NUREG/CR-6526-Vol. 1
EUR 16772-Vol. 1
CG-NA-16-772-EN-C
ISBN 92-827-6700-0
SAND97-2323-Vol. 1
Vol. 1

Probabilistic Accident Consequence Uncertainty Analysis

Uncertainty Assessment for Deposited Material and External Doses

Main Report

Manuscript Completed: September 1997
Date Published: December 1997

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NRC Job Code W6352

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200, rue de la Loi
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EC Contract Numbers F13P-CT92-0023 and
93-ET-023

Publication No. EUR 16772
Luxembourg: Office for Official Publications of the European Communities, 1997
ISBN 92-827-6700-0
Catalog No. CG-NA-16-772-EN-C

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This report was written under the following contracts:

Contract No. W6352, United States Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Division of Systems Technology.

Contract No. F13P-CT-92-0023, European Commission, Directorate-General for Science, Research and Development, XII-F-6 Radiation Protection Research Action.

Contract No. 93-ET-023, European Commission, Directorate-General of Environment, Nuclear Safety and Civil Protection, XI-A-1 Radiation Protection.

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Abstract

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

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

After the first feasibility study on atmospheric dispersion and deposition parameters, a second expert judgment exercise was carried out on food chain and external dose (calculation) parameters. This report refers only to the external dose part of the study. The work relating to food chains is described in a companion report. The goal again was to develop a library of uncertainty distributions for the selected consequence parameters. Following this work, a panel of ten experts on deposited material and related doses was chosen. They represent nine countries and the results of their assessments are presented here. Their results were processed with an equal-weighting aggregation method, and the aggregated distributions were processed into the code input variables of the external dose models in COSYMA and for 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 uncertainty in the code predictions will be quantified.

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Contents

Preface.....	x
Acknowledgments	xii
List of Acronyms	xiii
Executive Summary.....	ES-1
1. Background of Joint Program.....	1-1
1.1 Introduction	1-1
1.2 Establishment of Joint European Commission/Nuclear Regulatory Commission Uncertainty Study.....	1-1
1.3 Objectives	1-2
1.4 Project Development	1-2
1.5 Brief Chronology of Joint Effort	1-3
1.6 Structure of Document.....	1-4
1.7 References	1-4
2. Technical Issues Considered Relevant	2-1
2.1 Introduction	2-1
2.2 Types of Uncertainty	2-1
2.3 Use of Uncertainty Analyses for Decision Making.....	2-2
2.4 Brief Description of MACCS and COSYMA Models for Deposited Material and External Doses.....	2-2
2.5 Selection of Variables for Presentation to Formal Expert Elicitation Panels.....	2-4
2.6 Formal Expert Judgment Methods.....	2-7
2.7 Scope of Analysis	2-7
2.8 References	2-7
3. Summary of Expert Elicitation Methods for Deposited Material and External Doses	3-1
3.1 Introduction	3-1
3.2 Definition of Elicitation Variables and Case Structures	3-1
3.2.1 Case Structure for Deposited Material and External Doses	3-3
3.2.2 Elicitation Variables.....	3-5
3.3 Expertise Required for the Elicitation Process	3-6
3.3.1 Selection of Phenomenological Experts.....	3-6
3.3.2 Selection of Normative Specialists.....	3-6
3.4 Expert Elicitation.....	3-7
3.4.1 Dry Run Meeting to Finalize Case Structure.....	3-7
3.4.2 First Expert Meeting	3-7
3.4.3 Preparation of the Distributions	3-8
3.4.4 Second Expert Meeting: Elicitation	3-8
3.5 Mathematical Processing of Elicited Distributions.....	3-8
3.5.1 Aggregation of Elicited Distributions	3-8
3.5.2 Combining Dependencies	3-9
3.6 References	3-9
4. Results and Analysis.....	4-1
4.1 Introduction	4-1
4.2 Summary of Elicitation Meetings	4-1
4.2.1 Dry Run Elicitation Meeting	4-1
4.2.2 Summary of First Expert Meetings	4-1

4.2.3	Summary of Second Expert Meeting	4-1
4.3	Summary of Individual Expert Assessments.....	4-1
4.3.1	Summary of Individual Assessments of Elicitation Questions	4-2
4.3.1.1	Gamma Dose Rate and Effective Dose Rate.....	4-2
4.3.1.2	Location Factors	4-3
4.3.1.3	Time-Integrated Air Concentration Ratios.....	4-3
4.3.1.4	Population Distributions	4-3
4.4	Summary of Aggregated Results	4-4
	Summary of Aggregated Assessments of Elicitation Questions	4-4
4.5	Comparison of Results from Current Study with Ranges Used in Past Uncertainty Studies	4-4
4.6	References	4-5
5.	Summary and Conclusions	5-1
5.1	Project Accomplishments	5-1
5.2	Uncertainty Included in Distributions.....	5-1
5.3	Application of Distributions	5-1
5.4	Conclusions	5-2

List of Figures

2.1	Structure and data flow for each subsystem of COSYMA.....	2-5
2.2	Structure and data flow for MACCS.....	2-6
3.1	Sequence of methods used to develop the uncertainty distributions.	3-2
4.1	Median results for the distributions of gamma dose rate (Gy s^{-1}) above an open lawned area following an initial dry deposition of 1 Bq/m^2 of ^{137}Cs	4-6
4.2	Range factors (ratio of 95th/5th percentile) for the distributions of gamma dose rate (Gy s^{-1}) above an open lawned area following an initial dry deposition of 1 Bq/m^2 of ^{137}Cs	4-6
4.3	Median results for the distributions of gamma dose rate (Gy s^{-1}) above an open lawned area following an initial wet deposition of 1 Bq/m^2 of ^{137}Cs	4-7
4.4	Range factors (ratio of 95th/5th percentile) for the distributions of gamma dose rate (Gy s^{-1}) above an open lawned area following an initial wet deposition of 1 Bq/m^2 of ^{137}Cs	4-7
4.5	Median results for the distributions of effective dose rate (Sv s^{-1}) in a typical urban environment following an initial dry deposition of 1 Bq/m^2 of ^{137}Cs to the lawned areas of the ground.....	4-8
4.6	Range factors (ratio of 95th/5th percentile) for the distributions of effective dose rate (Sv s^{-1}) in a typical urban environment following an initial dry deposition of 1 Bq/m^2 of ^{137}Cs to the lawned areas of the ground.....	4-8
4.7	Median results for the distributions of the integrated adult effective dose (Sv) in a typical urban environment following an initial dry deposition of 1 Bq/m^2 of ^{137}Cs to the lawned areas of the ground.....	4-9
4.8	Range factors (ratio of 95th/5th percentile) for the distributions of the integrated adult effective dose (Sv) in a typical urban environment following an initial dry deposition of 1 Bq/m^2 of ^{137}Cs to the lawned areas of the ground.....	4-9
4.9	Median results for the distributions of effective dose (Sv) in a typical urban environment following an initial wet deposition of 1 Bq/m^2 of ^{137}Cs to the lawned areas of the ground.....	4-10
4.10	Range factors (ratio of 95th/5th percentile) of the distributions of effective dose (Sv) in a typical urban environment following an initial wet deposition of 1 Bq/m^2 of ^{137}Cs to the lawned areas of the ground.....	4-10
4.11	Median results for the distributions of integrated adult effective dose (Sv) in a typical urban environment following an initial wet deposition of 1 Bq/m^2 of ^{137}Cs to the lawned areas of the ground.....	4-11
4.12	Range factors (ratio of 95th/5th percentile) of the distributions of the integrated adult effective dose (Sv) in a typical urban environment following an initial wet deposition of 1 Bq/m^2 of ^{137}Cs to the lawned areas of the ground.....	4-11
4.13	Median results for the ratio of the effective dose received by an adult at several indoor locations to the effective dose received by an adult outdoors in an open lawned area shortly after an initial uniform deposit of 1 Bq/m^2 of ^{137}Cs to the lawned areas of the ground.....	4-12
4.14	Range factors (ratio of 95th/5th percentile) for the ratio of the effective dose received by an adult at several indoor locations to the effective dose received by an adult outdoors in an open lawned area shortly after an initial uniform deposit of 1 Bq/m^2 of ^{137}Cs to the lawned areas of the ground.....	4-12
4.15	Median results for the ratio of the effective dose received by an adult at several indoor locations to the effective dose received by an adult outdoors in an open lawned area one year after an initial uniform deposit of 1 Bq/m^2 of ^{137}Cs to the lawned areas of the ground.....	4-13
4.16	Range factors (ratio of 95th/5th percentile) for the ratio of the effective dose received by an adult at several indoor locations to the effective dose received by an adult outdoors in an open lawned area one year after an initial uniform deposit of 1 Bq/m^2 of ^{137}Cs to the lawned areas of the ground.....	4-13
4.17	Median results for the ratio of the time integrated air concentration (TIAC) indoors to that outdoors given an initial concentration 1 Bq s/m^3 for four different nuclides with the doors normally open and closed.....	4-14
4.18	Range factors (ratio of 95th/5th percentile) for the ratio of the time integrated air concentration (TIAC) indoors to that outdoors given an initial concentration of 1 Bq s/m^3 for four different nuclides with the doors normally open and closed.....	4-14

4.19	Median results for the average population classed outdoor workers, indoor workers, nonactive adult population, or school children.....	4-15
4.20	Range factors (ratio of 95th/5th percentile) for the average population classed outdoor workers, indoor workers, nonactive adult population, or school children.....	4-15
4.21	Median annual average fraction of time that people working outdoors spend indoors in various types of housing or vehicles	4-16
4.22	Range factors (ratio of 95th/5th percentile) for annual average fraction of time that people working outdoors spend indoors in various types of housing or vehicles	4-16
4.23	Median annual average fraction of time that people working indoors spend indoors in various types of housing or vehicles	4-17
4.24	Range factors (ratio of 95th/5th percentile) for annual average fraction of time that people working spend indoors in various types of housing or vehicles	4-17

List of Tables

	Experts on deposited material and external doses	ES-2
1.1	Phenomenological areas for the joint NRC/EC study.....	1-3
3.1	Contributions to the joint methodology from US and EC studies	3-1
3.2	Experts on deposited material and external doses	3-6
4.1	Summary of results for time spent in designated locations.....	4-4

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Preface

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

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

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Acknowledgments

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

We would like to acknowledge several institutes that facilitated the collection of unpublished experimental information used in the probabilistic training and evaluation of the experts on deposited materials and external doses. In particular we want to thank Dr. M. Ogan at AEA Technology in the UK.

We also greatly appreciate the technical assistance of Ms. Ina Bos of Delft University of Technology, The Netherlands; the editorial help of Ruth Haas and Sally Kmetz at Tech Reps, the support of Judy Jones at Sandia National Laboratories, and the guidance provided by Ms. Reeta Garber of Sandia National Laboratories in preparing this report.

On January 22, 1996, Peter Roelofsen, manager of the risk analysis group at the Netherlands Energy Research Foundation (ECN), died after a long period of illness. Peter prepared the first discussion documents for the early health effects expert panel, and provided valuable comments on early versions of the documents on deposited materials and related doses. He will be missed by the project staff, and in particular by the staff at ECN.

List of Acronyms

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

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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 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 the prioritization of activities and research; they were also interested in initiating a comprehensive assessment of the uncertainty in the consequence calculations used for risk assessments and regulatory purposes. Therefore, the ultimate objective of the NRC/EC joint effort is to systematically develop credible and traceable uncertainty distributions for the respective code input variables using a formal expert judgment elicitation process.

The specific goals of this study are to: (1) develop a library of uncertainty distributions for external doses from deposited radionuclides by using a formal expert judgment elicitation process and (2) further determine whether the technology is appropriate for the development of credible uncertainty distributions on the input variables of the external dose models for deposited materials used in MACCS and COSYMA. This report focuses on the methods used and the results of the study of deposited materials and external doses.

Approach

To ensure the quality of the elicited information, a formal expert judgment elicitation procedure, built on the process developed for and used in the NUREG-1150 study, was followed.¹ Refinements were based on the experience and knowledge gained from several formal expert judgment elicitation exercises performed in the US and EC since the NUREG-1150 study. These include the pilot study on atmospheric dispersion and deposition published

by Delft University of Technology for the EC, the joint NRC/EC study on atmospheric dispersion and deposition published as NUREG/CR-6244-EUR-15855, and performance assessments for waste repositories in the 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 was based on two important ground rules: (1) the current code models would not be changed because both the NRC and EC were interested in the uncertainties in the predictions produced by MACCS and COSYMA, respectively, and (2) the experts would be asked only to assess physical quantities that hypothetically could be measured in experiments. The reasons for these ground rules are that (1) the codes have already been developed and applied in US and EC risk assessments, and (2) eliciting physical quantities avoids ambiguity in definitions of variables; more important, the physical quantities elicited are not tied to any particular model and thus have a much wider potential application.

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

Preparation Stage

Elicitation variables were defined based on the results of past and contemporary probabilistic consequence code sensitivity/uncertainty studies, which screened for the important code input variables in the context of their contribution to the uncertainties in the code predictions. Elicitation questions, hereafter referred to as case structure, were developed in accordance with the sophistication of the respective code models so that sufficient information would be elicited from the experts to allow valid interpolation and extrapolation

of the resulting uncertainty distributions. The proposed case structure was then tested with several phenomenological experts internal to the project and refined.

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

Expert Training Meetings

Separate training meetings were held for the European and American experts to provide background on the project and its objectives, the MACCS and COSYMA codes, and the treatment of the elicited information. A probability training session was conducted to familiarize the experts with the concept of uncertainty and the potential pitfalls in preparing subjective assessments; practice exercises followed. Material for the training exercise was drawn directly from the field of deposited material and external doses. The training meetings were also used to ensure that the experts developed their respective uncertainty distributions based on common ground rules and initial and boundary conditions (it was considered critical that the experts all answer the same question). The full proposed case structure was presented to them for discussion, and when necessary, was modified in accordance with their feedback to ensure that all given problem conditions were clear, reasonable, and agreeable to them. In both meetings, a method to extract quantitative information on knowledge dependencies among the elicitation variables was developed.

Experts on deposited material and external doses

Mikhail Balonov	Russia
André Bouville	US
Joanne Brown	UK
Malcolm Crick	Austria
Eduardo Gallego	Spain
Peter Jacob	Germany
Olof Karlberg	Sweden
Ilya Likhtarev	Ukraine
Kevin Miller	US
Jørn Roed	Denmark

Preparation of the Assessments and Written Rationale

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

Expert Elicitation Sessions

All of the European experts were elicited individually in separate sessions held either at the expert's own institution, or at a common location. The American experts were elicited individually, in separate sessions held at a common location. The US elicitations occurred after a common session during which the experts presented the approach that they had taken in answering the questions posed. They did not reveal their probability assessments in order to avoid biasing the other experts.

In both European and American elicitation sessions, an attempt was made to use the method developed to extract quantitative information on knowledge dependencies. The issue of anonymity was discussed and the American experts agreed to preserve anonymity, as did their European counterparts.

Processing the Elicited Results

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

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

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

Some of the external dose variables elicited were code input variables so that the distributions obtained could be used directly in the uncertainty study. The location factors for shielding in houses, cars and buses, and the population distributions indoors and outdoors in urban and rural locations are examples of code input variables that were elicited directly. The gamma dose rates are examples of elicitation variables that required processing in order to use the distributions obtained in a COSYMA or MACCS uncertainty study.

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 obtained were developed by the experts from a variety of information sources and the aggregated distributions therefore include variations resulting from different modeling approaches and perspectives. The distributions for the elicitation and code input variables are available on computer media and can be obtained from the project staff.

The aggregated estimates of deposited materials and external dose distributions capture the uncertainty in gamma dose rates, effective dose rates, and integrated adult effective doses under average weather conditions, and for dry and wet conditions separately. The results refer to open lawned areas, and to urban and rural areas for various radionuclides. The elicited distributions also cover location factors in various types of buildings, cars and buses, and time-integrated air concentrations (TIACs) indoors compared with outdoors for doors and windows open and closed. Furthermore, the experts were elicited on fractions of the population in their own country spending time indoors, outdoors, and in several activities.

The actual values utilized in consequence programs represent the **average** value of the quantity for a particular population group or type of environment. Hence the uncertainties of interest in this study are those relating to possible variations in these **average** values, and not uncertainties defined by the possible range of the particular parameter for single individuals in the population or for single environments.

The experts were also asked to provide quantitative data on dependencies among the elicited variables. The results show areas where high dependency or none was identified.

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

Finally, in this exercise, formal expert judgment elicitation has proven to be a valuable vehicle for

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

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

1. Background of Joint Program

1.1 Introduction

The development of two new probabilistic accident consequence codes—MACCS¹ by the US and COSYMA² 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 consisted of uncertainty assessments for atmospheric dispersion and deposition modeling in the accident consequence analysis (ACA) codes.³ The part of the project reported in this document was designed to elicit from experts uncertainty distributions on important parameters in the code calculations for deposited material and external doses. Other reports describe the elicitation of uncertainty distribution variables in other code areas. The elicited distributions will be used in consequence uncertainty analyses using the MACCS and COSYMA codes.

Fairly comprehensive assessments of the uncertainties in the estimates of the consequences of postulated accidental releases of radioactive material have already been made, both in the US and by the European Commission, using predecessors of the MACCS and COSYMA codes (i.e., CRAC-2,⁴ MARC,⁵ and UFOMOD⁶). Fundamental to these assessments were estimates of uncertainty (or more explicitly, probability distributions of values) for each of the more important model parameters. In each case

these estimates were largely done by those who developed the accident consequence codes, as opposed to experts in the different scientific disciplines featured within an accident consequence code (e.g., atmospheric sciences, radioecology, metabolism, dosimetry, radiobiology, and economics). In addition, the underlying uncertainties in the submodels that constitute the consequence codes were addressed only to a limited extent.

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

In terms of probabilistic nuclear accident analyses, formal expert elicitation methods were used extensively in assessing core damage frequency and radionuclide transport from the melt to the environment in the NUREG-1150⁷ study of the risks of reactor operation. The use of these methods was not without criticism or difficulties, but a special review committee⁸ 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 study⁹ 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 use a larger pool of world-class experts than would be available to a project conducted solely by the US or EC.
3. To capture the potentially greater technical and political acceptability of a joint project. Because of the different technical approaches of the two teams, there is an opportunity to consider alternative approaches together and to develop a final product that would be better than either team could produce in isolation.
4. To share project costs. Expert elicitation projects require significant resources because of the staff and outside experts required.

1.3 Objectives

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

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

2. To apply the methodology to estimates of uncertainties associated with the predictions of probabilistic accident consequence codes (COSYMA and MACCS) designed for assessing the consequences of commercial nuclear power plant accidents;
3. To obtain better quantification and more valid estimates of the uncertainties associated with probabilistic accident consequence codes, thus enabling more informed and better judgments to be made in the areas of risk comparison and acceptability, and therefore to help set priorities for future research.

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

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

1.4 Project Development

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

Atmospheric dispersion and deposition parameters were the focus of the first phase of the study. The results are published in a multivolume main report³ and an additional report.¹⁰ The overall objective of

the first phase was to determine the efficacy and feasibility of the joint effort before spending resources on the additional phenomenological areas (health effects, ingestion pathways, dosimetry, etc.).

Table 1.1 Phenomenological areas for the joint NRC/EC study

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

This report provides the results of the expert judgment exercise on deposited material and the calculation of external dose parameters. The exercise had as its goal developing a library of uncertainty distributions on the behavior of the deposited material and the calculations of related doses that could be used in many different consequence uncertainty studies employing the MACCS and COSYMA consequence codes.

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

The state-of-the-art approach explored in this study was jointly formulated and was based on two important ground rules:

1. The current code models would not be changed because both the NRC and the EC were interested in the uncertainties in the predictions produced by MACCS and COSYMA and in the codes used to provide the associated databases to use the MACCS and COSYMA codes.
2. The experts would be asked to assess only physical quantities that hypothetically could be measured in experiments.

Because of the stricture against modifying MACCS and COSYMA, it was necessary to elicit distributions either over consequence code input variables or over variables from which distributions for code input

variables could be developed. In addition, the uncertainty distributions developed were constrained by the flexibility of the fixed models in the consequence codes. If any of the uncertainty distributions contain values prohibited by the fixed models, either the uncertainty distribution needs to be truncated (thereby neglecting part of the uncertainty range provided by the experts) or the fixed models need to be reevaluated.

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

1.5 Brief Chronology of Joint Effort

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

November 1992	Kickoff meeting for the atmospheric dispersion and deposition expert panels.
December 1993	Draft report on the results of the atmospheric dispersion and deposition expert panels submitted 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 external doses.
April 1994	Joint EC/NRC planning meeting in Brussels for the panels on the food chain and deposited material/external doses.
September 1994	NRC management decides to join the panels on the food chain and deposited material/external doses.
December 1994	Dry run meetings held in Europe for experts to review the case structure documents.
January 1995	Training meeting for the European experts on the food chain and deposited material/related doses.
January 1995	Publication of Vol. 1 of dispersion and deposition uncertainty assessment.
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/external doses.
July 1995	Elicitation meeting for the US experts on the food chain and deposited material/external doses.
November 1995	Processing meeting.
February 1996	Draft reports.
1997	Final reports.

1.6 Structure of Document

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

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2. Technical Issues Considered Relevant

2.1 Introduction

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

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

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

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

2.2 Types of Uncertainty

The NRC Probabilistic Risk Analysis (PRA) Working Group² has defined two types of uncertainty that may be present in any calculation. These are (1) stochastic uncertainty caused by the natural variability in a parameter and (2) state-of-knowledge uncertainty, which results from a lack of complete information about phenomena. The latter may be further divided into (1) parameter uncertainty, which results from a lack of knowledge about the correct inputs to analytical models; (2) model uncertainty, which is a result of the fact that perfect models cannot be constructed; and (3) completeness uncertainty, which refers to the uncertainty as to whether all the significant phenomena and relationships have been considered.

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

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

2.3 Use of Uncertainty Analyses for Decision Making

Section 2.3 of Volume 1 of the main report on atmospheric dispersion and deposition³ briefly describes the history of consequence uncertainty analyses. The US and European developments are sketched and summarized as lessons learned from past uncertainty analyses.

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

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

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

Accident consequence codes compute many quantities of interest to the decision maker, including time-varying radiation levels over a large spatial grid, numbers of acute and chronic fatalities, number of persons evacuated, amount of land lost to use, and economic and environmental damage. In the point value mode of calculation, the consequence codes have the capability to 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 MACCS and COSYMA Models for Deposited Material and External Doses

The uncertainty distributions developed in this study will be used to perform uncertainty studies using the EC consequence code COSYMA⁴ and the NRC code MACCS.⁵ COSYMA and MACCS are described here solely to familiarize the reader with the models. The expert elicitations are not constrained by these models. COSYMA and MACCS model the offsite consequences of postulated severe reactor accidents that release a plume of radioactive material to the atmosphere. These codes contain data on the transport and deposition of radioactive gases and aerosols into the environment and the potential human health and economic consequences. These codes are typically used as part of a probabilistic assessment of risk. For this reason, the meteorological conditions at the time of release are commonly varied by sampling over historical data. This sampling allows uncertainty to be included in meteorological conditions at the time of the accident in the calculation. This section reviews the external dose calculations implemented in MACCS and COSYMA and the code input variables required by these models for which uncertainty distributions were developed in this study.

ACA codes produce a number of results (endpoints) that relate to the behavior of deposited material and the calculation of its external doses. These include the doses (as a function of time) received by chosen individuals in the population exhibiting various patterns of behavior and subject to various countermeasures, in addition to the radiation dose received by the population as a whole (collective dose). These endpoints are used as an input to calculations of radiation risk and ultimately help determine the health effects anticipated to occur within the population under consideration.

The external deposited dose models in COSYMA and MACCS are designed to predict the doses that individuals in the population will receive from radioactive material deposited onto the ground. Although the majority of any population lives or works in urban and suburban areas, these models generally take as their baseline the doses predicted for individuals (adults) who are outdoors in an open area (e.g., a large open field). These doses are then translated, using simple scaling factors, to predict doses to those individuals in urban/suburban areas who are exhibiting particular patterns of behavior—for example, spending a certain percentage of their time in cars, cellars, or houses with various levels of shielding. The doses thus predicted are input to health risk models to calculate the overall detriment to the population. They are often used to assess the necessity to enforce particular mitigating actions in order to reduce the doses received by the population in the long term. These mitigating actions may involve moving the population out of the area or decontaminating the land surrounding the accident site.

Complexity in the external dose calculations within ACA codes therefore exists in two areas: (1) predicting the initial dose to individuals who are outdoors in an open area, where the behavior of the radionuclides in undisturbed soil, and energy-dependent attenuation and buildup of radiation is considered as a function of time following initial deposition; (2) the variation in the retention and weathering properties of those surfaces that are more common to the urban or suburban environments (i.e., those environments in which most people live or work).

The results of calculations using these outdoor dose models are commonly known as "dose conversion

factors" (DCFs) and they relate the initial deposited activity on the ground (Bq/m^2) to the dose (Sv) as a function of time following initial deposition. These DCFs are generally precalculated and held in data libraries that are accessed during normal running of the code (e.g., COSYMA or MACCS).

Consequence codes predict, for particular meteorological scenarios, dispersion and deposition during plume travel. The amount of material deposited depends on the outcome of two processes—dry and wet deposition. The dry deposition calculation is driven by the dry deposition velocity for a particular nuclide or nuclide group. Usually one value of dry deposition velocity is defined for all locations around the release point, thus ignoring any effects of varying surface type. The overall activity is often assumed to be typical of a uniform surface similar to that of undisturbed grassland. Wet deposition is driven by the rainfall occurring during plume travel and is modeled using a washout coefficient that takes material uniformly from the passing plume. The deposition (both wet and dry) is scaled using the DCFs from the data library to predict the external dose to individuals outdoors in an open area. The dose indoors is then estimated by reducing the outdoor dose using a location or shielding factor that is representative of either a particular type of dwelling or averaged over a range of types. The total dose to a group of individuals takes account of the fraction of time on average that each individual spends outdoors and indoors.

For the inhalation dose delivered to individuals indoors, a reduction in the time-integrated air concentration (TIAC) indoors relative to that outdoors is also calculated using a scaling or reduction factor that again is typical of a particular type of dwelling or is averaged over a range. Therefore, the input variables to the consequence codes that drive the dose models under consideration are of the following form:

1. Adult dose conversion factors (Sv per Bq/m^2 deposited on the ground), which translate deposited activity to the individual dose outdoors in an open area as a function of time;
2. Shielding or location factors, which represent the necessary reduction in outdoor (open area) dose that would be necessary to approximate the dose to individuals indoors in a typical dwelling;

3. Reduction factors, which represent the ratio of the time-integrated air concentration indoors in a typical dwelling to that outdoors in an open area;
4. Fraction of time that the average adult spends in each location under consideration.

As already mentioned, the values in (1) are derived using dose models that are incorporated into other programs external to the main consequence code. Few programs consider calculating doses for other age groups than adults, and those that do quite often use a simple scaling factor to relate the adult dose to that for children.

The uncertainties in these and other related quantities were the "problems" that the expert panel needed to address. The actual values utilized in consequence programs represent the **average** value of the quantity for a particular population group or type of environment. Hence the uncertainties of interest in this study are those relating to possible variations in these **average** values, and not uncertainties defined by the possible range of the particular parameter for single individuals in the population or for single environments. The questions were formulated so that ranges and median values could be derived for each of the above quantities, together with more generic background information that may be of use for future studies.

Correlations among the uncertainties expressed for several parameters may obviously exist and, where possible, questions were derived to obtain the experts' opinions on these correlations. Any other correlations that were not explicitly discussed, but which the experts felt important to consider, were stated in the rationale provided by the expert following the elicitation sessions.

The structure of the external dose calculations in COSYMA and MACCS is essentially the same. As described above, they both use data libraries of conversion factors with other factors input directly by the user.

The data flow of the main subsystems within COSYMA is illustrated in Figure 2.1. The dosimetric data are used in several modules (POTDOS, PROTEC, EARLY, LATDOS, LATRSK), depending on whether the dose is used for measurement against countermeasure criteria, being prepared for output as

individual or collective doses, used to estimate the risk of early effects, or is being used indirectly in activity/risk coefficients for late effects. For MACCS (Figure 2.2) the dosimetric information is used directly in the EARLY and CHRONC modules where the doses delivered to individuals over short and longer time scales are considered separately.

2.5 Selection of Variables for Presentation to Formal Expert Elicitation Panels

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

The variables to be elicited were chosen systematically using the methods summarized below. A full outline is provided in the main report on atmospheric dispersion and deposition³:

1. Variables shown to be important in sensitivity studies performed in the US and Europe using predecessors of the ACA codes were considered.
2. Variables chosen from a joint list of important code input variables developed by EC and US consequence experts for the current project were considered.
3. Only code input variables that were not highly specific to situations in either the US or the EC were chosen for joint US/EC elicitation. For this reason, variables in the countermeasures and economics modules were excluded from consideration.
4. Only code input variables for which insufficient data are available to develop statistical uncertainty distributions were selected.

Figure 2.1 Structure and data flow for each subsystem of COSYMA. (From COSYMA: A New Program Package for Accident Consequence Assessment, EVR 13028, CEC, 1991.)

Subsystems: NE, Near to source early effects module; NL, near to source late effects module; and FL, far from source late effects module.

Routines: MAIN, reads INDAT input data file.

Calculates: ATMOS, atmospheric dispersion and deposition; CONCEN, air and deposited concentrations; POTDOS, potential doses in the absence of countermeasures; POTRSK, potential risks in the absence of countermeasures; PROTEC, extent and duration of countermeasures; AMOUNT, numbers of people, areas, and quantities of food affected by countermeasures; EARLY, early health risks, taking account of countermeasures; COLLEC, total numbers of health effects in population; ECONOM, economic consequences of release; LATDOS, late doses taking account of countermeasures; and LATRSK, late health risks taking account of countermeasures.

Figure 2.2 Structure and data flow for MACCS. (From NRC, PRA Working Group, Probabilistic Risk Assessment, NUREG-1489, Washington, DC, March 1994.)

5. From the list of selected code input variables, elicitation variables were selected or developed that were experimentally or potentially observable. The experimentally observable constraint was inserted for two reasons (1) to avoid ambiguity when presenting the definition of the variables to be elicited (if the experts assess poorly defined variables, the potential for incompatible assessments is high) and (2) to ensure that the elicited distributions would be applicable beyond the context of the present study.

In many cases, the experimentally observable constraint resulted in choosing elicitation variables that were 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 for containing uncertainty resulting from the fundamental limitations in the model's physics, from data uncertainties, and from random or stochastic uncertainties in observational data. Additional criteria used to select elicitation variables and a summary of those chosen for the panel on deposited material and related doses are provided in Section 3.2.

2.6 Formal Expert Judgment Methods

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

2.7 Scope of Analysis

It is impossible to develop distributions for deposited material and related dose variables that are valid for all nuclear power plants. The external dose models in COSYMA and MACCS are used in a broad generic sense and do not usually require detailed localized weather conditions or local variations in surface roughness, building locations, and types. In order to mimic this approach, the experts were requested to consider various generic populations and conditions during the assessments. In some cases, however, the specifications were more detailed, for example, stating wet or dry initial deposition mechanisms or the location of individuals within particular types of dwellings.

Since the variations in average values of particular parameters were being considered in this study, extreme events such as snow or floods were not considered by the experts when assessing the likely ranges in the elicitation variables. In fact, most ACA codes have only a limited description of the different processes by which rain and snow remove material, and combine them into a single set of input variables.

The accidents being modeled by ACA codes may happen at some unknown time in the future. It is assumed that population behavior is not altered other than where people follow the countermeasures strategy adopted. Therefore, for the scope of this panel, it was assumed that no modification of the behavior of the population (either self-imposed or otherwise) would occur as a result of the accident, and hence sheltering or any other protective measures were not considered in the assessment of uncertainties.

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 considered outside the scope of the project.

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3. Summary of Expert Elicitation Methods for Deposited Material and External Doses

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 the variables on deposited material and related doses. 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 was termed a "case." The ensemble of all cases for the elicitation variable was termed the "case structure." The primary consideration in developing elicitation variables, cases, and case structures was the importance of designing elicitation questions that were not dependent on specific analytical models.

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

Furthermore, it was considered important to choose those variables for elicitation that would be of most use to other ACA codes in the future. Model-specific parameters have therefore been avoided, and previous studies carried out to assess the uncertainties of similar consequence programs (e.g., UFOMOD, MARC, CONDOR) were used as much as possible in choosing the input variables important for this study.

As mentioned earlier, dosimetric calculations in ACA codes rely heavily on precalculated dose conversion factors. The actual model is used independently of the system, and it had to be decided at which point the consideration of uncertainty should start. If the actual variables

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

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

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

input to the ACA code are chosen, then estimates of uncertainties in the dose conversion factors themselves would have to be made. The advantage of this option is that the databases supporting the ACA code can remain static, with uncertainty ranges superimposed on the data prior to or immediately following input to the system. This method will be used in the COSYMA uncertainty analysis. Conceptually, however, it is sometimes easier to elicit those variables input directly to the supporting programs generating the database. These quantities may have a more fundamental physical basis, with experimental evidence more readily available for comparison. The disadvantage of this option, however, is that the uncertainty ranges specified have to be propagated throughout the supporting programs, generating possibly several tens to hundreds of databases during the course of the full uncertainty analysis. The starting point chosen therefore has significant implications for pre- and postprocessing of the results during the uncertainty analysis itself.

3.2.1 Case Structure for Deposited Material and External Doses

The detailed case structure is provided in Vol. 2 of this report and is only summarized here. Several physical processes are considered in assessing external doses to individuals outdoors and indoors and in urban or rural environments, together with various assumptions about population behavior. Some of the processes considered are also related to the estimation of inhalation doses indoors, in particular processes that affect the amount of radioactivity deposited on internal surfaces and the rate of air exchange in buildings. Each of these processes is considered in turn.

First, there are the processes of deposition. Naturally, the exposure of individuals in any environment is related to the distribution of the deposited material in the living environment of the individual. Deposition on a uniform flat terrain within an ideal rural environment presents a relatively simple modeling problem, and one for which a great deal of consensus may be reached. On the other hand, assessments of deposition within urban and suburban environments can be a significant source of uncertainty. Deposition patterns are distinctly nonuniform in these areas, with preferential deposits occurring, for example, on roofs, lawns, and trees compared with walls and windows. Any assumptions about deposition patterns will directly

influence the estimates of external dose received by the population. Furthermore, the mechanisms driving the deposition (e.g., dry or wet deposition processes) will also influence the patterns of radioactivity. During heavy rainstorms, initial runoff and loss of radionuclides from roofs through drains, etc., may occur. Such events may also enhance the movement of radioactivity down the soil column. Conversely, in the longer term, the fixing of nuclides to the urban surface or to soil particles may reduce the rate at which radionuclide concentrations decrease.

Immediately following deposition on a particular type of surface, some attenuation of the gamma radiation emitted by the nuclides may occur due to the presence of surface roughness. This attenuation may also be enhanced by the initial migration of the activity into the soil or between pavements, particularly during heavy rain. A further source of uncertainty is therefore the variability in the depth of distribution of the activity below the surface on which it is initially deposited.

The doses to individuals assumed to be standing at a particular location indoors or outdoors are based on the translation of air kerma, or absorbed dose in air, to the dose to individual body organs. Generally these organ/air ratios are derived from calculations using anthropomorphic phantoms, and for which there seems relatively good consensus. The variations in assumptions for the size and shape of the phantoms, particularly with age, will obviously influence the overall estimate, but the uncertainties involved may be small compared with other significant processes.

An additional source of uncertainty within the assessment of dose, particularly in urban environments, is the assumption made about the geometry of "the problem." The flat terrain models are based on the assumption that uniform surfaces of infinite extent, and as such remain relatively simple. The location of buildings, and of the individuals within those buildings, together with a general reduction in source size for the various areas considered in urban areas (e.g., pavements and lawns) will add to the complexity in assessing exposure.

Buildings within urban or suburban areas provide shielding for individuals against the gamma radiation emitted by the deposited material outdoors. The building materials also enhance the scattering of the radiation, thus providing indirect paths to the individuals located inside. The assumptions made about building materials and geometry of the buildings will have an influence on any uncertainties

derived. Radiation scattering and absorption will be taken into account by most experts, but their estimates will be directly influenced by their assumptions about building materials, in particular the mass per unit area, and the location of individuals within the buildings. The number and location of windows and total area of glass will also affect the overall estimate.

The ratio of the dose indoors, or at any given location, to that at 1 m above an open lawn surface has often been called a location factor. These factors are not only dependent on the environmental characteristics but also on source energy and they have been observed to vary most between energy values for locations providing the highest shielding (e.g., in basements or high up in multistory blocks). Variations in the estimates of these location factors also depend on the assumed split between wet and dry deposition mechanisms, since this will influence the location of the activity on the external surfaces of the house.

The air exchange rate of buildings and the amount of activity deposited on internal surfaces also need to be considered when estimating the uncertainties in predicting the location factors or the actual doses to individuals indoors. For example, external exposures to individuals in basements of single-family homes are often dominated by the indoor, rather than the outdoor, contamination. The assumptions regarding numbers of windows and doors will also have a direct influence on the uncertainties associated with penetration of radioactivity.

Some ACA models take account of the doses received by individuals during evacuation, thus considering the shielding effects of cars and buses. Questions will also be asked concerning external exposure in vehicles, but experience within the International Atomic Energy Agency VAMP (validation of models for the transfer of radionuclides in terrestrial urban and aquatic environments) exercise has shown that these situations are quite well understood.¹

Long-term reductions in activity concentrations for each type of environment can be influenced not only by the rate of decay of the nuclides, but also by the rate of migration of radioactivity into the soil and weathering on other less permeable surfaces. The assumptions made about the soil type, particularly the mass density, will affect the migration of the activity and the associated depth profiles in the soil, as well as

having an impact on attenuation. There are also obvious correlations between the ability of the nuclides to fix themselves to the soil matrix and the rate at which these nuclides are assumed to migrate from the soil surface. In the urban and suburban environments, both natural and human processes will affect the removal of particles from various surfaces, the most important of these being wash-off caused by rain impacting on and running over the surface, removing radioactivity in its wake, or street-cleaning activities.

Short-term weathering will be influenced by the nature of the initial deposition conditions (i.e., wet or dry). Experience with cesium isotopes suggests that wet deposits are usually quite strongly fixed to the surface compared with dry cesium deposits, which are loosely fixed in the short term, but which may attach themselves more strongly with time. Removal of activity is more likely to occur in the short term if there is heavy rain immediately following the initial dry deposition event, which would remove the more loosely bound material. More important, the removal of activity from urban environments depends strongly on the type of surface, in particular the roughness of the surface, which is more likely to enhance fixation of the particles, and the dust loading already on the surface prior to deposition. It has been demonstrated that the position of material on roofs and the slope of the roof will also influence the effectiveness of weathering. The rate of removal of activity from walls has, however, been observed to occur quite slowly, which is of particular interest during dry deposition events in which the radioactivity deposited on the walls of a building may be more significant. Street cleaning and other human activities (e.g., driving) tend to enhance the removal of activity from paved areas. The assumptions made about the relative contributions of activity deposited on each of these surface types will have a significant impact, therefore, on the overall estimate of weathering behavior and reduction in external dose rate with time.

Some modelers also consider the redistribution of radioactivity following removal from particular surface types (e.g., from walls onto pavements, or into sewerage systems) or the enhanced contamination indoors from nuclides brought inside on shoes.

There are obviously many sources of uncertainty inherent in estimates of external doses from deposited material, and some or all of these processes were

considered important by the experts when they defined the ranges associated with particular parameter values.

3.2.2 Elicitation Variables

The following list was derived for consideration by the experts, based on the definition of the dose conversion factors utilized within COSYMA and MACCS, the modification of these factors to take account of the actual locations of individuals in the population, and the possible range of observable quantities for this phenomenological area:

External Gamma Doses:

- Absorbed dose rate in air 1 m above a uniform, flat, and open lawned area at several times following initial deposition of 1 Bq/m² of ⁹⁵Zr/⁹⁵Nb, ¹⁰⁶Ru/¹⁰⁶Rh, ¹³¹I, and ¹³⁷Cs/^{137m}Ba to the ground. Average deposition conditions together with both dry and wet deposition mechanisms are considered separately;
- Effective dose rate and effective dose to an adult outdoors in "typical" urban and rural (open field) environments, at several times following initial deposition of 1 Bq/m² of ⁹⁵Zr/⁹⁵Nb, ¹⁰⁶Ru/¹⁰⁶Rh, ¹³¹I and ¹³⁷Cs/^{137m}Ba to the lawned areas of the ground;
- Ratio of adult external dose indoors to that received outdoors in an open lawned area shortly after an initial deposition of 1 Bq/m² to the ground (lawns) of ⁹⁵Zr/⁹⁵Nb, ¹⁰⁶Ru/¹⁰⁶Rh, ¹³¹I and ¹³⁷Cs/^{137m}Ba for several locations within buildings of various levels of shielding;
- Ratio of adult external dose inside a vehicle to the outdoor dose in an open lawned area following initial deposition of 1 Bq/m² to the ground (lawns) of ⁹⁵Zr/⁹⁵Nb, ¹⁰⁶Ru/¹⁰⁶Rh, ¹³¹I and ¹³⁷Cs/^{137m}Ba for a "typical" car and bus.

Indoor Inhalation Doses:

- Ratio of time-integrated air concentration indoors to that outdoors, given an outdoor value of 1 Bq s m⁻³ for ²⁴⁰Pu (particulate, representative of ≈ 10 μm), ¹³⁷Cs (particulate, representative of ≈ 1 μm) and ¹³¹I (gaseous, forms I₂ and CH₃I) for two situations (1) doors or windows normally open

for ventilation and (2) all doors and windows closed.

Behavior:

- Fraction of an average population in expert's own country that would be classed as (1) agricultural and other outdoor workers, (2) indoor workers, (3) nonactive adult population, and (4) schoolchildren;
- Fraction of time each population group, (1) to (4) above, spends indoors in various types of housing and in cars/buses, considering both a typical urban environment and a representative rural area (open fields);
- Fraction of time an "average" member of the population in the expert's own country spends indoors in various types of housing and in cars/buses.

Various initial and boundary conditions were specified for each elicitation question to define the scope of the problem. The following items were not specified in the question definition. The additional uncertainty from these items was included by the experts in the distributions for the elicitation questions.

- Parameter variations and conditions typical of a warm temperate climate, for example northwestern Europe and northeastern/southeastern US;
- Variations with wet and dry deposition. This will affect the initial depth that radioactivity reaches following deposition and also the activity levels indoors compared with outdoors;
- Variation in deposition outdoors and indoors with particle size;
- Relative contamination levels on lawns, paved areas, and roofs, etc., following deposition;
- Influence of weathering in both rural and urban areas (e.g., variations with soil type and weather conditions);
- Variations in dose rate due to surface roughness;
- Actual extent of areas within urban or rural environments containing buildings, paved areas, open grassland, trees etc;

- Proximity of buildings, trees, etc., to the dose reference point.

This list is not exhaustive and did not preclude the experts from considering other factors they believed were important contributors to uncertainty.

3.3 Expertise Required for the Elicitation Process

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

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

The substantive assistant brings knowledge of project assumptions and conditions to the study. The role of this participant is to promote a common understanding of the issues and to clarify and articulate how the data will be interpreted in the modeling activities. This team member also assists the experts with documentation of rationales.

3.3.1 Selection of Phenomenological Experts

The project staff sought to engage the best experts available in the fields of deposited material and related dose processes. Experience in the NUREG-1150 study and elsewhere has shown that

the selection of experts can be subjected to much scrutiny. Thus, it was necessary to construct a defensible selection procedure. The selection procedure for this study involved the following:

1. A large list of experts was compiled from the literature and by requesting nominations from organizations familiar with the areas.
2. The experts were contacted and curriculum vitae (CVs) were requested.
3. Two selection committees that included members both external and internal to the project, one in the EC and one within the US, were established and charged with expert selection based on a common set of criteria. These included:

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

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

3.3.2 Selection of Normative Specialists

Normative specialists are responsible for managing the elicitation sessions. These specialists come from various fields such as psychology, decision analysis, statistics, or risk and safety analysis. The

Table 3.2 Experts on deposited material and external doses

Mikhail Balonov	Russia
André Bouville	US
Joanne Brown	UK
Malcolm Crick	Austria
Eduardo Gallego	Spain
Peter Jacob	Germany
Olof Karlberg	Sweden
Ilya Likhtarev	Ukraine
Kevin Miller	US
Jørn Roed	Denmark

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. Drs. Goossens and Hora have extensive experience in probability elicitation. Dr. Goossens has managed a number of studies involving expert judgment for the safety institute at TU Delft and Dr. Hora was a key participant in the NUREG-1150 expert elicitation activities. Mr. Bernd Kraan of TU Delft is experienced in probability elicitation (and processing) of expert judgments.

3.4 Expert Elicitation

The expert elicitation process consisted of the following activities:

1. Dry run elicitation. A dry run elicitation was conducted with the European experts on deposited material and related doses to test the methodologies to be used in the actual expert elicitation meetings and to evaluate the case structures.
2. First expert meetings. The purpose of these meetings was to train the experts in providing their judgments in terms of probability distributions and to present the technical problems to be assessed.
3. Expert prepares assessment. The expert prepared his or her assessment of the problems posed in the first meeting. The expert also prepared to provide the staff with the rationale behind his or her distributions in written form before leaving the second meeting. No requirements on the form of the written rationale were imposed.
4. Second expert meeting. Different approaches were taken by the EC and the US. In the US, the second expert meeting was conducted

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

3.4.1 Dry Run Meeting to Finalize Case Structure

The dry run meeting was conducted in December 1994 with two of the experts on deposited material and external doses that had been chosen in the formal selection process, Dr. P. Jacob from GSF in Germany and Dr. J. Roed from Risø National Laboratory in Denmark. The meeting began with training in probability elicitation that 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 finalized according to the lessons learned in the dry run.

3.4.2 First Expert Meeting

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

Training was conducted to introduce the experts to psychological biases in judgment formation and to give them feedback on their performance in assessing probability distributions. In the NUREG-1150 study, feedback was provided to the experts by measuring their performance on the development of probabilistic distributions for training variables. In that study, the training variables were nontechnical, almanac-type questions for which the answers were known. In the current study, performance was measured by querying the experts about variables whose true values are uncertain for the experts but known to project staff from actual experiments. These training variables were chosen to resemble the variables of interest as closely as possible. Two separate training meetings were held: one in Europe (January 1995) and one in the US (April 1995).

3.4.3 Preparation of the Distributions

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

3.4.4 Second Expert Meeting: Elicitation

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

In the US a joint meeting was held on July 20 and 21, 1995. On the first day of the elicitation meeting, a common session was conducted at which the experts presented the technical approach and rationale behind their assessments. No distributions were provided in these sessions to avoid biasing the other experts. The

elicitation of each expert took place privately with a normative specialist and a substantive assistant. In both cases, the experts were allowed to change their elicitation results at any point. The interviews allowed for significant interaction between the assessment team and the expert in the encoding of probabilities.

3.5 Mathematical Processing of Elicited Distributions

At the end of the elicitation sessions, the project staff had from each expert the 5th, 50th, and 95th percentile values from the cumulative distribution of each elicited variable for each case structure. It was the responsibility of the project staff to aggregate the individual expert distributions (5th, 50th, and 95th percentile values) for each elicitation variable for each case structure into a single cumulative distribution for each elicitation variable for each case structure. This section briefly reviews the mathematical processing of the elicited distributions.

3.5.1 Aggregation of Elicited Distributions

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

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

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

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 for this study was to ensure the inclusion of different modeling perspectives in the aggregated uncertainty distributions. The implications of different weighting schemes are discussed elsewhere.³

3.5.2 Combining Dependencies

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

new strategy⁶ has been employed for eliciting dependencies from experts.

3.6 References

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4. Results and Analysis

4.1 Introduction

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

4.2 Summary of Elicitation Meetings

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

4.2.1 Dry Run Elicitation Meeting

The robustness of the basic expert elicitation methodology developed for this project was validated by a dry run exercise. Several important issues were raised and subsequently evaluated as a result. These were:

1. What is meant by a typical "urban" and "rural" environment and how can an "average" dwelling be defined?
2. Are we dealing with doses to an average member of a population group or variabilities over individuals within those groups?
3. How should we calculate the concentrations when the deposition conditions are not specified (e.g., with what ratios should we combine wet and dry conditions)?
4. Do we assume uncertainties for a single event or an average event?
5. How are the population groups defined for which behavioral information is requested; in particular, will they be country specific?
6. For the doses to individuals indoors, what was meant by doors/windows open for normal ventilation and should the penetration of radioactivity indoors be explicitly accounted for?

4.2.2 Summary of First Expert Meetings

The initial reception of the project by the experts was excellent. They expressed a deep interest in the

prospect of addressing uncertainty in their field of expertise. After the probabilistic training exercise, the elicitation variables and the case structure were discussed. In the first (European) training meeting, several issues with respect to the questions were raised. Minor changes to the definition of the elicitation variables and the case structure were proposed. It was decided not to rephrase the questions as a result of the meeting.

In the second (American) training meeting, the questions as handed out to the European experts were discussed. Although the differences in approaches between Europe and the US were discussed, the questions were not changed.

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

4.2.3 Summary of Second Expert Meeting

All European experts were elicited individually without a common session. The individual sessions were held at each expert's own establishment and were carried out by two analysts, a normative specialist and a substantive specialist. Following a common session, the American experts were also elicited individually. The first day of the second expert meeting consisted of presentations by the experts on their approaches to the assigned problem. The approaches were given, but the actual probability assessments were not revealed in order to avoid biasing other experts. At the end of the first day, the issue of anonymity was discussed. The remainder of the second expert meeting consisted of individual expert elicitation sessions. The initial common session was videotaped and the individual sessions were audiotaped.

4.3 Summary of Individual Expert Assessments

Representative results are summarized and discussed in this section. The figures are presented at the end of

the chapter so as not to interrupt the flow of the text. The complete set of expert rationales and the elicited distributions are published in Appendix C in Volume 2 of this report. In this section, the figures plot some of the elicited results along with the results of the equal-weighted aggregation of the elicited distributions. The figures use the numbers 1 to 10 to indicate the results of different experts while Appendix C uses the letters A through J. There is no correlation between the two systems. This section discusses only the individual assessments. Section 4.4 reviews the results of the equal aggregation of the distributions.

4.3.1 Summary of Individual Assessments of Elicitation Questions

4.3.1.1 Gamma Dose Rate and Effective Dose Rate

Six out of thirteen questions addressed the absorbed gamma dose rates in air, adult effective dose rates, and integrated adult effective dose as a function of time under average weather conditions and separately following initial deposition during dry and wet conditions. Some experts considered the variations with the mode of deposition to be minimal and presented the same results for each of the three cases. An assessment was requested for open lawned area because this condition provides one set of default values for the code input parameters representing the dose rates in time, and also provides a simple case for a comparison of the expert opinions. Dose rates were requested for four radionuclides: ^{95}Zr , ^{106}Ru , ^{131}I , and ^{137}Cs . Most experts based their assessments on observations from the Chernobyl accident. For all radionuclides the experts assessed relatively narrow 90% central range factors, ranging from 2 to 10 for most times (Ru, I, and Cs are assessed comparably, Zr has somewhat wider bands: roughly a factor of 2 wider). For the longest times (1 year for Zr and 100 years for Cs), much wider bands are found: on the order of a factor of 100. The individual experts' assessments do not show overlap in all cases despite the narrow range of values. The greatest agreement is observed for ruthenium and particularly cesium, for which more extensive experimental information is available. No significant differences are found in the assessments under different weather conditions.

There are too many results to display the entire set in this chapter. The complete set is available in

Appendix C of Volume 2. What are displayed here are some examples so that the reader can get a feel for the level of information obtained.

Figure 4.1 shows an example median result for the distributions of gamma dose rate (Gy s^{-1}) above an open lawned area following an initial dry deposition 1 Bq/m^2 of ^{137}Cs . Figure 4.2 shows example range factors for the results of the same question (range factors refer to the ratio of the 95th percentile to the 5th percentile and are used throughout this section as a measure of uncertainty). Figure 4.3 shows an example result for Question 2, the distributions of gamma dose rate (Gy s^{-1}) above an open lawned area following an initial wet deposition of 1 Bq/m^2 of ^{137}Cs . Figure 4.4 shows example range factors for the results of the same elicitation question.

Figure 4.5 shows an example median result for the distributions of effective dose rate (Sv s^{-1}) in a typical urban environment following an initial dry deposition of 1 Bq/m^2 of ^{137}Cs to the lawned areas of the ground. Figure 4.6 shows example range factors for the results of the same question. Figure 4.7 shows the distributions of the integrated adult effective dose (Sv) for the same problem, and Figure 4.8 shows the corresponding range factors.

Figure 4.9 shows an example median result for the distributions of effective dose rate (Sv s^{-1}) in a typical urban environment following an initial wet deposition of 1 Bq/m^2 of ^{137}Cs to the lawned areas of the ground. Figure 4.10 shows example range factors for the results of the same question. Figure 4.11 shows the distributions of the integrated adult effective dose (Sv) for the same problem, and Figure 4.12 shows the corresponding range factors.

Question 7 asks the experts to make comparisons between the behavior of the nuclides mentioned in Questions 1 to 6, covering dose rates and integrated doses with respect to time, and several other nuclides considered to be important to external doses following nuclear power plant accidents. The detailed responses to this question should enable future users of the assessments to apply the information to other radionuclides. The experts strongly agreed that the behavior of nuclides of the same element was similar: i.e., the behavior of ^{103}Ru and ^{105}Ru was similar to that of ^{106}Ru , ^{134}Cs and ^{136}Cs were similar to ^{137}Cs , and all iodine nuclides were similar to ^{131}I . Some nuclides show a modest similarity: ^{140}Ba and ^{137}Cs , and ^{144}Ce and ^{95}Zr .

In addition, the experts were asked to present a similar comparison between nuclides for their estimates of the ratio of the inhalation dose indoors to that outdoors. It was more difficult in this case for the experts to compare the behavior between nuclides unless it was another isotope of the same element. Therefore, no strong correlations were given.

4.3.1.2 Location Factors

Question 8 was asked in order to derive uncertainty assessments on the location factors for an adult indoors in various types of houses/buildings and in a car or a bus. The location factor is a simple ratio relating the dose indoors to that outdoors above an open lawn area. It does not relate the dose indoors to that outdoors in an urban area and therefore should be used with care. Although the width of the individual experts' range factors (ratio of 95th/5th percentiles) may differ by a factor of 10 or more in some cases, the 50th percentile assessments are close.

Figure 4.13 shows example median results for Question 8, the ratio of the effective dose received by an adult at several indoor locations to the effective dose received by an adult outdoors in an open lawn area shortly after an initial uniform deposit of 1 Bq/m² of Cs-137 to the lawn areas of the ground. Figure 4.14 shows example range factors for the results of the same question.

Figure 4.15 shows example median results for Question 8, the ratio of the effective dose received by an adult at several indoor locations to the effective dose received by an adult outdoors in an open lawn area 1 year after an initial uniform deposit of 1 Bq/m² of Cs-137 to the lawn areas of the ground. Figure 4.16 shows example range factors for the results of the same question.

The greatest deviation in opinion was observed for the two basement cases (family house and multistory block), which are obviously more sensitive to the assumptions regarding basement location relative to the surrounding ground level, window areas, ventilation and penetration of the activity indoors. The experts were also asked if in their opinion the initial location factors given would vary significantly with time. Some experts felt that the variation was significant enough to warrant recalculating the estimated location factors; others presented a simple scaling factor by which the individual values could be multiplied to obtain the changes in values over time,

for example, 1 and 10 years after deposition. There were sometimes large differences among individuals in this scaling factor.

For questions 8 through 10, one expert explicitly distinguished two separate cases, with differing results: one case had no initial deposition indoors and one case had initial deposition. All experts were asked about the difference caused by the presence or absence of initial deposition indoors. All other experts considered the difference not significant enough to derive separate assessments.

4.3.1.3 Time-Integrated Air Concentration Ratios

The experts' individual assessments for the indoor/outdoor time-integrated air concentration ratios show a pattern similar to that for the location factors. Figure 4.17 shows example median results for the ratio of the time-integrated air concentration indoors to that outdoors given an initial time-integrated concentration of 1 Bq/m³ for four different nuclides with the doors and windows normally open and with them closed. Figure 4.18 shows example range factors for the results of the same question.

4.3.1.4 Population Distributions

Question 13 addressed population distributions and associated living and working patterns in the expert's own country. Since all experts came from different countries (except the two from the US), the assessments can only provide a reasonable picture of the variation in population distribution between the US and both Western and Eastern Europe. All experts had difficulty in deriving the assessments for this question, because none of them were experts in population distributions. They all relied on national statistics, if they were available. Large differences are found among countries.

Figure 4.19 shows the median results for the average population classed as outdoor workers, indoor workers, or nonactive adult population, or schoolchildren. Figure 4.20 shows the associated range factor. Figure 4.21 shows the median annual average fraction of time that people working outdoors spend indoors in various types of housing or vehicles. Figure 4.22 shows the corresponding range factors. Figure 4.23 shows the median annual average fraction of time that people working indoors spend indoors in various types of housing or vehicles. Figure 4.24 shows the corresponding range factors.

4.4 Summary of Aggregated Results

Summary of Aggregated Assessments of Elicitation Questions

This section presents the results of the equal-weighted aggregation of the individual elicited distributions into single distributions over each elicited parameter. The 50th percentile and range factors for the aggregated distributions are presented along with the individual assessments in Figures 4.1 through 4.24. The 50th percentiles for all aggregated distributions are consistent with the individual assessments. The plots for the 95th/5th percentile ratios show that aggregation of the distributions may result in distributions that have a wider range factor than any of the individual distributions.

For the dose rates over open lawned areas, the range factors are on the order of 3 to 10 except for some long periods after deposition (over 100). For urban and rural outdoor conditions, these ratios tend to be somewhat larger (10 to 30) and may go to 1000 for large times (such as cesium under outdoor/urban conditions).

The range factors for the location factors largely depend on the building type. For buildings with low and medium shielding, and for the inside of a typical car or bus, the ratio is typically on the order of 15 to 0. Buildings with high shielding have an assessed aggregated ratio on the order of 100 to 400, while the

ratio is close to 1000 or even exceeds that value for both types of basement. These high-ratio values are mainly caused by the very low 5th percentile values (close to zero). Table 4.1 shows the aggregated median assessments.

The median values of the aggregated distributions for the location factors 1 year after initial deposition are lower than the initial values with the exception of the cases inside a typical car. (These values remain approximately the same.) For the 10-year cases, the medians either stay at the same level as the 1-year values or drop drastically to lower ranges in the inside typical car cases and the inside typical building cases. The 95th/5th percentile ratios of inhalation indoors to outdoors for cases where the doors and windows are either open or closed vary between 2 and 5 (for Cs and methyl iodide, doors open) to almost 100 (for Pu, doors closed).

4.5 Comparison of Results from Current Study with Ranges Used in Past Uncertainty Studies

The spread in uncertainties suggested by the aggregated results for the integrated dose and location factors reflects ranges similar to those used in previous uncertainty studies for short times following initial deposition of radionuclides.^{1,2} The increased spread of uncertainty in the dose with time, and the uncertainty variations among nuclides have not been

Table 4.1 Summary of results for time spent in designated locations^a

Nuclide	Location factors (for the fraction of the time spent in designated locations)				
	<0.01	0.01-0.1	0.1-0.3	0.3-0.7	>0.7
Zr	BMB	HSB	MSB/BFH	LSB/ITC/ITB	
Ru	BMB	MSB/HSB/BFH			
I	BMB	MSB/HSB/BFH			
Cs	BMB	MSB/HSB/BFH			
Ce	BMB	MSB/HSB/BFH	LSB		

^a LSB = low shielding building, MSB = medium shielding building, HSB = high shielding building, BFH = basement family house, BMB = basement multistory block, ITC = inside typical car, ITB = inside typical bus.

fully utilized in prior studies, but may obviously be taken into account in any future work. The variation in inhalation dose indoors compared with that received outdoors has not always been considered as a dominant parameter when uncertainty was assessed in current-generation consequence codes, and has sometimes been ignored. Population behavior patterns are often condensed into one parameter, which represents the fraction of time an "average" individual spends indoors. The data elicited during this study would have to be evaluated in order to make a comparison with such a simple representation. However it is likely, from the expert opinions obtained in this study, that the level of uncertainty will be much greater than previously assumed.¹

4.6 References

1. Jones, J.A., M.J. Crick, and J.R. Simmonds, "An Uncertainty Analysis Using the NRPB Accident Consequence Code MARC," *Proceedings of Seminar on Methods and Codes for Assessing the Off-Site Consequences of Nuclear Accidents*, Vol. 2, pp. 929-948, EUR-13013, Commission of European Communities, Luxembourg, pp. 929-948, 1991.
2. J. Boardman et al. Uncertainty Analysis of the CONDOR Probabilistic Consequence Analysis Program, AEA/16423549/R1, AEA Technology, UK, 1996.

Figure 4.1 Median results for the distributions of gamma dose rate (Gy s^{-1}) above an open lawned area following an initial dry deposition of 1 Bq/m^2 of ^{137}Cs . *Immediately after deposit.

Figure 4.2 Range factors (ratio of 95th/5th percentile) for the distributions of gamma dose rate (Gy s^{-1}) above an open lawned area following an initial dry deposition of 1 Bq/m^2 of ^{137}Cs . *Immediately after deposit.

Figure 4.3 Median results for the distributions of gamma dose rate (Gy s⁻¹) above an open lawned area following an initial wet deposition of 1 Bq/m² of ¹³⁷Cs. *Immediately after deposit.

Figure 4.4 Range factors (ratio of 95th/5th percentile) for the distributions of gamma dose rate (Gy s⁻¹) above an open lawned area following an initial wet deposition of 1 Bq/m² of ¹³⁷Cs. *Immediately after deposit.

Figure 4.5 Median results for the distributions of effective dose rate (Sv s⁻¹) in a typical urban environment following an initial dry deposition of 1 Bq/m² of ¹³⁷Cs to the lawned areas of the ground. *Immediately after deposit.

Figure 4.6 Range factors (ratio of 95th/5th percentile) for the distributions of effective dose rate (Sv s⁻¹) in a typical urban environment following an initial dry deposition of 1 Bq/m² of ¹³⁷Cs to the lawned areas of the ground. *Immediately after deposit.

Figure 4.7 Median results for the distributions of the integrated adult effective dose (Sv) in a typical urban environment following an initial dry deposition of 1 Bq/m² of ¹³⁷Cs to the lawned areas of the ground.

Figure 4.8 Range factors (ratio of 95th/5th percentile) for the distributions of the integrated adult effective dose (Sv) in a typical urban environment following an initial dry deposition of 1 Bq/m² of ¹³⁷Cs to the lawned areas of the ground.

Figure 4.9 Median results for the distributions of effective dose (Sv) in a typical urban environment following an initial wet deposition of 1 Bq/m² of ¹³⁷Cs to the lawned areas of the ground. *Immediately after deposit.

Figure 4.10 Range factors (ratio of 95th/5th percentile) of the distributions of effective dose (Sv) in a typical urban environment following an initial wet deposition of 1 Bq/m² of ¹³⁷Cs to the lawned areas of the ground. *Immediately after deposit.

Figure 4.11 Median results of the distributions of the integrated adult effective dose (Sv) in a typical urban environment following an initial wet deposition of 1 Bq/m² of ¹³⁷Cs to the lawned areas of the ground.

Figure 4.12 Range factors (ratio of 95th/5th percentile) of the distributions of the integrated adult effective dose (Sv) in a typical urban environment following an initial wet deposition of 1 Bq/m² of ¹³⁷Cs to the lawned areas of the ground.

Figure 4.13 Median results for the ratio of the effective dose received by an adult at several indoor locations to the effective dose received by an adult outdoors in an open lawned area shortly after an initial uniform deposit of 1 Bq/m^2 of ^{137}Cs to the lawned areas of the ground.

Figure 4.14 Range factors (ratio of 95th/5th percentile) for the ratio of the effective dose received by an adult at several indoor locations to the effective dose received by an adult outdoors in an open lawned area shortly after an initial uniform deposit of 1 Bq/m^2 of ^{137}Cs to the lawned areas of the ground.

Figure 4.15 Median results for the ratio of the effective dose received by an adult at several indoor locations to the effective dose received by an adult outdoors in an open lawned area one year after an initial uniform deposit of 1 Bq/m^2 of ^{137}Cs to the lawned areas of the ground.

Figure 4.16 Range factors (ratio of 95th/5th percentile) for the ratio of the effective dose received by an adult at several indoor locations to the effective dose received by an adult outdoors in an open lawned area one year after an initial uniform deposit of 1 Bq/m^2 of ^{137}Cs to the lawned areas of the ground.

Figure 4.17 Median results for the ratio of the time-integrated air concentration (TIAC) indoors to that outdoors given an initial concentration of 1 Bq s/m^3 for four different nuclides with the doors normally open and closed.

Figure 4.18 Range factors (ratio of 95th/5th percentile) for the ratio of the time-integrated air concentration (TIAC) indoors to that outdoors given an initial concentration of 1 Bq s/m^3 for four different nuclides with the doors normally open and closed.

Figure 4.19 Median results for the average population classed as outdoor workers, indoor workers, nonactive adult population, or schoolchildren.

Figure 4.20 Range factors (ratio of 95th/5th percentile) for the average population classed as outdoor workers, indoor workers, nonactive adult population, or schoolchildren.

Figure 4.21 Median annual average fraction of time that people working outdoors spend indoors in various types of housing or vehicles.

Figure 4.22 Range factors (ratio of 95th/5th percentile) for annual average fraction of time that people working outdoors spend indoors in various types of housing or vehicles.

Figure 4.23 Median annual average fraction of time that people working indoors spend indoors in various types of housing or vehicles.

Figure 4.24 Range factors (ratio of 95th/5th percentile) for annual average fraction of time that people working indoors spend indoors in various types of housing or vehicles.

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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 a creative and synergistic interplay of ideas that would not have been possible in isolation. Potential deficiencies in processes and methodologies that might not have received sufficient attention in independent studies were addressed. The final product of this study, therefore, was enhanced by this cooperation.

Distributions on measurable external dose parameters were successfully elicited from distinguished experts. Aggregated distributions, developed by combining the individual elicited distributions, are now available for measurable external dose parameters. The aggregated elicited uncertainty distributions represent state-of-the-art knowledge in modeling external doses. Uncertainty distributions on code input variables for external doses are also now available for use in consequence uncertainty analyses using the MACCS and COSYMA codes. The distributions for the elicitation and code input variables are available on computer media and can be obtained from the project staff.

5.2 Uncertainty Included in Distributions

The distributions elicited from the experts concern physically measurable quantities, conditional on the case structures provided to the experts. The individual distributions contain uncertainty that includes the coarseness of the initial conditions of the case structure and natural variability. The experts were not directed to use any particular modeling approach but were allowed to use whatever models, tools, and perspectives they considered appropriate for the problem. The elicited distributions obtained were developed by the experts from a variety of information sources. The aggregated elicited distributions, therefore, include variations that result from different modeling approaches and perspectives. They capture the uncertainty in gamma radiation

doses from radionuclides for various location factors in houses, cars, and buses, and for fractions of populations outdoors and indoors, and in urban and rural areas.

5.3 Application of Distributions

The results of this project will allow the external dose and location components of consequence uncertainty analyses to be performed in a manner consistent with the NUREG-1150 methodology. The risk integration step in the NUREG-1150 methodology (the step in which the uncertainty in all modules of the analyses was assessed) relied on Latin hypercube sampling (LHS) techniques. The external dose 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 external dose model available. However, different processing techniques may be required to transform the elicited distributions into distributions that are compatible with different models. The distributions obtained here will be processed for both COSYMA and MACCS uncertainty studies. In some cases, different distributions will be needed for MACCS than for COSYMA. In addition, some experts provided numerical data on dependencies between the external doses and the location factors.

The methods of this project were also consistent with the NUREG-1150 philosophy because all modeling perspectives are included and consensus among the experts was not required. Although this project focused on the development of distributions for MACCS and COSYMA input parameters, the elicited information is not specific to a model and consequently can be used by many other analytical models. In addition, the development of distributions over physically measurable parameters means that the distributions will have applications beyond the scope of consequence code uncertainty analysis (e.g., emergency response planning). The library of external dose uncertainty distributions will have many applications outside of this project. The distributions also provide additional insights regarding areas where current consequence codes are deficient, and they can be a useful guide for directing future research.

5.4 Conclusions

Valuable information has been obtained from this exercise. The goal of creating a library of uncertainty distributions for external dose parameters was fulfilled. Furthermore, in this exercise, formal expert judgment elicitation has proven to be a valuable vehicle for synthesizing the best available information by a highly qualified group.

With a thoughtfully designed elicitation approach that addresses such issues as selection of elicitation

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

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER
(Assigned by NRC, Add Vol., Supp., Rev.,
and Addendum Numbers, if any.)

NUREG/CR-6526
EUR 16772
SAND97-2323
Vol. 1

2. TITLE AND SUBTITLE

Probabilistic Accident Consequence Uncertainty Analysis

Uncertainty Assessment for Deposited Material and External Doses

Main Report

3. DATE REPORT PUBLISHED

MONTH	YEAR
December	1997

4. FIN OR GRANT NUMBER

W6352

5. AUTHOR(S)

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6. TYPE OF REPORT

Technical

7. PERIOD COVERED (Inclusive Dates)

8. PERFORMING ORGANIZATION - NAME AND ADDRESS (If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)

Sandia National Laboratories
Albuquerque, NM 87185-0736

Commission of European Communities
DG XII and XI
200, rue de la Loi
B-1049 Brussels, Belgium

9. SPONSORING ORGANIZATION - NAME AND ADDRESS (If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)

Division of Systems Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES

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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 deposited material and external dose models.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

uncertainty analysis, accident consequence analysis, nuclear accident analysis, probabilistic analysis,
expert elicitation, MACCS, COSYMA, consequence uncertainty analysis, behavior of deposited
radiological material, external dosimetry, radiological dosimetry

13. AVAILABILITY STATEMENT

unlimited

14. SECURITY CLASSIFICATION

(This Page)

unclassified

(This Report)

unclassified

15. NUMBER OF PAGES

16. PRICE