

# Probabilistic Accident Consequence Uncertainty Analysis

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



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Early Health  
Effects Uncertainty  
Assessment

Volume 1 Main Report

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**Early Health Effects Uncertainty Assessment**

**Main Report**

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Prepared by  
F. E. Haskin  
University of New Mexico  
USA

B.C. P. Kraan  
Delft University of Technology  
The Netherlands

F. T. Harper  
Sandia National Laboratories  
USA

J. B. Grupa  
Netherlands Energy Research Foundation  
The Netherlands

L. H. J. Goossens  
Delft University of Technology  
The Netherlands

Sandia National Laboratories  
Albuquerque, NM 87185-0748

J. Randall, NRC Project Manager

**Prepared for**

**Division of Systems Technology  
Office of Nuclear Regulatory Research  
U.S. Nuclear Regulatory Commission  
Washington, DC 20555-0001  
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**Commission of the European Communities  
DG XII and XI  
200, rue de la Loi  
B-1049 Brussels  
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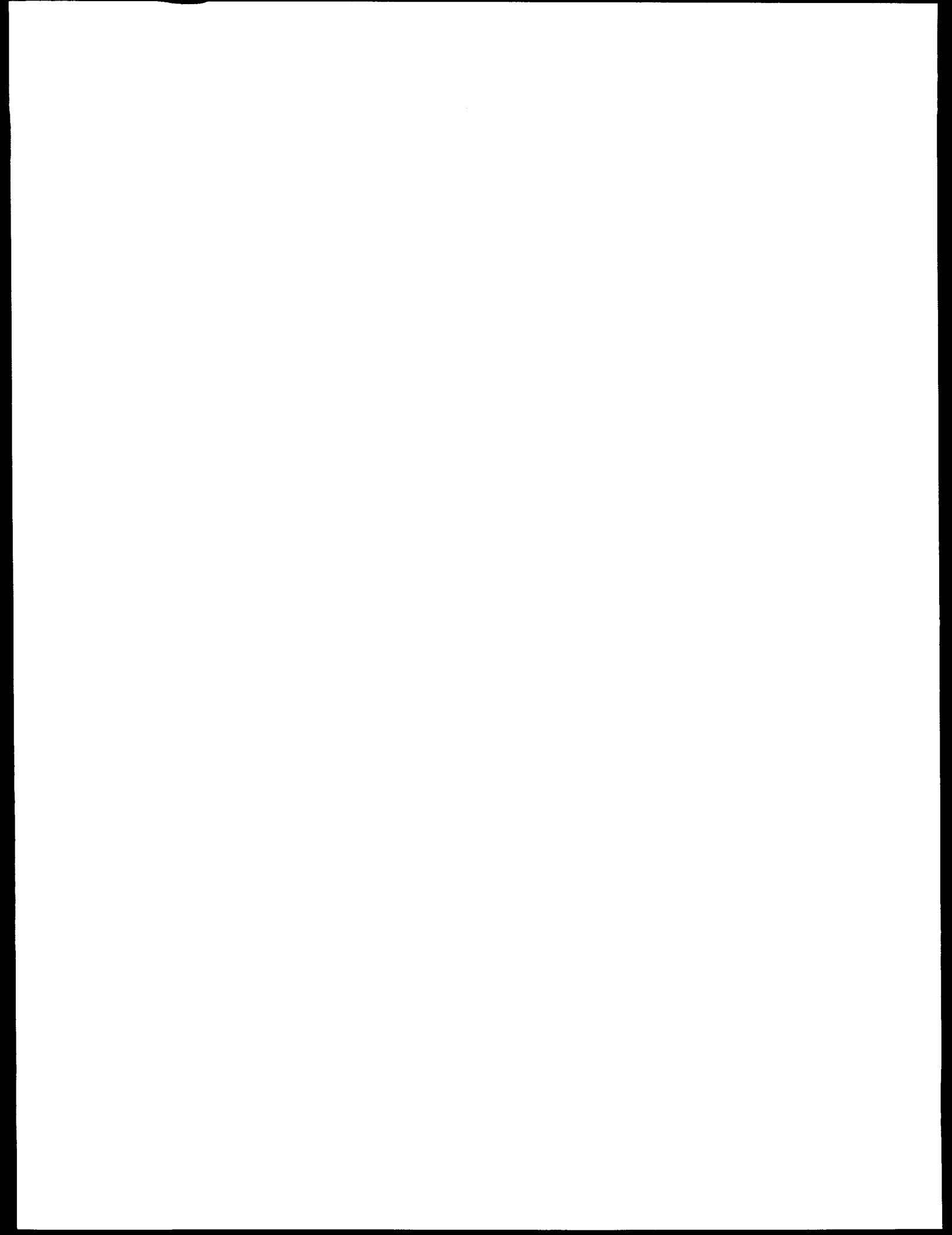
## Abstract

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

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

After the first feasibility study on atmospheric dispersion and deposition parameters, further expert judgment exercises were carried out. This report is on the early health effects part of the study. The goal again was to develop a library of uncertainty distributions for the selected consequence parameters. Nine experts were selected for the early health effects panel. Their results were processed with an equal-weighting aggregation method, and the aggregated distributions will be processed into the code input variables for the early health effects models in COSYMA and MACCS.

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



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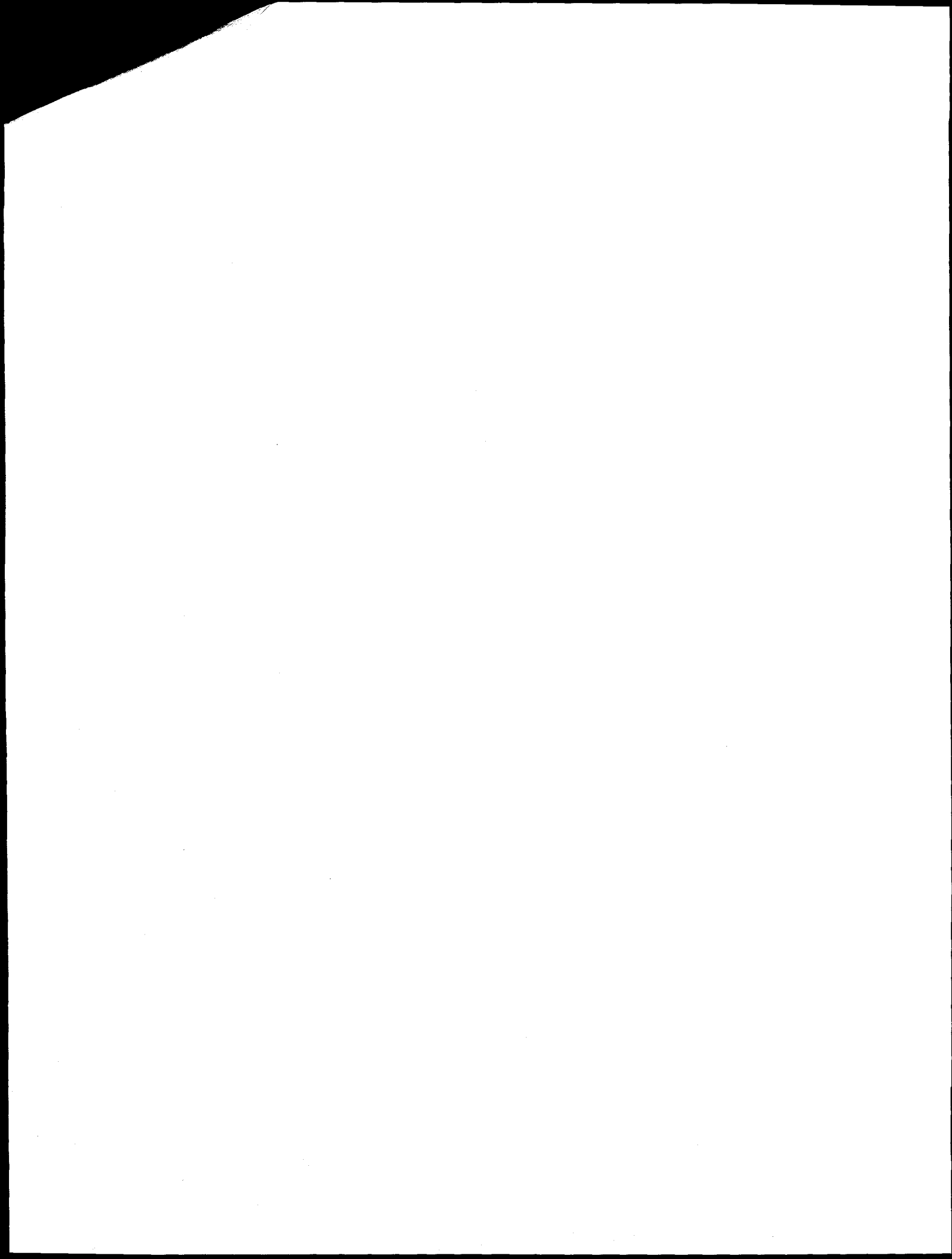
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## Preface

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

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



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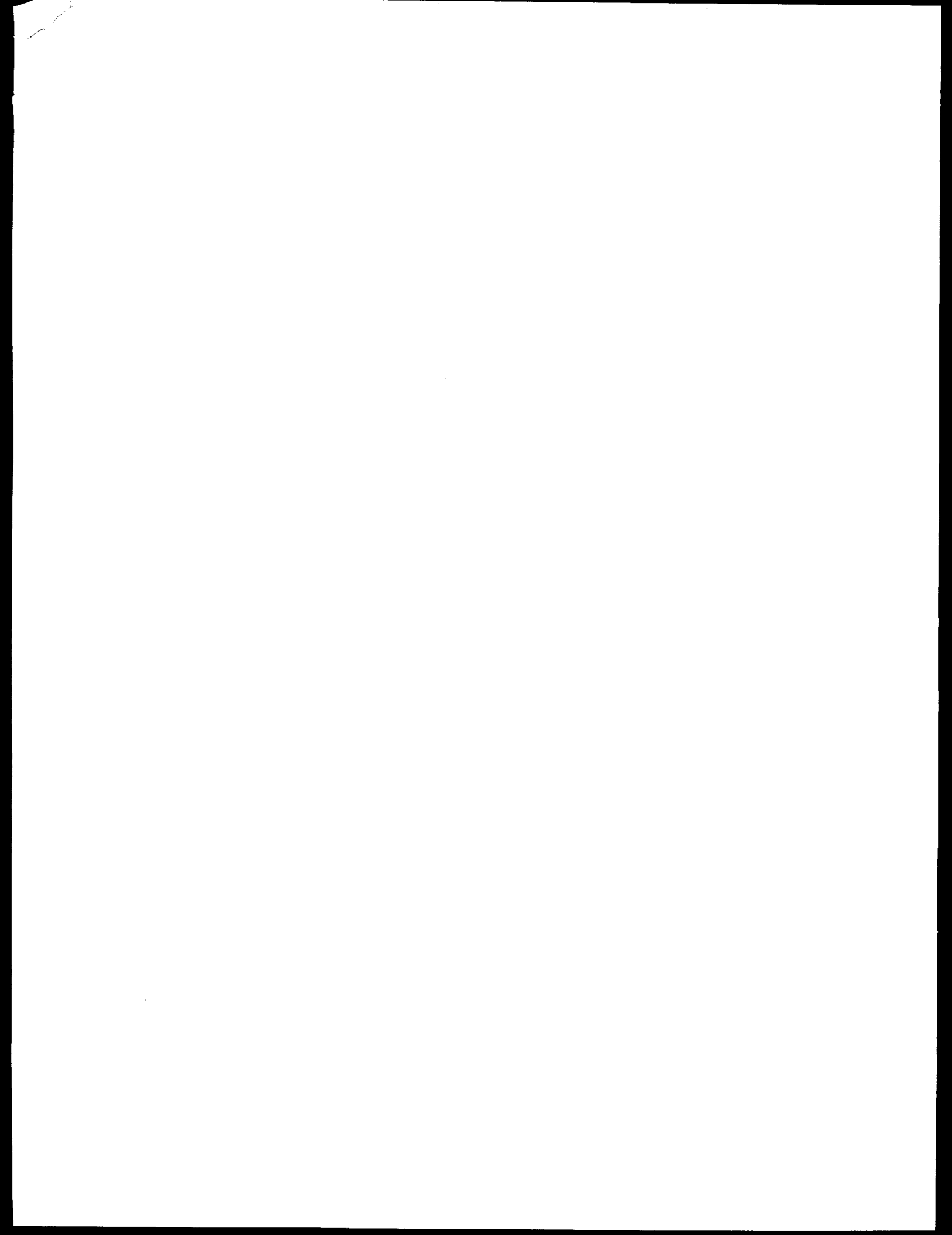
The authors would like to acknowledge all the participants in the expert judgment elicitation process, in particular the expert panel on early health effects. While we organized the process, processed the results, and wrote and edited the report, the experts provided the technical context that is the foundation of this report. Dr. Steven C. Hora and Dr. Detlof von Winterfeldt are acknowledged for their contributions as elicitors.

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. In particular we want to thank Prof. Th. Fliedner and co-workers at the University of Ulm in Germany. We also want to thank Dr. Hermans and Dr. Kal for their support of Dr. Broerse's assessments and rationale.

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.

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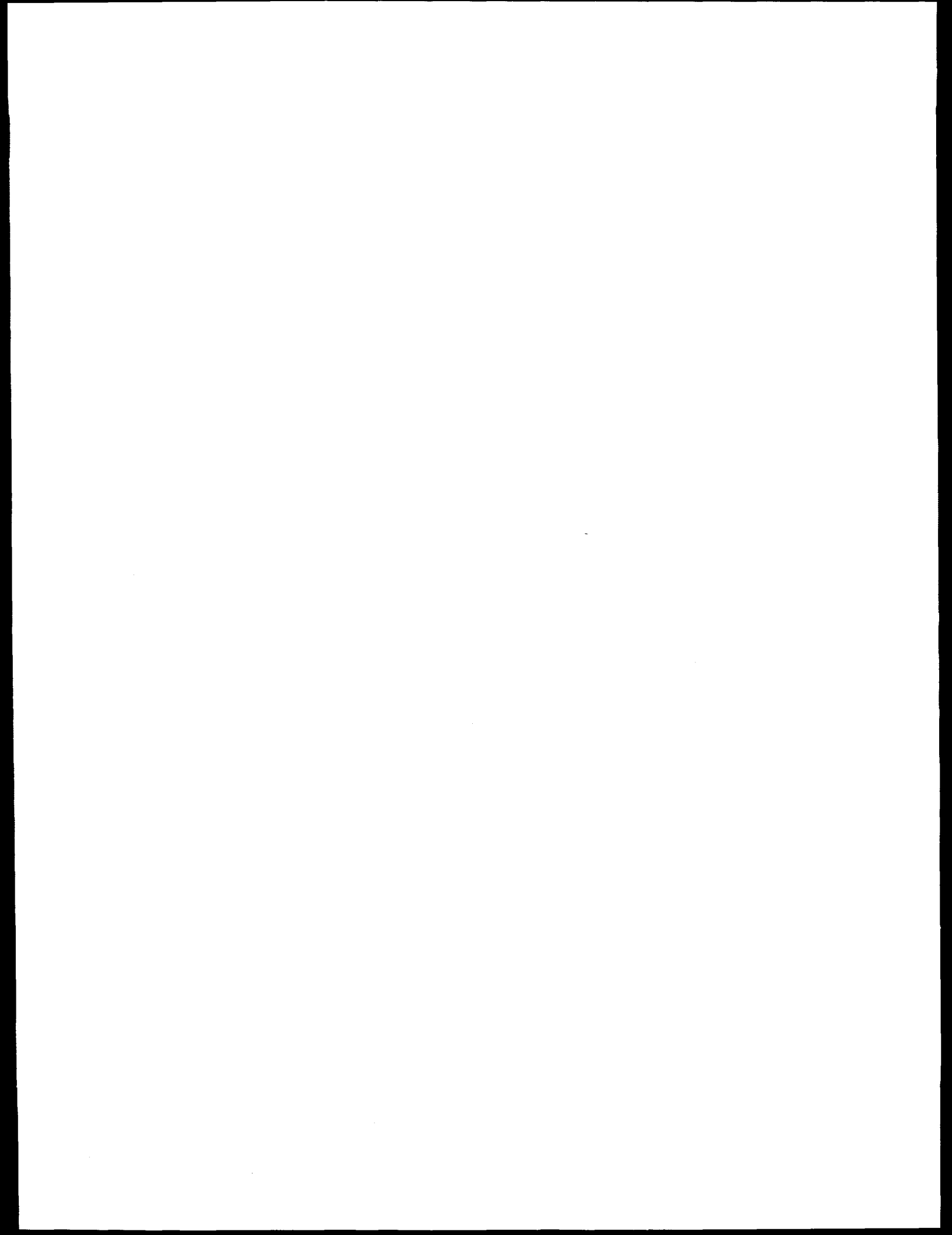
On Monday January 22, 1996, Peter Roelofsen, manager of the risk analysis group at the Netherlands Energy Research Foundation (ECN), died after a long period of illness. Peter prepared the first discussion documents for the early health effects expert panel, and provided valuable comments on early versions of the deposited materials and related doses documents. 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)
EC	European Commission
LHS	Latin hypercube sampling
MACCS	MELCOR accident consequence code system
NRC	Nuclear Regulatory Commission
PRA	probabilistic risk assessment





# Executive Summary

## Introduction

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

The specific goal of this study is to develop a library of uncertainty distributions by using a formal expert judgment elicitation process on the input variables of the risk coefficients used in MACCS and COSYMA. This report focuses on the methods used in the study on early health effects and its results.

## Approach

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

Expert judgment techniques are used only for the most important code input variables in terms of contribution to the uncertainty in code predictions. Less resource-intensive methods will be used to develop uncertainty

distributions for the remainder of the code input variables. Each organization will then propagate and quantify the uncertainty in the predictions produced by their respective codes.

This approach was jointly formulated and based on two important ground rules: (1) the current code models would not be changed because both the NRC and EC were interested in the uncertainties in the predictions produced by MACCS and COSYMA, respectively, and (2) the experts would be asked only to assess physical quantities that hypothetically could be measured in experiments. The reasons for these ground rules are that: (1) the codes have already been developed and applied in US and EC risk assessments, and (2) eliciting physical quantities avoids ambiguity in variable definitions; more important, the physical quantities elicited are not tied to any particular model and thus have a much wider potential application. The actual study involved several phases: preparation stage, expert training meetings, preparation of the assessments and written rationale, expert elicitation sessions, and processing the elicited results. Each phase is summarized below.

## Preparation Stage

Elicitation variables were defined based on the results of past and contemporary probabilistic consequence code sensitivity/uncertainty studies. These results were used to screen for the important code input variables in the context of their contribution to the uncertainties in the code predictions. Elicitation questions, hereafter referred to as case structure, were developed in accordance with the sophistication of the respective code models so that sufficient information would be elicited from the experts to allow valid interpolation and extrapolation of the resulting uncertainty distributions. The proposed case structure was then tested with several internal phenomenological experts and refined.

Two external expert selection committees were established: one in the US and one in the EC, respectively. (The selection committees included members external and internal to the project.) The committees were charged with selecting experts based on a common set of criteria, which included reputation in the relevant fields, number and quality of publications, familiarity with the uncertainty concepts, diversity in background, balance of viewpoints, interest in this project, and

availability to undertake the task in the time scale prescribed. As a result of this process, the experts listed in the table were selected to participate in the formal elicitation of early (deterministic) health effects issues. Brief biographies are provided in Volume 2. A brief description of the objective of the joint program was sent to the selected experts before the training meeting to familiarize them with the project.

#### Early health effects experts

Expert	Country
Johan Broerse*	Netherlands
Marvin Goldman	US
Jolyon Hendry	UK
John Hopewell	UK
Natalja Nadejina	Russia
Robert Scott	US
Elizabeth Travis	US
Niel Wald	US
Robert Young	US

\*Joint effort with A.F. Hermans and H.B. Kal.

### Expert Training Meetings

A training meeting was held for both European and American experts to provide background on the project and its objectives, the MACCS and COSYMA codes, and the treatment of the elicited information. The training meeting was held in Annapolis, Maryland, and was attended by the early health effects expert panel, the late health effects panel, and the internal dosimetry panel. A probability training session was conducted to familiarize the experts with the concept of uncertainty and the potential pitfalls in preparing subjective assessments; practice exercises followed. Material for the training exercise was drawn directly from the early health effects field. The training meetings were used to ensure that the experts developed their respective uncertainty distributions based on common ground rules and initial and boundary conditions. (It was considered critical that the experts all answer the same questions.) The full proposed case structure was presented to them for discussion and, when necessary, was modified in accordance with their feedback to ensure that all given problem conditions were clear, reasonable, and agreeable to them. In both meetings, a method to extract

quantitative information on knowledge dependencies between the elicitation variables was developed.

### Preparation of the Assessments and Written Rationale

The experts were instructed to use any information sources available, such as analytical models and experimental databases, to assist them in developing their distributions 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

The experts were elicited individually, after a common session during which they presented the approach they had taken in answering the questions posed, but did not reveal their probability assessments in order to avoid biasing the other experts. The common session was held jointly with European and American experts in attendance using video conferencing capabilities (the American experts were located in Albuquerque, NM, and the European experts were located in Brussels, Belgium). The issue of anonymity was discussed and the experts agreed to preserve anonymity. The remainder of the meeting consisted of individual expert elicitation sessions. In both European and American elicitation sessions, an attempt was made to use the method developed to extract quantitative information on knowledge dependencies.

### 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, that is, all experts on each panel would be treated as being equally credible. One of the primary reasons the equal-weighting aggregation method was chosen was to ensure the inclusion of different modeling perspectives in the aggregated uncertainty distributions. However, additional information was elicited from the experts that would allow performance-based weighting schemes to be applied to the

elicited results. These results will be reported separately. The following aggregation scheme was used to combine unique distributions from individual experts for all weighting schemes:

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

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

## Results and Conclusions

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

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

This exercise provided valuable information. Thus, the goal of creating a library of uncertainty distributions for early health effects that will have many applications outside of this project has been fulfilled. In this project, teams supported by the NRC and EC were able to work together successfully to create a unified process for developing uncertainty distributions for consequence code input variables. Staff with diverse experience and expertise from different organizations provided a creative and synergistic interplay of ideas—something that

would not have been possible if they had worked in isolation. Similarly, potential deficiencies in processes and methodologies were identified and addressed in this study. The final product, therefore, is more credible than an independent study produced by either organization would be.

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

# 1. Background of Joint Program

## 1.1 Introduction

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

This document describes an ongoing project designed to assess the uncertainty in the MACCS and COSYMA calculations for offsite consequences of radionuclide releases in hypothetical nuclear power plant accidents. The first exercise performed uncertainty assessments for atmospheric dispersion and deposition modeling in the accident consequence analysis (ACA) codes.<sup>3</sup> The part of the project reported in this document was designed to elicit from experts uncertainty distributions for important parameters in the early health effects calculations of the codes. Other reports describe the elicitation of uncertainty distributions on variables in other code areas. The elicited distributions will be used in consequence uncertainty analyses using the MACCS and COSYMA consequence codes.

Fairly comprehensive assessments of the uncertainties in the estimates of the consequences of postulated accidental releases of radioactive material have already been made, both in the US and by the European Commission, using predecessors of the MACCS and COSYMA codes (i.e., CRAC-2,<sup>4</sup> MARC,<sup>5</sup> and UFOMOD<sup>6</sup>). 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 sub-models 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 benefits of an improved expression of uncertainty, greater clarity and consistency of judgments, and an analysis that is more open to scrutiny. Formalized expert elicitation methods have been used for other applications as well. For a short overview, see Harper et al.<sup>3</sup>

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

Formal expert judgment has found increasing use in recent years within the EC. A pilot study<sup>9</sup> 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.<sup>3</sup>

## 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 cur-

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

1. To combine the knowledge and experience of the EC and US in the areas of uncertainty analysis, expert elicitation, and consequence analysis, and to establish an internationally recognized probability elicitation protocol based on the NUREG-1150 probability elicitation methodology.
2. To gain access to a greater pool of experts. The experts in the areas relevant to consequence calculations are located in both Europe and the United States. A joint project presents an opportunity to identify and utilize a larger pool of world-class experts than would be available to a project conducted solely by the US or EC.
3. To capture the potentially greater technical and political acceptability of a joint project. Because of the different technical approaches of the two teams, there is the opportunity to consider alternative approaches together and to develop a final product that would be better than either team could produce in isolation.
4. To share project costs. Expert elicitation projects require significant resources because of the staff and outside experts required.

### 1.3 Objectives

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

1. To formulate a generic, state-of-the-art methodology for estimating uncertainty that is capable of finding broad acceptance;
2. To apply the methodology to estimates of uncertainties associated with the predictions of probabilistic accident consequence codes (COSYMA and MACCS) designed for assessing the consequences of commercial nuclear power plant accidents;

3. To obtain better quantification and more valid estimates of the uncertainties associated with probabilistic accident consequence codes, thus enabling more informed and better judgments to be made in the areas of risk comparison and acceptability, and therefore to help set priorities for future research.

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

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

### 1.4 Project Development

The primary phenomenological areas included in a consequence calculation, which were identified as appropriate for consideration by a joint study, are listed in Table 1.1. The areas have been slightly modified since the first phase of the study. The calculations for countermeasures were considered to be specific for the European countries and the US, and will not be subjected to a joint expert elicitation.

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

This report provides the results of the expert judgment exercise on the early health effects parameters. The exercise had as its goal developing a library of uncer-

**Table 1.1 Phenomenological areas for the NRC/EC study**

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

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tainty distributions for early health effects 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., nonreactor nuclear facilities, radiotope power and irradiation sources, and other radiation sources).

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

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

Because MACCS and COSYMA were not to be modified, it was necessary to elicit distributions either over consequence code input variables or over variables from which distributions for code input variables could be developed. In addition, the uncertainty distributions developed were constrained by the flexibility of the fixed models in the consequence codes. If any of the uncertainty distributions contain values prohibited by the fixed models, either the uncertainty distribution needs to be truncated (thereby neglecting part of the uncertainty range provided by the experts) or the fixed models need to be reevaluated.

Eliciting physical quantities avoids possible ambiguity in definition of variables. In addition, elicited variables

that are physical parameters have the advantage of not being tied to any particular analytical model and thus have a much wider application.

## 1.5 Brief Chronology of Joint Effort

July 1991	First meeting between the EC and the NRC held in the US. Possibility of a joint consequence uncertainty project discussed.
October 1991	Second meeting between the NRC and the EC held in Europe. Further programmatic and technical details discussed.
January 1992	Outlined specifications of the project submitted to NRC and EC management.
April 1992	Agreement between EC and NRC management to proceed with the implementation planning stage of the joint effort.
May 1992	General planning meeting in Brussels. Possibility of proceeding with one panel to demonstrate the efficacy and feasibility of the joint effort before continuing with the remainder of the study discussed.
September 1992	Decision to proceed with one panel on atmospheric dispersion and deposition parameters.
November 1992	Kickoff meeting for atmospheric dispersion and deposition expert panels.
December 1993	Draft report on the results of the atmospheric dispersion and deposition expert panels published for review by NRC and EC.
January 1994	Kickoff meeting in the UK to proceed with three more panels in the EU: two food chain panels and one panel on deposited material and the calculation of related doses.

April 1994	Joint EC/NRC planning meeting held in Brussels for the panels on the food chain and deposited material/related doses.
September 1994	Decision by NRC management to join the panels on the food chain and deposited material/related doses.
December 1994	Dry run meetings held in Europe for experts to review the case structure documents.
January 1995	Publication of Vol. 1 of dispersion and deposition uncertainty assessment.  Training meeting for the European experts on the food chain and deposited material/related doses.
February/ March 1995	Elicitation meetings for the European experts on the food chain and deposited material/related doses.
April 1995	Training meeting for the US experts on the food chain and deposited material/related doses.
July 1995	Elicitation meeting for the US experts on the food chain and deposited material/related doses.
December 1995	Joint training meeting for US and EC experts on early health effects, late health effects, and internal dosimetry parameters
February 1996	Elicitation meeting for late health effects and internal dosimetry experts (common session included UK and US experts using video conferencing)
March 1996	Elicitation meeting for early health effects experts (common session included UK and US experts using video conferencing)

## 1.6 Structure of Document

Section 2 contains a discussion of the technical issues that were considered before the actual elicitation process. It provides a short characterization of consequence

uncertainty studies, briefly describes why uncertainty information is necessary for decision making, briefly describes the MACCS and COSYMA models, describes the process used to select the variables that were assessed, explains why formal expert elicitation methods were chosen, and delineates the scope of the project.

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

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

## 1.7 References

1. Chanin, D.I. et al., MELCOR Accident Consequence Code System (MACCS), User's Guide, NUREG/CR-4691, SAND86-1562, Vol. 1, Sandia National Laboratories, Albuquerque, NM, February 1990.
2. Kelly, G.N., ed., COSYMA: A New Programme Package for Accident Consequence Assessment, EUR-13028, Commission of European Communities, Luxembourg, 1991.
3. Harper, F. T. et al., Probabilistic Accident Consequence Uncertainty Analysis, NUREG/CR-6244, EUR-15855EN, SAND94-1453, Vol. 1, Sandia National Laboratories, Albuquerque, NM, 1995.
4. Ritchie, L.T. et al., CRAC-2 Model Description, NUREG/CR-2552, SAND82-0342, Sandia National Laboratories, Albuquerque, NM, March 1984.
5. Jones, J.A., P.A. Mansfield, and M.J. Crick, An Uncertainty Analysis of the Predicted Consequences of the Nuclear Accidents Using the NRPB Code MARC-2A, NRPB-R274, London, HMSO, 1995.
6. Fischer, F., J. Ehrhardt, and I. Hasemann, Uncertainty and Sensitivity Analyses of the Complete



- Program System UFOMOD and of Selected Sub-models, KfK 4627, Nuclear Research Center, Karlsruhe, Germany, 1990.
7. NRC (US Nuclear Regulatory Commission), *Severe Accident Risks: An Assessment for Five US Nuclear Power Plants*, NUREG-1150, Washington, DC, December 1990.
  8. Kouts, H.J.C. et al., *Special Committee Review of the Nuclear Regulatory Commission's Severe Accident Risks Report (NUREG-1150)*, NUREG-1420, US Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Washington, DC, August 1990.
  9. Cooke, R., "Expert Judgment Study on Atmospheric Dispersion and Deposition," Reports of the Faculty of Technical Mathematics and Informatics No. 91-81, Delft University of Technology, Delft, The Netherlands, 1991.
  10. Cooke, R.M., L.H.J. Goossens, and B.C.P. Kraan, *Methods for CEC/NRC Accident Consequence Uncertainty Analysis of Dispersion and Deposition – Performance-Based Aggregating of Expert Judgments and PARFUM Method for Capturing Modeling Uncertainty*, EUR-15856-EN, Commission of European Communities, Luxembourg, June 1994.

## 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).<sup>1</sup> Although the technique has undergone considerable development since this study, the essentials have remained unchanged. The intent of uncertainty analysis is to estimate the uncertainty in the output of quantitative decision support modeling in order to provide the decision maker with a measure of the robustness or accuracy of the conclusions based on the model. To accomplish this, a joint distribution is placed on the input variables of models and propagated through the model to yield distributions on the model's output.

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

ues that arise in carrying out an uncertainty analysis for accident consequence models.

### 2.2 Types of Uncertainty

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

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

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

### 2.3 Use of Uncertainty Analyses for Decision Making

Section 2.3 of Volume 1 in the main report on atmospheric dispersion and deposition<sup>3</sup> briefly describes the

history of consequence uncertainty analyses. The US and European developments are also sketched and summarized as lessons learned from past uncertainty analyses.

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

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

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

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

The question of how best to compress the information into a form that can be used by decision makers requires considerable attention. In some applications of

the information, it may be important for the decision maker to distinguish statistical uncertainty resulting from variation in meteorological conditions or other sources from state-of-knowledge uncertainty in code variables. Stochastic uncertainty is here to stay, whereas state-of-knowledge uncertainty may change as knowledge grows; distinguishing between stochastic and state-of-knowledge uncertainty could be helpful in setting research priorities. In allocating future research resources, it is important to know the contribution of each variable's uncertainty to the overall risk uncertainty, and to identify those variables for which uncertainty can be significantly reduced by future research efforts.

## 2.4 Brief Description of Early Health Effects Models Used with MACCS and COSYMA

The early health effect risk models implemented in COSYMA and MACCS have sigmoid dependencies of individual risk  $R$  on dose  $D$  to the target organ in an exposed individual. These models have the following form

$$R = 1 - \exp(-H)$$

where the hazard  $H$  is expressed by a two-parameter Weibull function:

$$H = \ln(2) \left( \frac{D}{D_{50}} \right)^{\nu} \quad \text{for } D \geq T$$
$$H = 0 \quad \text{for } D < T$$

Here  $D$  is the biologically effective dose delivered to the target organ, and  $D_{50}$  is the dose that would induce the effect (impaired functioning of the target organ or fatality if the combined impairments are too large) in half the exposed population. When  $D$  is equal to  $D_{50}$ , the risk  $R$  is one half. The quantity  $\nu$  is a shape parameter. Increasing  $\nu$  has the effect of increasing the slope of a plot of  $R$  versus  $D$ . Note that the risk below the threshold dose  $T$  is set to zero.

$D_{50}$  depends on the rate at which the dose  $D$  is delivered. Doses delivered at lower rates are less likely to cause early health effects than like doses delivered at higher rates. When a dose is delivered over long periods of time at rates that are not constant, the normalized dose  $D/D_{50}$  to be used for estimating  $R$  is calcu-

lated in MACCS and COSYMA by summing over successive time periods using the equation

$$\frac{D}{D_{50}} = \sum_t \frac{D_t}{(D_{50})_t}$$

Here  $D_t$  is the dose received in the  $t$ 'th time period, and the  $(D_{50})_t$  is the dose that would induce the health effect in half the exposed population.  $(D_{50})_t$  is calculated using the expression

$$(D_{50})_t = D_{\infty} + \frac{D_o}{(\dot{D}_{avg})_t} = D_{\infty} + \frac{D_o}{D_t / \Delta t_t}$$

where  $D_{\infty}$  is the  $D_{50}$  value at very large dose rates,  $D_o$  is a parameter required to estimate  $D_{50}$  at lower dose rates, and  $\Delta t_t$  is the duration of the  $t$ 'th time interval.

COSYMA applies the preceding equations to account for dose rate effects for all exposure pathways. When calculating early health effects caused by external exposures (cloudshine and short-term groundshine exposures), MACCS uses only one term in the preceding equation and the  $D_{50}$  value used with that term is chosen to be appropriate for intense exposures delivered over a 24-hr period. When inhalation doses contribute to the risk of early health effects, MACCS uses several (two or more) terms in the preceding equations.

The cumulative risk of early fatality is calculated as if each cause were an independent event. For example, in MACCS, doses to three organs (red marrow, lungs, and gastrointestinal tract) can cause early fatalities. Letting  $R_{RM}$ ,  $R_{LU}$ , and  $R_{GI}$  denote risks of early fatality calculated for the respective organs, the composite risk is

$$R = 1 - (1 - R_{RM})(1 - R_{LU})(1 - R_{GI})$$

Noting that  $1 - R_{organ} = \exp(-H_{organ})$ , the composite risk of early fatality is then

$$R = 1 - \exp(-H_{RM} - H_{LU} - H_{GI}) = 1 - \exp(-H)$$

where  $H = H_{RM} + H_{LU} + H_{GI}$ . That is, the composite hazard  $H$  is the sum of the hazards by organ. A fourth organ, skin, is included in COSYMA estimates of early fatality risks.

Finally, it should be noted that the  $D_{50}$  values can depend on the level of medical treatment received.

Usually three levels of treatment are distinguished: minimal, supportive, and intensive. With MACCS, all of the population is assumed to receive the same level of treatment.

## 2.5 Selection of Variables for Presentation to Formal Expert Elicitation Panels

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

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

1. Sensitivity studies using MACCS in the US and UFOMOD in the EC were performed. Lists of code input variables that were shown to be important to the different consequence measures were generated independently by the US and EC. Lists of important code input variables were generated for both prompt and latent consequences. As an example, the US list is summarized in Table 2.1. Sensitivity studies from the US relied on traditional regression techniques and additional parametric importance assessment techniques developed at Los Alamos National Laboratories specifically for this program to prioritize code input variables.<sup>3</sup>
2. A team of US and EC consequence experts developed a joint list of important code input variables from a review of the lists generated from the sensitivity studies performed in the US and the EC. This list is presented in Table 2.2.
3. It was not considered feasible to jointly assess code input variables that are highly specific to conditions in the EC or in the US. For this reason, any variables related to policy or economics

**Table 2.1. Code input variables for prompt and latent consequences**

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

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

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

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

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

were eliminated from consideration by the joint study (evacuation policy, food interdiction criteria, and costs of countermeasures are all examples of these variables). For the purposes of the uncertainty calculations, these variables will be assessed independently by the EC and NRC using the methods developed in the joint project.

4. If there were any analytical or experimental alternatives to obtaining defensible distributions for any of the code input variables, the variable in question was dropped from the list of assessed elicitation variables using expert judgment techniques. The selected variables represent only parameters for which insufficient experimental data are available for developing uncertainty distributions. Some of the reasons for lack of sufficient experimental evidence could be unacceptable costs and lack of technology.
5. From the final list of code input variables, elicitation variables that were experimentally observable were selected or developed. The experimentally observable constraint was inserted for two reasons (a) to avoid ambiguity when presenting the definition of the elicitation variables (if the experts assess poorly defined variables, the potential for incompatible assessments is high) and (b) to ensure that the elicited distributions are applicable beyond the context of the present study.

In many cases, the experimentally observable constraint results in elicitation variables that are the output of specific submodels rather than the code input variable in the submodels. The distributions obtained by eliciting only on experimentally observable parameters have the potential of containing uncertainty due to the

fundamental limitations in model physics, data uncertainties, and random or stochastic uncertainties in observational data. Additional criteria used in the selection of elicitation variables and a summary of the elicitation variables chosen for the early health effects panel are provided in Section 3.2.

## **2.6 Formal Expert Judgment Methods**

The health effects panels used the same formal expert judgment method as the food chain atmospheric dispersion and deposition panels. The reasons are further specified in Section 2.8 of the main report on atmospheric dispersion and deposition.<sup>4</sup>

## **2.7 Scope of the Early Health Effects Panel**

Assessment of the risks of radiation-induced early health effects depends upon a number of factors, such as the different doses delivered to various organs, the effects of dose rate, the linear energy transfer (LET) of the radiation giving rise to the dose, the degree of medical treatment received, and the age and health of the exposed individuals. The expert panel on early health effects characterizes the degree of uncertainty in estimates of radiation-induced health effects, taking into account the correlations introduced by the variables listed above.

In their first meeting, the members of the early health effects panel generated a list of factors that contribute to uncertainty (Table 2.3) and agreed on the column in which each potential contributor belonged for the purpose of his or her elicitations.

Table 2.3. Factors contributing to uncertainty

Initial condition does <u>not</u> contribute to uncertainty	In case structure contributes to uncertainty	Out of scope and <u>not</u> to be considered in uncertainty
Doses and dose rates as functions of time	Uncertainties in dose reconstruction (e.g., for A-bomb survivors)	Sample-to-sample variabilities of population subgroups
Population distribution	Underreporting in database	Impact of intensive treatment
Minimal versus supportive medical treatment	Sparse database	Psychological and psychosomatic effects
	Some data are for injured persons	Death due to concomitant illness
	Average population with varying health states of members of population	
	Efficacy of medical treatment	
	Extrapolating from animal data	
	Limited data on synergistic effects	

## 2.8 References

1. NRC (US Nuclear Regulatory Commission), Reactor Safety Study - An Assessment of Accident Risks in US Commercial Nuclear Power Plants, WASH-1400 (NUREG-75/014), Washington, DC, October 1975.
2. NRC (US Nuclear Regulatory Commission), PRA Working Group, A Review of NRC Staff Uses of Probabilistic Risk Assessment, NUREG-1489, Washington, DC, March 1994.
3. Helton, J.C., et al., "An Exploratory Sensitivity Study with the MACCS Reactor Accident Consequence Model," *Reliability Engineering and System Safety*, 36:137-164, 1992.
4. Harper, F. T. et al., Probabilistic Accident Consequence Uncertainty Analysis, NUREG/CR-6244, EUR-15855EN, SAND94-1453, Vol. 1, Sandia National Laboratories, Albuquerque, NM, 1995.



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

#### 3.1 Introduction

This section summarizes the joint methodology used to develop uncertainty distributions for the consequence calculations in this project, and the use of this methodology in developing the distributions for early health effects code input variables. The joint methodology is shown graphically in Figure 3.1. It is a combination of methods from previous US and EC studies as well as methods developed specifically for this project. Table 3.1 summarizes some of the major contributions to the joint methodology from previous US and EC studies.

#### 3.2 Definition of Elicitation Variables and Case Structures

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

##### 3.2.1 Definition of Elicitation Variables

It was the responsibility of the probability elicitation team to develop elicitation variables that 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 as-

sessments 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.

Code input variables are not always physically measurable parameters. In the case of early health effects, the important parameters are those used to determine the shapes of the curves defining the risks of particular health effects as a function of doses to sensitive organs. In MACCS and COSYMA these are the Weibull shape parameter  $\nu$  and the parameters used to estimate the Weibull  $D_{50}$  value as a function of dose rate. For example, the  $D_{50}$  for effects attributable to dose  $D_i$  delivered to the  $i$ 'th organ over time interval  $\Delta t$  is often modeled as

$$D_{50_i} = (D_\infty)_i + (D_o)_i \Delta t / D_i$$

where  $D_\infty$  is the  $D_{50}$  value at very high dose rates and  $D_o$  is a model parameter used to account for the decrease in  $D_{50}$  with dose rate. Because model parameters like  $\nu$ ,  $D_\infty$ , and  $D_o$  are not physically measurable, it is necessary to elicit distributions on physically measurable parameters from which distributions on  $\nu$ ,  $D_\infty$ , and  $D_o$  can be derived. This was done by eliciting distributions on physically measurable doses that would give rise to specified health effects in 10, 50, or 90% of a large population.

Further, COSYMA and MACCS use the equivalent dose (Sv) for quantifying the magnitude of the exposure. However, the experts preferred to use the absorbed dose (Gy) for quantifying the exposure. Therefore, in each case the radiation type has been described. The transformation from absorbed dose to equivalent dose was not part of the elicitation.

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

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

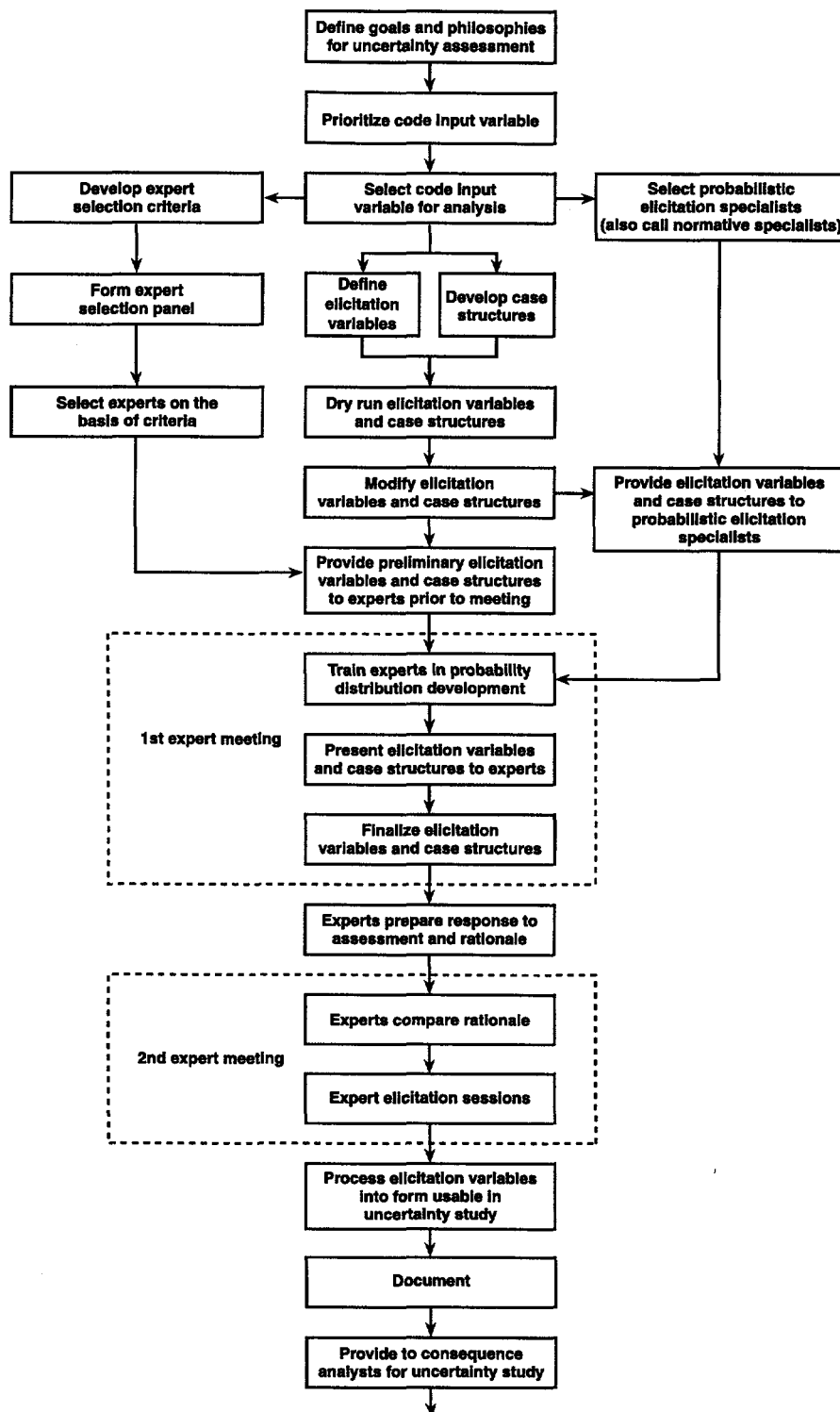


Figure 3.1 Sequence of methods used to develop the uncertainty distributions. Due to programmatic constraints, the EC and the US experts held separate first expert meetings; however, some project staff attended both European and American meetings. The EC and US communicated through a teleconference in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

### 3.2.2 Development of Case Structure

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

For the early health effects questions, the case structure consisted of many variations of exposure conditions: organ(s) exposed, and dose rate associated with the exposure. The case structure underwent twelve iterations before it was presented to the experts and four more iterations to address comments and suggestions received from the experts prior to the formal elicitation. The result of the final iteration contains nine main questions, each with several exposure scenarios.

The questions and associated exposure scenarios are summarized in Table 3.2. Note that Questions 1, 2, 3, and 5 deal with exposures via single pathways to all organs simultaneously (whole body) or to individual organs. These exposure scenarios were deliberately contrived to elicit information concerning the susceptibility of the key organs and to permit the postprocessing of uncertainties in organ-specific parameters of the early health effect risk models. Each of these questions is asked for different dose rates in order to assess the importance of dose rate to organ susceptibility.

Questions 6 and 7 deal with more realistic exposure scenarios. Question 6 simulates whole-body and lung exposures that might be associated with an accidental release by postulating a realistic ratio between the dose rate during the first hour, which corresponds to plume passage, and that during the balance of the first day. In Question 7 the exposure is to multiple organs via multiple pathways over three exposure periods. The relative dose rates for this question were based on estimates obtained from COSYMA code calculations. This question was included to permit code predictions of health effect incidences for realistic exposure scenarios to be compared with the health effect risks elicited from the experts for the same exposure scenarios.

For each exposure scenario, experts were asked to provide three percentile values, 5th, 50th, and 95th, from the cumulative distribution functions for threshold dose,  $D_{10}$ ,  $D_{50}$ , and  $D_{90}$ . In some cases, as indicated in Table 3.1, the information was elicited for both minimal and supportive levels of medical treatment or for more than one population age group. The project staff

believed that sufficient information would be obtained from these questions to allow valid interpolation and extrapolation for coverage of the variable space.

### 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 expert whose judgments are sought, a normative specialist who manages the session, and a substantive assistant from the project staff who aids communication between the expert and the specialist and helps answer questions about the assumptions and conditions of the study.

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

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

#### 3.3.1 Selection of Phenomenological Experts

The project staff sought to engage the best experts available in the field of early health effects. Experience in the NUREG-1150 study and elsewhere has shown that the selection of experts can be subjected to much scrutiny. Thus, it was necessary to construct a defensible selection procedure. The procedure for this study involved the following:

Table 3.2 Early health effects case structure

	Radiation source	Organ(s) exposed	Health effect	Dose rate or exposure period	Subcase structure
1	External gamma	Whole body	Fatality	100 Gy/hr, 10 Gy/hr 1 Gy/hr, 0.2 Gy/hr	Minimal versus supportive treatment
2a	Internal beta	Lung	Fatality	100 Gy/hr, 10 Gy/hr 1 Gy/hr, 0.2 Gy/hr	By age group
2b	Internal beta	Lung	Morbidity	100 Gy/hr, 10 Gy/hr 1 Gy/hr, 0.2 Gy/hr	By age group
3	Internal alpha	Lung	Fatality	Elicited constant DR	By age group
5	External beta	Skin	Fatality	100 Gy/hr, 10 Gy/hr 1 Gy/hr, 0.2 Gy/hr	Three bare skin fractions
6a	External gamma	Whole body	Fatality	1 hour : 1 day 10:1 Dose rate	Minimal versus supportive treatment
6b	External gamma	Whole body	Fatality	1 hour : 1 day 100:1 Dose rate	Minimal versus supportive treatment
6c	Internal beta	Lungs	Fatality	1 day : 1 week 14:1 Dose rate	By age group
7a1	Mixed	All	Fatality	1 hour : 1 day : 1 week $D_{\text{Skin}} = 21 D_{\text{Red marrow}}$	Minimal versus supportive treatment, 4 bare skin fractions
7a2	Mixed	All but lungs		Zero lung dose, otherwise same as 7a1	Minimal versus supportive treatment, 4 bare skin fractions
7b1	Mixed	All	Fatality	1 hour : 1 day : 1 week $D_{\text{Lung}} = 10 D_{\text{Red marrow}}$	Minimal versus supportive treatment, 4 bare skin fractions
7b2	Mixed	All but lungs		Zero lung dose, otherwise same as 7b1	Minimal versus supportive treatment, 4 bare skin fractions

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

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

The result was a panel of internationally recognized scientists (see Table 3.3). Brief biographies are provided in Volume 2.

**Table 3.3 Early health effects experts**

Expert	Country
Johan Broerse*	Netherlands
Marvin Goldman	US
Jolyon Hendry	UK
John Hopewell	UK
Natalja Nadejina	Russia
Robert Scott	US
Elizabeth Travis	US
Niel Wald	US
Robert Young	US

\*Joint effort with A.F. Hermans and H.B. Kal.

### 3.3.2 Selection of Normative Specialists

Normative specialists are responsible for managing the elicitation sessions. These specialists come from various fields such as psychology, decision analysis, statistics, or risk and safety analysis. The characteristic that distinguishes them is familiarity with the methods and literature for probability elicitation, and experience in applying these methods. Normative

specialists must be able to manage the elicitation sessions by providing assistance in developing and expressing quantitative judgments.

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

## 3.4 Expert Elicitation

The expert elicitation process consisted of the following activities:

1. Dry run elicitation. A dry run elicitation was conducted with experts employed by the Lovelace Inhalation Toxicology Research Institute (ITRI) of Albuquerque, NM to test the questions 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. The second expert meeting was conducted approximately 6 weeks after the first expert meeting and was held to elicit the percentile values from the cumulative distributions of the elicitation variables. The experts presented their qualitative assessments

without quantification in a video conference between the US and Europe.

### **3.4.1 Dry Run Meeting to Finalize Case Structure**

A dry run meeting was conducted in November 1995 with F. Hahn and R. Scott, both of whom were with ITRI. The meeting began with training in probability elicitation, which focused on the meaning of subjective probabilities, the structure of formal expert judgment processes, biases in probability formation, and practice in expressing judgments as probabilities. The draft case structure document and elicitation questionnaires were handed out before the dry run meeting. The dry run experts were not asked to prepare quantitative responses to the questions, but were requested to judge the merits of the questions, to detect possible ambiguities in the questionnaires, and to indicate the relevance of the questions in general. The case structures and questionnaires to be presented to the experts in the first meeting were finalized according to the lessons learned in the dry run.

### **3.4.2 First Expert Meeting**

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

Training was conducted to introduce the experts to psychological biases in judgment formation and to give them feedback on their performance in assessing probability distributions. In the NUREG-1150 study, feedback was provided to the experts by measuring their performance on the development of probabilistic distributions for training variables. In that study, the training variables were nontechnical, almanac-type questions for which the answers were known. In the current study, performance was measured by querying

the experts about variables whose true values are uncertain for the experts but known to project staff from unpublished data. These training variables were chosen to resemble the variables of interest as closely as possible. The training meeting was held in Annapolis, Maryland in December 1995 and both US and EC experts participated.

### **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 their distributions. The experts were encouraged by project staff to use whatever modeling techniques or experimental results they felt appropriate to assess the problems. The only constraints placed on the experts by the project were that: (1) the initial conditions had to be defined at the same level of detail as the code input (i.e., uncertainty due to lack of detail in the initial conditions had to be included in the uncertainty distributions provided) and (2) the rationale behind the distributions had to be thoroughly documented.

### **3.4.4 Second Expert Meeting: Elicitation**

The elicitation meeting was held in March 1996. A normative specialist and a substantive assistant were present at all elicitation sessions. On the first day of the elicitation meeting, the experts presented the technical approach and rationale behind their assessments in a common session. This was a videoconference session in which the US experts were in Albuquerque, New Mexico, and the EC experts were in Brussels. 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. Following the common sessions, 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 exposure scenario in the case structure. It was the responsibility of the project staff to aggregate the individual expert distributions (5th, 50th, and 95th percentile values) for each elicitation variable into a single cumulative distribution for each exposure scenario in the case structure.

Further mathematical processing is required to obtain organ-specific distributions of the Weibull shape factor  $\nu$  and the dose rate parameter  $D_o$  for red marrow, lungs, gastrointestinal tract, and skin. The following section discusses the aggregation process applied to the elicited percentiles. It was decided to publish the results of the mathematical processing in separate reports.

### 3.5.1 Aggregation of Elicited Distributions

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

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

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

where  $F_{ji}$  is the cumulative probability associated with expert  $j$ 's assessment for variable  $i$ .

Investigating the different weighting schemes was not the objective of this joint effort. A decision was therefore made within the program to assign all experts equal weight (i.e., all experts on each panel were treated as being equally credible). One of the primary reasons the equal-weighting aggregation method was chosen was to ensure the inclusion of different modeling perspectives in the aggregated uncertainty distributions. However, additional information was elicited to allow the application of performance-based weighting schemes to the distributions. The implications of different weighting schemes are discussed elsewhere.<sup>2</sup>

### 3.5.2 Combining Dependencies

It has long been known that significant errors in uncertainty analysis can be caused by ignoring dependencies between uncertainties.<sup>3</sup> The best source of information about dependencies is considered to be the experts themselves. The most thorough approach would be to elicit the experts' joint distributions directly. The practical drawbacks to this approach have forced analysts to look for other dependency elicitation strategies. Because the experts were already convened to respond to the formal elicitation questions, the project took advantage of their availability to test a new methodology in which dependency information was elicited.<sup>4</sup> The methodology and results obtained from this activity will be reported in a separate publication.

## 3.6 References

1. Cooke, R., and D. Solomatine, Delft University of Technology and SoLogic Delft, EXCALIBR, Integrated System for Processing Expert Judgments, Version 3.0: User's Manual, Delft, The Netherlands, 1992.

2. Cooke, R.M., L.H.J. Goossens, and B.C.P. Kraan, Delft University of Technology, Methods for CEC/USNRC Accident Consequence Uncertainty Analysis of Dispersion and Deposition—Performance Based Aggregating of Expert Judgments and PARFUM Method for Capturing Modeling Uncertainty, EUR-158546-EN, Luxembourg, June 1994.
3. Apostolakis, G., and S. Kaplan. "Pitfalls in Risk Calculations," *Reliability Engineering* 2, 135–145, 1981.
4. Cooke, R.M. and B.C.P. Kraan, "Dealing with Dependencies in Uncertainty Analysis," *Probabilistic Safety Assessment and Management*, P.C. Cacciabue and I.A. Papazoglou, Eds., Vol. 1, pp. 625–630, Springer-Verlag, Berlin, 1996.



## 4. Results and Analysis

### 4.1 Introduction

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

### 4.2 Summary of Elicitation Meetings

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

#### 4.2.1 Dry Run Elicitation Meeting

The robustness of the basic expert elicitation methodology developed for this project was validated by a dry run exercise. Some important issues were raised and evaluated as a result: (1) there was a need to clarify the underlying conditions for some questions; and (2) strong references to particular models in the case structure that might bias the thinking of the expert needed to be removed.

#### 4.2.2 Summary of First Expert Meetings (Training Meetings)

The experts decided to keep the elicitation results and the written rationales anonymous. The names of the experts are published in Table 3.2 and the assessments are published in Volume 2, where they are identified by letter only. No link is made between the experts' names and the assessments provided.

#### 4.2.3 Summary of Second Expert Meeting

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

### 4.3 Summary of Individual Expert Assessments

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

The complete set of expert rationales and the elicited distributions are published in Volume 2 of this report. In this chapter, Figures 4.1 through 4.18 plot some of the elicited results along with the results of the equal-weighted aggregation of the elicited distributions. This section discusses the individual assessments. Section 4.4 reviews the results of the equal aggregation of the distributions.

Most of the written rationales cited published data on early health effects. These include the Nagasaki and Chernobyl data. In general, where human data were available, they provided the basis for the experts' 50% values. Where human data were deemed insufficient, extrapolations from animal data were often cited as the primary basis of the 50% estimates. Some of the experts relied heavily on published statistical and/or mechanistic models, and one expert relied on an available biokinetic model. In virtually all cases, judgment based on experience was used to establish 5% and 95% values. A notable exception is that one expert assigned distributions to the underlying parameters of a Weibull model and relied on Monte Carlo sampling to assist in establishing the 5% and 95% values of elicited quantities.

Figure 4.1 shows the elicited percentiles of LD<sub>50</sub> for whole-body exposure to gamma radiation at dose rates of 100, 10, 1, and 0.2 Gy/hr (question 1a) assuming minimal medical treatment, which involves basic first aid. Note the tendency for the uncertainty to increase with decreasing dose rate due to the scarcity of human data at lower dose rates. Also note the wide variations in ranges assigned by the experts. These two trends are also evident for the other elicited quantities. Figures 4.2, 4.3, and 4.4 show the elicited percentiles of the threshold dose, LD<sub>10</sub>, and LD<sub>90</sub> for whole-body exposure assuming minimal medical treatment. When compared with Figure 4.1, Figures 4.2 through 4.4 illustrate the wider uncertainties associated with the threshold, LD<sub>10</sub>, and LD<sub>90</sub> doses compared with the uncertainties in LD<sub>50</sub>. This

tendency also occurred in the responses to other questions.

Figure 4.5 shows the elicited quantiles of LD<sub>50</sub> for whole-body exposure assuming supportive (as opposed to minimal) medical treatment. Supportive medical treatment as defined for this study includes decontamination of skin and clothing, hospitalization with routine isolation procedures (not including laminar airflow), wound dressing, electrolyte replacement, administration of blood products (especially fresh platelets), treatment with broad-spectrum antibiotics, antifungals and antivirals, and parenteral feeding. Some of the experts assumed that growth factors would be used in supportive treatment. Figure 4.5a shows the results obtained from these experts. Figure 4.5b shows the results obtained from the experts that did not assume the use of growth factors. The median LD<sub>50</sub> values with growth factors are clearly greater than those without growth factors. Several individual experts expressed support for the use of growth factors, and no expert opposed their use. The tendency for LD<sub>50</sub> to increase given supportive versus minimal medical treatment is evident by comparison with Figure 4.1. The uncertainties assuming supportive treatment are, however, generally greater than those for minimal treatment.

Figures 4.6 and 4.7 show the elicited LD<sub>50</sub> values for deaths due to gastrointestinal syndrome as a result of whole-body exposures with minimal and supportive treatment, respectively. It was the consensus of the experts that such deaths would precede deaths due to the hemopoietic effect, which dominates the LD<sub>50</sub> values presented in Figure 4.1. Again, some of the experts assumed that growth factors would be used in supportive treatment. Figure 4.7a shows the results with growth factors whereas Figure 4.7b shows the results without growth factors. An advantage of growth factors is indicated in comparing the equal-weight results; however, this comparison is between mutually exclusive subsets of the experts. Note that unlike the results presented for the hemopoietic effect in Figures 4.1 through 4.5, there is considerably less overlap among the experts regarding LD<sub>50</sub> due to the gastrointestinal syndrome alone. This is also reflected in the written rationales provided by the experts.

Figure 4.8 shows the elicited LD<sub>50</sub> values for deaths due to beta lung dose assuming minimal medical treatment. The results shown are for the entire population. Of the four experts who provided a decomposition by age, only one indicated a significant de-

pendence on age (indicating that LD values would be roughly 75% lower for people over 40). Note that the agreement among the experts in Figure 4.8 is quite good except for Expert 7, who provided the following rationale for relatively optimistic values: "Because of the repair potential for lung injury, chronic exposures may accumulate a considerable total dose if administered at modest rates. For low LET radiations such as in long-lived mixed fission products, large doses can be absorbed before functional impairment occurs." Figure 4.9 provides LD<sub>50</sub> results for morbidity due to beta lung dose. Respiratory-functional morbidity was defined as having combinations of any three of the following radiation-induced effects in the lung: (1) a reduced volume, (2) an increased stiffness, (3) a non-uniform gas distribution, or (4) a reduced alveolar-capillary gas exchange efficiency. Again the agreement is remarkable except for the one expert. Figure 4.10 shows the elicited LD<sub>50</sub> values for alpha lung exposures. Little human data are available regarding such exposures, and the uncertainties are quite broad.

Figure 4.11 shows the elicited values for the threshold 24-hr beta skin dose that would lead to acute ulceration for various fractions of exposed skin. As indicated, the threshold is thought by most of the experts to be insensitive to the fraction of skin exposed. There is, however, disagreement as to the threshold value. Figure 4.12 presents the elicited values of the beta skin dose that would result in acute ulceration to 10, 50, and 90% of the exposed skin area. Figures 4.13 and 4.14 show the elicited values of the fraction that would be expected to die given acute ulceration to 50 and 90% of exposed skin, respectively. Three subcases are shown corresponding to three levels of clothing (20, 40, and 60% of skin exposed). As shown, only two experts responded, so the composite uncertainties are generally very wide. Only for 50% ulceration in 20% of the skin is the fraction of deaths expected less than 0.1 for both experts.

Figure 4.15a examines the effect of decreasing dose rate during a 24-hr whole-body gamma exposure. Two scenarios were elicited; both assume a high dose rate followed by a lower dose rate. In the first case, a 10:1 decrease in dose rate is assumed. In the second case, a 100:1 decrease in dose rate is assumed. The results are generally consistent with those shown in Figures 4.1 and 4.5. Figure 4.15b illustrates by age group effects with minimal medical treatment for two-step 7-day beta lung dose (14:1 relative dose rates).

Figures 4.16 and 4.17 present LD<sub>50</sub> bone marrow doses for the case of a 24-hr composite exposure in

which lung dose was assumed to be twice the red marrow dose and various skin fractions received a beta dose roughly 20 times the red marrow dose. Figure 4.16 presents results for minimal medical treatment, and Figure 4.17 presents results for supportive medical treatment. (Figure 4.17a shows the results with growth factors whereas Figure 4.17b shows the results without growth factors.) Clearly the impact of skin dose is to decrease the LD<sub>50</sub> value, although there is considerable uncertainty regarding the extent of the reduction.

#### 4.4 Summary of Aggregated Results

The 5, 50, and 95% values for the equal-weighted aggregated distributions are presented along with the individual assessments in Figures 4.1 through 4.17. The 50th percentiles from the aggregated distributions are consistent with the individual assessments. As expected, the 5 and 95% ranges of the aggregated distributions tend to be wider than the corresponding uncertainty bands of the individual elicited distributions. The aggregated distributions clearly show the wider uncertainties associated with threshold, LD<sub>10</sub>, and LD<sub>90</sub> values; the wider uncertainties associated with effects induced at low dose rates; and the wide uncertainties associated with effects attributable to lung and skin doses.

It should be emphasized that in some cases the composite distributions are based on input from only two or three experts whose individual uncertainty bands do not overlap. This is not a desirable outcome, merely the best outcome that could be obtained from

the selected panel of experts. Such disagreements may reflect two or more legitimate but conflicting theories. They may also reflect the need for a particular kind of expertise that was not anticipated in the original selection process. For example, the two to three experts who responded to questions involving beta skin doses often provided nonoverlapping distributions. Although they disagreed on levels of damage associated with beta skin burns, they agreed that the expertise of burn specialists would be required in order to resolve their differing opinions. In such situations, one should carefully consult the individual expert's written rationales before applying the composite distributions.

#### 4.5 Comparison of Results from Current Study with Code-Calculated Results

Table 4.1 compares the elicited high-dose rate LD<sub>50</sub> values obtained by the present study with the LD<sub>50</sub> values typically used in MACCS and COSYMA, which are taken from NUREG/CR-4214, Rev. 2. As can be seen, the LD<sub>50</sub> values at high dose rates approach the D<sub>0</sub> values from NUREG/CR-4214, Rev. 2.

For the hematopoietic and pulmonary syndromes, the 50% values of the equal weight distributions are within 10% of the corresponding central estimates from NUREG/CR-4214 Rev. 2. For the gastrointestinal syndrome, the corresponding difference is 30 or 50%, depending on the reference point. In all cases the uncertainty bands overlap; however, the equal-weight bands tend to be more conservative in that they include lower LD<sub>50</sub> values.

**Table 4.1 Equal-weight aggregate of elicited percentiles of LD<sub>50</sub> at 100 Gy/hr versus NUREG/CR-4214, Rev. 2 values assuming minimal medical treatment**

	Equal-weight aggregate of elicited percentiles of LD <sub>50</sub> (Gy) at 100 Gy/hr <sup>a</sup>			D <sub>0</sub> (Gy) from NUREG/CR-4214 Rev.2		
	5%	50%	95%	Lower	Central	Upper
Hematopoietic syndrome	2.0	3.3	5.5	2.5	3.0	3.5
Pulmonary syndrome	6.7	9.3	11.7	8	10	12
Gastrointestinal syndrome	5.7	9.6	17.2	10	15	20

<sup>a</sup> For hypothetical average EU/US population of all ages and sexes.

## 4.6 Reference

1. J.S. Evans, S. Abrahamson, M.A. Bender, B.B. Boecker, E.S. Gilbert, and B.R. Scott, Health Effects Models for Nuclear Power Plant Accident Consequence Analysis, Part 1: Introduction, Integration, and Summary, NUREG/CR-4214, Rev. 2, Part 1, ITRI-141, Inhalation Toxicology Research Institute, Albuquerque, NM, October 1993.

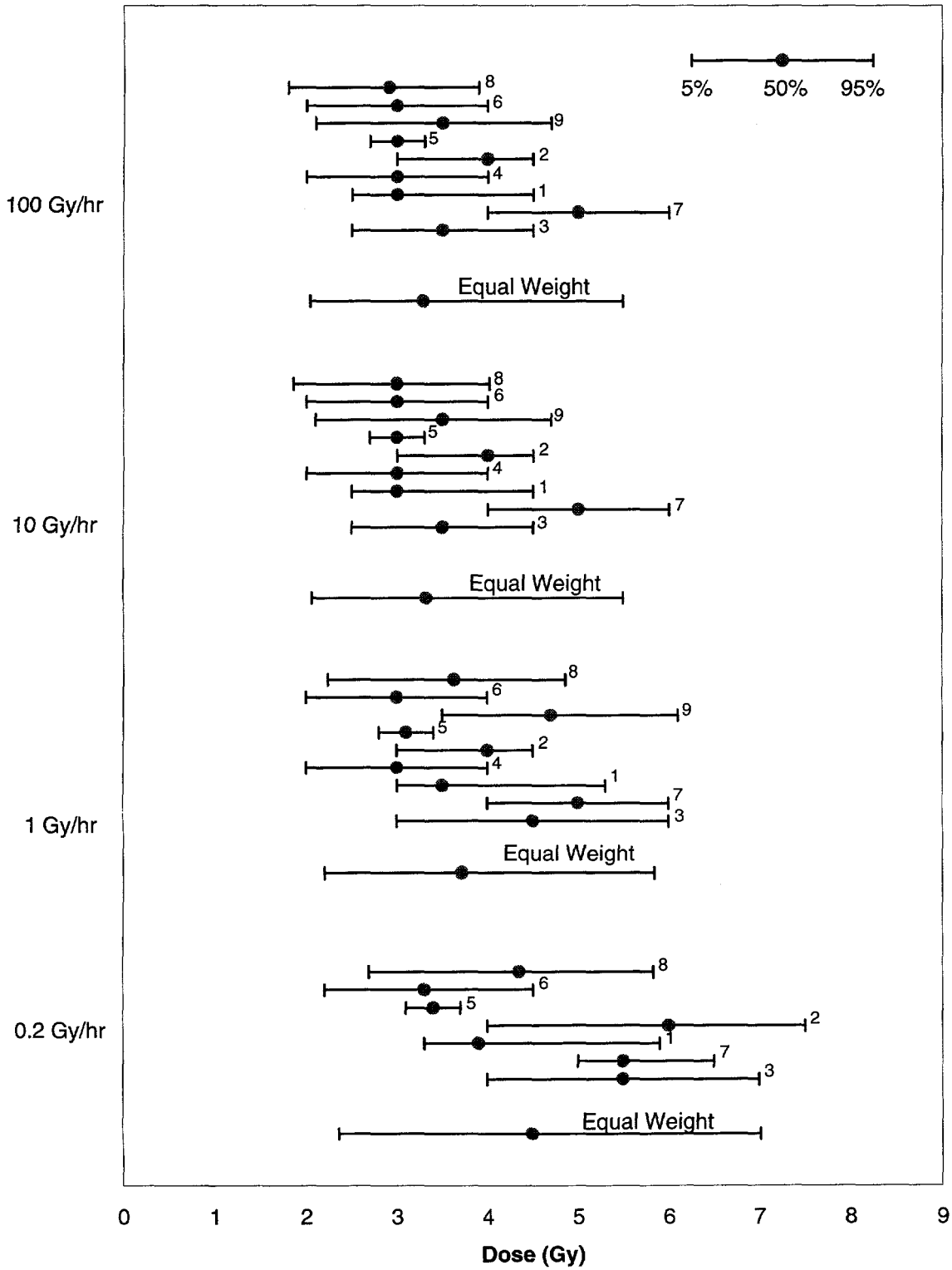


Figure 4.1. LD<sub>50</sub> for whole-body gamma exposure, minimal medical treatment.

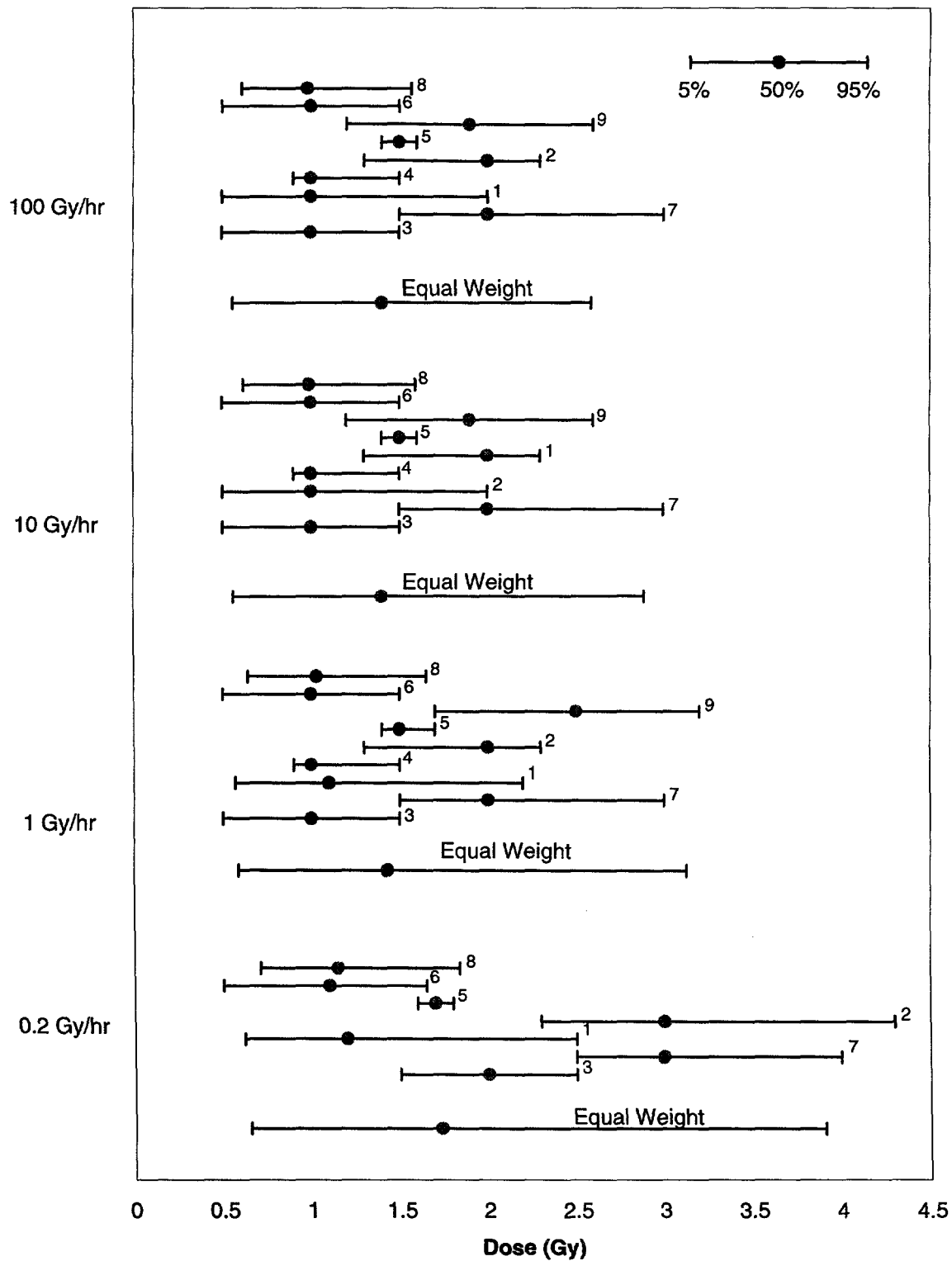


Figure 4.2. Threshold for fatalities from whole-body gamma exposure, minimal medical treatment.

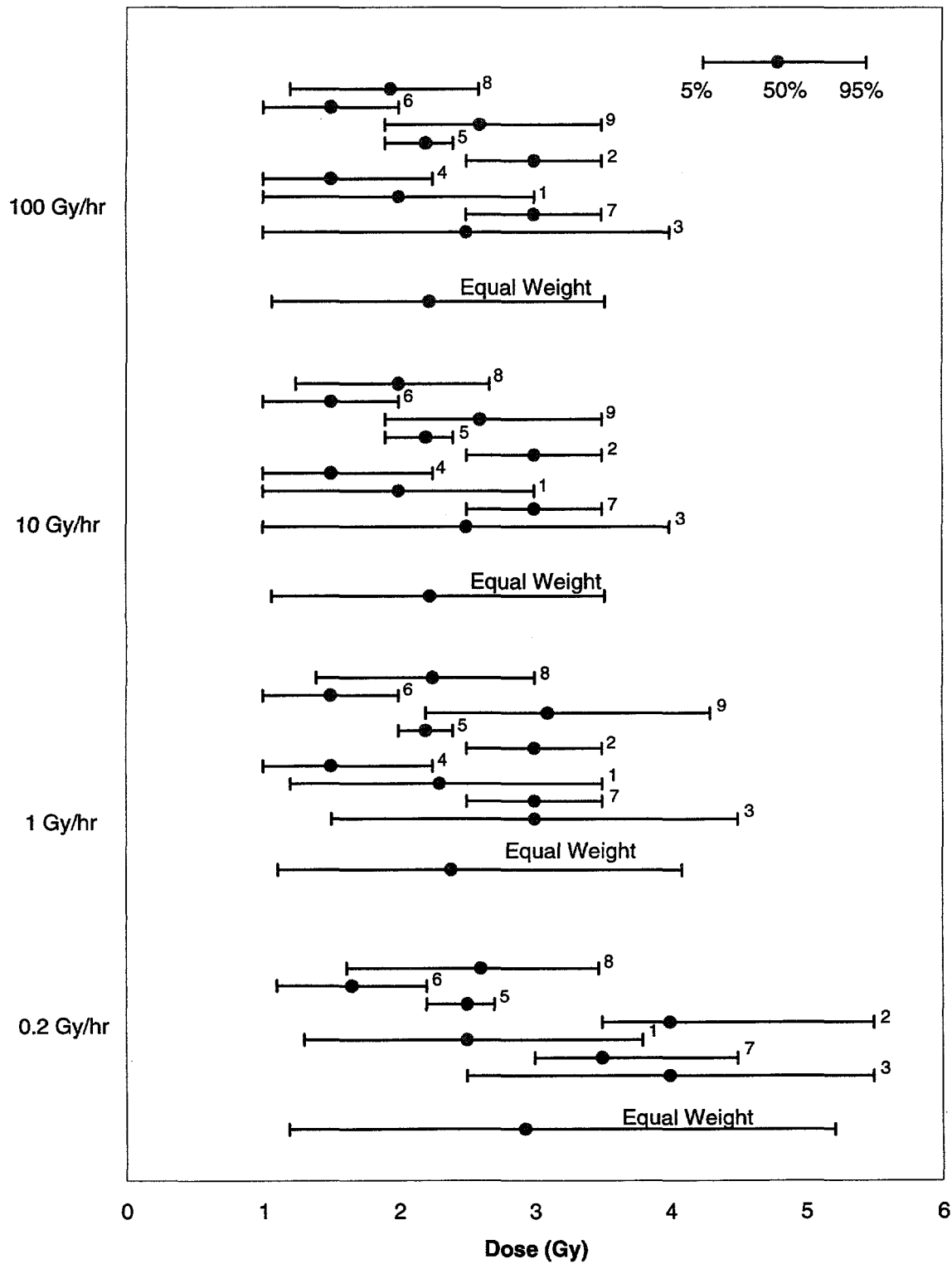


Figure 4.3. LD<sub>10</sub> for whole-body gamma exposure, minimal medical treatment.

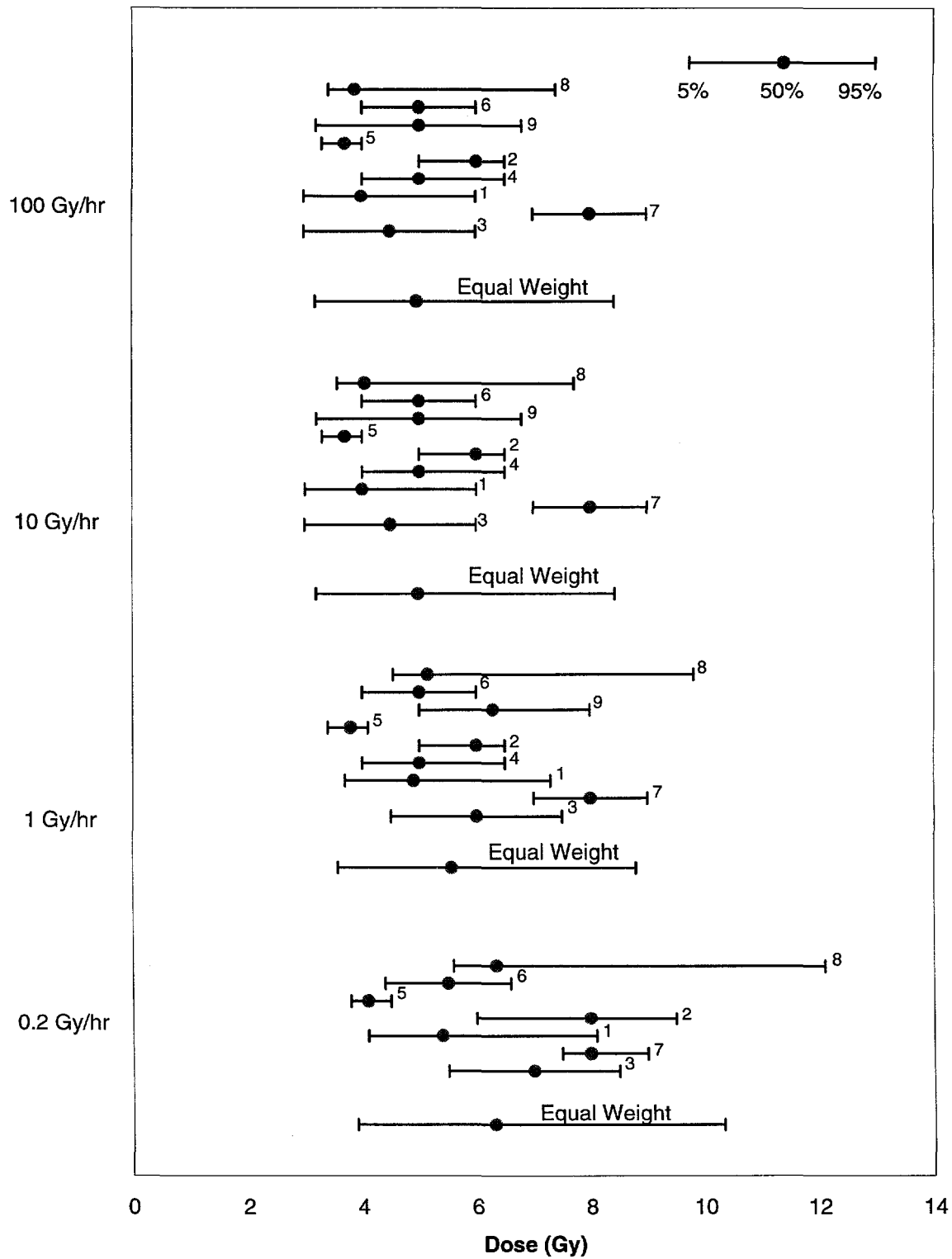


Figure 4.4. LD<sub>90</sub> for whole-body gamma exposure, minimal medical treatment.



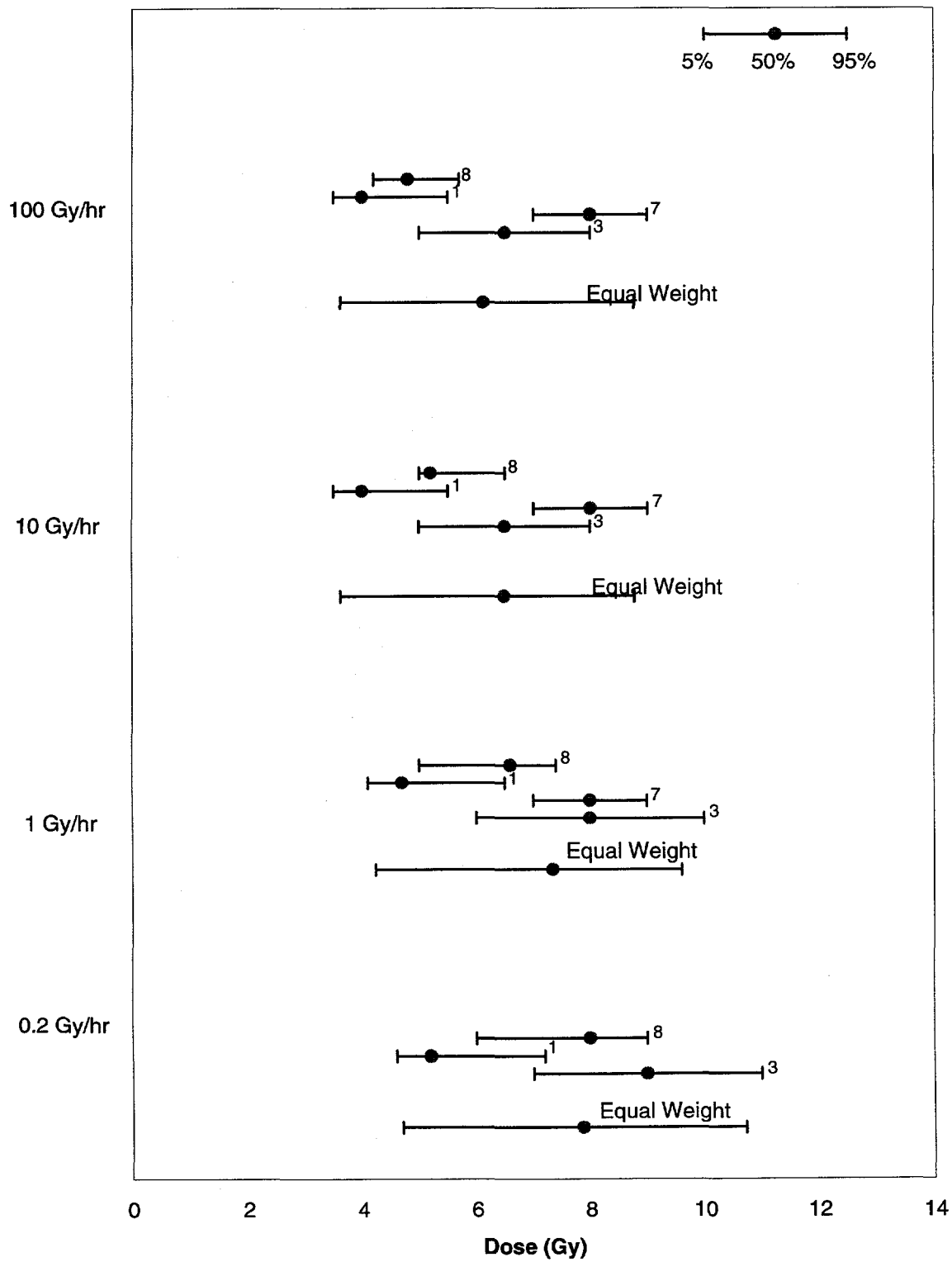


Figure 4.5a. LD<sub>50</sub> for whole-body gamma exposure, supportive medical treatment, with growth factors.

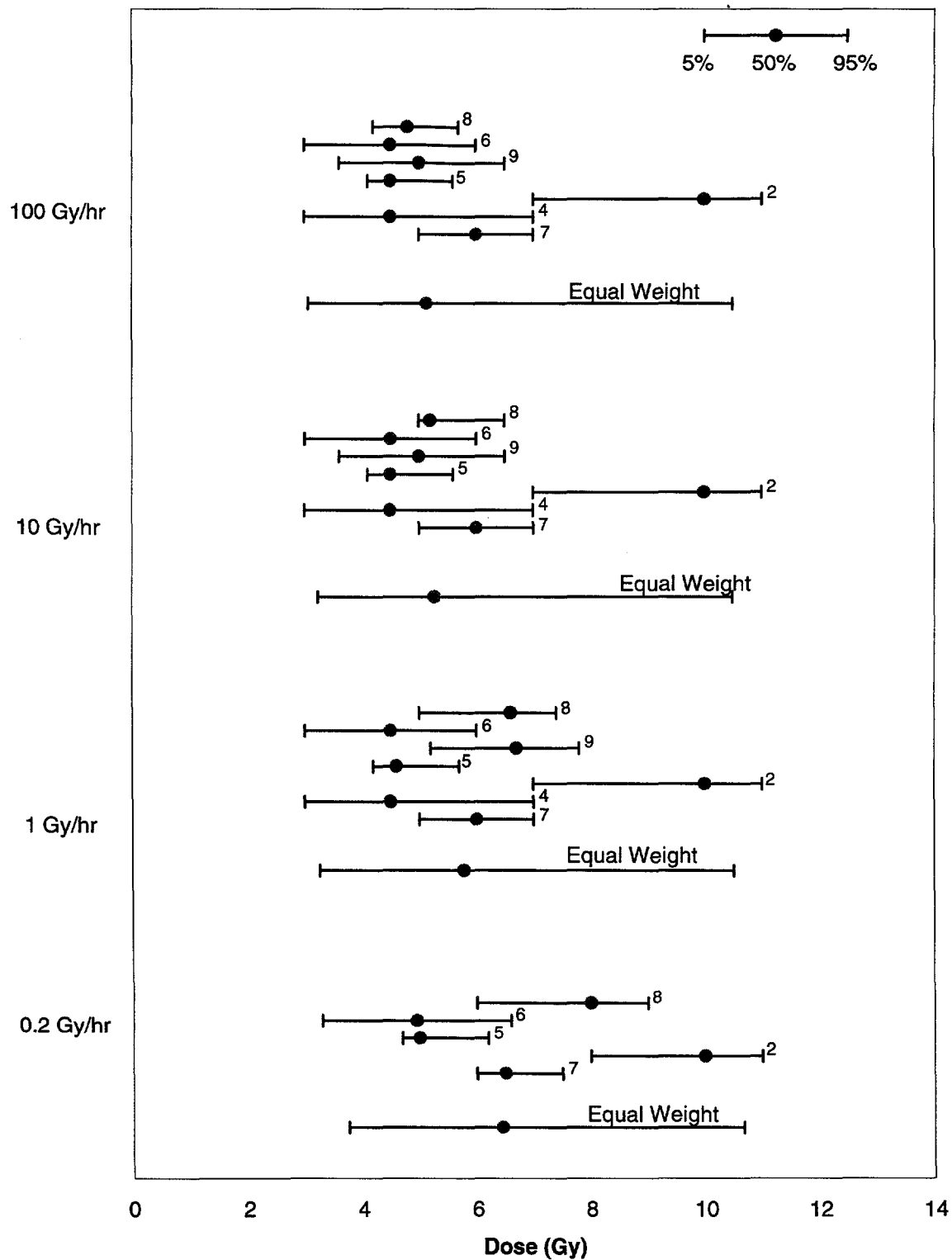


Figure 4.5b. LD<sub>50</sub> for whole-body gamma exposure, supportive minimal medical treatment, without growth factors.

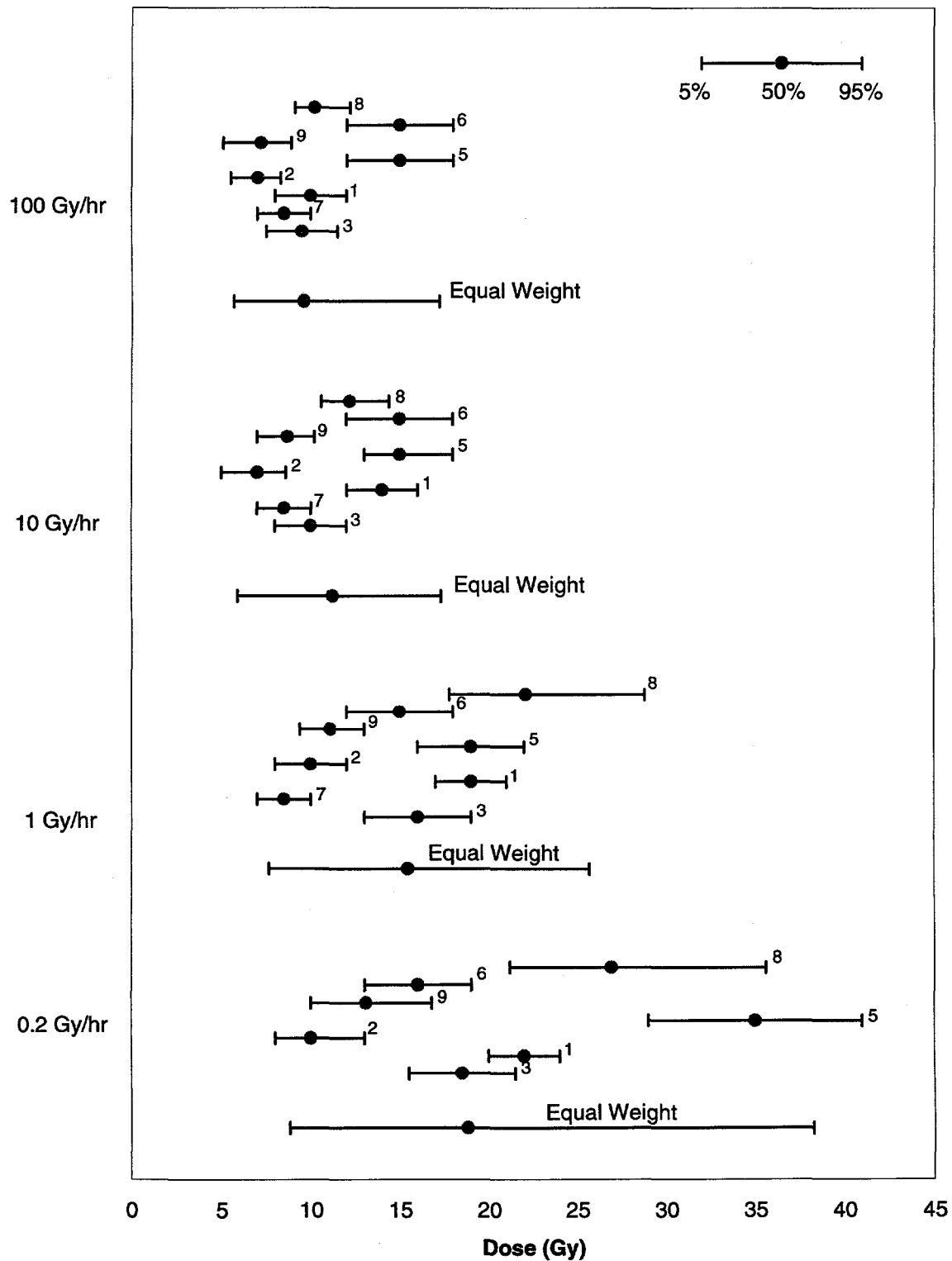
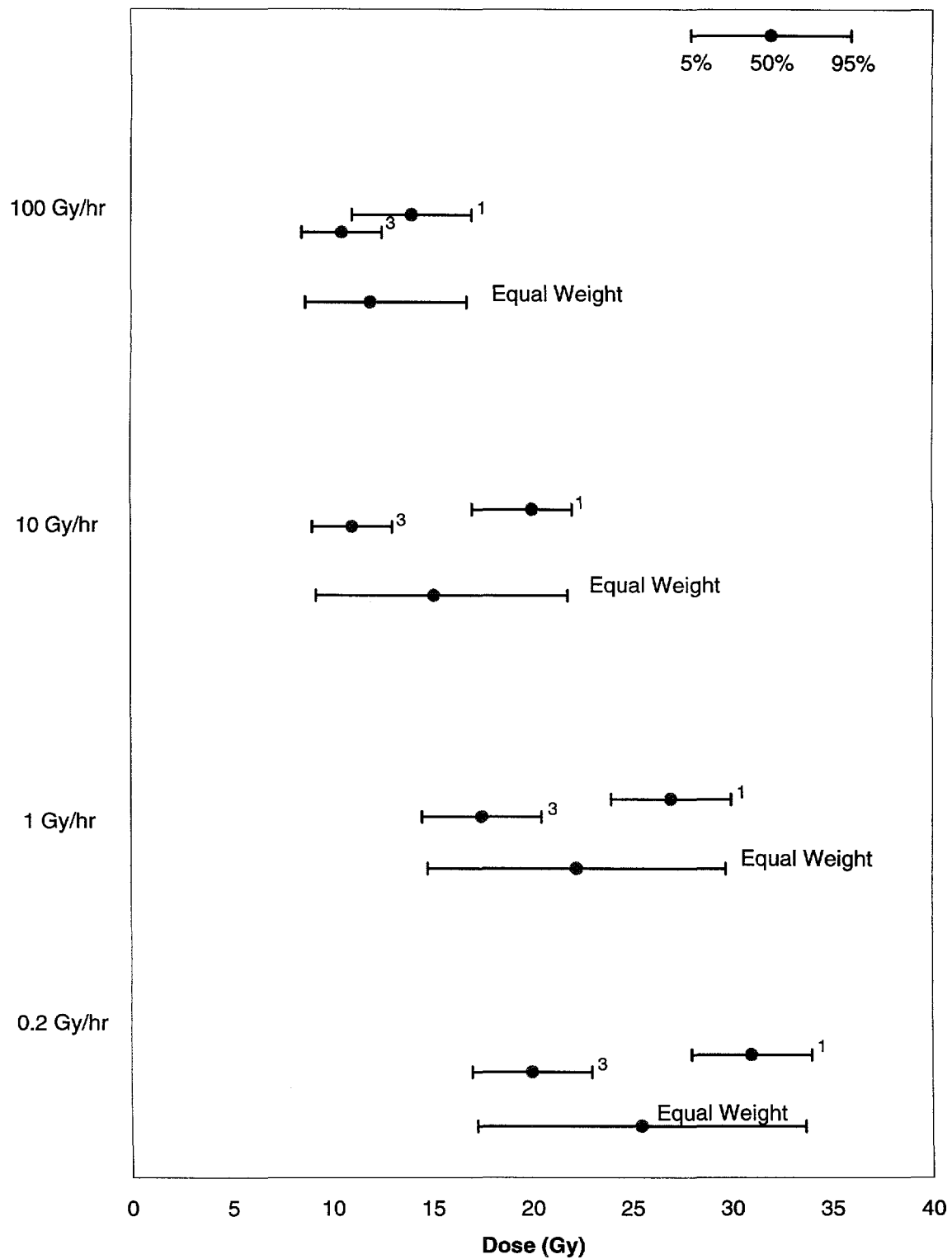


Figure 4.6. LD<sub>50</sub> for gastrointestinal syndrome, minimal medical treatment.



1

Figure 4.7a. LD<sub>50</sub> for gastrointestinal syndrome, supportive medical treatment, with growth factors.

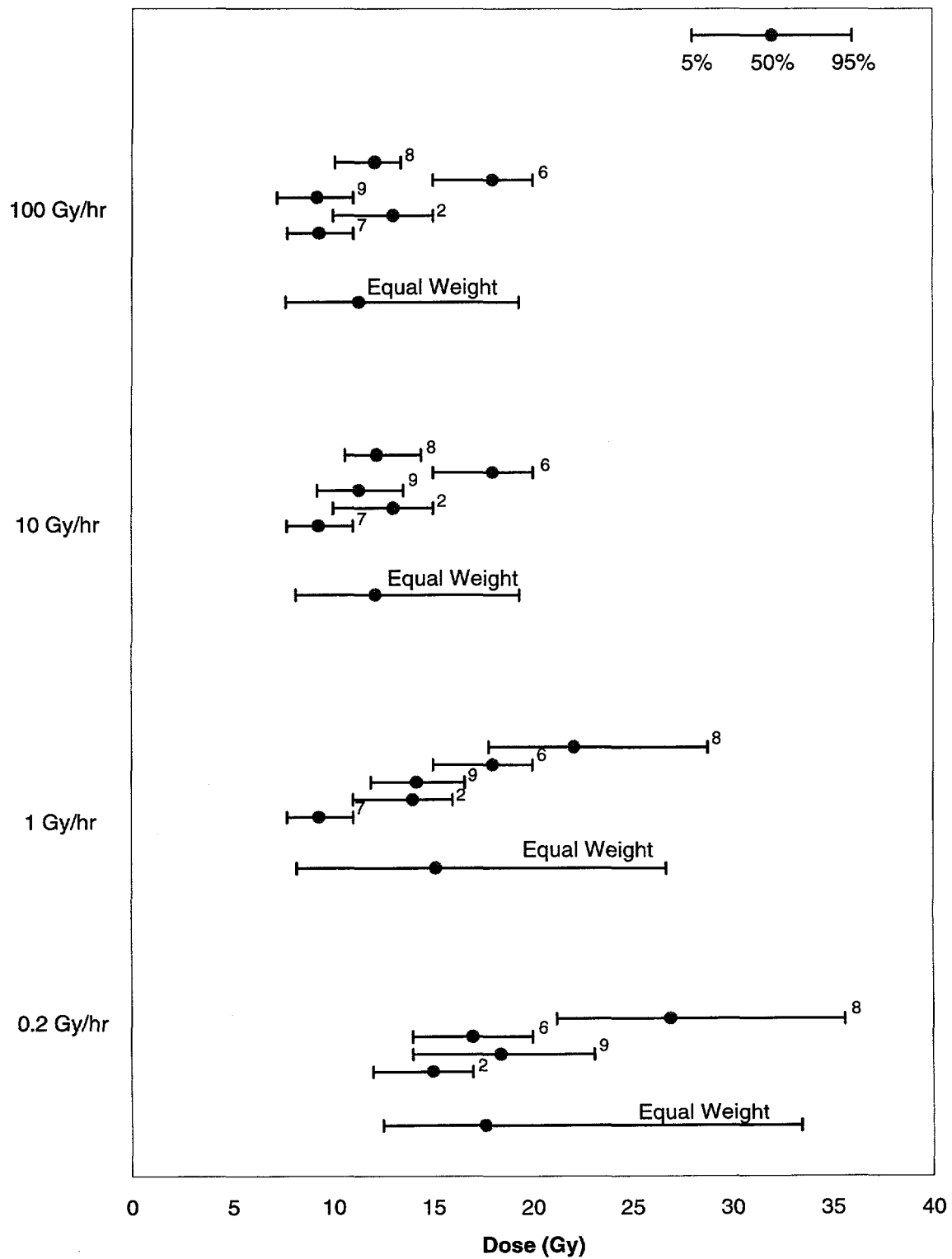


Figure 4.7b. LD<sub>50</sub> for gastrointestinal syndrome, supportive medical treatment, without growth factors.

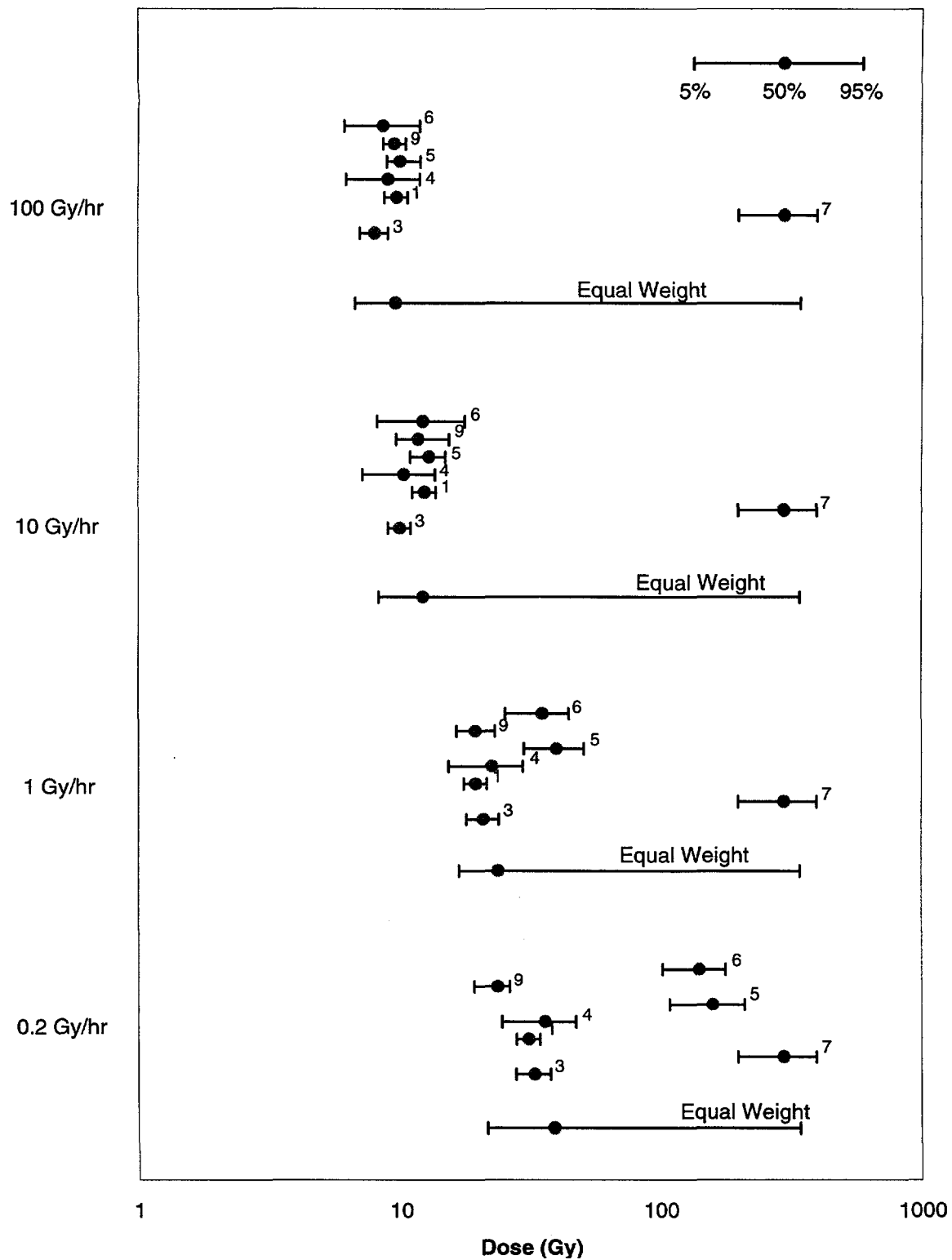


Figure 4.8. LD<sub>50</sub> for beta lung exposure.

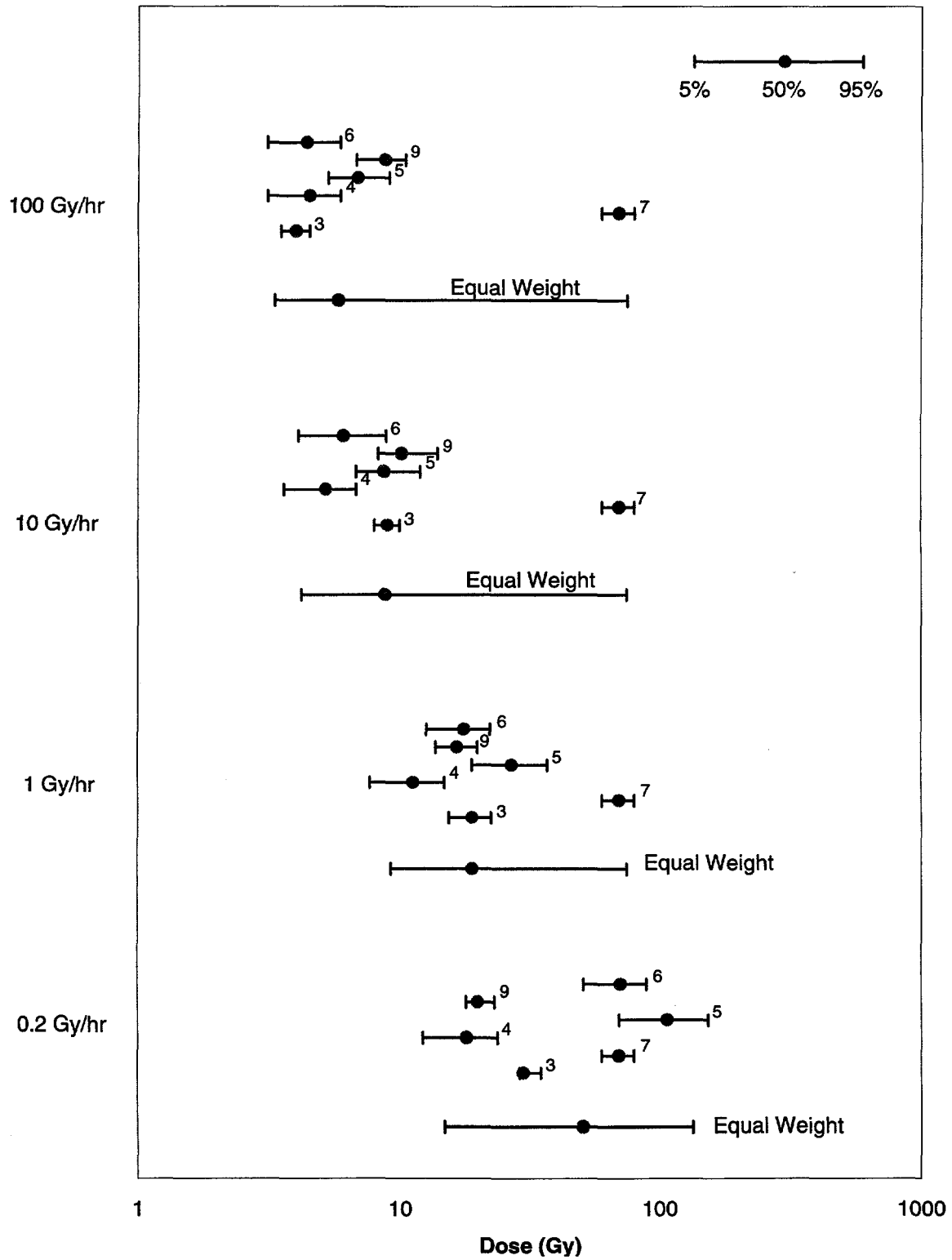


Figure 4.9. LD<sub>50</sub> for morbidity due to beta lung exposure.

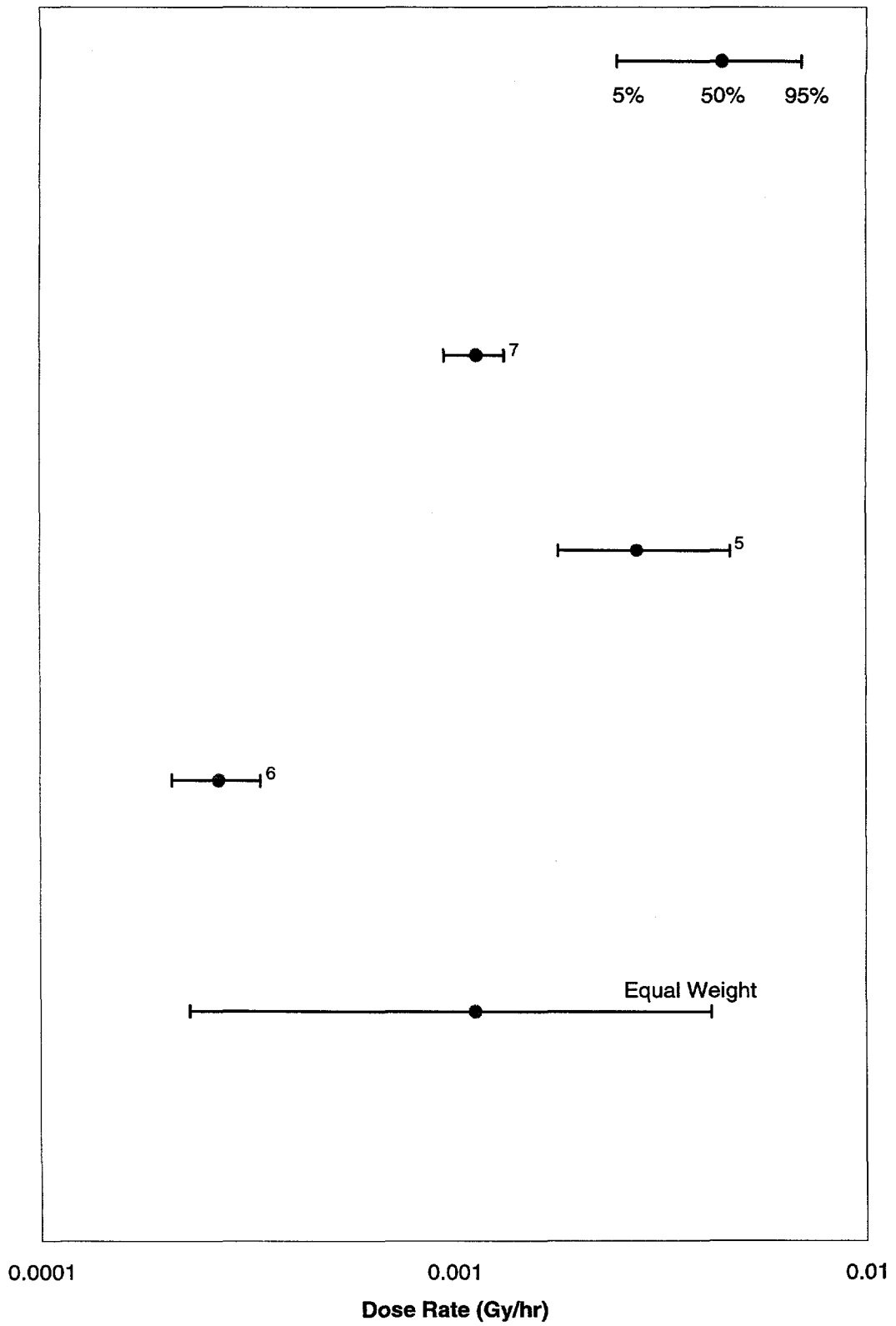


Figure 4.10. LD<sub>50</sub> for alpha lung exposure.



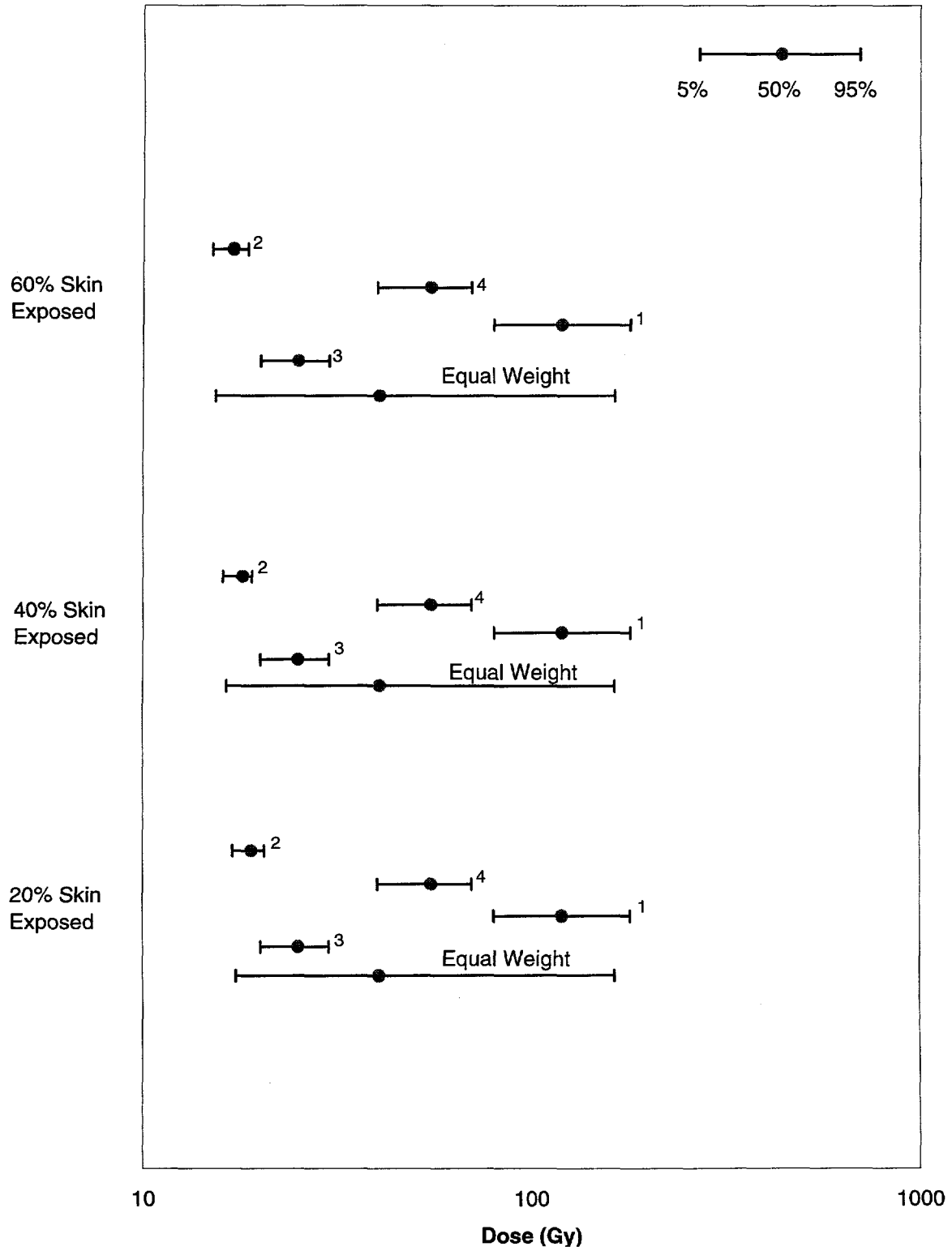


Figure 4.11. Threshold for acute ulceration from 24-hour beta skin dose.

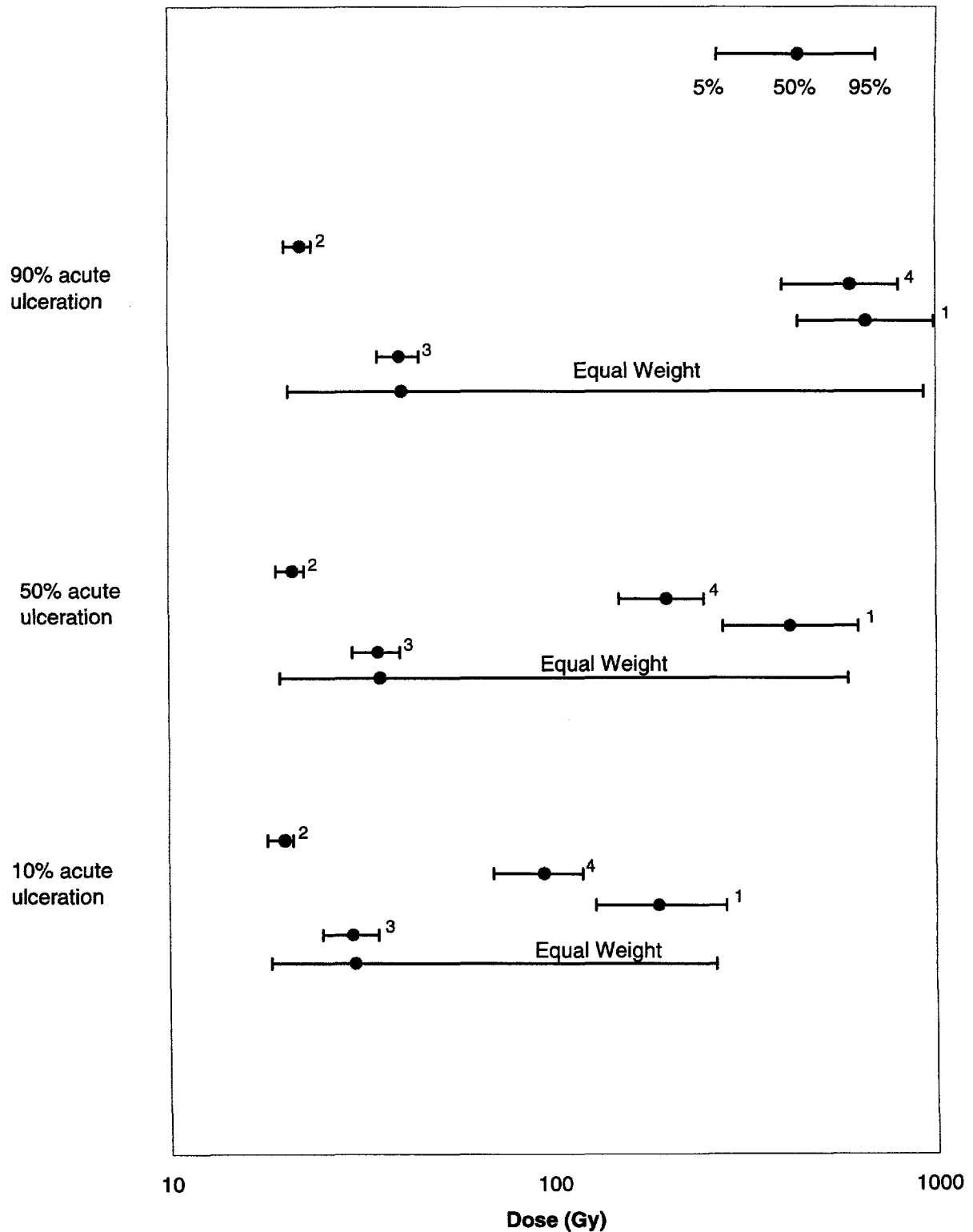


Figure 4.12. 24-hour beta skin dose for acute ulceration in specified fraction of exposed skin (40% of total skin exposed), supportive medical treatment.

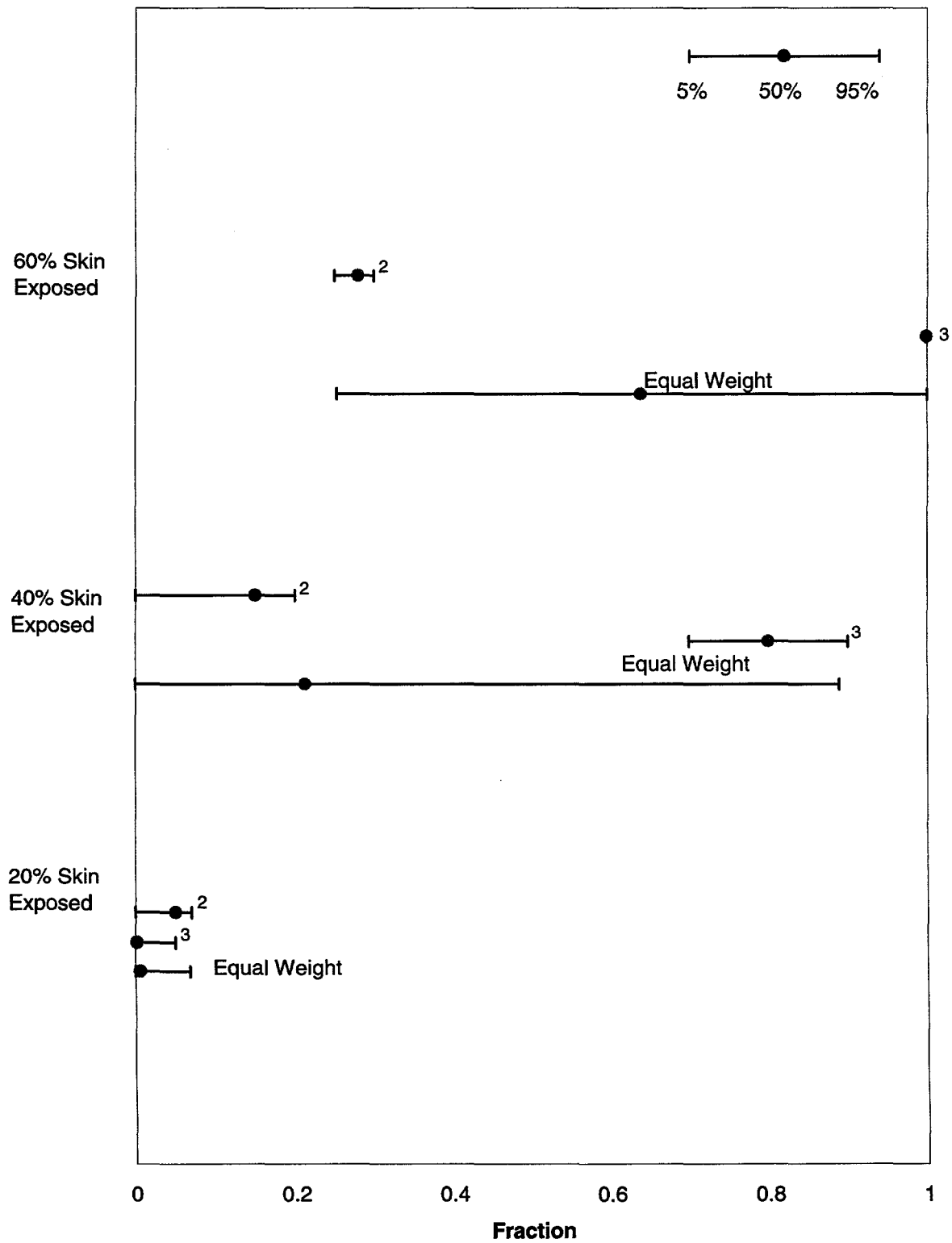


Figure 4.13. Fraction that die from 50% acute ulceration of exposed skin following 24-hr beta skin dose.

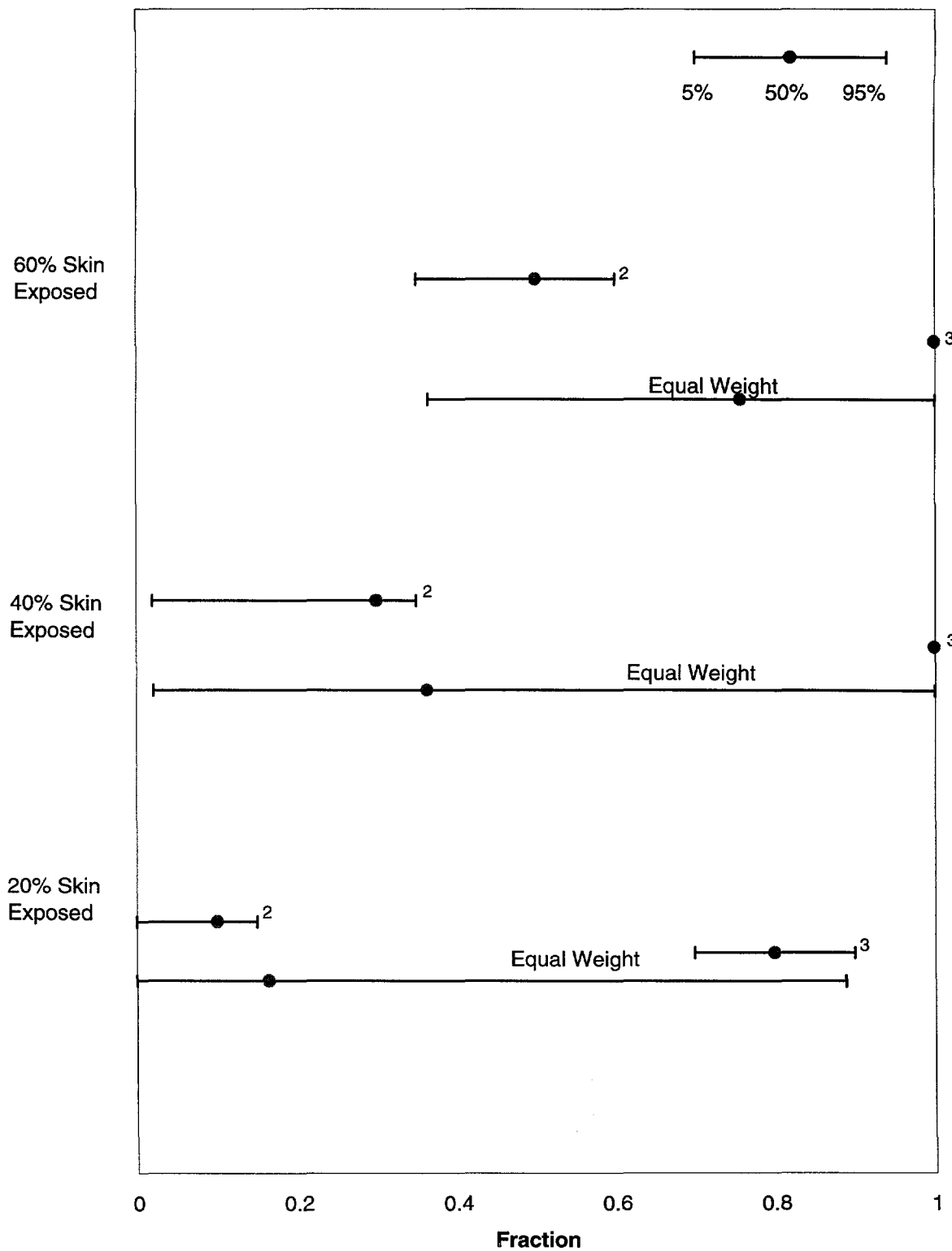


Figure 4.14. Fraction that die from 90% acute ulceration of exposed skin following 24-hr beta skin dose.

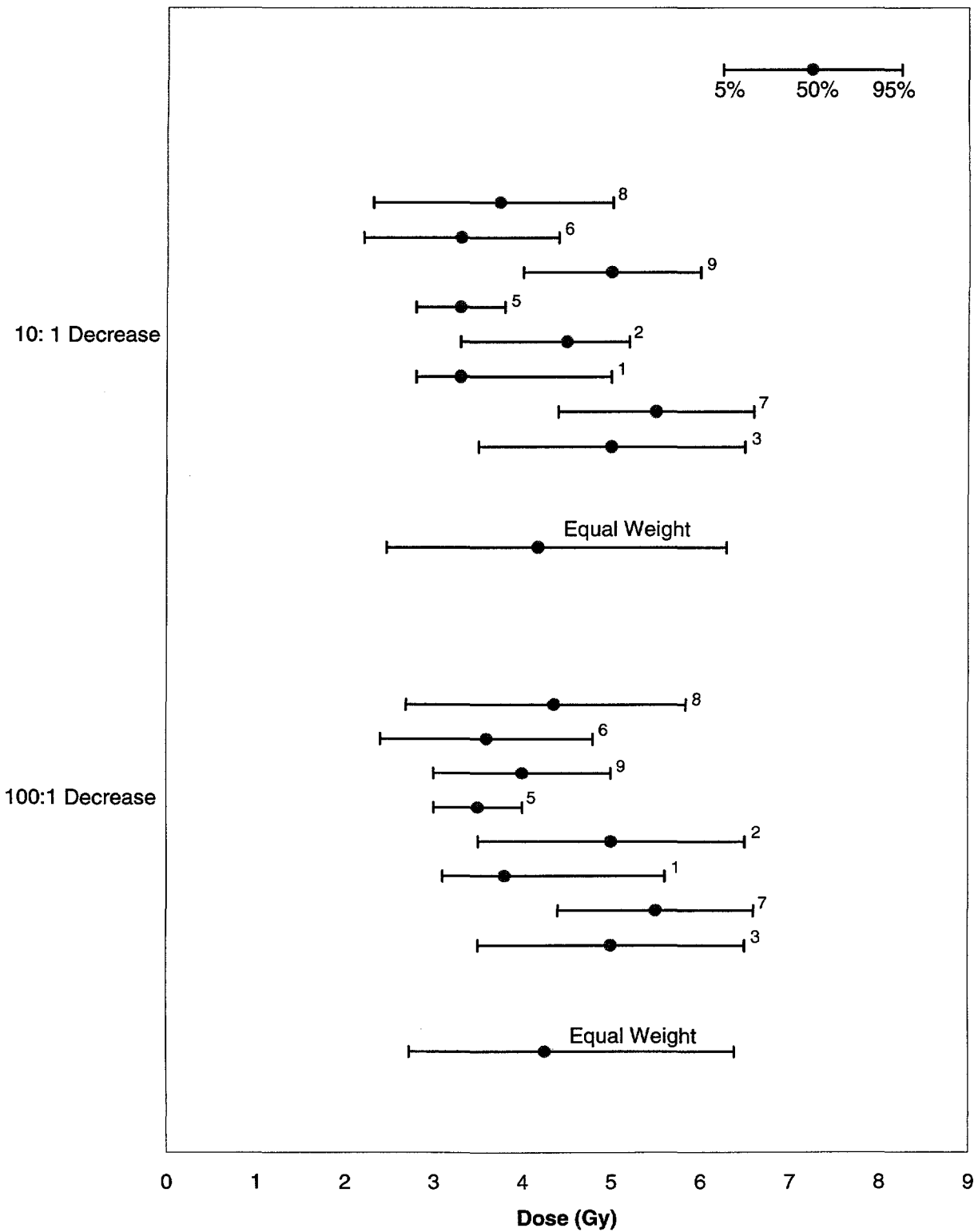


Figure 4.15a. LD<sub>50</sub> for two-step 24-hour whole-body gamma dose, 10:1 and 100:1 relative dose rates, minimal medical treatment.

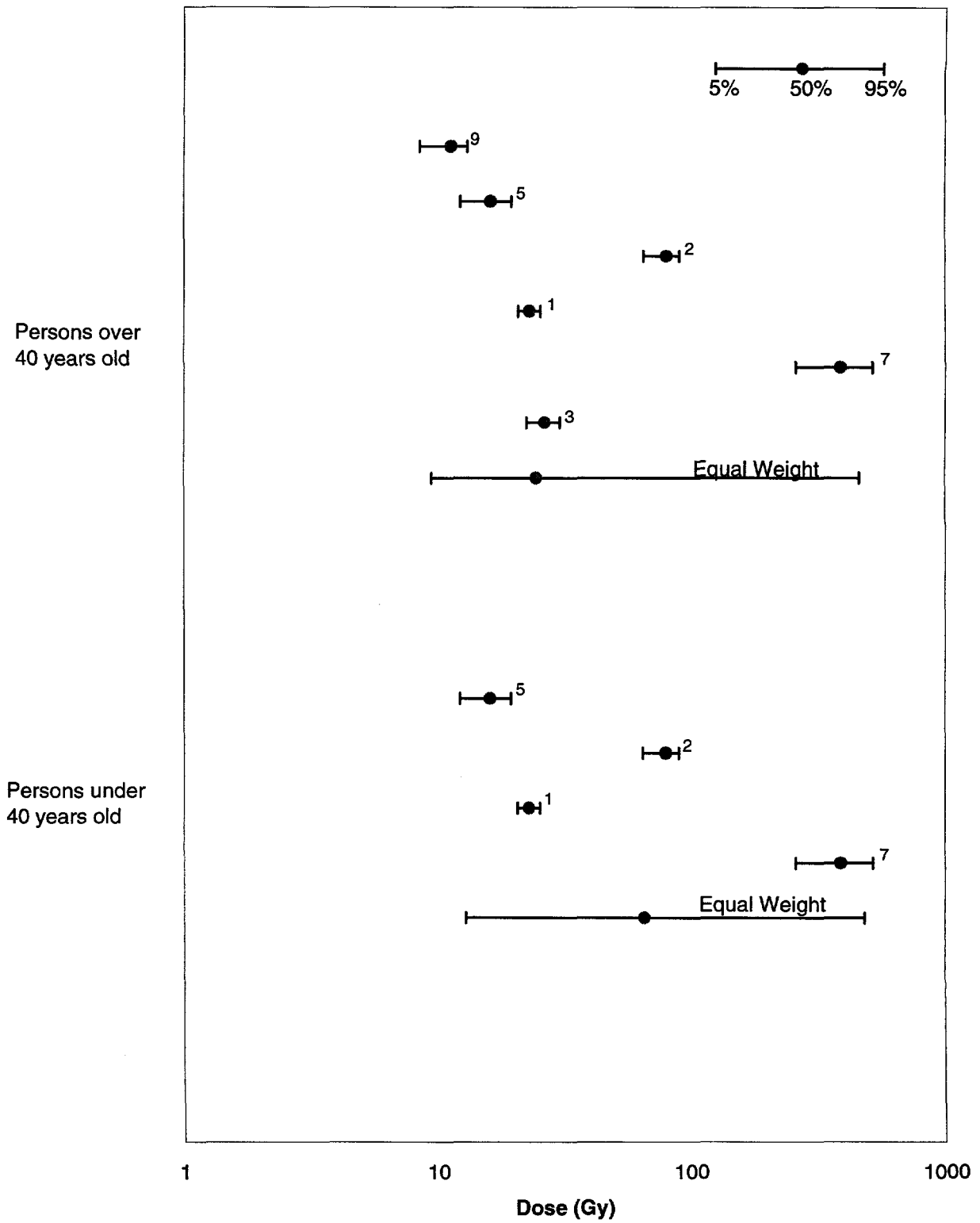


Figure 4.15b. LD<sub>50</sub> for two-step 7-day beta lung dose 14:1 relative dose rates by age groups supportive medical treatment.

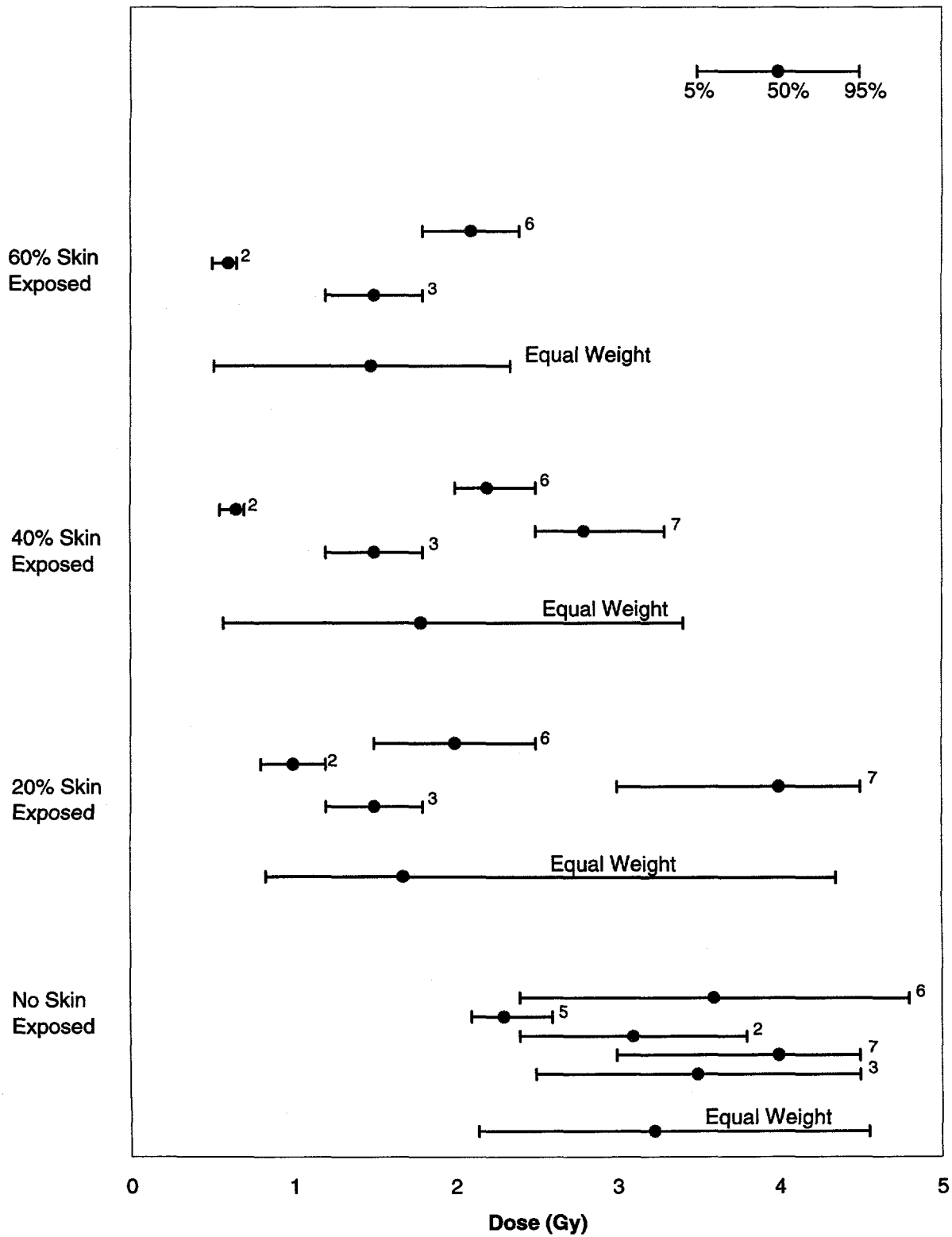


Figure 4.16. LD<sub>50</sub> red marrow dose for composite exposure:  $D_{LU} = 2D_{RM}$ ,  $D_{SK} = 21D_{RM}$ , minimal medical treatment..

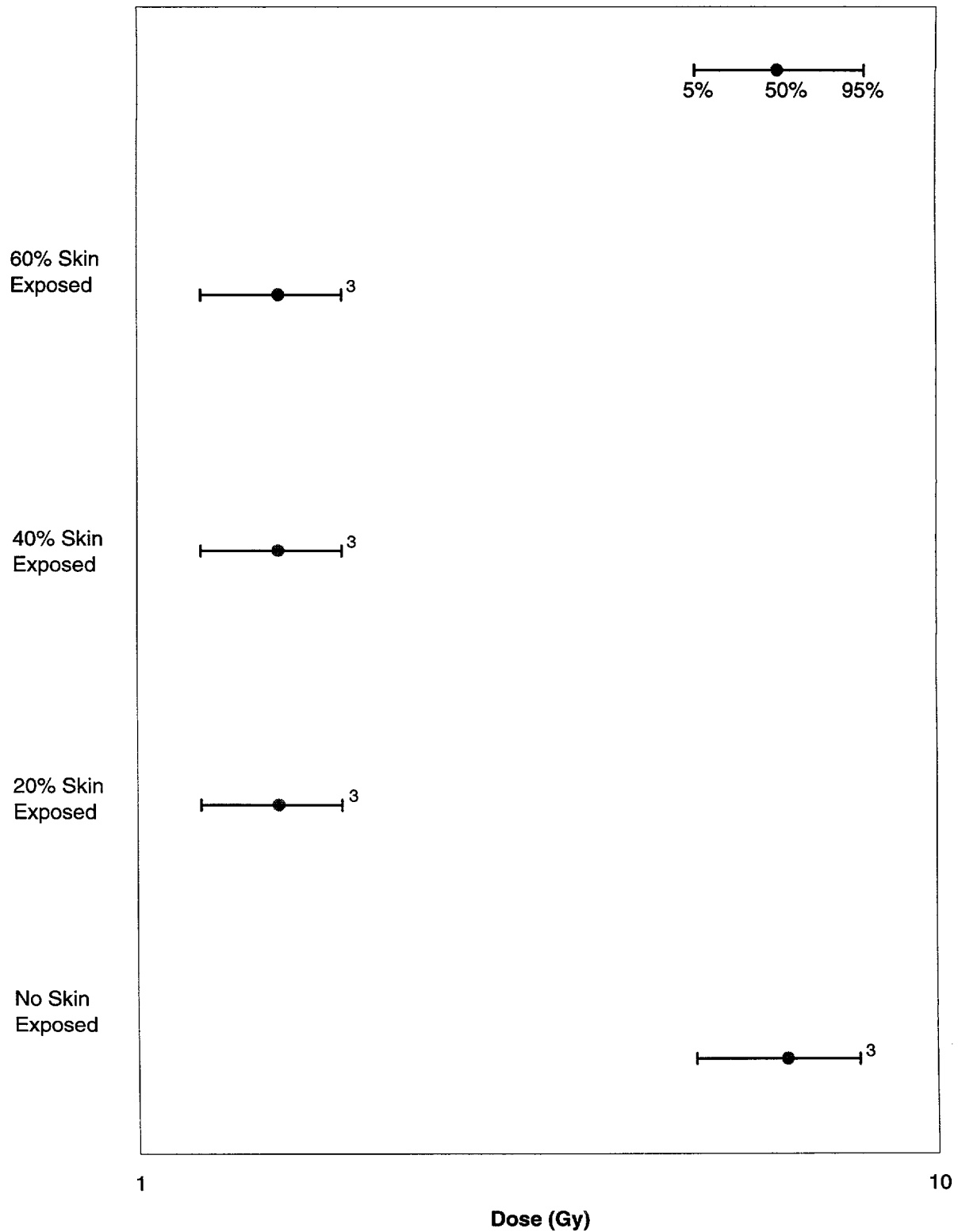


Figure 4.17a. LD<sub>50</sub> red marrow dose for composite exposure:  $D_{LU} = 2D_{RM}$ ,  $D_{SK} = 21D_{RM}$ , supportive medical treatment, with growth factors.



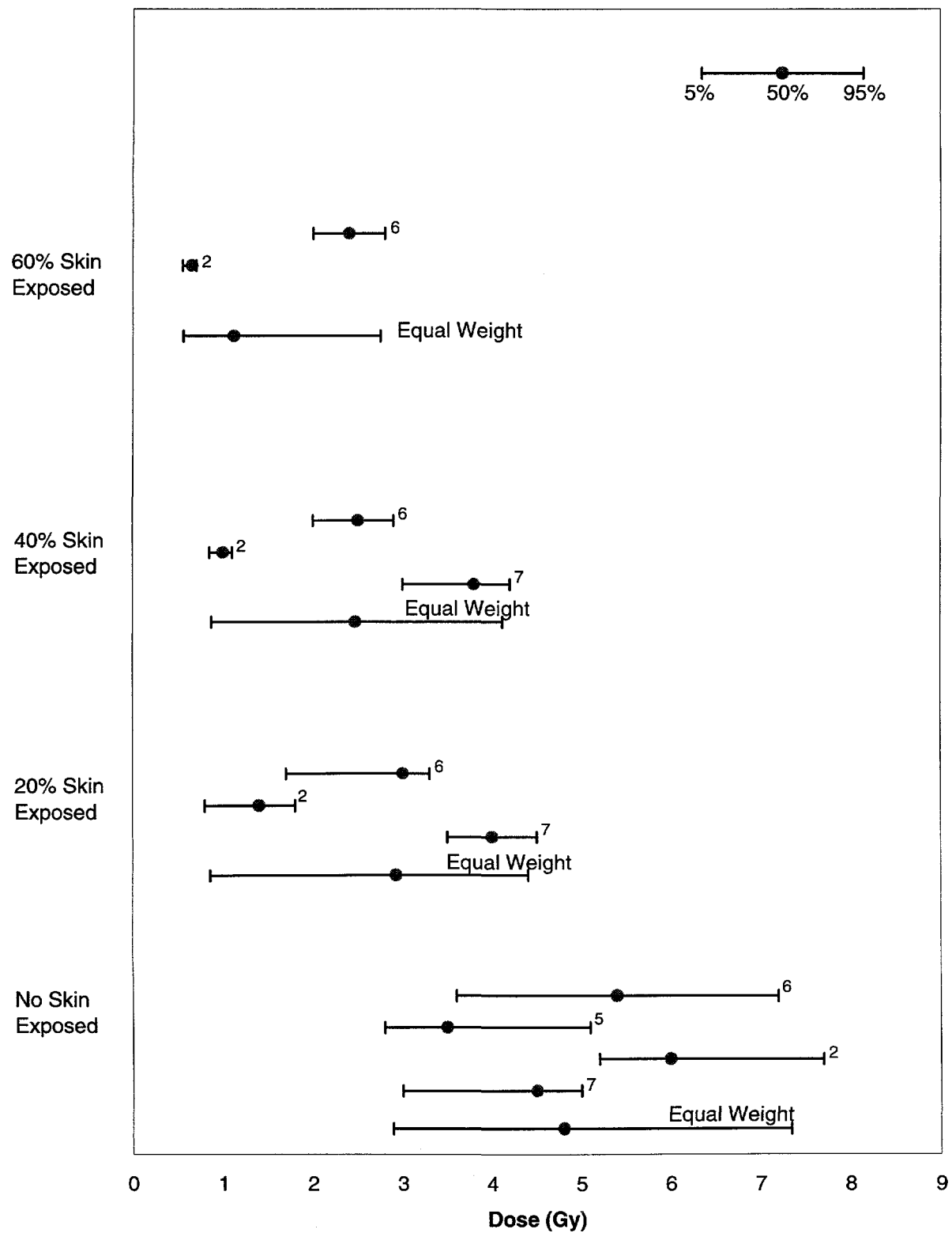


Figure 4.17b. LD<sub>50</sub> red marrow dose for composite exposure:  $D_{LU} = 2D_{RM}$ ,  $D_{SK} = 21D_{RM}$ , supportive medical treatment, without growth factors.

## 5. Summary and Conclusions

### 5.1 Project Accomplishments

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

Distributions on early health effects parameters were successfully elicited from distinguished experts. Aggregated distributions, developed by combining the individual elicited distributions, are now available. The aggregated distributions represent state-of-the-art knowledge in a form suitable for use in performing consequence uncertainty analyses. The individual and composite distributions are available on computer media and can be obtained from the project staff.

### 5.2 Uncertainty Included in Distributions

The distributions elicited from the experts concern conceptually measurable quantities, conditional on the case structures provided to the experts. The radiological exposure pathways considered in the case structure are ones that would arise in postulated accidents at nuclear facilities. In order for the experts to quantify parameters such as  $LD_{50}$  for specific early health effects, some scenarios had to emphasize the potential for exposure by one pathway to the exclusion of others.

The experts were not directed to use any particular modeling approach but were allowed to use whatever data, models, tools, and perspectives they considered appropriate for the problem. The elicited distributions were developed by the experts from a variety of information sources. The aggregated elicited distributions, therefore, include variations that result from different modeling approaches and perspectives.

Mathematical processing of the aggregated elicited data was not necessary for the distributions of thresh-

old,  $LD_{10}$ ,  $LD_{50}$ , and  $LD_{90}$  doses. Since the early health effects models are implemented differently in COSYMA and MACCS, other early health effects parameters such as Weibull shape parameters, will be processed separately for COSYMA and MACCS applications.

### 5.3 Application of Distributions

The results of this project will allow the uncertainties in early health effect parameters to be treated in a manner consistent with the NUREG-1150 methodology. The risk integration step in the NUREG-1150 methodology (the step in which the uncertainty in all modules of the analyses was assessed) relied on Latin hypercube sampling (LHS) techniques. Distributions of threshold,  $LD_{10}$ ,  $LD_{50}$ , and  $LD_{90}$  doses 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 early health effects model. However, different processing techniques may be required to modify the elicited distributions into distributions that are compatible with different models. The distributions obtained here will be utilized in both COSYMA and MACCS uncertainty studies. In many cases, a different approach will be needed for MACCS than for COSYMA.

The methods of this project were also consistent with the NUREG-1150 philosophy because all modeling perspectives are included, and a consensus among the experts was not required. Although this project focused on the development of distributions for MACCS and COSYMA input variables, the elicited information is not specific to a model. The development of distributions over physically measurable parameters means that the distributions may have applications beyond the scope of the current project. The distributions also provide insights regarding areas where current early health effects models are deficient, and they can be a useful guide for directing future research.

### 5.4 Conclusions

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

thesizing the best available information by a highly qualified group.

With a thoughtfully designed elicitation approach that addresses such issues as selection of elicitation variables, development of case structures, probability training, communication between the experts and proj

ect staff, and documentation of the results and rationale—followed by an appropriate application of the elicited information—expert judgment elicitation can play an important role. Indeed, it may be the best method available for assembling the required information when existing data are ambiguous, controversial, inconclusive, or only partially relevant.

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F.E. Haskin (UNM), F.T. Harper (SNL), L.H.J. Goossens (TUD),  
B.C.P. Kraan (TUD), J.B. Grupa (NERF)

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10. SUPPLEMENTARY NOTES

J. Randall, NRC Project Manager

11. ABSTRACT (200 words or less)

The development of two new probabilistic accident consequence codes, MACCS and COSYMA, was completed in 1990. These codes estimate the consequences 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 early health effects models.

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uncertainty analysis, early health effects, radiological health effects, deterministic health effects, accident consequence analysis, nuclear accident analysis, probabilistic analysis, expert elicitation, MACCS, COSYMA, consequence uncertainty analysis

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