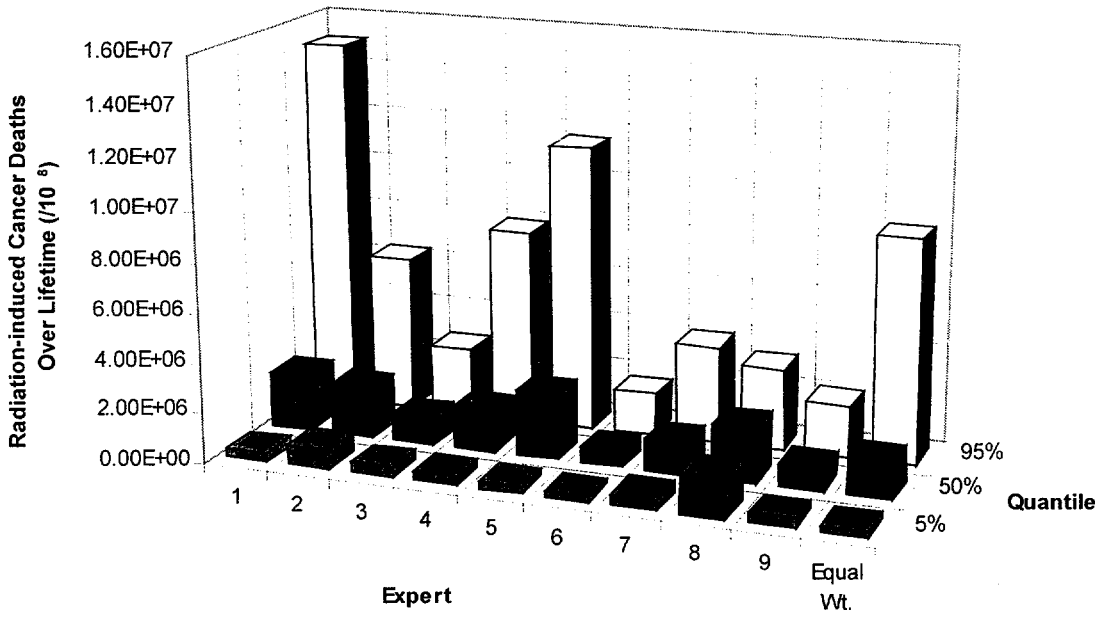

Figure 4.13 Breast cancer, radiation exposure-induced deaths (REID) per 10^8 children, 1 Gy low LET over 1 minute.

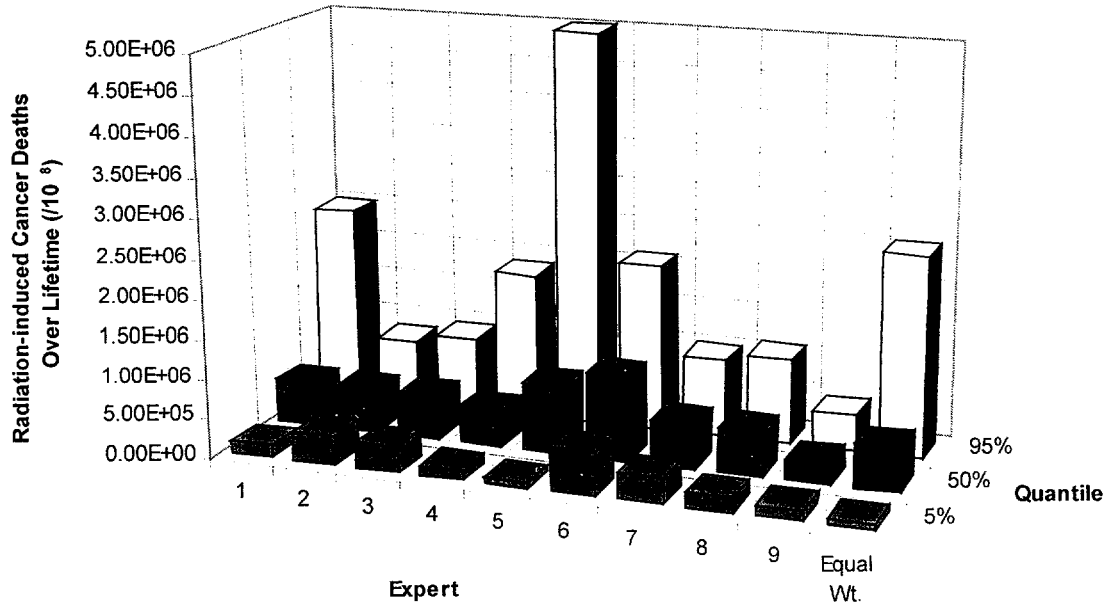

Figure 4.14 Leukemia, radiation exposure-induced deaths (REID) per 10^8 children, 1 Gy low LET over 1 minute.

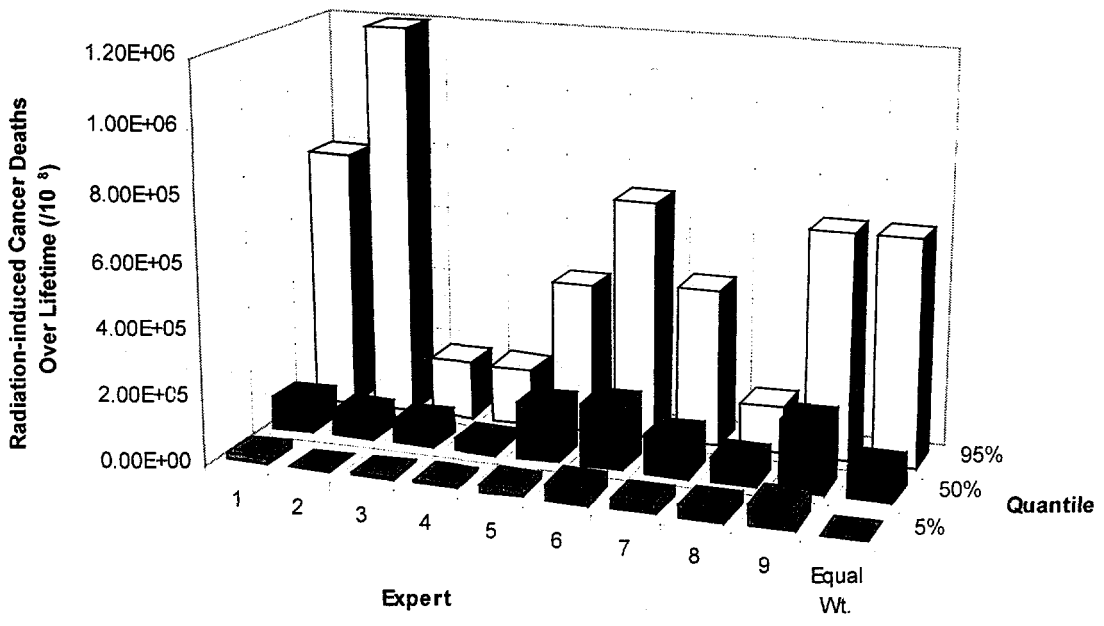

Figure 4.15 Thyroid cancer, radiation exposure-induced deaths (REID) per 10^8 children, 1 Gy low LET over 1 minute.

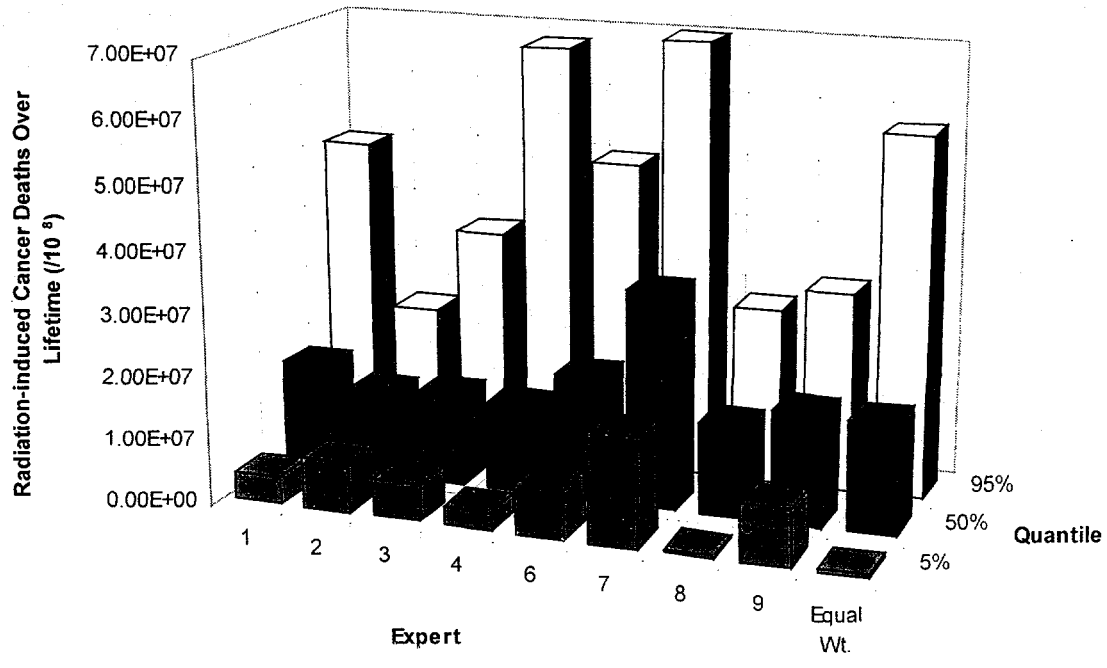

Figure 4.16 All cancers, radiation exposure-induced deaths (REID) per 10^8 children, 1 Gy low LET over 1 minute.

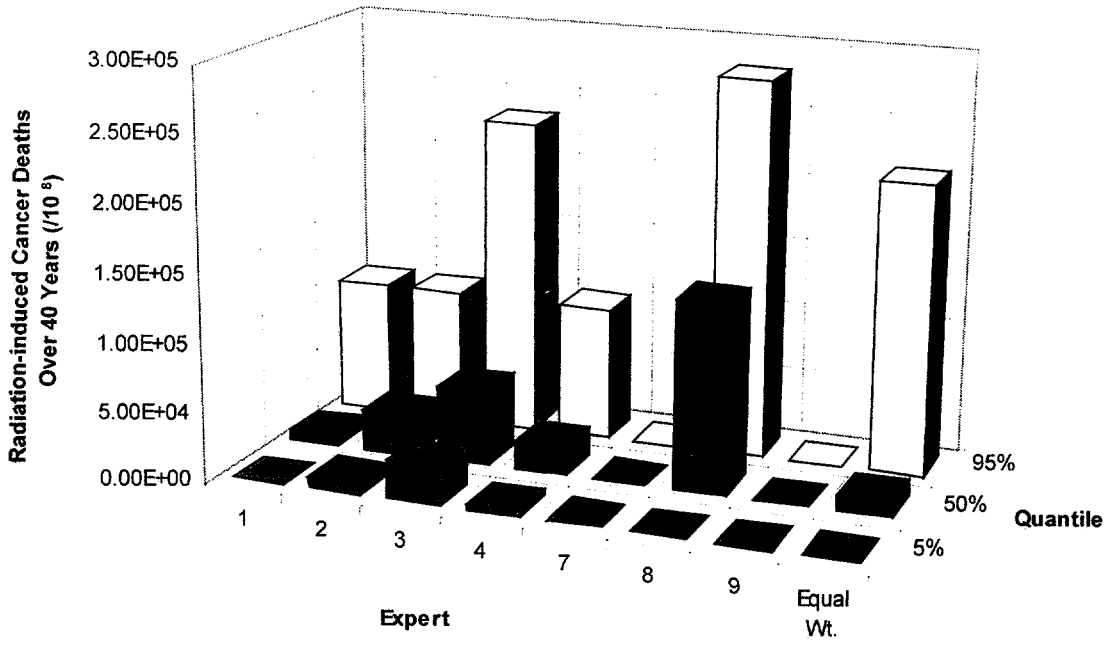

Figure 4.17 Nonmelanoma skin cancer, radiation exposure-induced cases per 10^8 persons, 1 mGy plutonium alpha particles over 1 year.

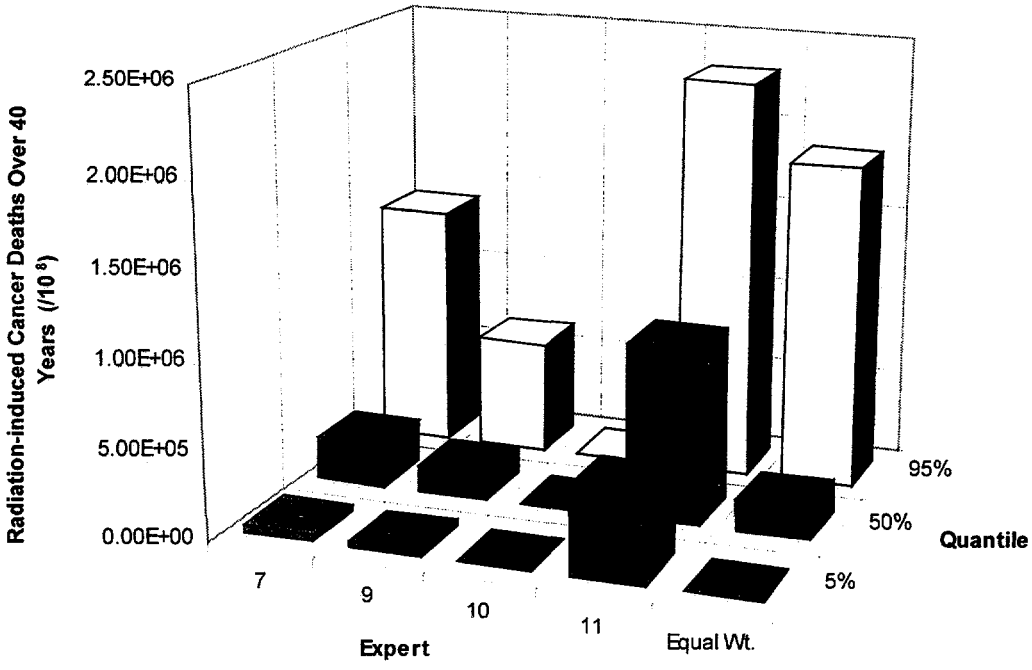

Figure 4.18 All cancers, radiation exposure-induced deaths (REID) per 10^8 persons, 10 kBq inhalation of plutonium-239 (1 μm AMAD).

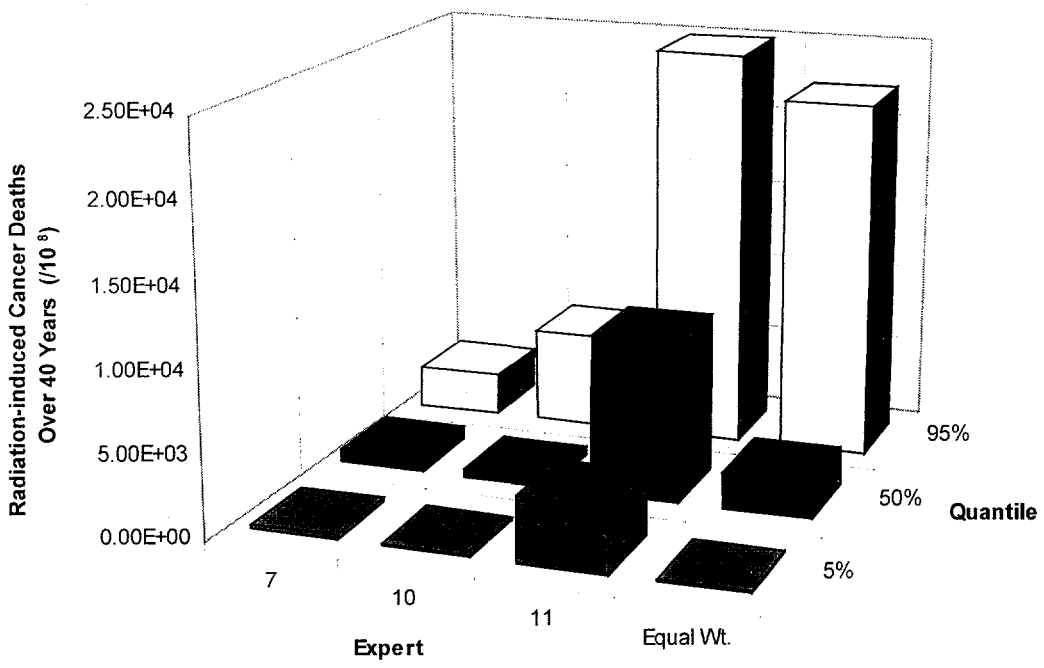

Figure 4.19 All cancers, radiation exposure-induced deaths (REID) per 10^8 persons, 10 kBq inhalation of strontium-90 (1 μm AMAD).

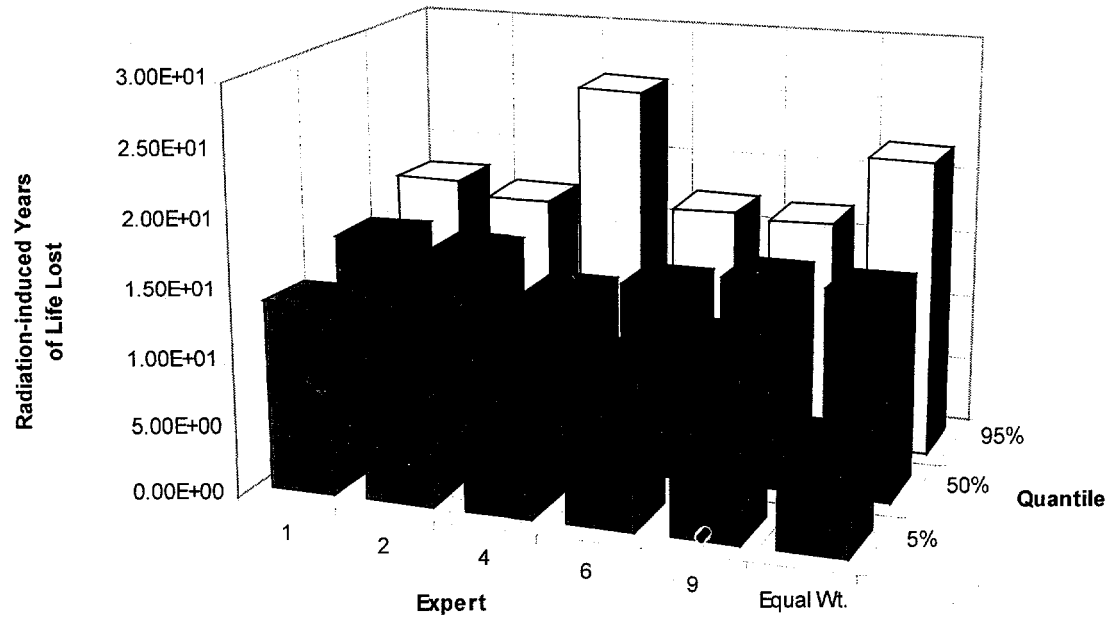

Figure 4.20 All cancers, years of life lost given that radiation-induced cancer death has occurred.

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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 an 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 was, therefore, enhanced by this cooperation.

Distributions of cancer risk parameters were successfully elicited from a panel of experts. Aggregated distributions, developed by combining the individual elicited distributions, are now available for these cancer risk parameters. The aggregated distributions represent state-of-the-art knowledge in a form suitable for use in performing consequence uncertainty analyses. The individual and composite distributions 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 conceptually 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 data, models, tools, and perspectives they considered appropriate for the problem. The elicited distributions 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 cancer risk coefficient distributions capture the uncertainty in the stochastic processes to be expected after induction by radiation.

Mathematical processing of the aggregated elicited data was not necessary because the cancer risk coefficients are the high dose-rate code input parameters required by COSYMA and MACCS. Additional MACCS processing must be performed when the required risk coefficients relate to low dose rates or higher exposures.

5.3 Application of Distributions

The results of this project will allow the uncertainties in late health effect parameters to be treated 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 risk coefficient 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 cancer risk model. 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 utilized in both COSYMA and MACCS uncertainty studies. In many cases, a different approach will be needed for MACCS than for COSYMA.

The methods of this project were also consistent with the NUREG-1150 philosophy because all modeling perspectives are included, and a 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 other analytical models. The development of distributions over physically measurable parameters means that the cancer risk distributions will have applications beyond the scope of the current project. The distributions also provide insights regarding areas where current consequence codes are deficient, and they can be a useful guide for directing future research.

5.4 Conclusions

The goal of creating a library of uncertainty distributions for late health effects parameters was fulfilled. Furthermore, in this exercise, formal expert judgment elicitation has proven to be a valuable vehicle for syn-

thesizing the best available information by a highly qualified group.

With a well-designed elicitation approach that addresses such issues as selection of elicitation variables, development of case structures, 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 may be the best method available for assembling the required information when existing data are ambiguous, controversial, inconclusive, or only partially relevant.

Appendix A
Reference information provided to experts at Annapolis meeting

Mortality rates (per 100,000 per year) and equilibrium population distribution for the hypothetical EU/US population

Mortality Rates per 100,000 per year

	Bone		Colon		Breast		Leukemia		CLL	
	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
0-	0.00	0.00	0.03	0.00		0.00	0.84	0.89	0.00	0.00
1-4	0.00	0.00	0.00	0.00		0.00	1.27	0.97	0.00	0.00
5-9	0.12	0.00	0.01	0.00		0.00	1.61	0.95	0.00	0.00
10-14	0.44	0.59	0.01	0.00		0.00	1.24	0.59	0.00	0.00
15-19	0.44	1.19	0.05	0.04		0.04	2.25	1.13	0.00	0.00
20-24	0.50	0.53	0.10	0.10		0.12	1.71	1.37	0.00	0.00
25-29	0.37	0.14	0.51	0.34		2.34	1.57	0.91	0.00	0.00
30-34	0.41	0.16	0.61	0.64		4.48	1.52	1.15	0.00	0.05
35-39	0.23	0.35	2.23	1.75		15.44	1.58	1.95	0.00	0.00
40-44	0.40	0.17	3.20	2.70		22.33	2.61	1.48	0.11	0.00
45-49	0.24	0.18	9.28	8.85		45.67	3.12	2.24	0.18	0.06
50-54	0.44	0.22	13.46	11.44		56.68	4.34	3.96	0.81	0.29
55-59	0.78	0.15	34.46	25.44		83.17	9.52	5.02	1.79	0.77
60-64	0.65	0.31	45.95	35.36		92.37	13.27	7.97	3.50	0.92
65-69	0.97	0.46	88.15	58.34		113.09	21.69	11.91	6.91	2.32
70-74	1.52	0.92	103.14	72.07		125.24	32.61	17.57	10.54	3.01
75-79	1.41	1.42	182.22	131.74		159.87	46.86	23.50	13.16	5.77
80-84	2.31	1.84	214.76	156.86		188.02	65.42	35.71	23.86	11.95
85+	2.91	1.56	251.40	185.14		228.83	96.16	52.21	36.91	17.77

	Liver		Lung		Pancreas		Skin		Stomach	
	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
0-	0.31	0.00	0.05	0.03	0.00	0.00	0.00	0.00	0.00	0.00
1-4	0.08	0.06	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00
5-9	0.12	0.04	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
10-14	0.06	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
15-19	0.12	0.06	0.03	0.02	0.00	0.07	0.00	0.00	0.01	0.03
20-24	0.21	0.11	0.08	0.02	0.00	0.11	0.05	0.05	0.06	0.06
25-29	0.22	0.08	0.43	0.33	0.18	0.05	0.18	0.00	0.23	0.21
30-34	0.28	0.12	0.84	0.44	0.10	0.21	0.41	0.05	0.24	0.35
35-39	0.72	0.28	6.28	3.67	0.93	0.71	0.47	0.24	1.50	0.81
40-44	0.93	0.30	9.15	6.14	1.99	1.59	0.11	0.00	1.79	1.14
45-49	2.45	0.82	43.37	23.99	4.06	2.89	0.18	0.18	5.18	2.51
50-54	3.80	0.98	62.12	30.86	9.19	6.31	0.73	0.07	8.35	3.12
55-59	7.03	2.37	163.35	71.21	17.87	10.65	0.78	0.39	18.44	6.77
60-64	7.80	3.05	213.26	94.74	29.23	19.76	1.38	0.77	29.43	9.92

Mortality Rates per 100,000 per year (Continued)

65-69	3.42	5.16	394.57	153.28	38.70	28.61	2.04	1.31	54.49	20.40
70-74	12.27	5.62	466.18	167.92	62.62	43.01	4.57	2.26	65.82	25.69
75-79	13.69	7.78	579.27	168.19	80.39	58.95	6.74	2.94	106.28	47.46
80-84	18.48	9.26	634.48	167.50	84.40	74.58	12.06	3.68	131.08	64.94
85+	20.50	11.71	632.08	140.13	112.68	77.15	27.20	13.40	151.16	79.96

	Thyroid		All Other Cancers		All Cancers		All Cause		Population	
	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
0-	0.00	0.00	1.22	1.33	2.45	2.24	930.83	736.55	681,992	650,432
1-4	0.00	0.00	2.47	2.41	3.83	3.50	45.95	37.11	2,700,831	2,581,197
5-9	0.00	0.00	2.00	2.09	3.86	3.08	24.97	16.25	3,370,479	3,222,457
10-14	0.00	0.00	2.22	1.36	3.97	2.56	25.97	16.05	3,366,206	3,219,854
15-19	0.06	0.00	2.80	1.41	5.77	4.00	103.34	40.19	3,356,643	3,215,718
20-24	0.00	0.00	3.64	2.48	6.37	4.95	113.88	42.10	3,338,640	3,209,140
25-29	0.00	0.00	7.24	6.43	10.94	10.85	137.81	54.62	3,318,098	3,201,590
30-34	0.00	0.05	8.77	8.37	13.17	16.01	145.84	62.54	3,294,784	3,192,353
35-39	0.00	0.18	19.50	17.51	33.43	42.87	216.38	110.43	3,266,243	3,179,343
40-44	0.11	0.17	23.28	23.37	43.59	59.39	246.41	135.46	3,229,161	3,160,256
45-49	0.18	0.24	63.01	52.66	131.06	140.22	481.12	284.10	3,174,736	3,129,625
50-54	0.07	0.51	81.63	67.45	184.12	181.63	605.36	356.33	3,091,626	3,081,043
55-59	0.78	1.24	185.48	135.32	438.49	341.74	1300.42	739.72	2,958,435	3,003,642
60-64	0.57	1.69	237.16	158.71	578.72	424.63	1673.77	951.34	2,751,877	2,882,456
65-69	2.66	1.55	454.96	265.34	1071.64	659.45	3285.21	4593.99	2,452,639	2,560,600
70-74	1.20	3.51	545.61	293.32	1295.52	757.13	4146.82	5083.62	2,046,870	2,016,217
75-79	1.41	3.95	1004.21	462.09	2022.48	1067.88	8769.73	5965.39	1,525,728	1,537,841
80-84	2.31	5.78	1182.29	515.50	2347.59	1223.65	10800.22	7426.68	948,695	1,110,530
85+	1.46	5.77	1390.92	560.23	2686.46	1356.11	14724.47	11195.72	1,126,316	1,845,704

Cancer incidence rates (per 100,000 per year) for the hypothetical EU/US population

	Bone		Colon		Breast		Leukemia		CLL	
	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
0-	0.19	0.22	0.00	0.00		0.30	5.05	4.62	0.00	0.00
1-4	0.09	0.17	0.00	0.00		0.05	7.10	6.22	0.00	0.00
5-9	0.73	0.42	0.00	0.00		0.05	3.56	2.61	0.00	0.00
10-14	1.19	1.55	0.05	0.00		0.05	2.79	2.18	0.00	0.00
15-19	1.71	1.00	0.21	0.05		0.10	2.52	1.42	0.03	0.00
20-24	0.94	0.42	0.27	0.22		1.12	2.09	1.11	0.02	0.00
25-29	0.63	0.40	0.82	0.57		7.89	1.92	1.26	0.00	0.08
30-34	0.61	0.39	1.82	1.36		25.82	2.37	2.13	0.15	0.14
35-39	0.54	0.41	3.34	3.24		61.52	3.24	2.81	0.33	0.17
40-44	0.50	0.49	7.82	7.56		115.01	4.21	3.10	0.68	0.28
45-49	0.54	0.77	15.49	13.71		170.21	6.24	4.36	1.55	0.86
50-54	0.95	0.76	29.83	28.13		196.59	9.35	6.61	2.95	1.49
55-59	1.58	0.73	54.65	47.93		238.92	15.04	9.74	5.60	2.63
60-64	1.68	1.20	95.56	72.20		291.20	23.25	14.46	9.02	4.43
65-69	1.96	1.33	148.49	107.45		315.99	35.89	19.04	13.84	6.50
70-74	1.98	1.92	213.56	157.41		329.96	54.36	31.15	21.43	10.85
75-79	4.02	1.89	300.39	217.53		354.50	76.22	38.70	26.62	12.84
80-84	3.63	2.65	369.16	265.65		361.25	96.77	54.46	37.94	17.03
85+	4.05	2.26	398.35	327.43		380.35	119.55	66.42	44.56	24.50

	Liver		Lung		Pancreas		Skin		Stomach	
	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
0-	0.22	0.23	0.00	0.00	0.30	0.00	1.10	0.60	0.15	0.00
1-4	0.27	0.28	0.05	0.10	0.00	0.00	0.10	0.00	0.00	0.00
5-9	0.06	0.00	0.07	0.00	0.00	0.05	0.00	0.10	0.00	0.00
10-14	0.06	0.15	0.04	0.04	0.00	0.00	0.10	0.50	0.00	0.00
15-19	0.04	0.21	0.18	0.13	0.00	0.00	0.50	0.90	0.09	0.09
20-24	0.09	0.13	0.21	0.25	0.00	0.05	1.60	1.80	0.00	0.04
25-29	0.27	0.17	0.30	0.43	0.14	0.10	2.70	3.50	0.19	0.26
30-34	0.27	0.14	1.57	1.03	0.43	0.30	7.00	6.60	0.86	0.46
35-39	0.44	0.31	4.98	3.35	1.01	0.70	10.80	12.30	1.83	0.83
40-44	0.84	0.53	16.95	11.86	2.67	2.02	19.90	22.50	3.25	1.91
45-49	1.74	0.91	42.94	25.37	5.74	4.19	38.00	33.70	8.10	3.32
50-54	3.02	1.63	90.87	48.09	11.01	7.31	60.30	49.80	14.98	5.63
55-59	6.39	2.89	176.33	86.47	19.19	14.33	99.10	64.70	28.99	10.21
60-64	10.63	3.23	294.88	138.81	31.33	24.35	155.50	100.10	47.01	16.04
65-69	13.89	4.64	432.91	172.25	45.84	33.97	220.60	137.70	73.08	26.97
70-74	15.45	6.46	562.70	191.32	66.35	50.35	324.20	209.20	105.16	41.99

Cancer incidence rates (per 100,000 per year) for the hypothetical EU/US population (Continued)

75-79	20.74	8.53	644.71	182.26	85.09	61.59	419.80	252.70	140.63	61.24
80-84	21.28	10.61	664.14	157.12	101.60	78.87	503.40	291.50	174.04	85.98
85+	19.51	11.70	550.64	117.75	107.16	88.44	609.50	366.30	182.14	106.17

	Thyroid		All Other Cancers		All Cancers	
	Male	Female	Male	Female	Male	Female
0-	0.00	0.00	11.55	11.61	18.56	17.58
1-4	0.00	0.00	11.38	9.49	18.99	16.31
5-9	0.00	0.04	6.45	5.34	10.87	8.62
10-14	0.18	0.49	5.92	5.27	10.33	10.23
15-19	0.38	1.64	13.28	10.70	18.92	16.24
20-24	0.66	3.15	21.86	16.48	27.71	24.77
25-29	0.88	4.45	30.89	27.60	38.74	46.63
30-34	1.41	5.77	43.58	42.99	59.92	86.99
35-39	1.91	5.88	57.67	60.17	85.76	151.52
40-44	2.36	5.60	76.08	78.00	134.58	248.60
45-49	2.27	6.60	112.84	114.58	233.90	377.74
50-54	3.04	6.78	196.20	169.61	419.56	520.95
55-59	2.96	5.83	327.81	244.80	732.04	726.53
60-64	4.11	6.19	541.39	325.21	1205.34	993.00
65-69	4.93	6.68	822.76	409.48	1800.36	1235.51
70-74	4.83	6.84	1141.35	455.45	2489.93	1482.05
75-79	4.47	5.71	1468.87	505.13	3164.94	1689.78
80-84	4.63	7.08	1757.95	587.57	3696.60	1902.74
85+	4.75	6.51	1793.44	592.90	3789.09	2066.23

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11. ABSTRACT *(200 words or less)*

The development of two new probabilistic accident consequence codes, MACCS and COSYMA, was developed 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 late health effects models.

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