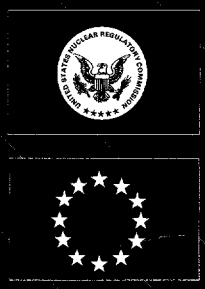
Probabilistic Accident Consequence Uncertainty Analysis

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



NUREG/CR-6555, Vol. 2

Late Health Effects Uncertainty Assessment

Volume 2 Appendices

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Abstract

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

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

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

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

Contents

Preface

This volume is the second of a two-volume document that summarizes the results of one phase of a joint project conducted by the US Nuclear Regulatory Commission and the European Commission to assess uncertainties in the MACCS and COSYMA probabilistic accident consequence codes. These codes were developed primarily for estimating the risks presented by radionuclide releases from hypothetical nuclear power plant accidents, based on postulated frequencies and magnitudes of potential accidents. A panel of ten experts was formed to compile credible and traceable uncertainty distributions for late health effects variables that affect calculations of offsite consequences. The expert judgment elicitation procedure and its outcomes are described in this volume. 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, (3) the rationales and results for the expert panel on late health effects, (4) short biographies of the experts, and (5) the aggregated results of their responses.

Acknowledgments

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

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List of Acronyms

AA	attained age
AAE	age at exposure
ASS	British ankylosing spondylitis study
BEIR	Committee on Biological Effects of Ionizing Radiation
CI	confidence intervals
DDREF	dose and dose rate effectiveness factor
DS86	Dosimetry System of 1986
EAR	excess absolute risk
ELR	excess lifetime risk
ERR	excess relative risk
ICRP	International Commission on Radiological Protection
LEOF	linear extrapolation overestimation factor
LET	linear energy transfer
LSS	Life Span Study
NM	non-melanoma
NRPB	National Radiation Protection Board
OSCC	Oxford Study of Childhood Cancers
PSv	person sievert
RBE	relative biological effectiveness
REIC	risk of radiation-induced cancer
REID	risk of exposure-induced death
RERF	Radiation Effects Research Foundation
RR	relative risk
TSE	time since exposure
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
UV	ultraviolet
WR	radiation weighting factors

APPENDIX A

Summary of the MACCS and COSYMA Consequence Codes

Summary of the MACCS and COSYMA Consequence Codes

Introduction

The information developed in this study will be used to perform uncertainty studies using the European Commission (EC) consequence code COSYMA and the US Nuclear Regulatory Commission (USNRC) code MACCS. COSYMA and MACCS model the offsite consequences of postulated severe reactor accidents that release a plume of radioactive material to the atmosphere. These codes model the transport and deposition of radioactive gases and aerosols into the environment and the potential resulting human health and economic consequences. They calculate the health effects, impact of countermeasures and economic costs of the releases. The processes considered in the calculations, and the routes of exposure following accidental releases to atmosphere, are illustrated in Figure A-1. The calculations are divided into a number of steps, illustrated in Figure A-2. COSYMA and MACCS are modular codes, with different modules addressing the different stages of the calculation. However, while Figure A-1 illustrates the steps in the calculation, the modules of the codes do not correspond exactly with the boxes shown.

The following sections give brief descriptions of the COSYMA and MACCS codes.

Brief Description of MACCS and COSYMA Dispersion and Deposition Models

COSYMA and MACCS both employ a Gaussian plume model (GPM) for atmospheric dispersion. At a given downwind distance and given atmospheric conditions, the Gaussian model predicts the time-integrated concentration at various horizontal and vertical displacements from the center-line of the plume. When the plume is not constrained by the ground or the inversion layer, the basic Gaussian plume equation for determining the concentration relative to the release rate is:

$$\frac{\chi}{Q} = \frac{1}{2\pi\sigma_y\sigma_z\overline{U}} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \exp\left(-\frac{(z-h)^2}{2\sigma_z^2}\right)$$

where:

χ = time-integrated air concentration,
Q = the source strength,
y = the horizontal displacement relative to the plume centerline,
z = the vertical displacement,
h = the vertical height of the plume centerline,
$\overline{U}$ = the average wind velocity, and
σ_y and σ_z are plume expansion parameters.

In MACCS and COSYMA, the plume expansion parameters, σ_y and σ_z, are modeled by the following power law:

$$\sigma_y = a_y x^{b_y} \; ; \; \sigma_z = a_z x^{b_z}$$

where x = the downwind distance from the plume release point.

Currently, constant values for a_y, b_y and a_z, b_z are provided in the codes. The values for the parameters are determined by the atmospheric stability class and the roughness length of the terrain.

Two types of deposition are modeled in the MACCS and COSYMA codes: wet and dry. Dry deposition incorporates removal from the plume by diffusion, impaction, and settling; it is modeled through a dry deposition velocity, which is a user input. The dry deposition velocity depends on particle size; therefore, if the aerosol size distribution is divided into ranges, a dry deposition velocity must be specified for each range. The washout of radioactive material from the plume, wet deposition, is modeled as dependent on the rain intensity. The fraction of material, f_w, that remains in the plume is given by:

$$f_w = \exp\left\{-a\, I^b\, \Delta t\right\}$$

where I is the rain intensity and Δt is the amount of time the plume is exposed to the rain. The parameters a and b are the user-specified parameters that determine the amount of material washed from the plume as a result of rain intensity. Rainout, in which droplets nucleate on the aerosol particles, is not modeled.

Summary of the MACCS Radiological Consequence Code

The MACCS code was originally developed under NRC sponsorship to estimate the offsite consequences of

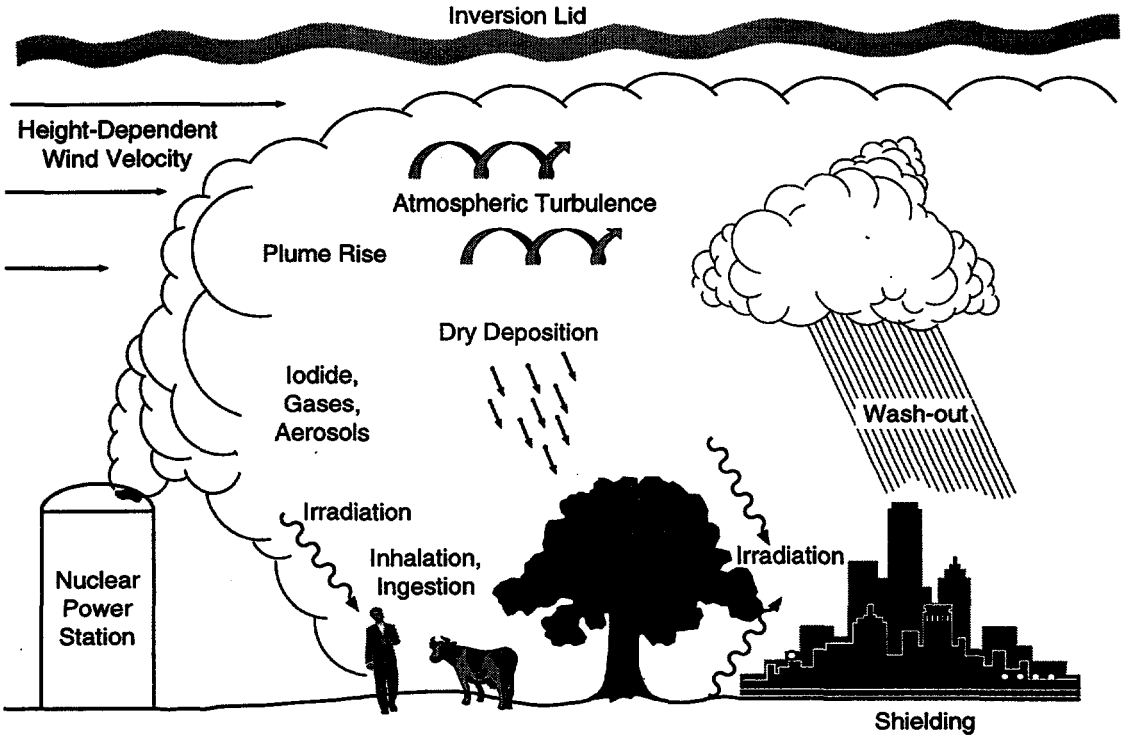

Figure A-1. Dispersion and deposition phenomena considered in an accident consequence analysis.

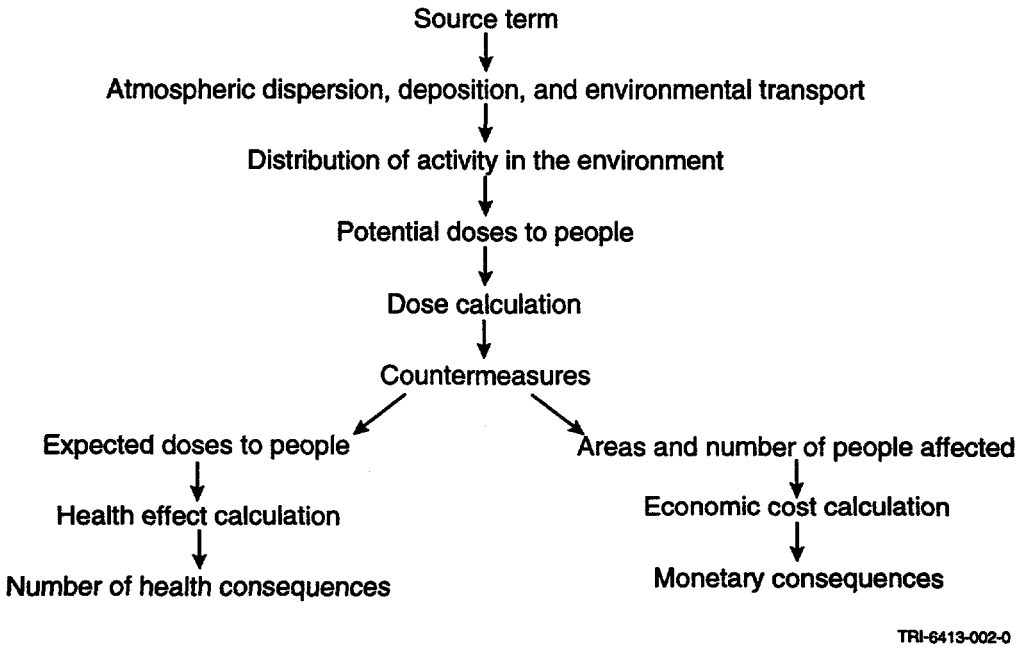

Figure A-2. Basic features and relationships of an accident consequence analysis.

potential severe accidents at nuclear power plants by using meteorological data that vary on an hourly basis. The code models the transport and dispersion of plumes of radioactive material released from the facility to the atmosphere. As the plumes travel through the atmosphere, material may be deposited on the ground via wet and dry deposition processes. There are seven pathways through which the general population can be exposed: cloudshine, groundshine, direct inhalation, resuspension inhalation, ingestion of contaminated food, ingestion of contaminated water, and deposition on skin. Emergency response and protective action guides for both the short and long term are also considered as means for mitigating the extent of the exposures. As a final step, the economic costs that would result from the mitigative actions are estimated. Variability in consequences as a result of weather may be obtained in the form of a complementary cumulative distribution function.

MACCS is organized into three modules. The ATMOS module performs the atmospheric transport and deposition portion of the calculation. The EARLY module estimates the consequences of the accident immediately following the incident (usually within the first week), and the CHRONC module estimates the long-term consequences of the accident. A schematic representation of these modules and the input files that provide information to them is shown in Figure A-3. The following sections describe the phenomena modeled in MACCS in more detail.

Atmospheric Dispersion and Transport

The release of radioactive materials to the atmosphere can be divided into successive plume segments, which can have different compositions, release times, durations, release heights, and amounts of sensible heats. The plume segment lengths are determined by the product of the segment's release duration and the average windspeed during release. The initial vertical and horizontal dimensions of each plume segment are user-specified.

A lift-off criterion based on a critical windspeed determines whether or not a plume is subject to buoyant plume rise. Momentum plume rise is not modeled. If the windspeed at release is greater than the critical windspeed, plume rise is prevented.

After release from the facility, windspeed determines the rates at which plume segments transport in the downwind direction, and the wind direction at the time of release determines the direction of travel. MACCS neglects wind trajectories, as do most other consequence codes. Sixteen compass-sector population distributions are assumed to constitute a representative set of downwind exposed populations. The exposure probability of each of the 16 compass-sector population distributions is assumed to be given by the frequency with which the wind blows from the site into the sector. During transport, dispersion of the plume in the vertical and horizontal directions is estimated using an empirical model, the GPM. In this model, dispersion depends on atmospheric stability and windspeed. Horizontal dispersion of the plume segments is unconstrained. However, vertical dispersion is bounded by the ground and by the mixing layer, which are both modeled as totally reflecting layers. A single value for the mixing layer is specified by the user for each season of the year and is constant during a calculation. Eventually the vertical distribution of each plume segment becomes uniform and is so modeled.

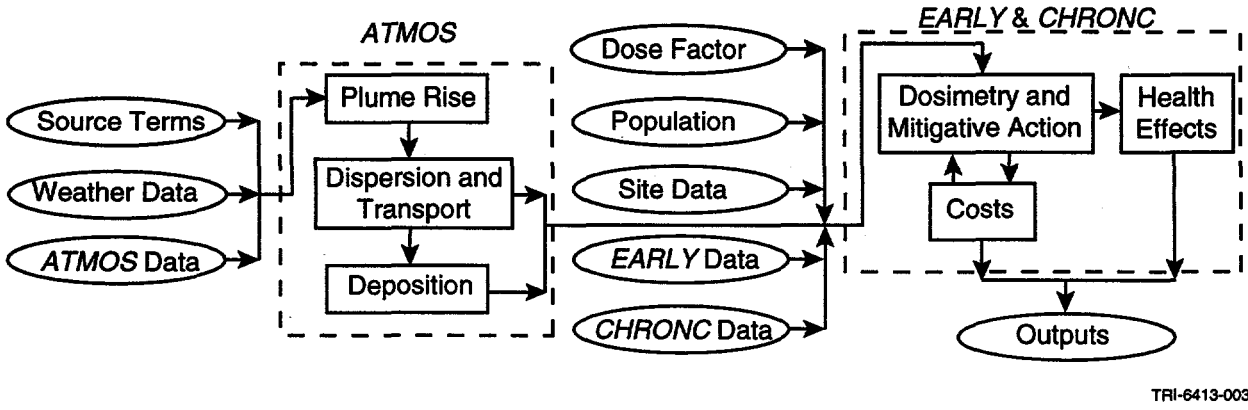

Figure A-3. Progression of a MACCS consequence calculation.

Deposition, Weathering, Resuspension, and Decay

As noted earlier, two types of deposition are modeled in MACCS: wet deposition and dry deposition. Weathering, resuspension, washoff, and radioactive decay decrease the deposited concentrations of radioactive materials. Radioactive decay treats only first generation daughter products.

Weather

Plume rise, dispersion, downwind transport, and deposition depend on the prevailing meteorological conditions. These conditions can be modeled as time-invariant or as varying hour-by-hour. If they are modeled as variable, the user may specify them directly or through an input file.

Dosimetry

The MACCS dosimetry model consists of three interacting processes: (1) the projection of individual exposures to radioactive contamination for each of the seven exposure pathways modeled over a user-specified time, (2) mitigation of these exposures by protective-measure actions, and (3) calculation of the actual exposures incurred after mitigation by protective-measure actions. For each exposure pathway, MACCS models the radiological burden for the pathway as reduced by the actions taken to mitigate that pathway dose. The total dose to an organ is obtained by summing the doses delivered by each of the individual pathways.

Dose Mitigation

The time after accident initiation is divided into three phases: (1) an emergency phase, (2) an optional intermediate phase, and (3) a long-term phase. During the emergency phase, which can last up to seven days, doses are reduced by evacuation, sheltering, and temporary relocation of people. During the intermediate phase, doses may be avoided by temporary relocation of people. During the long-term phase, doses are reduced by decontamination of property that is not habitable, by temporary interdiction of property that cannot be restored to habitability by decontamination alone, by condemnation of property that cannot be restored to habitability at a cost below or equal to the worth of the property, by disposal of contaminated crops, and by banning farming on contaminated farmland.

Exposure Pathways

MACCS models seven exposure pathways: (1) exposure to the passing plume (cloudshine), (2) exposure to materials deposited on the ground (groundshine), (3) exposure to materials deposited on skin, (4) inhalation of materials directly from the passing plume (inhalation), (5) inhalation of materials resuspended from the ground by natural and mechanical process (resuspension inhalation), (6) ingestion of contaminated foodstuffs (food ingestion), and (7) ingestion of contaminated water (water ingestion). Ingestion doses do not contribute to the doses calculated for the emergency phase of the accident. Only groundshine and inhalation of resuspended materials produce doses during the optional intermediate phase of the accident. Long-term doses are caused by groundshine, resuspension inhalation, water ingestion, and food ingestion. Ingestion of contaminated food or water generates doses to people who reside at unknown locations both on and off of the computational grid.

Population Cohorts

People on the computational grid are assigned to three groups: (1) evacuees, (2) people actively taking shelter, and (3) people who continue normal activities. Shielding factors for each of the groups are specified by the user.

Health Effects

Health effects are calculated from doses to specific organs using dose conversion factors. Early injuries and fatalities (those occurring within one year of the accident) are estimated using nonlinear dose-response models. Latent cancers are estimated using a piecewise linear dose-response model that is discontinuous. Two equations are implemented in the code, one for high exposures and one for low exposures.

Economic Effects

Economic consequences result from the implementation of mitigative actions. The following costs are considered in this estimate: (1) evacuation costs, (2) temporary relocation costs, (3) costs of decontaminating land and buildings, (4) lost return-on-investments from temporarily interdicted properties, (5) value of crops destroyed or not grown, and (6) value of condemned property. Costs associated with damage to the reactor, the purchase of replacement power, medical care, life-shortening, and litigation are not considered.

Summary of COSYMA Radiological Consequence Code

COSYMA was developed by the National Radiological Protection Board (NRPB) of the UK and Forschun–

gszentrum Karlsruhe (FZK) of Germany, as part of the European Commission's MARIA project (FZK and NRPB, 1991). It represents a fusion of ideas from the NRPB program MARC (Hill et al., 1988), the FZK program system UFOMOD (Ehrhardt et al., 1988) and input from other MARIA contractors. The program package was first made available in 1990 for use on mainframe computers, and several updates have been released since then. A PC version was first released in 1993 and has since been updated (Jones et al., 1995).

COSYMA is a system of programs and data bases, rather than a single program. The mainframe version contains three main accident consequence assessment programs together with a number of preprocessing and evaluation programs. The three main sub-systems of COSYMA are known as the NE, NL, and FL sub-systems (Figure A-4). The NE (near, early) sub-system is limited to calculating early health effects and the influence of emergency actions to reduce those effects and applies to the region near the accident site. The NL (near, late) subsystem is limited to calculating late health effects and the associated countermeasures, and applies mainly to the region near the site. The FL (far, late) sub-system calculates late health effects and appropriate countermeasures at greater distances from the site. Each of these programs is subdivided into a series of modules for the various steps in the calculation.

PC COSYMA incorporates the NE and NL sub-systems of the mainframe version.

The main endpoints of COSYMA are the numbers of health effects, the impact of countermeasures, and the economic costs resulting from the accidental release. A large number of intermediate results are obtained in the process of calculating the major endpoints; these results include activity concentrations, individual and collective doses, and the countermeasures assumed at different locations. COSYMA contains a series of evaluation programs that allow these results to be presented in a variety of ways.

Following an accidental release to atmosphere, people can be irradiated by a number of exposure paths. Those considered in COSYMA are cloudshine, groundshine, exposure to materials deposited on skin, direct inhalation of plume material, inhalation of resuspended materials, and ingestion of contaminated foods.

COSYMA includes some models directly within the various modules or subsidiary programs, such as atmospheric dispersion models. In other cases, COSYMA uses data libraries giving the results of other models which are not part of COSYMA itself, but whose uncertainty is considered within the current study.

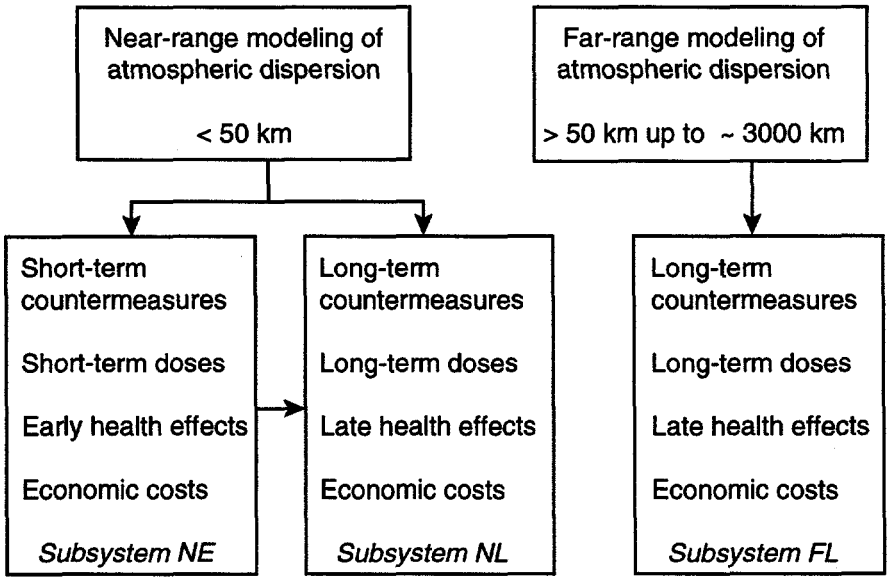

Figure A-4. General structure of the COSYMA program system.

Atmospheric dispersion and deposition

Mainframe COSYMA contains five different models of atmospheric dispersion that are appropriate for different applications or are based on different assumptions and approximations (Panitz et al., 1989).

The NE and NL sub-system include the MUSEMET (Straka et al., 1981) model, originally written at Forschungsanlage Julich and extensively modified at FZK for use with COSYMA. This is a segmented Gaussian plume model allowing for changes of atmospheric conditions and wind direction during plume travel. This model derives the sequences of atmospheric conditions affecting the plume from hourly averages for wind speed and direction, stability category, precipitation intensity and mixing layer depth. It allows for the effects on the subsequent dispersion of plume rise and buildings near the release point. It also includes the effects of wet and dry deposition of the dispersing material. This model is also included in PC COSYMA.

The NE and NL sub-systems can also be used with the COSGAP or RIMPUFF dispersion models, which are provided as separate programs. COSGAP (Jones and Charles, 1982) is a Gaussian plume dispersion model, which is similar to MUSEMET but does not consider changes of wind direction during plume travel. It is based on the dispersion model in MARC. RIMPUFF (Mikkelsen et al., 1984), developed by Risø National Laboratory, Denmark, is a Gaussian puff trajectory model which derives the atmospheric conditions affecting the plume by interpolating between data from a number of meteorological stations in the region of interest.

The NL sub-system also contains the ISOLA (Hübschmann and Raskob) model for very long release durations. This uses statistics of atmospheric conditions and is only appropriate for releases that are sufficiently small that no countermeasures and no early health effects would be expected.

The FL sub-system is linked to the Mesos model (ApSimon and Goddard, 1983), developed by Imperial College, UK. This is a trajectory model for dispersion over long distances using meteorological data for a large area, such as the whole of Europe.

Accident consequence assessment programs need to consider that the accident could occur in any of a wide range of atmospheric conditions. It is not possible to calculate the consequences for every sequence of conditions that might arise, so a method of sampling a representative set of conditions from those possible is needed. Both the mainframe and PC versions of COSYMA include a flexible program to conduct this sampling.

Dose calculations

As stated earlier, COSYMA does not include dosimetric models but uses information from data libraries which are calculated with these models. The libraries include information on doses from 197 nuclides.

The data library used for calculating external exposure from activity deposited on the ground contains outdoor doses per unit deposit for a series of times. These doses are mitigated by location factors describing the reduction in exposure due to shielding by buildings. The library is drawn from a number of sources, using results of models developed at NRPB (Charles et al., 1982; Crick and Brown, 1990) and Forschungszentrum für Umwelt und Gesundheit (GSF) (Jacob et al., 1988), Germany. The doses for major contributing nuclides in a fission reactor accident are derived from a model describing the deposition patterns in urban areas and the subsequent transfer of material between the different surfaces.

The doses from internal irradiation following ingestion or inhalation are calculated using data libraries of dose per unit intake derived using models which are consistent with those in International Commission on Radiological Protection (ICRP) publications 56, 67 and 69 (ICRP, 1990, 1994, 1995). COSYMA requires information on the dose received during different periods after the accident, which is included in the data libraries. Because the method used for calculating doses and risks of health effects in the mainframe version of COSYMA allows for the variation of dose per unit intake with age at intake, the libraries contain information on doses for different age groups in the population. The PC version, however, uses a simpler method which considers only the doses to adults.

Food chain models

COSYMA requires information on the concentration of material in foods as a function of time after the accident. It does not include a food chain model, but uses the results of such models through data libraries which give concentrations for a range of radionuclides in a number of foods at a series of times following unit deposition. The concentration of material in foods depends on the time of year at which the deposition occurs. COSYMA uses two data libraries for deposition in summer and in winter.

COSYMA uses libraries derived from the NRPB model FARMLAND (Brown and Simmonds, 1995) and the GSF model ECOSYS (Matthies et al., 1982). The libraries were created using accepted values for the food chain parameters for application within the EC, but differences exist because of other modeling assumptions made and because of the foods considered in each. The foods which can be considered with FARMLAND are: milk; meat and liver from cattle; pork; meat and liver from sheep; green vegetables; grain products; and potatoes and other root vegetables. The foods which can be considered with ECOSYS are: milk; beef; pork; grain products; potatoes and other root vegetables; and leafy and non-leafy green vegetables.

The intakes of these foods are calculated within COSYMA using one of two assumptions about the distribution of food between harvest and consumption. One method assumes that all food consumed is produced locally, and is used in calculating individual ingestion doses. The other method uses information on the amount of food produced in the area of interest, and calculates collective doses on the assumption that all food produced is consumed somewhere.

Countermeasures

COSYMA allows the user to consider the effects of a wide range of countermeasures in reducing the exposure of the population, and gives the user considerable freedom in specifying the criteria at which the actions will be imposed or withdrawn (Hasemann and Ehrhardt, 1994).

Sheltering alone or combined with evacuation may be implemented automatically or on the basis of dose. The distribution of iodine tablets, automatically or on the basis of dose, can also be considered. These actions are assumed to be implemented sufficiently rapidly to reduce the risks of both early and late health effects. Relocation is considered as an action to reduce doses and risks over longer time periods. It can be implemented on a dose criterion, as can return from evacuation or relocation. The effects of decontamination in reducing the period of relocation can be considered. If these actions are initiated on the basis of dose, the user can specify the intervention levels, organs and pathways to be considered, and the time over which the dose is to be integrated. The behavior of the population considered in the dose criteria can also be described using location factors.

Food bans can also be considered (Steinhauer, 1992). They can be implemented or withdrawn on the basis of doses received within specified time periods or on the basis of the instantaneous concentration of radionuclides in foods.

Health effects

COSYMA considers both early and late health effects in the population, using methods recommended by NRPB (Edwards, pers. comm; NPRB, 1993), the USNRC (Evans et al., 1990) and GSF (Paretzke et al., 1991).

The risk of early health effects is calculated using "hazard functions." The method allows for the variation of risk with the rate at which dose is accumulated over the first few days following the accident. Ten different fatal and non-fatal effects are considered.

The risk of late health effects is calculated using the linear dose response relationship. COSYMA considers the risk of fatal and non-fatal cancers in ten organs, as well as the risk of leukemia. It also considers the risk of hereditary effects. The method adopted in the mainframe version of COSYMA allows for the variation of risk with age at exposure (Ehrhardt et al., 1995). PC COSYMA uses a simpler method which only considers the doses and risks to adults. The mainframe version of COSYMA can provide information on the numbers of cancers in the people alive at the time of the accident, and in their descendants. It also gives information on the times at which the cancers occur.

Economic effects

COSYMA can calculate the off-site economic effects of the accident, considering the costs arising from the countermeasures and the costs of health effects. The assumptions and models are described in Haywood et al. (1991) and Faude (1992). The countermeasures for which costs are considered are movement of the population, food restrictions, and decontamination. The costs arising from lost production in the area from which people are moved can be assessed in terms of the per capita contribution of the relocated population to gross domestic product (GDP) or in terms of the value of the land affected. For longer periods of relocation, the lost capital value of the land and its assets may be calculated. The costs of food bans include contributions to GDP as well as the lost capital value and the disposal costs of the food affected. The cost arising from health effects may be calculated in terms of the treatment costs and the lost economic productivity of the affected individuals, or an estimation of the cost of health effects may be obtained using a more subjective approach to the valuation of life.

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APPENDIX B

Structure Document and Elicitation Questionnaire for the Expert Panel on Late Health Effects

ELICITATION QUESTIONS

Expert Panel on Late Health Effects

CEC/USNRC Joint Project on
Uncertainty Analysis of Consequence Assessment Programs

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1. Introduction

The EC/USNRC Joint Study has been initiated to develop further and apply expert judgement elicitation techniques to estimate the uncertainties associated with the predictions of Probabilistic Risk Assessment (PRA), or Accident Consequence Assessment (ACA) codes. The uncertainties in the various aspects of consequence assessment modeling are being considered separately by several expert panels. These panels will be formed jointly, where possible, between experts from the European Union (EU) and the United States of America.

Codes for PRA analysis, such as COSYMA and MACCS, incorporate estimates of the late health effects following radiation exposure. In the case of COSYMA, information on the numbers of radiation-induced cancer deaths per Sv as a function of age and sex can be entered. The code then uses preset values to determine, for a given dose scenario, how the risks and time of life lost would vary with age and time.

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

This document provides introductory information for the members of the late effects panel relevant to the parameters of interest and the questions for expert elicitation are listed.

2. Objectives of the Study

The overall aim of the Joint Study is to assess the uncertainties associated with consequence calculations for accidental releases of radionuclides from nuclear power plants. It is envisaged that the uncertainty analyses of at least two accident consequence assessment codes (COSYMA from the EC, MACCS from the US) will make use of information derived from this project. However, the results of the Joint Study will be used to develop a library of uncertainty distributions that can be used for many different uncertainty studies in the future. The physical "processes" modeled in ACA codes, such as COSYMA and MACCS, are identical, even though the models representing the processes in the codes may be different. One of the guiding principles of this expert elicitation exercise is that the experts should be asked to respond only to questions about physically observable or measurable quantities, even though the actual measurement of these quantities may be impracticable due to resource constraints. Therefore, the experts will not be expected to answer questions on the mathematical models themselves, to which they may not be able to easily relate, particularly when the models have been derived empirically. The advantages of this approach are that all ACA codes may make use of the information derived from the elicitation questions posed to the experts, since they are somewhat divorced from the basic modeling. The disadvantage, however, is that the uncertainty distributions suggested by the experts will have to be processed in order to derive the distributions for these model parameters used within a particular program.

The Joint Study will be limited to those issues where alternative sources of information, such as experimental or observational data or even validated computer models, are not available to directly calculate late effect risks, or where multiple sources of information provide conflicting or incomplete evidence of the uncertainties.

3. Choice of Experts and Elicitation Process

The experts have been chosen in such a way as to provide a wide diversity of expertise and experience. Alternative points of view are encouraged and the experts will have the opportunity to discuss the issues together at the initial training meeting to be held on December 11-13, 1995. Following this meeting, the experts will be given time to assess the problems contained in the elicitation questions. They will not be asked to use the methods contained in the consequence codes themselves, but will be free to use whatever models or tools that they feel appropriate to answer the questions. They are encouraged, however, to write down all the assumptions made and methods used during this process, together with a clear statement of all the uncertainties they have considered in the assessments (in the so-called rationale). The actual elicitation questions will be carried out some weeks later (January-February, 1996) during a private meeting between the expert and up to two analysts, one specializing in probability assessment and the other in the specific aspect of consequence modeling under consideration.

4. Formal Expert Elicitation Process

Expert judgements applicable for uncertainty analysis must be cast in the form of subjective probability distributions. Subjective probability measures degree of belief with respect to possible observations. Subjective measures of uncertainty should be contrasted with the rather narrower range of uncertainties due to purely observational error (e.g., Poisson error in the number of cases of cancer observed) which are usually reported in epidemiological studies. In this study, experts are asked only about physically observable quantities.

Degree of belief is elicited in the form of 5%, 50% and 95% quantiles of subjective probability distributions. The 5% quantile of the distribution for an uncertain quantity X is the number x(0.05) such that

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

and similarly for the other quantiles. For each assessment, certain background information is supplied. It is not the intention to provide all physically relevant information; rather the information provided corresponds to the information which ACA codes require.

5. Combining Expert Judgements

There are two reasons for using panels of experts in this study. Firstly, eliciting differing viewpoints gives a better representation of the true uncertainty about the physical phenomena under consideration. In contrast, a single expert would normally offer only one viewpoint. Secondly, empirical evidence shows that when the judgments of a number of experts, expressed in the form of probabilities, are combined using some reasonable aggregation procedure, the resulting probability distributions are more reliable. Such aggregated distributions express better the true uncertainty than the probability distribution of a single expert.

Two concepts are important when evaluating probability distributions:

Calibration

Calibration refers to the faithfulness of probabilities. In principle, events that are assigned a given probability should occur with a relative frequency equal to that probability. For example, an expert who assigns probability distributions to a set of uncertain quantities should find that 5% of quantities fall below the 5% quantile of his or her subjective distribution, half below the 50% quantile etc.

Calibration is a concept that applies to sets of distributions, not to individual probabilities. An expert is said to be well calibrated if, over a large number of assessments, the probabilities assigned are correctly reflected in the relative frequencies. Of course, the measurement of calibration can occur only when the true values of the uncertain quantities become known. Calibration can be measured, in a statistical sense, through goodness-of-fit statistics and relative entropy.

Informativeness

Informativeness refers to how well probabilities define the value of a variable or the likelihood of an event. Probabilities near zero and one better resolve uncertainty than probabilities near one half. Similarly, sharp or peaked density functions better resolve uncertainty than flat or diffuse densities.

Calibration and high informativeness may not be compatible, however. A set of probability distributions may be very peaked but very wrong. In fact, there is a common tendency for elicited probability distributions to be more "informative" than is warranted. Combined judgements tend to be better calibrated but less informative (more diffuse).

Many ways of combining judgements have been suggested. The simplest rule for combining expert judgements is to take a simple average of their probability distributions. Another method is to weight the experts on the basis of how well they perform on questions of which the true values are known. This approach is known as performance based weighting.

6. Scope of the Late Health Effects Panel

Assessment of the risks of radiation-induced cancer depends upon a number of factors, such as the incidence of and mortality from cancers in the unexposed population, the effects of dose and dose-rate, and the temporal patterns of risk among the various cancer types. Information on the possible effects resulting from non-uniform spatial deposition of radiation within the relevant tissue following the intake of specified radionuclides will in general not be considered by the internal dosimetry panel, and so should not be considered further by the late health effects panel. The expert panel on late health effects will quantify the degree of uncertainty in estimates of radiation-induced cancer risk for a number of cancer sites, taking account of the correlations introduced by the variables listed above.

7. Exclusions in Uncertainty Assessments

The population is assumed to be exposed to uniform whole body doses of external ionizing radiation or uniform doses to specific organs from internal exposure. With the exception of question (xi) (relating to ingestion of Sr-90 and Pu-239) non-uniform deposition of radiation to the relevant target tissue within an organ is not assumed. Deterministic effects arising from high radiation doses to the whole body are not assumed to take place. For that part of the population which is assumed to be exposed *in utero*, doses are assumed to be delivered uniformly to all tissues of the embryo and fetus, and dose is administered uniformly in time over the three trimesters of gestation. All mortality and incidence rates are assumed to be stable over time. The population is assumed to be in equilibrium, so that the numbers of persons in each age interval are constant over time. Tumors other than those corresponding to the Ninth International Classification of Diseases (ICD9) codes 140 - 208 are not considered. Non-malignant diseases (e.g., cardiovascular disease) are also not included. Medical treatment and surveillance is assumed to be constant, and in particular is not assumed to change after the accident. The population is assumed to be subject to its normal diet after the accident and non-radiological environmental conditions are assumed to be constant.

8. Elicitation Questions

The basis for the questions below is exposure of a hypothetical "average" EC/US population of all ages and both sexes. The Appendix lists baseline mortality rates, by sex and in mainly five-year age groups, for all causes taken together and for specific cancer types and groupings of cancer in a population representative of the EC/USA. The Appendix also provides the numbers in the population, at equilibrium, within the specified age and sex groups. The mortality and incidence rates are assumed to be constant, at the values specified in the Appendix, within each age interval (0-, 1-4,5-9,10-14,..., 80-84, 85+). This implies in particular, given that the population is in equilibrium, that the numbers of persons in age group y for $y \geq 85$ is proportional to

e^{-my}, where m = 14724.47/100,000 for males and m = 11195.72/100,000 for females. The mortality rates are calculated from the rates for the 1992 England and Wales population (OPCS, 1993) and for the 1987 USA population (WHO, 1989). Corresponding data for baseline cancer incidence are also listed. The cancer incidence rates are calculated from the rates for the 1989 England and Wales population (OPCS, 1994) and for the 1983-1987 US Surveillance, Epidemiology and End Results (SEER) registry data (Parkin et al., 1992). The SEER registries only cover certain regions within the USA.

Experts should base all their answers on a population which is assumed to be subject to these mortality and incidence rates. For convenience, the mortality and incidence rates given in the Appendix are also provided on a (MS DOS formatted) diskette. Unless otherwise specified, the age and sex distribution of the population is as given in the Appendix. When specific subsets of the population are being considered e.g., those exposed *in utero* or in childhood the age distribution at exposure (and afterwards) is as given by suitable parts of the Appendix.

The measure of cancer risk which should be used in most of the questions ((i) - (xi)) is risk of exposure-induced death (REID) (Thomas et al., 1992) and the analogous measure for cancer incidence, as used by UNSCEAR (1994), rather than the measure of excess cancer deaths employed by the BEIR IV (1988) and BEIR V (1990) committees. Other than the two questions ((vi) and (vii)) specifically relating to *in utero* exposures, those parts of the population who are exposed *in utero* are excluded.

Ranges of Uncertainty

For suitable subsets of the cancer sites listed in Table 1 and for the population described in the Appendix, the experts should provide 5th, 50th and 95th percentiles for their range of uncertainty on each of the following variables. The experts should give for each quantile only the expected values of cancer risk; no account should be taken of the Poisson uncertainty in the radiation-induced excess cancer risk.

Table 1. Key to Primary Cancer Sites, with the Relevant Codes for the 9th Revision of the International Classification of Diseases (ICD9)

Abbreviated Title	ICD9 Code	Full Description
Bone	170	Bone
Colon	153	Colon
Breast	174	Female Breast
Leukemia	204-208	Leukemia
CLL	204.1	Chronic lymphocytic leukemia
Liver	155.0, 155.1	Liver and intrahepatic bile ducts
Lung	162	Lung
Pancreas	157	Pancreas
Skin	173	Non-Melanoma Skin
Stomach	151	Stomach
Thyroid	193	Thyroid
All other cancers	140-208 other than above sites	All cancers other than those listed above
All cancers	140-208	All cancers

Question 1. The number of radiation-induced cancer deaths up to 20 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone			
Colon			
Breast			
Leukemia			
Liver			
Lung			
Pancreas			
Skin			
Stomach			
Thyroid			
All other cancers			
All cancers			

Question 2. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone			
Colon			
Breast			
Leukemia			
Liver			
Lung			
Pancreas			
Skin			
Stomach			
Thyroid			
All other cancers			
All cancers			

Question 3. The number of radiation-induced cancer deaths over a lifetime (following the population up until it has become extinct) in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone			
Colon			
Breast			
Leukemia			
Liver			
Lung			
Pancreas			
Skin			
Stomach			
Thyroid			
All other cancers			
All cancers			

Question 4. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 years) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Breast			
Leukemia			
Thyroid			
All cancers			

Question 5. The number of radiation-induced cancer deaths over a lifetime (following the population up until it has become extinct rather than up to 40 years following exposure) in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 years) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Breast			
Leukemia			
Thyroid			
All cancers			

Question 6. The number of radiation-induced cancer deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure of a dose of 1 Gy low LET (= gamma) radiation administered uniformly over their three trimesters (9 months) *in utero* and followed-up for 20 years after birth.

	Quantile		
	5%	50%	95%
Leukemia			
All cancers			

Question 7. The number of radiation-induced cancer deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure of a dose of 1 Gy low LET (= gamma) radiation administered uniformly over their three trimesters (9 months) *in utero* and followed over a lifetime (following the population up until it has become extinct rather than up to 20 years following exposure).

	Quantile		
	5%	50%	95%
Leukemia			
All cancers			

Question 8. The number of radiation-induced cancer cases (fatal and non-fatal) up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone			
Colon			
Breast			
Leukemia			
Liver			
Lung			
Pancreas			
Skin			
Stomach			
Thyroid			
All other cancers			
All cancers			

Question 9. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 year (rather than 1 minute).

	Quantile		
	5%	50%	95%
Bone			
Colon			
Breast			
Leukemia			
Liver			
Lung			
Pancreas			
Skin			
Stomach			
Thyroid			
All other cancers			
All cancers			

Question 10. The number of radiation-induced skin cancer cases (fatal and non-fatal) up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a uniform skin dose of 1 mGy high LET (= plutonium alpha particle) radiation at a uniform rate over 1 year.

	Quantile		
	5%	50%	95%
Skin			

Question 11. Joint dosimetry/late effect question: The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each of whom inhales 10 K Bq of the radionuclides specified.

Nuclide	Physical Form	Chemical Form	Cancer Type	Number of Cancers Quantile		
				5%	50%	95%
Pu-239	1 μm AMAD	Oxide	Lung			
			Bone			
			Liver			
			Leukemia			
			All cancers			
Sr-90	1 μm AMAD	Oxide	Lung			
			Bone			
			Leukemia			
			All cancers			

Question 12. Given that radiation induced cancer death due to the specified cause has occurred as a result of a dose of radiation delivered over 1 minute, the average expected length of life lost in years, for a population followed up to extinction after exposure.

	Quantile		
	5%	50%	95%
Bone			
Colon			
Breast			
Leukemia			
Liver			
Lung			
Pancreas			
Skin			
Stomach			
Thyroid			
All other cancers			
All cancers			

Question 13. For each of the cancer sites listed, give the estimate of the threshold dose in Gy, for low LET (= gamma) radiation administered at a uniform rate over 1 minute, below which value there is no radiation-induced cancer risk.

	Quantile		
	5%	50%	95%
Bone			
Colon			
Breast			
Leukemia			
Liver			
Lung			
Pancreas			
Skin			
Stomach			
Thyroid			
All other cancers			
All cancers			

Seed Variables

There are various possible strategies for combining the views of the different experts on each panel. The simplest is to "average" the views of all experts, and at least for the initial assessments of uncertainty using COSYMA and MACCS this is the approach that will be adopted. Alternatively, one can weight the answer given by each expert by some performance measure. The performance measure can be evaluated by asking the expert questions about some dataset which is (to some extent) unknown to the experts.

Part of the objective of the EC/NRC Joint Study is to explore different weighting schemes for aggregating expert judgment for ACA uncertainty analyses (e.g., performance based aggregation schemes). For this reason, for the late health effects panel information is being elicited on a "large" dataset (the Japanese atomic bomb survivors) the results from which have yet to be assembled, and which can be used to calibrate the judgements of the experts retrospectively; this will provide useful input to a longer term project to evaluate alternative means of weighting elicited expert judgements.

In order to provide a performance measure of each expert, each expert is asked to provide an estimate of the aggregate excess relative risk coefficient per Sv (neutron RBE = 20) to the colon (bone-marrow for leukemia) (averaged over both sexes, both cities (Hiroshima and Nagasaki), all age at exposure groups and all dose groups), and associated uncertainty intervals, for cancer mortality in the Japanese atomic bomb survivor Life Span Study cohort followed up from January 1, 1991 to the end of 1995. This information will be published as part of Life Span Study Report 13 in about the year 2000. In the Table below are given for comparison the best estimate values in the follow-up from 1950 to 1985 (Life Span Study Report 11) (Shimizu et al., 1990) obtained by fitting a stratified relative risk model of the sort employed by Shimizu et al., 1990). As above, the uncertainty intervals that you should estimate should reflect not only the observational uncertainty (Poisson error), but all other sources of uncertainty as well.

	Follow-Up to 1985 50% Quantile	Follow-up from 1991 to 1995		
		5%	50%	95%
Colon	0.72			
Breast	1.24			
Leukemia	4.00			
Liver	0.14			
Lung[1]	0.48			
Pancreas	-0.15			
Stomach	0.28			
Solid tumors[2]	0.36			

[1] This now refers to respiratory and intrathoracic cancers (ICD9 160 -165)
[2] This refers to ICD9 140-203

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Appendix: Mortality and Incidence Rates for EC/USA Population

Mortality Rates per 100,000 per year

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

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

Mortality Rates per 100,000 per year (Continued)

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

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

Incidence Rates per 100000 per year

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

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

Incidence Rates per 100000 per year (Continued)

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

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

Scoping Cancer Risks Document Sent by M P Little to the Somatic Health Effects Experts on 23 January 1996

To all members of the CEC/US NRC Somatic Health Effects Panel

Enclosed you should find slightly revised details of model fitting and population cancer risk calculations for the combined EU/US population described in the Appendix of the Somatic Health Effects Case Structure Document. The main difference from the previous version of this document arise in Model Set B (and so also Model Set C), in which the model that was fitted to the Japanese incidence solid cancer dataset was slightly different from that used in the cancer risk calculations. (The fitted model has been changed for consistency.)

Models Used

A variety of models were fitted to the two Japanese atomic bomb survivor cancer incidence datasets, that is the solid cancer incidence dataset analysed by Thompson et al. (1994), and the leukaemia and lymphoma incidence dataset analysed by Preston et al. (1994). These datasets contain numbers of cancers and person-years in each year-after-exposure and age-at-exposure group and broken down by city, sex and radiation dose. The BEIR V committee (1990) in their analysis of the Japanese bomb survivor data decided to omit all data records with organ doses greater than 4 Sv, because of the possible errors in the dosimetry for these higher dose points. Their example was followed here. Models which are linear in dose were employed; given the marked non-linearity in the dose-response for cancer mortality at the highest doses in the bomb survivors (Shimizu et al., 1990, BEIR V, 1990), these higher dose groups in the bomb survivors were omitted from the analyses. As with the analyses of Thompson et al. (1994) and Preston et al. (1994), all survivors with air-kerma dose >4 Gy were also omitted from the analysis.

The first sort of model fitted assumed that the excess relative risk (ERR) varied with time since exposure (TSE) and age at exposure (AAE), so that the expected number of cases of whichever cancer is under consideration in stratum j and average dose d (in Sv (neutron relative biological effectiveness = 20)) is given by:

$$PYR_{jd} \cdot \lambda_j \cdot [1 + \beta_s \cdot d \cdot e^{\delta \cdot t + \mu \cdot a}] \qquad (1)$$

This is a relative-risk model allowing for exponential time variation and exponential age variation of the ERR, where:

- PYR_{jd} is the number of person-years in stratum j, and average dose d;
- λ_j is the base cancer rate in stratum j;
- β_s is a scaling factor for the ERR in sex s;
- δ is the factor determining the exponential adjustment for TSE t in the ERR;
- μ is the factor determining the exponential adjustment for AAE a in the ERR;

As well as model (1), which incorporates exponential adjustments for TSE and AAE, we also fit models which incorporate power adjustments for TSE, AAE and attained age (AA), given by:

$$PYR_{jd} \cdot \lambda_j \cdot [1 + \beta_s \cdot d \cdot t^{\gamma} \cdot a^{\rho} \cdot (t+a)^{\alpha}]$$
$$= PYR_{jd} \cdot \lambda_j \cdot [1 + \beta_s \cdot d \cdot e^{\gamma \cdot \ln[t] + \rho \cdot \ln[a] + \alpha \cdot \ln[t+a]}] \qquad (2)$$

This is a relative-risk model allowing for a power of TSE variation, a power of AAE variation and a power of AA variation of the ERR, where:

γ is the power of TSE t by which the ERR is adjusted;
ρ is the power of AAE a by which the ERR is adjusted;
α is the power of AA t + a by which the ERR is adjusted.

All parameters other than PYR_{jd} (which were defined by the data) were determined by a maximum-likelihood fit to the data, whereby the numbers of cases in each cell is assumed to be independently distributed as Poisson with mean given by expressions (1) - (2).

Preliminary investigations (Little et al., 1996) suggest that the best fitting solid cancer model is one in which the $ERR = \beta_s \cdot d \cdot t^{\gamma} \cdot (t+a)^{\alpha}$, and that there is no significant variation among the cancer sites in the values of γ and α. Accordingly, such a model was fitted jointly to the 10 solid cancer sites, with a common value assumed for the parameters γ and α, allowing only the scaling coefficients β_s to vary by cancer site. These models we shall denote as Model Set A in all that follows. The coefficients of the fitted models are set out in Table I. For the purposes of sensitivity analysis we also fit a version of model (1) with only exponential AAE adjustment, again obtained by fitting simultaneously to all 10 solid cancer sites, allowing for site specific variation of the scaling parameters β_s. These we shall denote by Model Set B. Finally, we also consider the cancer risks predicted by Models B when the solid cancer ERR for those exposed in childhood (age < 15 at exposure) is assumed to diminish by 5% per year 42 or more years after exposure. (The incidence datasets of Thompson et al. (1994) and Preston et al. (1994) have been followed-up to the end of 1987, approximately 42 years after the atomic bombings of Hiroshima and Nagasaki.) Reductions in solid cancer ERR of rather more than 5% per year of TSE for those exposed in childhood have been documented in the Japanese and in various other datasets (Little et al., 1991, 1996). These set of models will be denoted by Model Set C. For leukaemia a slight variant of model (1) will be used, namely:

$$PYR_{jd} \cdot \lambda_j \cdot [1 + \beta \cdot (d + \varepsilon \cdot d^2) \cdot e^{\delta \cdot t + \mu \cdot a}] \qquad (3)$$

Table I gives details of the parameter values of the fit of this model to the three main leukaemia subtypes (ALL, AML, CML) in the Japanese leukaemia and lymphoma incidence dataset (Preston et al., 1994). All exclusions are as for the fits to the solid cancer data (organ dose < 4 Sv, air-kerma dose < 4 Gy). This model for leukaemia is used in all three Model Sets.

Assumptions underlying population risk calculations

The population cancer risk estimates set out in Tables II - IV were evaluated for the equilibrium population described in the Appendix to the Case Structure Document. A test dose of 0.001 Sv was used to calculate these risks. The population was truncated at the age of 120 years i.e. at the end of the 120th year of life each person remaining alive was assumed to die (from some non-malignant disease). The underlying population rates and risks exclude chronic lymphocytic leukaemia (CLL). A latent period of 2 years was assumed for leukaemia and a latent period of 5 years was assumed for all other tumours.

Mark Little

23 January 1996

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Table I Parameter Values of Fits to Solid Cancer and Leukaemia Data

Model Set A: Solid Cancer

$$ERR = \beta_s \cdot d \cdot t^{\gamma} \cdot (t + a)^{\alpha}$$

$\gamma = 6.78 \times 10^{-1}$
$\alpha = -2.55$

Cancer Site	Organ Dose Used	β_m (Sv^{-1})	β_f (Sv^{-1})
Bone	Skeleton	1.11×10^{4}	3.16×10^{3}
Colon	Colon	2.19×10^{3}	2.86×10^{3}
Female Breast	Breast	-	3.21×10^{3}
Liver	Liver	1.94×10^{3}	4.61×10^{1}
Lung	Lung	1.54×10^{3}	7.17×10^{3}
Pancreas	Pancreas	8.93×10^{2}	1.45×10^{3}
Non-Melanoma Skin	Eye lens	1.12×10^{3}	8.08×10^{3}
Stomach	Stomach	4.91×10^{2}	1.86×10^{3}
Thyroid	Thyroid	4.44×10^{3}	4.41×10^{3}
All Other Solid Tumours	Colon	1.11×10^{3}	7.48×10^{2}

Model Set B: Solid Cancer

$$ERR = \beta_s \cdot d \cdot e^{\mu \cdot a}$$

$\mu = -4.71 \times 10^{-2}$ year^{-1}

Cancer Site	Organ Dose Used	β_m (Sv^{-1})	β_f (Sv^{-1})
Bone	Skeleton	1.75×10^{1}	4.92
Colon	Colon	2.36	3.07
Female Breast	Breast	-	3.82
Liver	Liver	2.14	-1.48×10^{-1}
Lung	Lung	1.61	8.34
Pancreas	Pancreas	1.20	2.05
Non-Melanoma Skin	Eye lens	1.67	1.07×10^{1}
Stomach	Stomach	5.80×10^{-1}	2.48
Thyroid	Thyroid	6.92	5.88
All Other Solid Tumours	Colon	1.34	9.97×10^{-1}

Model Set A/B: Leukaemia (ALL, AML, CML) (Using Bone Marrow Dose)

$$ERR = (\beta \cdot d + \varepsilon \cdot d^2) \cdot e^{\delta \cdot t + \mu \cdot a}$$

$\beta = 5.42 \times 10^{1}$ Sv^{-1}
$\varepsilon = 1.99 \times 10^{1}$ Sv^{-2}
$\delta = -1.06 \times 10^{-1}$ year^{-1}
$\mu = -1.66 \times 10^{-2}$ year^{-1}

Table II Cancer Mortality Risks for Models A, B and C for General Population

	20 Years After Exposure[a]	40 Years After Exposure[a]	Lifetime[a]	Lifetime Years Of Life Lost[b]
Model Set A				
Bone	0.046	0.067	0.087	0.0325
Colon	0.115	0.374	0.920	0.1262
Female Breast	0.178	0.570	1.135	0.2149
Leukaemia	0.843	0.979	1.001	0.2128
Liver	0.009	0.027	0.055	0.0095
Lung	0.451	1.484	3.373	0.5194
Pancreas	0.026	0.084	0.205	0.0286
Skin	0.007	0.021	0.056	0.0075
Stomach	0.021	0.068	0.172	0.0233
Thyroid	0.006	0.018	0.041	0.0063
All Other Tumours	0.261	0.785	1.787	0.2689
Total	1.963	4.478	8.832	1.4500
Model Set B				
Bone	0.021	0.044	0.103	0.0225
Colon	0.076	0.297	1.432	0.1784
Female Breast	0.134	0.515	1.747	0.2903
Leukaemia	0.843	0.979	1.001	0.2128
Liver	0.006	0.021	0.075	0.0109
Lung	0.325	1.278	5.183	0.7399
Pancreas	0.022	0.086	0.407	0.0520
Skin	0.005	0.020	0.117	0.0133
Stomach	0.016	0.063	0.325	0.0399
Thyroid	0.005	0.018	0.079	0.0109
All Other Tumours	0.188	0.709	3.096	0.3987
Total	1.642	4.032	13.566	1.9695
Model Set C				
Bone	0.021	0.044	0.078	0.0197
Colon	0.076	0.297	0.922	0.1235
Female Breast	0.134	0.515	1.226	0.2236
Leukaemia	0.843	0.979	1.001	0.2128
Liver	0.006	0.021	0.052	0.0083
Lung	0.325	1.278	3.495	0.5329
Pancreas	0.022	0.086	0.264	0.0361
Skin	0.005	0.020	0.071	0.0089
Stomach	0.016	0.063	0.206	0.0271
Thyroid	0.005	0.018	0.053	0.0078
All Other Tumours	0.188	0.709	2.034	0.2863
Total	1.642	4.032	9.402	1.4869

[a]Radiation Exposure-Induced Death (REID) calculated in units of 10^{-2} Sv^{-1}
[b]Years of life lost in units of years Sv^{-1}

Table III Cancer Mortality Risks For Models A, B and C for Population Exposed in Childhood (Age at Exposure < 15 Years)

	40 Years After Exposure[a]	Lifetime[a]
Model Set A		
Bone	0.231	0.291
Colon	0.120	1.566
Female Breast	0.461	2.171
Leukaemia	0.513	0.545
Liver	0.023	0.108
Lung	0.467	6.000
Pancreas	0.025	0.351
Skin	0.013	0.092
Stomach	0.023	0.289
Thyroid	0.009	0.072
All Other Tumours	0.498	3.229
Total	2.383	14.714
Model Set B		
Bone	0.110	0.313
Colon	0.107	3.826
Female Breast	0.456	4.761
Leukaemia	0.513	0.545
Liver	0.015	0.205
Lung	0.478	13.958
Pancreas	0.029	1.088
Skin	0.012	0.310
Stomach	0.024	0.866
Thyroid	0.008	0.214
All Other Tumours	0.398	8.324
Total	2.151	34.410
Model Set C		
Bone	0.110	0.185
Colon	0.107	1.256
Female Breast	0.456	2.137
Leukaemia	0.513	0.545
Liver	0.015	0.090
Lung	0.478	5.461
Pancreas	0.029	0.367
Skin	0.012	0.080
Stomach	0.024	0.266
Thyroid	0.008	0.078
All Other Tumours	0.398	2.981
Total	2.151	13.445

[a]Radiation Exposure-Induced Death (REID) calculated in units of 10^{-2} Sv^{-1}

Table IV Cancer Incidence Risks for Models A and B for General Population 40 Years After Exposure[a]

Model Set A	
Bone	0.155
Colon	0.684
Female Breast	1.796
Leukaemia	1.438
Liver	0.027
Lung	1.745
Pancreas	0.097
Skin	1.869
Stomach	0.098
Thyroid	0.215
All Other Tumours	1.518
Total	9.642
Model Set B	
Bone	0.090
Colon	0.547
Female Breast	1.630
Leukaemia	1.438
Liver	0.022
Lung	1.518
Pancreas	0.100
Skin	1.853
Stomach	0.091
Thyroid	0.185
All Other Tumours	1.333
Total	8.808

[a]Quality analogous to Radiation Exposure-Induced Death (REID) for cancer incidence, calculated in units of 10^{-2} Sv^{-1}

APPENDIX C

Rationales and Responses of the Expert Panel on Late Health Effects

Note: Tables without data indicate that the expert had no response.

EXPERT A

1. General Approach for Obtaining Median Estimates.

As a starting point in developing risk estimates, I considered the approach used in the 1994 Report of the United Nations Scientific Committee on the Effects of Atomic Radiation (1994), hereafter referred to as UNSCEAR (1994)*. These are the most recent available estimates, and are based on excess relative risk (ERR) estimates obtained from mortality data from the Life Span Study (LSS) of A-bomb survivors in Hiroshima and Nagasaki for the period 1950-1987. The UNSCEAR approach applied ERR estimates for several specific cancer types to obtain lifetime risk estimates for the Japanese population, and made use of lifetable information and age- and sex-specific cancer death rates for Japan. With the exception of leukemia, calculations were based on a constant relative risk model. Under this model, the ratio of the radiation-induced cancer risk to the baseline risks (ERR) is assumed to be constant over time. However, the ERR was allowed to depend on age at exposure. In the UNSCEAR (1994) calculations, age at exposure was treated as a continuous variable, and a parameter quantifying its effect on the ERR was estimated for each type of cancer evaluated.

I also calculated estimates that made use of lifetable information and age-and sex-specific cancer death rates provided for the combined populations of the Europe and the United States (EU/USA). These calculations were made using the sex-specific ERRs and the estimated age-at-exposure parameters presented in UNSCEAR (1994), the same values that had been applied to Japanese data to obtain the risk estimates discussed above. For some cancer types, calculations were made using alternative coefficients as described below (Section 4). Calculations were made for lifetime risks and for the periods 20 and 40 years following exposure, and included both estimation of the number of radiation-induced deaths, and the number of years of life lost per cancer. Calculations for cancer incidence (including non-fatal cancers) were also made using the EU/USA cancer incidence rates.

To perform needed calculations, an available computer program that I had developed for use in making the calculations described in NUREG (1989) was used. This is a fairly crude program in that age is considered only in 5-year intervals, and in that it does not correct for the impossibility of dying from more than one radiation-induced cancer. For an exposure of 1 Gy, this latter problem is likely to overestimate risk for the entire population by about 10%, and thus lifetime mortality estimates were reduced by 10%. For those exposed under age 15, it is likely to overestimate risks by about 20%, and thus lifetime mortality estimates for this group were reduced by 20%. No adjustment was made to estimate risks for the first 20 or 40 years. It was not feasible to obtain or develop more refined software.

In several cases, estimates from sources other than the A-bomb survivor data were used. Because UNSCEAR (1994) did not calculate lifetime risk estimates for bone, skin, and thyroid cancer, it was necessary to obtain ERR and age at exposure effect estimates from other sources for these sites. Alternative estimates were also used for female breast cancer. In selecting the ERR coefficients to be used in risk calculations, I gave special consideration to estimates used in the most recent update of the NUREG (1991) health effects model, but I also considered newer information presented in UNSCEAR (1994) and elsewhere. Because I was responsible for preparing the late effects section of the NUREG document, it largely reflects my thinking.

For bone, colon, leukemia, liver, lung, stomach, and "other" cancers, my estimates were based on A-bomb survivor data. However, these were modified to account for a) differences in baseline risks in Japan and the US/UK population, b) various dosimetric problems including random error and the possibility of underestimation of neutrons in Hiroshima, and c) errors in the underlying cause of death as obtained from death certificates. Uncertainty from each of these sources was also evaluated.

To obtain cancer incidence estimates (including non-fatal cases), I first applied the ERR estimates used to obtain mortality estimates to the EU/USA cancer incidence rates. The ratio of incidence and mortality estimates was then used to adjust mortality estimates. I judged the uncertainties in cancer incidence estimates to be the same as those for mortality, and thus the same uncertainty factors were applied.

Leukemia risks have shown very different patterns than risks for other cancers, and thus different models have been used. I have based leukemia risk calculations on the model used by UNSCEAR (1994), which was based on A-bomb survivor incidence data and was developed by Preston et al. for estimating lifetime risks. This model expresses the excess absolute risk as a function of sex, age at exposure

* Because I had very nearly completed this work before the results of calculations by Mark Little were received, I did not consider these results in developing risk estimates and uncertainties.

and time since exposure. Details on the application of this model for this report are given in Section 4.4.

2. General Approach for Quantifying Uncertainty.

To quantify uncertainties in the various risk estimates, I evaluated uncertainty from each of several contributing sources, and then combined them to obtain an overall assessment. To obtain the required 5th and 95th percentiles for the overall distributions, it was necessary to specify distributions for each of the contributing sources. For convenience (and because it was not feasible to conduct the computer simulations that would be required for many distributions that might have been chosen), lognormal distributions were used to describe uncertainty. I judged it reasonable to assume that uncertainty from the sources considered was independent.

In general, let $\hat{R}$ indicate the median estimate of risk. $\hat{R}$ can be expressed as the product of the true (but unknown) risk R, and n factors B_i, where $b_i = \log B_i$ follows a normal distribution with mean 0 and standard deviation s_i. $S_i = \exp(s_i)$ is used to denote the geometry standard deviation (GSD) of the distribution of B_i, and K_i is used to denote the factor that $\hat{R}$ should be multiplied (divided) by to obtain the 95th (5th) percentile of the distribution for uncertainty source i. The assumption that b_i has mean zero was made because, for each uncertainty source, the median value was selected as the most appropriate with any suspected bias accounted for. Because the uncertainty factors K_i were evaluated subjectively, intervals obtained with these factors should be referred to as credibility intervals rather than confidence intervals. In the material that follows, the K_i will be referred to as "uncertainty factors".

The selection of the uncertainty factors for each source is discussed in detail in the next section of this document. Once the factors K_i were determined, s_i was calculated as $\log K_i/1.645$, and the 95th (5th) percentile of the overall distribution of $\hat{R}$ was calculated as $\hat{R} \times K$, where $K = \exp[1.645(s_1^2 + \ldots + s_n^2)^{1/2}]$. Similarly the 5th percentile was calculated as $\hat{R}/K$.

A limitation of the use of the lognormal distribution is that uncertainties must be symmetric on a multiplicative scale. In some cases, it was necessary to force symmetry, usually by using the larger of the uncertainty factors based on the preferred 5th and 95th percentiles.

The above approach was not well suited to expressing the uncertainty in the modifying effect of exposure received at low dose rates. Thus an alternative approach was used for this uncertainty source, and is described below.

3. Sources of Uncertainty Evaluated.

All calculations of numbers of radiation-induced cancers include consideration of uncertainty in the risk coefficients (ERRs) used in the calculations including a) sampling variation, b) uncertainty in transporting risks from A-bomb survivors, c) uncertainty resulting from random and systematic error in dose estimates used in estimating the ERRs (including uncertainty resulting from possible underestimation of neutrons in Hiroshima), and d) errors in health endpoint data used in estimating ERRs.

Estimates of lifetime risks also include uncertainty resulting from extrapolating risks beyond the follow-up period for which data are available. Estimates of risk for the first 20 years include some additional uncertainty to allow for the fact that estimated risks for this period are not as stable as for the 40-year period. Finally, estimates of risks from exposures received at low dose-rates (1 Gy received at a uniform rate over a one-year period) include uncertainty in the modifying effects of dose rate on risks estimates obtained from data on persons exposed at high does rates.

The general treatment of each of these uncertainty sources is discussed below. Uncertainties in estimates of the numbers of years of life lost per cancer are subject to somewhat different uncertainties, and these are discussed at the end of the section.

3.1 Uncertainty resulting from sampling variation in the risk coefficients (ERR) used in the calculation.

The model that was used to obtain lifetime risks for several cancer types is that developed in the UNSCEAR (1994) report, and this model includes sex-specific estimates of the ERR and an age at exposure parameter. No indication of uncertainty in these parameters is given, and rigorous evaluation of the overall uncertainty in estimates of risk resulting from statistical variation in these parameters would require computer simulations. Because such simulations were not feasible for this exercise (and because the appropriate input data were not available), alternative approaches were necessary.

UNSCEAR (1994, Table 8) presents observed and expected deaths (cases) from each of several studies, and for several types of cancer. Estimates of the ERR presented in Table 8 are obtained as (O - E)/(E*d), where O is the observed number of deaths (or cases) in the exposed population, E is

the number expected without such exposure, and d is the average dose in the exposed populations. To use the lognormal formulation described above, the standard error of the logarithm of this estimate is needed. It can be shown that this is given approximately by $s = \sqrt{O/(O-E)}$, and thus the GSD can be estimated by exp(s), and the uncertainty factor (K) can be estimated by exp(1.645 s).

For thyroid cancer, a 95% confidence interval for the ERR used in calculations was presented. In this case, s = log(GSD) was obtained as log (U/L)/3.92, and the logarithm of the uncertainty factor was obtained as 1.645 log (U/L)/ 3.92, where U represents the upper limit and L represents the lower limit.

Table 1 shows the uncertainty factors for statistical precision for each type of cancer. Unless indicated otherwise, these were based on A-bomb survivor mortality data for the period 1950-87, using the observed and expected deaths presented in Table 8 of UNSCEAR (1994). The leukemia estimate was based on A-bomb survivor incidence data as presented in Table 6 of UNSCEAR (1994). Leukemia risks were based on an absolute risk model, and thus the estimate below is an estimate of the excess absolute risk (EAR) rather than the ERR.

It is noted that, in most cases, the estimates shown in Table 1 are not those used in the applied risk models; in particular, the A-bomb survivor estimates are not those used for calculating lifetime risks (as noted above, uncertainties for these estimates were not available). However, it is thought that the uncertainties below provide a reasonable basis for addressing statistical precision.

Sampling variation in estimates of risks for those exposed under age 15 is greater than for the entire population. The GSDs (and uncertainty factors) for this group are shown in Table 2. These were obtained using the method above, but using the observed and expected deaths for those exposed under age 20 (the numbers of deaths for those exposed under age 15 were not available).

Table 1. Uncertainty due to sampling variation for ERR estimates for entire population.[a]

Type of Cancer	Observed deaths	Expected deaths	GSD	Uncertainty factor (K)
Bone	24	19.3	2.84	5.55
Breast[b]	196	128.4	1.23	1.41
Breast[c]	104	74.1		
Colon	129	116.5	2.48	4.46
Liver	352	319.6	1.78	2.59
Lung	433	363.8	1.35	1.64
Stomach	1163	1107.5	1.85	2.75
Skin[d]	125	34.0	1.13	1.22
All solid tumors[e]	3452	3148.0	1.21	1.37
Other cancers[f]	1247	1147.2	1.42	1.79
Leukemia[g]	141	67.4	1.18	1.30

[a] Based on A-bomb survivor LSS data unless indicated otherwise.

[b] Based on combined data from the Massachusetts TB fluoroscopy study and the New York acute post-partum mastitis study.

[c] Based on A-bomb survivor data; needed to compute values for "other cancers".

[d] Based on combined data from the Israel and New York tinea capitis studies.

[e] Obtained from UNSCEAR (1994, Table 7).

[f] Obtained by subtraction.

[g] The estimate given is of the EAR expressed per 10^4 PYSv. For estimates based only on observed and expected deaths the GSD is the same for the EAR and ERR.

Table 2. Uncertainty for ERR estimates based on subjects exposed under age 20 in the A-bomb survivor LSS.

Type of cancer	Observed deaths	Expected deaths	GSD	Uncertainty factor (K)
Breast[a]	71	45.7	1.40	1.73
Leukemia[b,c]	46	17.9	1.27	1.49
All solid tumors[b]	360	294.7	1.34	1.61

[a] Based on data from Massachusetts TB fluoroscopy study as presented in UNSCEAR (1994, Table 11).

[b] Based on A-bomb survivor LSS data.

[c] The estimate given is of the EAR expressed per 10^4 PYSv. For estimates based only on observed and expected deaths the GSD is the same for the EAR and ERR.

It is emphasized that the above approach is a very crude way of evaluating uncertainty resulting from sampling variation. A much superior approach would be to conduct computer simulations as noted above and as described in detail in BEIR V (1990).

Those exposed as children contribute to risks for the entire population. For the first 40 years of follow-up, this contribution is generally not large (usually around 5%), but for extrapolating beyond the period for which follow-up data are available, the contribution is much larger (usually about one-third). For estimating lifetime risks, the effect of age at exposure-related uncertainty is very much interrelated with choices regarding the effects of time since exposure and attained age on risks.

3.2 Uncertainty in transporting risks from A-bomb survivors (or other populations) to the combined EU/USA population.

For some cancers, notably stomach, colon, liver, lung, and breast, baseline risks in Japan are markedly different from those in Europe and the United States. In these cases, it is not entirely clear whether relative or absolute risks are more comparable across populations. For breast cancer, this problem has been addressed by using ERR estimates derived from Caucasian populations (Section 4.3). For cancers of the bone, colon, leukemia, liver, lung, stomach, and other cancers, however, data from other studies were inadequate to avoid using the A-bomb survivor based estimates. The general approach taken was to use the estimates calculated in UNSCEAR (1994), which were based on a 1985 Japanese population, for one of the bounds (5th or 95th percentiles), and to use the estimate calculated using the EU/USA database as the other percentile. The median was then taken as the geometric mean of these two values. Note that estimates based on Japanese rates would be reasonably appropriate if absolute risks were comparable across countries, while the estimates based on the EU/USA rates would be reasonably appropriate if relative risks were comparable across countries. There are of course other differences in the two estimates used as bounds; e.g., the age-distribution of the Japanese population is not identical to that used for the EU/USA, and the computational methods used in UNSCEAR (1994) were slightly different than those I used based on the EU/USA rates. However, these latter differences are judged to be relatively small compared with the differences in cancer rates for specific cancers in the two populations.

Land and Sinclair (1991) also compared risks based on multiplicative and additive transportation models, and included in their comparisons were estimates for the United States and the United Kingdom. Table 3 shows the UNSCEAR (1994) lifetime risks, EU/USA lifetime risks, and their ratio. The table also shows the ratio of estimates calculated using the additive and multiplicative transportation models as applied to the United States and United Kingdom by Land and Sinclair. Generally the ratios obtained by Land and Sinclair are similar to ratios of UNSCEAR and EU/USA risks. An exception is lung cancer; because lung cancer rates in Japan may have increased over time, an additive transportation model might have yielded risks somewhat lower than the UNSCEAR (1994) model. I have accordingly used an estimate of 1.5% for the 5th percentile (instead of the 2.5% value in the table). The median for lung cancer was then taken as the geometric mean of 1.5% and 2.92%, yielding a value of 2.1%.

Table 3. Comparison of estimates resulting from different approaches to transporting risks from A-bomb survivors to Caucasian populations.

Cancer type	UNSCEAR (1994)	EU/USA	Ratio	Ratio obtained by Land and Sinclair	
				United States	United Kingdom
Stomach	1.4%	0.24%	5.8	7.3	5.9
Colon	0.6%	1.13%	0.53	0.39	0.47
Liver	1.2%	0.10%	12	Not available	
Lung	2.5%	2.92%	0.86	0.46	0.56
Other[a]	3.7%	4.6%	0.80	0.67	0.61
Leukemia			0.78	0.78	1.05

[a] This is obtained by adding the UNSCEAR (1994) lifetime risks for bladder, ovary, and other cancers. The UNSCEAR (1994) estimate differs slightly from the EU/USA estimate in that it includes cancer of the pancreas. The Land and Sinclair estimates include both cancer of the pancreas and cancer of the liver.

Even if risks are not being transported across countries, the studied population almost always differs in various respects from the "average" population for which risks are being estimated, and thus there is the possibility that estimated risk coefficients are not fully appropriate. I have judged that this could introduce a 95% uncertainty factor of 1.3. A minimum uncertainty factor of 1.3 has been applied to all cancer types including those based on data other than the A-bomb survivors.

3.3 Uncertainty resulting from random and systematic error in dose estimates used in estimating the ERRs (including uncertainty resulting from possible underestimation of neutrons in Hiroshima).

Virtually all dose estimates used in epidemiologic studies are subject to both random errors and also to the possibility of systematic bias. For the A-bomb survivor studies, both random error and the specific bias arising because of underestimation of neutron exposure in Hiroshima have been studied. Pierce et al. (1990) estimated that, if not accounted for, random error of 30-40% would lead to underestimation of the leukemia risks by about 4-7%, and of solid tumor risks by about 7-11%. Because estimates used in UNSCEAR calculations (and used in my assessment) did not account for random error, I have accordingly increased leukemia estimates by 6%, and estimates for bone, stomach, colon, liver, lung, and other cancers by 9%. Because there is uncertainty in the magnitude and nature of the random error in A-bomb survivor dose estimates, I have allowed an uncertainty factor of 1.2 (GSD = 1.11), to account for this uncertainty. It has also been estimated that the underestimation of neutrons in Hiroshima probably led to overestimation of risks by about 10-20%. To account for this, all A-bomb survivor-based estimates have been reduced by 15%. Additional uncertainties in A-bomb survivor estimates include uncertainty in the yield of the Hiroshima bias. Overall, an uncertainty factor of 1.2 (GSD = 1.11) has been allowed to account for the possibility of systematic bias, including the neutron problem.

Estimates for breast, thyroid, and skin cancer made use of data other than the A-bomb survivor data. Dosimetry errors in these studies have not been as extensively studied, but are undoubtedly present, and could potentially bias risk estimates obtained from these studies. An uncertainty factor of 1.5 (GSD = 1.28) has been assigned to take account of these uncertainties.

3.4 Uncertainties resulting from errors in health endpoint data used in estimating risk coefficients

Errors in the ascertainment of cases or in the assignment of cases and deaths to the appropriate disease can also lead to bias in estimated risk coefficients. This is especially true for data based on death certificates, as is the case of the A-bomb survivor LSS. Sposto et al. (1991) studied this and estimated that misclassification of deaths between cancer and non-cancer causes would have led to underestimation of the ERR for all cancer by about 10%. It is not clear what effect this might have on estimates of risk for specific cancers, but it would undoubtedly depend on the type of cancer, and would seem likely to be greater for specific cancer risk estimates than for all cancer risk estimates. This is evidenced by the fact that ERRs estimated from cancer incidence data (where diagnostic data can be expected to be more accurate) are generally larger than those based on

mortality data. I have increased all A-bomb survivor based estimates by 15%, and allowed an uncertainty factor of 1.4 (GSD = 1.23).

It is noted that this adjustment cancels the adjustment for underestimation of neutrons in Hiroshima. However, the uncertainties do not cancel. The combined uncertainty for A-bomb survivor based estimates from data errors (both dosimetry and health endpoint data) results in an uncertainty factor of 1.52 (GSD = 1.29).

Estimates for cancers of the breast, skin, and thyroid were not based on mortality data and seem much less likely to be subject to bias from this source, and this possibility has not been allowed for.

3.5 Uncertainty resulting from extrapolating risks beyond the follow-up period for which data are available.

Follow-up data from the A-bomb survivor study are available for the period 1950-1987, 42 years beyond the time that exposure occurred. No extrapolation is required for calculating the 40-year risks, but is required for calculating lifetime risks. Other studies from which risk estimates have been derived are also limited to no more than forty years, and in many cases less than this.

Because most of the unexpressed risk is in those exposed early in life, the treatment of age at exposure has a strong impact not only on the risks for those who are young at exposure, but also on the overall population risk. Lifetime risks also depend on assumptions that are made regarding the ERR over time. UNSCEAR (1994) presents estimates based on a model in which the ERR remains constant over time, and also on two alternative models in which a constant risk is assumed for the first 45 years of follow-up, and then assumed to decline linearly with age. In the first alternative model, risks were assumed to decline linearly until they reached the risk for age at exposure of 50. In the second alternative model, risks were assumed to decline linearly to reach zero risk at age 90. The first alternative reduced the lifetime risk for all solid tumors by 16% over that predicted by a constant relative risk model. The second alternative reduced these risks by 31% over that predicted by a constant relative risk model. Estimates for separate cancer types were not presented.

Kellerer and Barclay (1992) have proposed an alternative model in which the ERR is allowed to depend on attained age rather that age at exposure. They indicate that this model fitted the A-bomb survivors data just as well as the constant relative risk model, but would reduce lifetime risks for solid tumors by a factor of two over those as the more commonly used model based on age at exposure.

For lifetime risks for the entire population, I have reduced the estimate obtained using the age at exposure-specific constant relative risk model by 20%, and applied an uncertainty factor of 1.5 (GSD = 1.28). This leads to a 5th percentile that is about at the level predicted by Kellerer Barclay model, and a 95th percentile that is about 20% larger than the estimate obtained using the constant relative risk model. Because I would consider that the constant relative risk model would be appropriate for a 95th percentile for uncertainties related to extrapolation, this upper limit may appear a little large. However, some extra uncertainty is probably desirable to account for the effect of large sampling variation for those exposed as children on lifetime risks for the entire population.

For specific lifetime risks for those exposed under age 15, the uncertainty due to extrapolation is larger. For this age group, the first UNSCEAR alternative model reduces risks by 31% over a constant relative risk model, and the second model reduces risks by 50%. For this group, I have reduced risks over those obtained with the constant relative risk model by 40%, and used an uncertainty factor of 2.0 (GSD = 1.52).

3.6 Uncertainty in estimates of risk for the first 20 years of follow-up.

Although these estimates do not involve extrapolation beyond the period for which follow-up data are available, additional uncertainty results because the model used for the full 40-year period may not apply exactly. For cancers other than leukemia, I have included an additional uncertainty factor of 1.3 (GSD = 1.17) to account for this. For leukemia, a substantial portion of the risk would have been expressed in the first 20 years, and this is discussed in the specific discussion of leukemia risks given below.

3.7 Uncertainty in the modifying effects of dose rate on risks estimates obtained from data on persons exposed at high dose rates.

Experimental evidence indicates that effects are likely to be reduced when exposure is received at low dose rates. Some epidemiologic data has also suggested such reduction, although, in general, direct epidemiologic evidence is not conclusive. Some have suggested that if the dose rate is low enough, no risk will result. The factor by which risks resulting from exposure at low dose rates are reduced over those at low high rates is often referred to as the dose rate

effectiveness factor or DREF. (The expression dose and dose rate effectiveness factor, or DDREF, is also used. Here, however, we are asked only to address the reduction in risk resulting form low dose rates, so DREF seems more appropriate.)

Uncertainties in the DREF are not readily described using the lognormal distribution, in part because it seems reasonable to assign positive probabilities to zero risk at very low dose rates (a DREF of infinity), and to the possibility that there is no reduction (a DREF of one). My approach is to use the 5th, 50th, and 95th percentiles for high dose rate exposures, reduced by respective DREFs of four, two, and one. This approach to combining uncertainty in the DREF with uncertainties from other sources is not strictly rigorous, but it was not feasible to conduct simulations or to develop more complicated models. The assignment of a positive number for the 5th percentile implies that the probability assigned to zero risk for the scenario involving low dose rates is less than 0.05. In general, I would judge this probability to be about 1 in 40 or 0.025.

The DREF may vary by cancer type, but it is difficult to assess this variation. There is perhaps stronger evidence for reduction in risks for bone and lung cancer than for breast and thyroid cancer, but it is difficult to quantify this in a rigorous fashion. However, for several specific cancer types (bone, colon, liver, lung, pancreas, stomach, other cancers) I have used a DREF of 10 (instead of 4) for the 5th percentile, primarily because so little is known about the specific effects of dose rate on these cancer types.

3.8 Uncertainties in estimates of the number of life-years lost per cancer

The estimated years of life lost per cancer depends only on the pattern of risk over time, and does not depend on the overall level of risk. .Thus, many of the uncertainties discussed above to not apply to estimates of the years of life lost per cancer.

The main source of uncertainty is that resulting from extrapolating risks over time. UNSCEAR (1994) presents the number of life-years lost per cancer death for the constant relative risk model, and also for two alternative models. The first alternative model increased the years of life lost per cancer by about 6%, while the second such model increased it by 15%. Although Kellerer and Barclay (1992) do not present estimates of life-years lost for their model, presumably such estimates would be even larger. For my central estimate, I first calculated the years of life lost per cancer death based on EU/USA data using a constant relative risk model. This was then increased by 10% and an uncertainty factor of 1.2 was allowed for.

4. Specific Treatment of Various Cancer Types

In the material below, details of the models for each of the cancer types are summarized. A description of each of the items addressed follows.

Model for obtaining risk estimates:

1. *ERR coefficients.* These are the ERR estimates per Sv that form the basis for estimating the number of cancers expected to occur over a lifetime, or over the first 20 or 40 years following exposure. For cancer types based on the UNSCEAR model, sex-specific ERRs are presented and are intended to apply to persons exposed at age 25, with modification as indicated in 2 for exposures at other ages.

2. *Age at exposure parameter adjustment.* In nearly all models, risks have been modified by age at exposure, usually with a decrease in risk with increasing age at exposure. For cancer types based on the UNSCEAR model, this dependency is expressed by multiplying the ERR by $\exp[-\gamma(e - 25)]$, where e is age at exposure. For other cancer types, different ERRs are given for two or three categories defined by age at exposure.

3. *UNSCEAR (1994) lifetime risk estimate.* These are the estimates based on a constant relative risk model, and calculated as described in UNSCEAR (1994). The estimates are taken from Table 31 of the UNSCEAR report.

4. *EU/USA lifetime risk estimate.* These are estimates obtained by applying ERRs and the age at exposure dependencies indicated in 1 and 2 above to the EU/USA database.

5. *Transportation adjustment factor.* This is the factor by which estimates based on applying A-bomb survivor based ERRs to the EU/USA baseline risks are multiplied to adjust for differences in baseline rates between Japan and the EU/USA rates. This is usually the ratio of geometric mean of estimates in 3 and 4 to the estimate in 4. Lung cancer is treated slightly differently as discussed in Section 3.2. The factor is 1.0 for estimates based on sources of data other than the A-bomb survivors.

6. *Data quality adjustment factor.* This is the factor by which A-bomb survivor based estimates are multiplied to adjust for potential biases resulting from random errors in dosimetry, systematic errors in dosimetry, and errors in health effects data. This factor is 1.0 for estimates based on other sources of data, but allowance is made for uncertainty from this source in all cases.

7. *Median lifetime risk estimate based on the constant relative risk model.* This is the estimate in 4 multiplied by the adjustment factors in 5 and 6. For estimates based on sources of data other than the A-bomb survivors, the factors in 5 and 6 are one, and the estimate in 7 is the same as that in 4.

8. *Adjusted median lifetime risk estimate (elicitation Question iii).* For most cancers, this is the estimate in 7, reduced to reflect the possibility that the ERR per Sv may decline after the period 40 or more years after follow-up. Exceptions are bone cancer and leukemia, where lifetime risks are estimated to be nearly the same as 40-year risks.

9. *Risk expressed in first 40 years of follow-up (elicitation Question ii).* The parameters indicated in 1 and 2 above were applied to EU/USA data to estimate the risk after 40 years of follow-up. This estimate was then multiplied by the adjustment factors in 5 and 6.

10. *Risk expressed in first 20 years of follow-up (elicitation Question iii).* The parameters indicated in 1 and 2 above were applied to EU/USA data to estimate the risk after 20 years of follow-up. This estimate was then multiplied by the adjustment factors in 5 and 6.

11. *Median risk estimate for cancer cases (including non-fatal cases) expressed in the first 40 years of follow-up (elicitation Question viii).* This was obtained by multiplying the estimate given in 7 by the ratio of the 40-year incidence and mortality estimates obtained from the EU/USA data.

12. *Life-years lost per cancer death.* This was obtained from calculations based on the EU/USA database for lifetime risks. For most cancer types, this was increased by 10% to reflect a possible decline in the ERR/Sv after 40 years of follow-up.

13. *Median lifetime risk estimate for children based on the constant relative risk model.* The parameters indicated in 1 and 2 above were applied to EU/USA data to estimate the lifetime risk in those exposed under age . This estimate was then multiplied by the justment factors in 5 and 6.

ljusted median lifetime risk estimate for children licitation Question v). For cancers other than leukemia, this is the estimate in 13, reduced to reflect the possibility that the ERR per Sv may decline after the period 40 or more years after follow-up.

15. *Risk for children expressed in first 40 years of follow-up (elicitation Question iv).* The parameters indicated in 1 and 2 above were applied to EU/USA data to estimate the risk in those exposed under age 15 after 40 years of follow-up. This estimate was then multiplied by the adjustment factors in 5 and 6.

Uncertainties in risk estimates

In all cases the uncertainty factor K and the geometric standard error (GSD) associated with the uncertainty source are given. The uncertainty factor is defined as the value by which the median estimate would be multiplied (divided) to obtain the 95th (5th) percentile. Uncertainty factors (and GSDs) for combined uncertainties needed for various elicitation questions are also given.

4.1 Bone cancer

Model for obtaining risk estimates:

Bone cancer risk estimates have traditionally been based on data on persons exposed to high LET radium. This involves uncertainties in the relative biological effectiveness (RBE), uncertainties in dosimetry, and uncertainties related to the manner that available data have been analyzed. I have instead based estimates on the A-bomb survivor data. Even though these data are highly uncertain because of the small number of bone cancers that have occurred, these uncertainties can at least be more readily quantified. Because data on subjects exposed to ^{224}Ra have indicated that most risk has been expressed by 35 years or so after exposure, lifetime risks for bone cancer include only cancer expressed in the first 40 years of follow-up. Uncertainty for extrapolating risks over time is allowed for but is not as large as that used for most other types of cancer.

It is of interest to compare the risk estimate of 0.017% based on the above model with an estimate of 0.12% based on high-LET radiation and presented in NUREG (1991). This would imply an RBE of about 7, a reasonable value.

At the February 1996 meeting in Albuquerque, I realized that I had based my bone tumor estimates on A-bomb survivor data on bone and connective tissue instead of bone tumors alone. This would be fully appropriate only if the ERRs for bone tumors were the same as those for connective tissue. However, since the results are reasonably comparable to estimates that would be obtained from high-LET data, I have not modified my approach.

1. ERR coefficients: These were 1.26 per Sv for males and 0.81 per Sv for females. The estimates were based on A-bomb survivor mortality data as presented in Part VI of Table 8 of UNSCEAR (1994), and are intended to apply to an average of all exposure ages.

2. Age at exposure parameter adjustment parameter: UNSCEAR (1994) shows an ERR of 2.58 per Sv for those exposed under age 20, and an ERR of 0.92 per Sv for those exposed at ages 20 or older. In combination with the estimates in 1, the following sex- and age at exposure specific estimates were selected.

	Males	Females
0-19 years at exposure	3.14	2.02
20+ years at exposure	1.12	0.72

3. UNSCEAR (1994) lifetime risk estimate: Not available.

4. EU/USA lifetime risk estimate: 0.033%

5. Transportation adjustment factor: 1.00
6. Data quality adjustment factor: 1.09

7. Median lifetime risk estimate based on constant relative risk model: 0.036%

8. Adjusted median lifetime risk estimate (elicitation Question iii): 0.018%

   Because there is substantial evidence from data on radium exposure that bone cancer risks decrease with time since exposure, the estimate based on 40 years of follow-up has been used here.

9. Risk expressed in first 40 years of follow-up (elicitation Question ii): 0.018%

10. Risk expressed in first 20 years of follow-up (elicitation Question i): 0.007%

11. Median risk estimate for cancer cases (including non-fatal cases) expressed in the first 40 years of follow-up (elicitation Question viii): 0.034%

12. Life-years lost per cancer death (elicitation Question xii): 14.7

Uncertainties in risk estimates

1. Sampling variation of ERR estimate: K = 5.57 (GSD = 2.84)

2. Data quality.
   a) Random error in dose estimates: K = 1.2 (GSD = 1.11)
   b) Systematic error in dose estimates: K = 1.2 (GSD = 1.11)
   c) Errors in health effects data: K = 1.4 (GSD = 1.23)

   Overall uncertainty (a-c): K = 1.52 (GSD = 1.29)

3. Transportation: No data are available for this calculation; I have selected a value of K = 1.5 (GSD = 1.28).

   Overall uncertainty in 40-year risks (1-3): K = 6.13 (GSD = 3.01)

4. Uncertainty resulting from extrapolating risks beyond the follow-up period for which data are available (applied to lifetime risks only): K = 1.2 (GSD = 1.12).

   This uncertainty is reduced over that used for most other cancer types because evidence indicates there is little risk beyond 30 years or so.

   Overall uncertainty in lifetime risks (1-4): K = 6.19 (GSD = 3.03)

5. Additional uncertainty in estimates for the first 20 years of follow-up: K = 1.3 (GSD = 1.17)

   Overall uncertainty in 20-year risks (1-3, 5): K = 6.24 (GSD = 3.04)

6. Additional uncertainty in estimates for exposure received at low dose rates (applied to low dose-rate exposure only). The 5th percentile is taken to be the 5th percentile for high dose rate exposure reduced by a factor of 10. The 95th percentile is taken to be the 95th percentile for high dose rate exposure. (The estimate

for high dose rate exposure is divided by 2 to obtain the median estimate.)

4.2 Breast cancer

Model for obtaining risk estimates:

Estimates for breast cancer risks were based on consideration of studies of Caucasian women using the model described (and justified) in NUREG (1991) for the central estimate. The original estimates for this model were derived from the Massachusetts TB fluoroscopy study and the New York acute post-partum mastitis study, and data from these studies have been used as the basis for estimating uncertainty resulting from sampling variation. The lifetime risk estimates presented below apply to females, and need to be halved to apply to a population of both sexes.

1-2. ERR coefficients: The ERR was taken to be 0.7 per Sv for females exposed under age 20, 0.3 per Sv for females exposed between 20 and 40, and 0.1 per Sv for females exposed at ages 40 and over.

3. UNSCEAR (1994) lifetime risk estimate: 2.0% (not used in my model)

4. EU/USA lifetime risk estimate: 0.93%

5. Transportation adjustment factor: Not applicable

6. Data quality adjustment factor: 1.0

7. Median lifetime risk estimate based on constant relative risk model: 0.93%

8. Adjusted median lifetime risk estimate for elicitation Question iii: 0.75%

9. Risk expressed in first 40 years of follow-up (elicitation Question ii): 0.31%

10. Risk expressed in first 20 years of follow-up (elicitation Question i): 0.070%

11. Median risk estimate for cancer cases (including non-fatal cases) expressed in the first 40 years of follow-up (elicitation Question viii): 0.98%

12. Life-years lost per cancer (elicitation Question viii): 17.4

13. Median lifetime risk estimate for children based on constant relative risk model: 2.08%

14. Adjusted median lifetime risk estimate for children (elicitation Question v): 1.25%

15. Risk for children expressed in first 40 years of follow-up (elicitation Question iv): 0.25%

Uncertainties in risk estimates

1. Sampling variation of ERR estimate

   Total population: K = 1.41 (GSD = 1.23)
   Children: K = 1.74 (GSD = 1.40)

2. Data quality.

   Random and systematic errors in dose estimates: K = 1.5 (GSD = 1.28)

3. Transportation: K = 1.3 (GSD = 1.17)

   Overall uncertainty in 40-year risks (1-3):
   Total population: K = 1.80 (GSD = 1.43)
   Children: K = 2.08 (GSD = 1.56)

4. Uncertainty resulting from extrapolating risks beyond the follow-up period for which data are available (applied to lifetime risks only).

   Total population: K = 1.5 (GSD = 1.28)
   Children: K = 2.0 (GSD = 1.52)

   Overall uncertainty in lifetime risks (1-4):
   Total population: K = 2.05 (GSD = 1.55)
   Children: K = 2.73 (GSD = 1.84)

5. Additional uncertainty in estimates for the first 20 years of follow-up: K = 1.3 (GSD = 1.17)

   Overall uncertainty in 20-year risks (1-3, 5): K = 1.90 (GSD = 1.48)

6. Additional uncertainty in estimates for exposure received at low dose rates (applied to low dose-rate exposure only). The 5th percentile is taken to be the 5th percentile for high dose rate exposure reduced by a factor of 4. The 95th percentile is taken to be the 95th percentile for high dose rate exposure. (The estimate for high dose rate exposure is divided by 2 to obtain the median estimate.)

4.3 Colon cancer

Model for obtaining risk estimates:

1. ERR coefficients: These were 0.54 per Sv for males and 1.00 per Sv for females. The estimates were based on A-bomb survivor data as presented in Table 24 of UNSCEAR (1994), and are intended to apply to exposure at age 25.

2. Age at exposure parameter adjustment parameter: ERR modified by $\exp[-\gamma(e - 25)]$, where e is age at exposure in years.

   $\gamma = -0.033$ is the estimate in Table 24 of UNSCEAR (1994).

3. UNSCEAR (1994) lifetime risk estimate: 0.6%

4. EU/USA lifetime risk estimate: 1.13%

5. Transportation adjustment factor: 0.73

6. Data quality adjustment factor: 1.09

7. Median lifetime risk estimate based on constant relative risk model: 0.90%

8. Adjusted median lifetime risk estimate for elicitation Question iii: 0.72%

9. Risk expressed in first 40 years of follow-up (elicitation Question ii): 0.25%

10. Risk expressed in first 20 years of follow-up (elicitation Question i): 0.058%

11. Median risk estimate for cancer cases (including non-fatal cases) expressed in the first 40 years of follow-up (elicitation Question viii): 0.47%

12. Life-years lost per cancer death (elicitation Question viii): 13.2

Uncertainties in risk estimates

1. Sampling variation of ERR estimate: K = 4.46 (GSD = 2.48)

2. Data quality.
   a) Random error in dose estimates: K = 1.2 (GSD = 1.11)
   b) Systematic error in dose estimates: K = 1.2 (GSD = 1.11)
   c) Errors in health effects data: K = 1.4 (GSD = 1.23)

   Overall uncertainty (a-c): K = 1.52 (GSD = 1.29)

3. Transportation: K = 1.37 (GSD = 1.21)

   Overall uncertainty in 40-year risks (1-3): K = 4.87 (GSD = 2.62)

4. Uncertainty resulting from extrapolating risks beyond the follow-up period for which data are available (applied to lifetime risks only): K = 1.5 (GSD = 1.28)

   Overall uncertainty in lifetime risks (1-4): K = 5.13 (GSD = 2.70)

5. Additional uncertainty in estimates for the first 20 years of follow-up: K = 1.3 (GSD = 1.17)

   Overall uncertainty in 20-year risks (1-3, 5): K = 4.98 (GSD = 2.65)

6. Additional uncertainty in estimates for exposure received at low dose rates (applied to low dose-rate exposure only). The 5th percentile is taken to be the 5th percentile for high dose rate exposure reduced by a factor of 10. The 95th percentile is taken to be the 95th percentile for high dose rate exposure. (The estimate for high dose rate exposure is divided by 2 to obtain the median estimate.)

4.4 Leukemia

The model used to estimate leukemia risks is that used by UNSCEAR (1994). This model, which was based on analyses of A-bomb survivor incidence data by Preston et al. (1994), is based on expressions for the excess absolute risk as a function of sex, age at exposure and time since exposure. The UNSCEAR (1994) report presents only lifetime risks based on this model. To determine the fraction of the risk expressed in the 20- and 40-year post-exposure periods, this model was applied to the lifetable information provided for the EU/USA population. Because the UNSCEAR model is an excess absolute risk model, it does not involve use of the EU/USA baseline rates. However, uncertainty resulting from differences in baseline risks for EU/USA and Japan is still a possibility, although ratios (Japan/US and Japan/UK) obtained from Land and Sinclair (1991) indicate this uncertainty is small (Table 3).

The model was based on leukemia incidence data, and thus is more appropriate for estimating leukemia incidence than mortality. It is interesting that most leukemia mortality estimates have been based on the A-bomb survivor incidence data with no adjustment to account for the fact that leukemia is not 100% fatal. In the material below, I have provided both incidence and mortality estimates. The latter were obtained by multiplying the excess risk at each attained age by age and sex-specific mortality/incidence ratios from the EU/USA data for leukemia excluding chronic lymphatic leukemia. Because the patterns of leukemia risk and lethality may vary by the specific leukemia type, additional uncertainty is allowed for this adjustment.

Model for obtaining risk estimates:

1.-2.The model used was that used by UNSCEAR (1994) which was developed by Preston et al. (1994), and is summarized below:

3. UNSCEAR (1994) lifetime risk estimate: 1.1%

   Although indicated as a mortality estimate, it is more appropriately interpreted as an estimate of leukemia incidence.

4. Adjusted estimate for mortality obtained as described above: 0.759%

5. Transportation adjustment factor: 1.00

6. Data quality adjustment factor: 1.09

8. Median lifetime risk estimate for elicitation Question iii: Incidence – 1.17%, Mortality – 0.805%

9. Risk expressed in first 40 years of follow-up (elicitation Question ii): Incidence – 1.15%, Mortality – 0.78%

10. Risk expressed in first 20 years of follow-up (elicitation Question i): Incidence – 0.93%, Mortality – 0.65%

11. Median risk estimate for cancer cases (including non-fatal cases) expressed in the first 40 years of follow-up (elicitation Question viii): 1.15%

12. Life-years lost per cancer death (elicitation Question viii): 20.8

13. Median lifetime risk estimate for children (elicitation Question v): Incidence – 1.61%, Mortality – 1.07%

14. Risk for children expressed in first 40 years of follow-up (elicitation Question iv): Incidence – 1.58%, Mortality – 1.05%

Uncertainties in risk estimates

1. Sampling variation of ERR estimate

   Total population: K = 1.30 (GSD = 1.18)
   Children: K = 1.44 (GSD = 1.27)

2. Data quality.
   a) Random error in dose estimates:
   K = 1.2 (GSD = 1.11)
   b) Systematic error in dose estimates:
   K = 1.2 (GSD = 1.11)
   c) Errors in health effects data:
   K = 1.4 (GSD = 1.23)

   Overall uncertainty (a-c): K = 1.52 (GSD = 1.29)

3. Transportation: K = 1.2 (GSD = 1.12)

   Additional uncertainty in mortality estimates to account for fact that estimates based on incidence data: K = 1.3 (GSD = 1.17)

   Overall uncertainty in 40-year risks (1-3):

	Incidence	Mortality
Total population:	K = 1.76 (GSD = 1.41)	K = 1.86 (GSD = 1.46)
Children:	K = 1.88 (GSD = 1.47)	K = 1.98 (GSD = 1.52)

4. Uncertainty resulting from extrapolating risks beyond the follow-up period for which data are available (applied to lifetime risks only). Because risks have sharply declined with time since exposure, only a small amount of uncertainty is allowed for extrapolation.

   Total population: K = 1.2 (GSD = 1.12)
   Children: K = 1.2 (GSD = 1.12)

   Overall uncertainty in lifetime risks (1-4):

	Incidence	Mortality
Total population:	K = 1.76 (GSD = 1.41)	K = 1.86 (GSD = 1.46)
Children:	K = 1.88 (GSD = 1.47)	K = 1.98 (GSD = 1.52)

5. Additional uncertainty in estimates for the first 20 years of follow-up: K = 1.3 (GSD = 1.17)

   Overall uncertainty in 20-year risks (1-3, 5):

Incidence	Mortality
K = 1.81 (GSD = 1.43)	K = 1.90 (GSD = 1.48)

6. Additional uncertainty in estimates for exposure received at low dose rates (applied to low dose-rate exposure only). The 5th percentile is taken to be the 5th percentile for high dose rate exposure reduced by a factor of 4. The 95th percentile is taken to be the 95th percentile for high dose rate exposure. (The estimate for high dose rate exposure is divided by 2 to obtain the median estimate.)

4.5 Liver cancer

Estimates for risks of liver cancer have often been obtained from data on thorotrast patients exposed to high-LET radiation. Instead, I have based my estimate on A-bomb survivor data. It is interesting and perhaps reassuring that the lifetime risk obtained (0.33%) is very similar to that obtained by reducing the high-LET based estimate of 3.0% given in BEIR V) by an RBE of 10.

Model for obtaining risk estimates:

1. ERR coefficients: These were 0.97 per Sv for males and 0.32 per Sv for females. The estimates were based on A-bomb survivor data as presented in Table 24 of UNSCEAR (1994), and are intended to apply to exposure at age 25.

2. Age at exposure parameter adjustment parameter: ERR modified by $\exp[-\gamma(e - 25)]$, where e is age at exposure in years.

   $\gamma = -0.027$ is the estimate in Table 24 of UNSCEAR (1994).

3. UNSCEAR (1994) lifetime risk estimate: 1.2%

4. EU/USA lifetime risk estimate: 0.0968%

5. Transportation adjustment factor: 3.46

6. Data quality adjustment factor: 1.09

7. Median lifetime risk estimate based on constant relative risk model: 0.37%

8. Adjusted median lifetime risk estimate for elicitation Question iii: 0.29%

9. Risk expressed in first 40 years of follow-up (elicitation Question ii): 0.14%

10. Risk expressed in first 20 years of follow-up (elicitation Question i): 0.036%

11. Median risk estimate for cancer cases (including non-fatal cases) expressed in the first 40 years of follow-up (elicitation Question viii): 0.17%

12. Life-years lost per cancer death (elicitation Question viii): 14.7 years

Uncertainties in risk estimates

1. Sampling variation of ERR estimate: K = 2.58 (GSD = 1.78)

2. Data quality.
   a) Random error in dose estimates: K = 1.2 (GSD = 1.11)
   b) Systematic error in dose estimates: K = 1.2 (GSD = 1.11)
   c) Errors in health effects data: K = 1.4 (GSD = 1.23)

   Overall uncertainty (a-c): K = 1.52 (GSD = 1.29)

3. Transportation: K = 3.47 (GSD = 2.13)

   Overall uncertainty in 40-year risks (1-3): K = 5.05 (GSD = 2.68)

4. Uncertainty resulting from extrapolating risks beyond the follow-up period for which data are available (applied to lifetime risks only): K = 1.5 (GSD = 1.28)

Overall uncertainty in lifetime risks (1-4): K = 5.31 (GSD = 2.76)

5. Additional uncertainty in estimates for the first 20 years of follow-up: K = 1.3 (GSD = 1.17)

   Overall uncertainty in 20-year risks (1-3, 5): K = 5.17 (GSD = 2.71)

6. Additional uncertainty in estimates for exposure received at low dose rates (applied to low dose-rate exposure only). The 5th percentile is taken to be the 5th percentile for high dose rate exposure reduced by a factor of 10. The 95th percentile is taken to be the 95th percentile for high dose rate exposure. (The estimate for high dose rate exposure is divided by 2 to obtain the median estimate.)

4.6 Lung cancer

Model for obtaining risk estimates:

1. ERR coefficients: These were 0.37 per Sv for males and 1.06 per Sv for females. The estimates were based on A-bomb survivor data as presented in Table 24 of UNSCEAR (1994), and are intended to apply to exposure at age 25.

2. Age at exposure parameter adjustment parameter: ERR modified by $\exp[-\gamma(e - 25)]$, where e is age at exposure in years.

   $\gamma = 0.021$ is the estimate in Table 24 of UNSCEAR (1994).

3. UNSCEAR (1994) lifetime risk estimate: 2.5%

4. EU/USA lifetime risk estimate: 2.92%

5. Transportation adjustment factor: 0.72

6. Data quality adjustment factor: 1.09

7. Median lifetime risk estimate based on constant relative risk model: 2.28%

8. Adjusted median lifetime risk estimate for elicitation Question iii: 1.83%

9. Risk expressed in first 40 years of follow-up (elicitation Question ii): 1.63%

10. Risk expressed in first 20 years of follow-up (elicitation Question i): 0.66%

14. Median risk estimate for cancer cases (including non-fatal cases) expressed in the first 40 years of follow-up (elicitation Question viii): 1.80%

15. Life-years lost per cancer death (elicitation Question: 13.2

Uncertainties in risk estimates

1. Sampling variation of ERR estimate: K = 1.64 (GSD = 1.35)

2. Data quality.
   a) Random error in dose estimates: K = 1.2 (GSD = 1.11)
   b) Systematic error in dose estimates: K = 1.2 (GSD = 1.11)
   c) Errors in health effects data: K = 1.4 (GSD = 1.23)

   Overall uncertainty (a-c): K = 1.52 (GSD = 1.29)

3. Transportation: K = 1.39 (GSD = 1.22)

   Combined uncertainties for 1-3: K = 2.07 (GSD = 1.55)

4. Uncertainty resulting from extrapolating risks beyond the follow-up period for which data are available (applied to lifetime risks only): K = 1.5 (GSD = 1.28)

   Overall uncertainty in lifetime risks (1-4): K = 2.30 (GSD = 1.66)

5. Additional uncertainty in estimates for the first 20 years of follow-up: K = 1.3 (GSD = 1.17)

   Overall uncertainty in 20-year risks (1-3, 5): K = 2.15 (GSD = 1.59)

6. Additional uncertainty in estimates for exposure received at low dose rates (applied to low dose-rate exposure only). The 5th percentile is taken to be the 5th percentile for high dose rate exposure reduced by a factor of 10. The 95th percentile is taken to be the 95th percentile for high dose rate exposure. (The estimate for high dose rate exposure is divided by 2 to obtain the median estimate.)

4.7 Pancreatic Cancer

Cancer of the pancreas has not been unequivocally linked with radiation exposure, and estimates based on A-bomb survivor data are negative. However, this may be the result of random variation among risk estimates for different types of cancers. My model for cancer of the pancreas is based on the UNSCEAR (1994) model, using, for each sex, the minimum of the ERRs for cancers of the esophagus, stomach, colon, and liver; and using the age at exposure coefficient for all solid tumors. For males, the minimum ERR is that for stomach cancer of 0.16 per Sv; for females, the minimum ERR is that for liver cancer of 0.32 per Sv. These ERRs are then applied to baseline rates from the EU/USA database for cancer of the pancreas. All lower 5th percentiles for cancer of the pancreas have been taken to be zero. The 95th percentiles are obtained by multiplying the median estimate by the maximum of the uncertainty factors for cancers of the stomach, colon, and liver.

Model for obtaining risk estimates:

1. ERR coefficients: The ERR for males is 0.16 per Sv; the ERR for females is 0.32.

2. Age at exposure parameter adjustment parameter: RR modified by $\exp[-\gamma(e - 25)]$, where e is age at exposure in years.

   $\gamma = -0.026$ is the estimate in Table 24 of UNSCEAR (1994) for all solid tumors.

3. UNSCEAR (1994) lifetime risk estimate: Not available.

4. EU/USA lifetime risk estimate: 0.17%

5. Transportation adjustment factor: 1.0

6. Data quality adjustment factor: 1.0

7. Median lifetime risk estimate based on constant relative risk model: 0.17%

8. Adjusted median lifetime risk estimate for elicitation Question iii: 0.13%

9. Risk expressed in first 40 years of follow-up (elicitation Question ii): 0.054%

10. Risk expressed in first 20 years of follow-up (elicitation Question i): 0.014%

11. Median risk estimate for cancer cases (including non-fatal cases) expressed in the first 40 years of follow-up (elicitation Question viii): 0.062%

12. Life-years lost per cancer death (elicitation Question viii): 13.4

Uncertainties in risk estimates

See discussion at beginning of description of the pancreas model.

4.8 Skin cancer

Model for obtaining risk estimates:

Skin cancer risks are based on the model described and justified in NUREG (1991), and this model includes consideration of the fact that 90% of all skin cancers occur on those parts of the body exposed to ultra-violet radiation. The model is for skin cancer incidence, but the ERR can also be applied to mortality rates to obtain mortality estimates. Because the ratio of mortality to incidence rates varies substantially by the specific type of skin cancer, and because the risk resulting from radiation exposure may also vary by the specific cancer type, additional uncertainty has been allowed for skin cancer mortality estimates. This uncertainty has been taken to be a factor of 1.4 (GSD = 1.23).

The EU/USA skin cancer incidence rates are substantially (in the order of a factor of 4) lower than rates given by Scotto et al. (1974, 1983) and by Fears and Scotto (1982); these latter rates were used as the basis for an ICRP (1991) skin cancer model. Because we were asked to assume that the EU/USA rates were not subject to uncertainty, I have used these without question. However, an uncertainty factor of 2 (GSD = 1.52) has been allowed for transportation to account for the possible impact of variation in skin cancer rates among populations.

1. ERR coefficients: The single coefficient was 0.5 per Sv, and was obtained through consideration of several data sets, particularly the Israel and New York tinea capitis studies.

2. Age at exposure parameter adjustment parameter: No modification by age at exposure. Much of the data involved exposure in childhood.

3. UNSCEAR (1994) lifetime risk estimate: Not available.

4. EU/USA lifetime risk estimate: 0.038%

5. Transportation adjustment factor: 1.0

6. Data quality adjustment factor: 1.0

7. Median lifetime risk estimate based on constant relative risk model: 0.038%

8. Adjusted median lifetime risk estimate for elicitation Question iii: 0.031%

9. Risk expressed in first 40 years of follow-up (elicitation Question ii): 0.019%

10. Risk expressed in first 20 years of follow-up (elicitation Question i): 0.0063%

11. Median risk estimate for cancer cases (including non-fatal cases) expressed in the first 40 years of follow-up (elicitation Question viii): 1.08%

12. Life-years lost per cancer death (elicitation Question viii): 10.9

Uncertainties in risk estimates

1. Sampling variation of ERR estimate: K = 1.22 (GSD = 1.13)

2. Data quality.
   K = 1.5 (GSD = 1.28)

3. Transportation: K = 2 (GSD = 1.52)
   Note: Results for various studies vary considerably, although this may be at least partly attributable to the fact that in some studies, only parts of the body that would be covered by clothing were exposed.

   Additional uncertainty in mortality estimates to account for fact that estimates based on incidence data: K = 1.4 (GSD = 1.23)

   Overall uncertainty in 40-year risks (1-3):
   Incidence: K = 2.28 (GSD = 1.65)
   Mortality: K = 2.44 (GSD = 1.72)

4. Uncertainty resulting from extrapolating risks beyond the follow-up period for which data are available (applied to lifetime risks only): K = 1.5 (GSD = 1.28)

   Overall uncertainty in lifetime mortality risks (1-4): K = 2.66 (GSD = 1.81)

5. Additional uncertainty in estimates for the first 20 years of follow-up: K = 1.3 (GSD = 1.17)

   Overall uncertainty in 20-year mortality risks (1-3, 5): K = 2.53 (GSD = 1.76)

6. Additional uncertainty in estimates for exposure received at low dose rates (applied to low dose-rate exposure only). The 5th percentile is taken to be the 5th percentile for high dose rate exposure reduced by a factor of 4. The 95th percentile is taken to be the 95th percentile for high dose rate exposure. (The estimate for high dose rate exposure is divided by 2 to obtain the median estimate.)

4.9 Stomach cancer

Model for obtaining risk estimates:

1. ERR coefficients: These were 0.16 per Sv for males and 0.62 per Sv for females. The estimates were based on A-bomb survivor data as presented in Table 24 of UNSCEAR (1994), and are intended to apply to exposure at age 25.

2. Age at exposure parameter adjustment parameter: ERR modified by $\exp[-\gamma(e - 25)]$, where e is age at exposure in years.

   $\gamma = -0.035$ is the estimate in Table 24 of UNSCEAR (1994).

3. UNSCEAR (1994) lifetime risk estimate: 1.4%

4. EU/USA lifetime risk estimate: 0.24%

5. Transportation adjustment factor: 2.41

6. Data quality adjustment factor: 1.09

7. Median lifetime risk estimate based on constant relative risk model: 0.63%

8. Adjusted median lifetime risk estimate for elicitation Question iii: 0.50%

9. Risk expressed in first 40 years of follow-up (elicitation Question ii): 0.16%

10. Risk expressed in first 20 years of follow-up (elicitation Question i): 0.037%

11. Median risk estimate for cancer cases (including non-fatal cases) expressed in the first 40 years of follow-up (elicitation Question viii): 0.23%

12. Life-years lost per cancer death (elicitation Question viii): 13.1

Uncertainties in risk estimates

1. Sampling variation of ERR estimate: K = 2.75 (GSD = 1.85)

2. Data quality.
   a) Random error in dose estimates: K = 1.2 (GSD = 1.11)
   b) Systematic error in dose estimates: K = 1.2 (GSD = 1.11)
   c) Errors in health effects data: K = 1.4 (GSD = 1.23)

   Overall uncertainty (a-c): K = 1.52 (GSD = 1.29)

3. Transportation: K = 2.42 (GSD = 1.71)

   Overall uncertainty in 40-year risks (1-3): K = 4.08 (GSD = 2.35)

4. Uncertainty resulting from extrapolating risks beyond the follow-up period for which data are available (applied to lifetime risks only): K = 1.5 (GSD = 1.28)

   Overall uncertainty in lifetime risks (1-4): K = 4.33 (GSD = 2.44)

5. Additional uncertainty in estimates for the first 20 years of follow-up: K = 1.3 (GSD = 1.17)

   Overall uncertainty in 20-year risks (1-3, 5): K = 4.17 (GSD = 2.38)

6. Additional uncertainty in estimates for exposure received at low dose rates (applied to low dose-rate exposure only). The 5th percentile is taken to be the 5th percentile for high dose rate exposure reduced by a factor of 10. The 95th percentile is taken to be the 95th percentile for high dose rate exposure. (The estimate for high dose rate exposure is divided by 2 to obtain the median estimate.)

4.10 Thyroid cancer

Risk coefficients used for thyroid cancer are taken from a recent pooled analysis of data from several studies by Ron et al. (1995). The overall ERR estimate for exposure under age 15 was 7.7 per Sv with 95% confidence limits (2.1-28.7), where the confidence limits included heterogeneity among studies. Data on thyroid cancer resulting from exposure in adulthood are very limited, and have not unequivocally demonstrated risk. However, data from the A-bomb survivor cancer incidence study indicate that risks for those exposed as adults are about a factor of 10 lower than for those exposed as children. I have accordingly used an ERR of 0.77 for exposure at age 15 or older.

Model for obtaining risk estimates:

1-2. ERR coefficients: This was 7.7 per Sv for those exposed under age 15, and 0.77 per Sv for those exposed at age 15 and over.

3. UNSCEAR (1994) lifetime risk estimate: Not available.

4. EU/USA lifetime risk estimate: 0.091%

5. Transportation adjustment factor: 1.0

6. Data quality adjustment factor: 1.0

7. Median lifetime risk estimate based on constant relative risk model: 0.091%

8. Adjusted median lifetime risk estimate for elicitation Question iii: 0.073%

9. Risk expressed in first 40 years of follow-up (elicitation Question ii): 0.018%

10. Risk expressed in first 20 years of follow-up (elicitation Question i): 0.0053%

11. Median risk estimate for cancer cases (including non-fatal cases) expressed in the first 40 years of follow-up (elicitation Question viii): 0.19%

12. Life-years lost per cancer death (elicitation Question viii): 14.5

13. Median lifetime risk estimate for children based on constant relative risk model: 0.31%

14. Adjusted median lifetime risk estimate for children (elicitation Question v): 0.19%

15. Risk for children expressed in first 40 years of follow-up (elicitation Question iv): 0.015%

Uncertainties in risk estimates

1. Sampling variation of ERR estimate

   Total population: K = 4.00 (GSD = 2.32)
   Children: K = 3.00 (GSD = 1.95)

   The uncertainty factor for children was obtained from the confidence 95% interval (2.1-28.7) for those exposed under age 15. The uncertainty factor for the total population was increased to accommodate additional uncertainty because of limited data for exposure in adults.

2. Data quality.
   K = 1.5 (GSD = 1.28)

3. Transportation: Because confidence limits above included heterogeneity among studies, no additional uncertainty has been allowed for.

   Overall uncertainty in 40-year risks (1-3):
   Total population: K = 4.23 (GSD = 2.40)
   Children: K = 3.23 (GSD = 2.04)

4. Uncertainty resulting from extrapolating risks beyond the follow-up period for which data are available (applied to lifetime risks only).

   Total population: K = 1.5 (GSD = 1.28)
   Children: K = 2.0 (GSD = 1.52)

   Overall uncertainty in lifetime risks (1-4):
   Total population: K = 4.48 (GSD = 2.49)
   Children: K = 3.89 (GSD = 2.28)

5. Additional uncertainty in estimates for the first 20 years of follow-up: K = 1.3 (GSD = 1.17)

   Overall uncertainty in 20-year risks (1-3, 5): K = 4.32 (GSD = 2.43)

6. Additional uncertainty in estimates for exposure received at low dose rates (applied to low dose-rate exposure only). The 5th percentile is taken to be the 5th percentile for high dose rate exposure reduced by a factor of 4. The 95th percentile is taken to be the 95th percentile for high dose rate exposure. (The estimate for high dose rate exposure is divided by 2 to obtain the median estimate.)

4.11 All other cancers

Model for obtaining risk estimates:

1. ERR coefficients: These were 0.16 per Sv for males and 0.62 per Sv for females. The estimates were based on A-bomb survivor data as presented in Table 24 of UNSCEAR (1994), and are intended to apply to exposure at age 25. The estimates were obtained as a weighted average of the ERR estimates for other cancers and cancers of the esophagus, bladder, and ovary.

2. Age at exposure parameter adjustment parameter: ERR modified by $\exp[-\gamma(e - 25)]$, where e is age at exposure in years.

   $\gamma = -0.035$ is the estimate in Table 24 of UNSCEAR (1994).

3. UNSCEAR (1994) lifetime risk estimate: 3.7% (includes cancer of the pancreas)

4. EU/USA lifetime risk estimate: 4.57%

5. Transportation adjustment factor: 0.90

6. Data quality adjustment factor: 1.09

7. Median lifetime risk estimate based on constant relative risk model: 4.47%

8. Adjusted median lifetime risk estimate for elicitation Question iii: 3.58%

9. Risk expressed in first 40 years of follow-up (elicitation Question ii): 0.98%

10. Risk expressed in first 20 years of follow-up (elicitation Question i): 0.19%

11. Median risk estimate for cancer cases (including non-fatal cases) expressed in the first 40 years of follow-up (elicitation Question viii): 1.96%

12. Life-years lost per cancer death (elicitation Question viii): 12.5

Uncertainties in risk estimates

1. Sampling variation of ERR estimate: K = 1.78 (GSD = 1.42)

2. Data quality.
   a) Random error in dose estimates: K = 1.2 (GSD = 1.11)
   b) Systematic error in dose estimates: K = 1.2 (GSD = 1.11)
   c) Errors in health effects data: K = 1.4 (GSD = 1.23)

   Overall uncertainty (a-c): K = 1.52 (GSD = 1.29)

3. Transportation: K = 1.3 (GSD = 1.17)

   Overall uncertainty in 40-year risks (1-3): K = 2.13 (GSD = 1.59)

4. Uncertainty resulting from extrapolating risks beyond the follow-up period for which data are available (applied to lifetime risks only): K = 1.5 (GSD = 1.28)

   Overall uncertainty in lifetime risks (1-4): K = 2.36 (GSD = 1.69)

5. Additional uncertainty in estimates for the first 20 years of follow-up: K = 1.3 (GSD = 1.17)

   Overall uncertainty in 20-year risks (1-3, 5): K = 2.24 (GSD = 1.63)

6. Additional uncertainty in estimates for exposure received at low dose rates (applied to low dose-rate exposure only). The 5th percentile is taken to be the 5th percentile for high dose rate exposure reduced by a factor of 10. The 95th percentile is taken to be the 95th percentile for high dose rate exposure. (The estimate for high dose rate exposure is divided by 2 to obtain the median estimate.)

4.12 All solid tumors

Estimates for this specific category were not required, but I found it useful to consider this category before addressing uncertainties in risk estimates for all cancers. Most recent risk assessments have provided separate models for leukemia and for cancers other than leukemia.

Median estimates for all solid tumors were obtained as the sum of the risks for individual cancer types. However, for both sampling variation and transportation, uncertainty was judged to be smaller for all tumors than for individual types. For sampling variation, the total number of solid tumors in the A-bomb survivor study was used as discussed in Section 3.1 and indicated in Tables 1 and 2. For transportation, I used an uncertainty factor of 1.2 (GSD = 1.11), somewhat smaller than for any of the individual cancer types.

Model for obtaining risk estimates:

1. Not applicable. See above.

2. Not applicable. See above.

3. UNSCEAR (1994) lifetime risk estimate: 10.9%

4. EU/USA lifetime risk estimate: Not calculated.

5. Transportation adjustment factor: Obtained separately for individual cancer types.

6. Data quality adjustment factor: Obtained separately for individual cancer types.

7. Median lifetime risk estimate based on constant relative risk model: Not calculated.

8. Adjusted median lifetime risk estimate for elicitation Question iii: 9.90%

9. Risk expressed in first 40 years of follow-up (elicitation Question ii): 3.58%

10. Risk expressed in first 20 years of follow-up (elicitation Question i): 1.08%

11. Median risk estimate for cancer cases (including non-fatal cases) expressed in the first 40 years of follow-up (elicitation Question viii): 6.98%

12. Life-years lost per cancer death (elicitation Question viii): 13.9 (obtained as weighted mean of estimates for individual cancer types).

13. Median lifetime risk estimate for children based on constant relative risk model: Not calculated.

14. Adjusted median lifetime risk estimate for children (elicitation Question v): 19.2%

15. Risk for children expressed in first 40 years of follow-up (elicitation Question iv): 1.14%

Uncertainties in risk estimates

1. Sampling variation of ERR estimate

   Total population: K = 1.37 (GSD = 1.21)
   Children: K = 1.61 (GSD = 1.34)

2. Data quality.
   a) Random error in dose estimates: K = 1.2 (GSD = 1.11)
   b) Systematic error in dose estimates: K = 1.2 (GSD = 1.11)
   c) Errors in health effects data: K = 1.4 (GSD = 1.23)

   Overall uncertainty (a-c): K = 1.52 (GSD = 1.29)

3. Transportation: K = 1.2 (GSD = 1.11)

   Overall uncertainty in 40-year risks (1-3):
   Total population: K = 1.73 (GSD = 1.40)
   Children: K = 1.94 (GSD = 1.49)

4. Uncertainty resulting from extrapolating risks beyond the follow-up period for which data are available (applied to lifetime risks only).

   Total population: K = 1.5 (GSD = 1.28)
   Children: K = 2.0 (GSD = 1.52)

   Overall uncertainty in lifetime risks:
   Total population: K = 1.98 (GSD = 1.52)
   Children: K = 2.60 (GSD = 1.79)

5. Additional uncertainty in estimates for the first 20 years of follow-up: K = 1.3 (GSD = 1.17)

   Overall uncertainty in 20-year risks (1-3, 5): K = 1.84 (GSD = 1.45)

6. Additional uncertainty in estimates for exposure received at low dose rates (applied to low dose-rate exposure only). The 5th percentile is taken to be the 5th percentile for high dose rate exposure reduced by a factor of 4. The 95th percentile is taken to be the 95th percentile for high dose rate exposure. (The estimate for high dose rate exposure is divided by 2 to obtain the median estimate.)

4.13 All cancers

For all cancers, the median estimate can be obtained as the sum of the medians for all solid tumors and leukemia. The 5th (95th) percentile was obtained as the sum of the 5th (95th) percentiles for all solid tumors and leukemia. It is recognized that this may slightly overestimate the uncertainty.

4.14 Cancers resulting from in utero exposure

As median estimates for cancers expressed in the first 20 years of follow-up (elicitation Question vi), I used the estimates recommended by the NRPB as described by Wakeford (1995). For mortality, these are 1.25 fatal leukemias and 1.75 fatal cancers of other types. Confidence intervals presented in this paper suggest that an uncertainty factor of about 1.5 is needed for sampling variation. Additional uncertainty results from uncertainties in dosimetry used in the studies, particularly the Oxford Childhood Cancer Study, and the failure to detect effects in other studies. As a lower bound, I have used a value of 0.5 deaths per Gy, for both leukemia and all cancers (there is more credibility in the leukemia association than in that for other cancers). As an upper bound, I have used 3.5 for leukemia and 8 for all cancers (including leukemia).

For lifetime risks (elicitation Question vii), I have increased the median estimates and upper bounds. The upper bound for all cancers is chosen as the central estimate for exposure in childhood from elicitation Question v.

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Responses are in millions. Number in parentheses is leukemia incidence.

Question 1. The number of radiation-induced cancer deaths up to 20 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile (incidence in millions)		
	5%	50%	95%
Bone	0.001	0.007	0.044
Colon	0.012	0.058	0.29
Breast	0.018	0.035	0.067
Leukemia	0.34 (0.52)	0.65 (0.93)	1.24 (1.69)
Liver	0.007	0.036	0.19
Lung	0.31	0.66	1.42
Pancreas	0	0.014	0.070
Skin	0.0025	0.006	0.016
Stomach	0.009	0.037	0.15
Thyroid	0.001	0.005	0.023
All other cancers	0.086	0.19	0.43
All cancers	0.93	1.73	3.22
* Number in parentheses is leukemia incidence.			

Question 2. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile (incidence in millions)		
	5%	50%	95%
Bone	0.003	0.018	0.11
Colon	0.052	0.25	1.22
Breast	0.087	0.16	0.28
Leukemia	0.43 (0.68)	0.78 (1.15)	1.41 (1.96)
Liver	0.028	0.14	0.70
Lung	0.79	1.63	3.37
Pancreas	0	0.054	0.27
Skin	0.008	0.019	0.046
Stomach	0.040	0.16	0.66
Thyroid	0.005	0.018	0.076
All other cancers	0.46	0.98	2.09
All cancers	2.50	4.36	7.60
* Number in parentheses is leukemia incidence.			

Question 3. The number of radiation-induced cancer deaths over a lifetime (following the population up until it has become extinct) in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile (incidence in millions)		
	5%	50%	95%
Bone	0.003	0.018	0.11
Colon	0.14	0.72	3.68
Breast	0.18	0.37	0.77
Leukemia	0.43 (0.66)	0.81 (1.17)	1.50 (2.05)
Liver	0.055	0.29	1.55
Lung	0.79	1.83	4.20
Pancreas	0	0.13	0.70
Skin	0.012	0.031	0.081
Stomach	0.12	0.50	2.18
Thyroid	0.042	0.19	0.84
All other cancers	1.52	3.58	8.45
All cancers	5.43	10.7	21.1
* Number in parentheses is leukemia incidence.			

Question 4. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 years) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile (incidence in millions)		
	5%	50%	95%
Breast	0.060	0.13	0.26
Leukemia	0.55 (0.86)	1.05 (1.58)	2.01 (2.89)
Thyroid	0.0046	0.015	0.049
All cancers	1.13	2.19	4.23
* Number in parentheses is leukemia incidence.			

Question 5. The number of radiation-induced cancer deaths over a lifetime (following the population up until it has become extinct rather than up to 40 years following exposure) in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 years) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile (incidence in millions)		
	5%	50%	95%
Breast	0.23	0.62	1.70
Leukemia	0.54 (0.86)	1.07 (1.61)	2.12 (3.03)
Thyroid	0.048	0.19	0.73
All cancers	7.93	20.3	49.9
* Number in parentheses is leukemia incidence.			

Question 6. The number of radiation-induced cancer deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure of a dose of 1 Gy low LET (= gamma) radiation administered uniformly over their three trimesters (9 months) *in utero* and followed-up for 20 years after birth.

	Quantile (incidence in millions)		
	5%	50%	95%
Leukemia	0.5	1.25	3
All cancers	0.5	3	8
* Number in parentheses is leukemia incidence.			

Question 7. The number of radiation-induced cancer deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure of a dose of 1 Gy low LET (= gamma) radiation administered uniformly over their three trimesters (9 months) *in utero* and followed over a lifetime (following the population up until it has become extinct rather than up to 20 years following exposure).

	Quantile (incidence in millions)		
	5%	50%	95%
Leukemia	0.5	1.5	4
All cancers	0.5	6	20
* Number in parentheses is leukemia incidence.			

Question 8. The number of radiation-induced cancer cases (fatal and non-fatal) up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile (incidence in millions)		
	5%	50%	95%
Bone	0.006	0.034	0.21
Colon	0.097	0.47	2.29
Breast	0.27	0.49	0.89
Leukemia	0.68	1.15	1.96
Liver	0.033	0.17	0.84
Lung	0.87	1.80	3.73
Pancreas	0	0.062	0.31
Skin	0.47	1.08	2.46
Stomach	0.057	0.23	0.95
Thyroid	0.045	0.19	0.81
All other cancers	0.92	1.96	4.18
All cancers	4.71	8.13	14.0
* Number in parentheses is leukemia incidence.			

Question 9. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 year (rather than 1 minute).

	Quantile (incidence in millions)		
	5%	50%	95%
Bone	0.0003	0.009	0.11
Colon	0.005	0.13	1.22
Breast	0.022	0.078	0.28
Leukemia	0.11 (0.17)	0.39 (0.58)	1.41 (1.96)
Liver	0.003	0.070	0.70
Lung	0.079	0.81	3.37
Pancreas	0	0.027	0.27
Skin	0.002	0.009	0.043
Stomach	0.004	0.081	0.66
Thyroid	0.001	0.009	0.076
All other cancers	0.046	0.49	2.09
All cancers	0.63	2.18	7.60
* Number in parentheses is leukemia incidence.			

Question 10. The number of radiation-induced skin cancer cases (fatal and non-fatal) up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a uniform skin dose of 1 mGy high LET (= plutonium alpha particle) radiation at a uniform rate over 1 year.

	Quantile		
	5%	50%	95%
Skin			

Question 11. Joint dosimetry/late effects question: The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each of whom inhales 10 K Bq of the radionuclides specified.

Nuclide	Physical Form	Chemical Form	Cancer Type	Number of Cancers Quantile		
				5%	50%	95%
Pu-239	1 μm AMAD	Oxide	Lung			
			Bone			
			Liver			
			Leukemia			
			All cancers			
Sr-90	1 μm AMAD	Oxide	Lung			
			Bone			
			Leukemia			
			All cancers			

Question 12. Given that radiation induced cancer death due to the specified cause has occurred as a result of a dose of radiation delivered over 1 minute, the average expected length of life lost in years, for a population followed up to extinction after exposure.

	Quantile		
	5%	50%	95%
Bone	12.3	14.7	17.6
Colon	11.0	13.2	15.8
Breast	14.5	17.4	20.9
Leukemia	17.3	20.8	25.0
Liver	12.3	14.7	17.6
Lung	11.0	13.2	15.8
Pancreas	11.2	13.4	16.1
Skin	9.1	10.9	13.1
Stomach	10.9	13.1	15.7
Thyroid	12.1	14.5	17.4
All other cancers	11.4	13.7	16.4
All cancers	12.0	14.4	17.3

Question 13. For each of the cancer sites listed, give the estimate of the threshold dose in Gy, for low LET (= gamma) radiation administered at a uniform rate over 1 minute, below which value there is no radiation-induced cancer risk.

	Quantile		
	5%	50%	95%
Bone			
Colon			
Breast			
Leukemia			
Liver			
Lung			
Pancreas			
Skin			
Stomach			
Thyroid			
All other cancers			
All cancers			

EXPERT B

1. Introduction

It is the Life Span Study (LSS) cohort of more than 80,000 Japanese bomb survivors, maintained by the Radiation Effects Research Foundation (RERF) in Japan, which plays the major role in the current estimation of radiation risk figures for radiological protection purposes. The latest revision of the recommendations of the International Commission on Radiological protection (ICRP, 1990) relies largely on this information source. Because the Japanese survivors were subjected to high dose rate radiation exposure, and some were subjected to high doses, the directly evaluated risks have been reduced by the ICRP by a dose and dose rate effectiveness factor (DDREF) of 2 for application at low dose rates below the dose limits. The revised DS86 Japanese dosimetry system together with the ongoing collection of a growing mortality and incidence database, and the development of more sophisticated statistical modeling, has done much to maintain the importance of the Japanese data. The importance of other, non-bomb, sources of radiation risk figures was highlighted in the early 1980s when it was realized that the dosimetry of the bomb survivors was in need of reassessment (Charles and Lindop, 1981; Charles et al., 1984). Most of these, but not all, have involved high dose rate exposures to low LET radiation (X, γ and ß radiations). UNSCEAR (1994) provides an extensive up to date definitive review of bomb and non-bomb data. It is clear that the "non-bomb" data provide useful complementary information to that from Japan, particularly to the extent that they include a variety of ethnic groups, low doses/low dose rates, selected organ exposures, high LET exposures and internal as well as external irradiation. In general there are no great disparities in risk estimates between the LSS and other studies. The report (UNSCEAR, 1994, para. 18) concludes that the Japanese data is apparently the main source of low LET risk figures, and will remain for the foreseeable future. The other less powerful epidemiological studies, together with the results of laboratory based cell and animal studies, will continue to provide guidance on general issues such as DDREF values and radiation weighting factors (W_R). As a result of further likely minor revisions in neutron doses at Hiroshima the Japanese data may also be the source of the only human data on neutron radiation risks, and is also likely to lead to some reductions in low LET risk estimates (Grimwood and Charles, 1994). For this reason I have relied heavily on the Japanese bomb survivor data for my answers to the elicitation questions.

2. Modeling based on Little

Some "bench-mark" modeling has been carried out by Mark Little* for this elicitation process. He has evaluated cancer mortality and incidence over various populations and for periods after exposure of 20 years, 40 years and lifetime, using generalized relative risk models where the excess relative risk (ERR) is dependent on time after exposure (t) and age at exposure (a) or the attained age (t + a). The best fit to solid cancer data is a so called model A (Little et al., 1996):

$$ERR = \beta_s \cdot d \cdot t^{\gamma} \cdot (t + a)^{\alpha}$$

For the purpose of sensitivity analysis modifications to this model were also used based on:

$$ERR = \beta_s \cdot d \cdot \exp(\delta t + \mu a)$$

In particular a so called model B used only the exponential dependence on a, i.e., $\delta = 0$. A model C assumed that for solid cancer the ERR for those exposed in childhood (age <15) diminishes by 5% per year 42 or more years after exposure. The incidence datasets of Thompson et al. (1994) and Preston et al. (1994) were used. These represent follow-up to 1987, 42 years after the bombings. This model thus represents a reduction in ERR with increased follow-up from the latest currently available data. For leukemia, model C included a quadratic term in dose:

$$ERR = \beta_s \cdot (d + \varepsilon d^2) \cdot \exp(\delta t + \mu a)$$

Calculations were for the mixed US/UK equilibrium population described in the case structure document. Latent periods of 2 and 5 years were assumed for leukemia and all other tumors respectively. Doses were restricted to organ dose < 4 Sv, air kerma < 4 Gy.

These models gave some indication of the variations in predicted cancer mortality and incidence for reasonable variations in fitting models and parameters. Since model A has been shown to provide the best fit to the Japanese data (Little et al., 1996), this was used as the basis of the best fit (50% quantile values) in Tables i, ii, iii, iv, v, viii, ix, x and xii.

* M. Little. 1996. Memorandum (January 23, 1996), "Scoping Cancer Risks," sent to all members of the CEC/US NRC Somatic Health Effects Panel. Little's memorandum has been included in Appendix B of this volume.

3. Uncertainties in risk estimation

My initial approach to the elicitation questions is described in Section 4. There I use mainly the Japanese data to evaluate the 50% quantile best estimates of risk. I have relied heavily on model A because it provides the best statistical fit to the data. In my view, models such as B which have little or no reduction of RR with time after exposure are not tenable. The 5% and 95% quantiles are evaluated mainly on the basis of statistical uncertainties related to numbers of observed and expected cases. In most situations, the uncertainties in using different models such as models A, B, and C in Little's memorandum are small compared to statistical uncertainties inherent in the data. These uncertainties however may be too small in view of possible future changes, both systematic and random, in modeling, dosimetry, and epidemiological methodologies.

Table 1 is a summary of potential future revisions in low LET risk estimates for cancer mortality based on the LSS of the Japanese bomb survivors (Charles, 1995). Further details are given in Appendix A (Uncertainties in risk estimation - a broad perspective). The modeling of Little already includes projection with time so only the remaining factors need to be taken into account. Those elicitation questions which relate to high dose rates will not be affected by any future considerations of DDREF. On a most pessimistic assumption, it appears that there is the potential for some overall increase in risk, if all these factors are taken into account, by several tens of percent. I have come to a value judgement that not all of these uncertainties will be taken into account in the foreseeable future and that the overall impact will in fact be reasonably neutral. I have not therefore modified the 50% quantile values as described above. Although these possible modifying factors may balance out in terms of any systematic shift in risk figures their existence must widen the 90% confidence intervals on risk estimates. I have not attempted to carry out a full analysis of uncertainty as attempted in BEIR V (1990, Annex 4F) because this is an onerous task which time precluded. I have therefore reduced my 5% quantile values and increased the 95% quantile values by 25% based on my value judgement of the impact of factors in Table 1. No changes have been made for bone, pancreas, skin, and thyroid where the existing uncertainties are already large. I have not made this modification to the seed question since I do not believe that all of these modifications will be made on the relevant time scale of about 5 years.

Table 1. Sources of possible future changes in risk estimation

Source of change/ uncertainty	Potential impact on current ICRP risk estimates*	Comments
Projection with time	-20 $\Rightarrow$ - 40%	Some account has been taken of this by BEIR V but not by ICRP. This effect is particularly important for the youngest age at exposure who now dominate the Japanese survivors. Little has taken this into account.
Increased neutron doses at Hiroshima	- 11 $\Rightarrow$ - 33%	Need for increase now generally accepted. The revised data may also provide the basis for neutron RBEs which should be supportive of current ICRP neutron weighting factors.
Dosimetry bias errors	+ 4 $\Rightarrow$ + 11%	Larger uncertainties (6-17%) would apply if survivor doses above 4 Gy were included.
Uncertainties in the low LET standard	0 $\Rightarrow$ + 50%	Evidence for RBE values $\neq$ 1 for various low LET radiations was discussed by ICRP (1991a) but not incorporated into their latest recommendations.
Projection across populations	0 $\Rightarrow$ + 30%	The higher value may be applied if figures specific to the UK are used. Organ specific risks vary greatly between populations. The models of Little applied to a UK/US population to some extent take this into account.
Cancer ascertainment (misclassification)	0 $\Rightarrow$ + 13%	This effect depends on the assumption of a dose dependent misclassification of cancer mortality. There is no direct evidence that this has in fact taken place.
Dose and dose rate effects	0 $\Rightarrow$ + 33%	The upper value represents the possible change in risk estimates at low dose/ dose rates if the DDREF is changed from the current value used by the ICRP of 2 to a value of 1.5. A value of 1 would be counter to some human data and a wide range of animal and cell biology data. This is relevant only to elicitation questions relating to low dose rates.
* Note: - , + indicates a potential reduction/increase in low-LET risk estimates respectively. The range of uncertainties is only approximately estimated but corresponds approximately to a 90% CI.		

4. Individual elicitation questions – comments

Questions i - v

The 50% quantile estimates are based on the use of model A with the exception of bone. For bone, the Ra-224 clinical data were used, as for example reviewed in BEIR IV (1988). The best estimate 50% value was based on the lifetime risk of 2×10^{-2} Gy^{-1} for protracted alpha radiation. Using a radiation weighting factor W_R of 20 for alpha radiation, assuming no DDREF, gives a lifetime risk estimate for an acute low LET radiation exposure of 10^{-3} Gy^{-1}. Most, if not all, of this risk will be expressed in the first 20 years after exposure. The ^{224}Ra data has been used in preference to the Japanese data because no significant bone cancer excess has been reported in the survivors to date (UNSCEAR, 1994). Recent estimates of risk by Thompson et al. (1994) for bone are in fact estimates for bone and connective tissue combined and should not be used to infer risks for bone alone, unless desegregation can be achieved. In the bench-mark modeling of the Japanese data by Little, the risk is reached only after the full lifetime of the cohort rather than 20 years seen for the Ra-224 induced cases. The uncertainties in the bone cancer risk estimates at a dose of 1 Gy have been based on the analysis of Schlenker (1982) who has provided a confidence interval analysis of the Ra-224 data. The very wide confidence interval at a dose even of 1 Gy reflects the paucity of data and the non-linear dose response which is compatible with the Ra-224 data.

The 5% and 95% quantile values for solid cancers other than bone are based on the 90% CI (relative to the 50% estimate, as given by Ron et al. (1994) using the latest incidence and mortality data from the Japanese bomb survivors. For the "all other cancer" category in the elicitation questions there is no similar group in the publications related to the Japanese bomb survivors to be able to quote an immediate source for this evaluation. This grouping must however contain at least several organs such as ovary, bladder and urinary organs and kidney, for which there is a reported significant radiation related excess. The 50 year expression for these organs combined given by Ron et al. (1994) of 1% Sv^{-1} is near to the value of 0.8% Sv^{-1} for a 40 year expression given by model A of Little. The uncertainty in this value as given by Ron et al. for a 90% CI is between a factor of 3 less or 2 more than the best estimate. The thyroid and skin have negative lower 95% confidence levels and have been assigned a zero 5% quantile. Pancreas has a negative ERR for mortality according to Ron et al. (1994) and a positive but not significant ERR for incidence according to Thompson et al. (1994). On this basis, the 5% quantile is assigned zero and the upper 95% quantile is 5 times the 50% quantile based on incidence data of Thompson et al.

The uncertainties in leukemia mortality and incidence which are taken from Preston et al. and UNSCEAR (1994, Table 6, page 103) extend above and below the best estimate by factors of about 1.2. For all cancers combined uncertainties in mortality and incidence are taken from Ron et al. (1994) and extend above and below the best estimate by a factor of about 1.3.

Questions vi and vii

In utero data is based on the review of NRPB (1993) and UNSCEAR (1994) using primarily data from the Oxford Survey of Childhood Cancer (OSCC). The several studies which are useful for this evaluation generally provide risk evaluations up to age 15. NRPB (1993) give values for mortality for this age range of 1.25, 1.75 and 3.0% Sv^{-1} for leukemia, all other cancers and total risk, with a value of twice these for total cancers (fatal and non-fatal). To provide risk estimates for age up to 20 years, this value has been increased pro-rata by 33%. The risk over the whole of life following *in utero* exposure is difficult if not impossible to evaluate directly because of the paucity of relevant human data. There is a factor of 2 greater leukemia risk in those exposed *in utero*, compared to in childhood (NRPB, 1993). I have assumed that this factor will also apply to all solid cancers. UNSCEAR (1994) indicate a RR of 1.39 as an average of 15 studies for childhood cancer. The uncertainty on RR up to age 15 is relatively small (95% CI 1.31-1.47). There are however residual uncertainties of a factor of 2 in dose estimates and there is little direct information of cancer in adult life (Muirhead and Kneale, 1989). This factor of 2 has been used as the basis of my uncertainty evaluation.

Question viii

This question is subject to the comments made previously for Questions i - iv. I have also assumed lethality fractions for bone of 0.7 (ICRP, 1990) and uncertainties using the 95% CI given by Ron et al. (1994) for cancer incidence. It is reassuring to see that the answers to Questions viii and ii reflect sensible lethality fractions, reasonably in accord with values given by the ICRP (1990).

Table 2. 5% and 95% quantiles as a ratio of the 50% value – based on confidence intervals (CI) from various sources for individual organs. Where no estimates are given there is assumed to be little difference for mortality and incidence

Organ	Mortality		Incidence		Reference
	5%	95%	5%	95%	
Bone	0.1	10			Schlenker, 1982
Colon	0.2	2.4	0.4	2.0	Thompson et al., 1994
Breast	0.5	1.6	0.7	1.4	Ron et al., 1994
Leukemia	0.7	1.4	0.7	1.3	UNSCEAR, 1994
Liver	0.4	1.6	0.4	1.8	Ron et al., 1994
Lung	0.4	1.4	0.6	1.4	Ron et al., 1994
Pancreas			0	4	Thompson et al., 1994
Skin	0	5	0.4	2	Ron et al., 1994
Stomach	0.5	2	0.7	1.7	Ron et al., 1994
Thyroid	0	15	0.4	1.8	Ron et al., 1994
All other cancers	0.3	2			Ron et al., 1994
All cancers	0.7	1.3	0.8	1.2	Ron et al., 1994

Question ix

This question differs from Question ii only in that it relates to a low dose rate. No direct information is available which is relevant to this issue so answers are based on the use of a DDREF. Values of DDREF have been given by various committees and organizations. At least 2 problems arise in using DDREF values for Question ix. Firstly, since the assumed dose is not low (1 Gy) the "dose" part of DDREF is not necessarily applicable. Secondly, DDREF values are to some extent based on animal studies which follow-up over the whole of life. The ICRP DDREF value is presumably also meant to be applicable to exposure over the whole of life. The dose response and dose rate effects are however likely to vary depending upon time after exposure.

It is difficult for me on radiobiological grounds not to allow for some reduction in the stochastic risk when a dose of 1 Gy is delivered over 1 year compared to 1 minute. For this question what is required is a dose rate effectiveness factor (DREF) rather than a DDREF. I have therefore used a rather more restricted reduction factor of 1.5 (1.0-3.0) than that which has appeared in recent pronouncements/reviews of DDREF (e.g., ICRP, 1990; NCRP, 1980; NRPB, 1993; NUREG, 1989 and 1991; UNSCEAR, 1986, 1988 and 1994).

Question x

The RR for non-melanoma (NM) skin cancer incidence given by ICRP Publication 59 (1991b) is 1.61 Sv^{-1} (90% CI ~1.4-2.) for UV exposed skin. The value given by Thompson (1994) for the Japanese bomb survivors is somewhat higher (2, 1.5-2.9) Sv^{-1}, though surprisingly similar in view of the low natural incidence in the Japanese and their skin pigmentation. The RR for the Japanese is also rather similar to that for the only epidemiological study of skin cancer in man for alpha radiation exposure - that of the Czechoslovakian uranium miners (ICRP, 1991b) with a RR of 2.13 (1.75-2.62) Sv^{-1} determined using an alpha radiation weighting factor W_R of 20 to evaluate the equivalent dose to the basal layer of the skin.

Models A and B of Little's memorandum give somewhat similar results for the 40 year post-exposure predictions for skin cancer incidence. Using a W_R of 20 to convert an alpha absorbed dose of 1 mGy to an equivalent dose of 20 mSv gives a predicted 50% quantile incidence of 4×10^4.

There is considerable uncertainty in relative biological effectiveness (RBE) of high LET radiations for late stochastic effects in man, a reasonable range from recent reviews being 5-50. The calculation of alpha skin doses is also subject to significant uncertainty because of variations in skin thickness with body site and between individuals. For this reason the ICRP Publication 59 (ICRP, 1991b)

overall values (using mainly low LET exposures and Caucasian populations) may be more appropriate than using the Czechoslovak experience or the Japanese data directly. There is also some uncertainty in the skin doses for the Japanese bomb survivors since the DS86 doses are not necessarily appropriate for the skin. Possible lack of electronic equilibrium in the skin (which can give factors of 2 difference between kerma and tissue dose near the surface, particularly for high energy gamma radiations such as those experienced by the Japanese) has not yet been taken into account (Roesch, 1987). My 50% quantile estimate is based on the use of an ICRP Publication 59 RR (1.61 rather than 2) applied to model A or B with a W_R of 20. The 5% quantile is based on the use of a W_R of 5 and the 95% value is based on a W_R of 50 and using a RR more appropriate to the Japanese or miner data.

Question xi – not attempted

Question xii

The average years of life lost are not dramatically dependent upon modeling parameters. When for example a relative risk rather than an absolute risk model is used, this may significantly increase the extrapolated lifetime risk but will not give rise to such an increase in years of life lost because the extra predicted cancer deaths occur necessarily later in life. However, in this question what is required is the years of life lost per case and this is related to the time dependence of the particular projection model used and the time dependence of the base rates for particular cancers. Average values of year of life lost have been given for models A, B and C of Little's memorandum and the years of life lost per case can be obtained by dividing this by the lifetime risk. Years of life lost per case for models A, B and C for total cancers are then for example 16.4, 14.5 and 15.8. These relative values are as expected and reflect the fact that model C represents an intermediate dependence of cancer incidence with time after exposure compared with models A and B. For this reason I have chosen model C for all of the solid cancers (with the exception of bone) as the basis of the 50% quantile values. Values for a Japanese population given in UNSCEAR (1994, page 126, Table 3.1) give a value of 11.6 for a constant relative risk model and values of 15% more under the assumption of a strong decline with time after exposure. The 5% and 95% quantiles in this elicitation exercise have been taken as ± 10% of the 50% values i.e., 15.5 ± 1.5 years.

Bone has been treated differently in view of evidence that its temporal dependence after exposure is similar to that of leukemia and may be fully expressed after 25-30 years. The models of Little have bone cancer risk declining with time but being expressed over the majority of life. The years of life lost for bone cancer cases can be expected to be larger than for leukemia since, even though the time course for bone cancer is similar to leukemia, the background rate is relatively more elevated in young adult life compared to later life for bone in the US/EU population. I have taken Little's model A for bone to represent the 50% quantile with model B indicative of a 5% value. The 95% value is based on hand calculations assuming model C but using base rates for bone cancer.

For leukemia the difference between the models are small since little time projection is involved and a narrower range of uncertainties has been chosen to reflect this.

Question xiii

Of the cancers listed in Question xiii only bone and pancreas have not been significantly related to radiation exposure in the Japanese incidence data set (Thompson et al., 1994). An association between cancer of the pancreas and prior radiation exposure has not been seen at a statistically significant level in any study. Bone cancer has been seen in excess in cases of incorporated radionuclides but with a threshold of up to about 2 Gy for acute alpha radiation exposure (Ra-224) which might imply a threshold for acute low LET exposure of a few 10 s of Gy. An excess of bone cancer has been seen in childhood radiotherapy cases at mean doses of 27 Sv (low LET) and in treatment of skin haemangiomas at a mean dose of 0.4 Sv, but numbers of cases are small. Bone has not strictly been evaluated in the Japanese survivors since it is often included together with connective tissue. Prior to *ICRP Publication 59* (ICRP, 1991b) it was generally considered that a threshold dose existed for the radiation induction of skin cancer of at least about 10 Gy. *ICRP Publication 59* reviewed a number of studies in which there was a skin cancer excess at total doses down to about 2-3 or with some fractionated doses of down to 0.1 Gy per fraction. The latest incidence data from the Japanese survivors is compatible with a curvilinear response or a linear response with a threshold dose in the region of 1 Gy. For the majority of other cancers which have a significant correlation with dose there are statistically significant excess cases at doses above about 0.2 - 1 Sv (Figure 3, Thompson et al., 1994). For all solid cancers there is a significant excess in the Japanese incidence data in the dose category 0.01-0.19 Sv. For leukemia the excess is significant above about 0.3 Gy (Figure 3, Preston et al., 1994).

In all such cases it is possible to interpret the data in terms of a dose threshold, non-linearity at low doses, low organ sensitivity or lack of statistical power. It is therefore difficult to definitively answer this question without some further explanation of what is actually being sought from the question.

I have entered zero values for all quantiles for all organs to reflect my belief that all ionizing radiations produce some mutational change even at the lowest doses, and that it is not possible to preclude some level, no matter how small, of infidelity in the repair processes in some people. It is therefore not possible for me to infer the existence of a real absolute threshold on the basis of current epidemiological data. There may of course be practical threshold doses particularly for small populations and for low sensitivity tissues, or dose levels where no significant excess of cancers have yet been seen, as discussed above.

5. Seed Variables

Based on Shimizu et al. (1990) I have assumed that changes with time in RR observed in recent years will continue. Changes assumed are in Table 3.

Table 3. Assumed changes in RR

Organ	% changes per year
Colon	-7
Breast	+1
Leukemia	-9
Lung	-4.7
Stomach	+1.2
Solid tumors	-0.9

The data for liver and pancreas are difficult to project since they are not in significant excess. It has been assumed that this will continue. The 5% and 95% quantiles are given such that their values relative to the 50% quantile are the same as in 1985. One would expect some reduction in the confidence interval due to increased statistical power with continued follow up. This is considered to be a second order effect. None of the possible sources of uncertainty given in Table 1 have been included since on this timescale (5 years) the probability that many, if any, will have been implemented is small.

Question on dependencies among random variables

I found this series of questions initially rather confusing. A detailed worked example of a real health effects question rather than the idealized example would have helped. In some questions it was possible to give quite different answers depending on whether one thought in terms of possible dependencies that arose from possible modeling approaches (where dependencies could be forced through common dosimetry assumptions for example) or when one thought in terms of whether there was any possible fundamental biological basis for a dependency. I finally decided to answer my questions on the latter basis, that is on the basis of whether I felt there was any biological basis for a dependency.

Appendix A:

Uncertainties in Risk Estimation – A Broad Perspective

Uncertainty due to bias

It has been recognized for some time that the estimated radiation doses for the Japanese bomb survivors are subject to considerable systematic and random uncertainty. The recent Dosimetry System of 1986 (DS86) dosimetry revision is considered to have considerably reduced systematic uncertainties. Random uncertainties remain primarily as a result of subjective evaluation of parameters such as distance from the hypocentre, location of the hypocentre, and shielding configuration. This information was often obtained through interview many years after the bombings. Taking these points into account, Jablon (1971) evaluated that the uncertainties in a survivors distance was between 47 - 62 meters (a normal distribution was assumed around the nominal assumed distance, based on interview). The resultant uncertainty in T65 doses (the dosimetry system which preceded the DS86 system) was then estimated to be at least about ± 30%, and the same level of uncertainty is considered appropriate also for DS86. The doses to survivors are determined on the basis of the estimated "free in air" doses (no account taken initially of building or body shielding) at the nominal survivor distance from the hypocentre, together with shielding data. The probability of survival increases with distance whereas the dose received falls with distance. Jablon in fact assumed that survival was a sigmoid function of dose, that the dose fell rapidly (inverse square x exponential) with distance, and that the population density in terms of people per unit area was constant. This leads to a non-normal probability distribution of the actual (true) dose to an individual survivor. In contrast to a situation where the probability distribution was normal, this leads to actual true doses (on average) being less than the estimated dose at the nominal position of the survivor. The difference between the true and estimated doses depends on the city and the estimated distance. Jablon estimated this to be small at doses below about 4 Gy (T65). A 5% difference was estimated at doses of about 4-8 Gy (T65) in Hiroshima. The effect was negligible in Nagasaki. Jablon did not deal explicitly with the implications of this for risk evaluation but he pointed out that it would have some impact on the determination of the shape of dose response curves and the RBE of neutrons. The argument of course leads logically to the conclusion that risk estimates would tend to be underestimated by a few percent unless this correction was taken into account.

Jablon's initial approach was revisited 10 years later by Gilbert (1982) and another 10 years later by Pierce et al. (1989, 1990). Gilbert's approach and conclusions were similar to Jablon's but used actual dosimetry and survivor data information from the extended LSS, still using the T65 dosimetry. Pierce has followed a more formalized statistical approach which simultaneously takes account of uncertainties in both the dose estimates and the health effects data to arrive at estimates of the impact on overall risk figures. He concludes that risk estimates would require increases of 4 - 11% if doses below 4 Gy were used and 6 - 17% if all doses were used (the ranges are related to an assumed uncertainty in the dose estimates of 25 - 40%).

Pierce recommended that his statistical approach should be used to allow for the bias in risk estimates caused by a non-normal distribution of dose uncertainties. This does not appear to have been implemented by any of the international bodies such as BEIR, UNSCEAR or the ICRP. This may be because the effect is small, the estimation of dose uncertainties is controversial and the statistical procedure is not straightforward. The basis for this small increase in risk figures appears to be well founded. The level of the dosimetric uncertainties is still the subject of debate but the value most used in recent literature is ± 30%, which would give rise to increases in risk figures at the lower end of the suggested range, i.e., ~5%.

Uncertainties in neutron doses at Hiroshima

The individual estimates of radiation dose for members of the LSS of the Japanese survivors at Hiroshima and Nagasaki have been the subject of several revisions over the years. In the early 1980s a major revision of the radiation doses took place and after several years of work by Japanese and US scientists the DS86 was completed. The increased sophistication of the methods used in assessing the doses and the added power given by the developments in computer technology (for radiation transport calculations) meant that DS86 was soon adopted as the definitive dosimetry system for the A-Bomb survivors. The dosimetric inconsistencies of the previous (T65DR) dose estimates had apparently been resolved. The most significant change was probably a general and significant decrease (factor of about 10) in the estimated neutron doses, particularly in Hiroshima.

The only major discrepancy at the time of the release of the DS86 system was that there appeared to be an underestimate of calculated thermal neutron doses compared with measured values at distances between about 1.0 to 1.6 km (the range where survivors with significant doses were situated). Recently Straume et al. (1992) have collated the contemporary measurements of neutron activation of various environmental materials at the two cities to derive neutron dose information. Their results show that beyond 1000 m in Hiroshima the thermal neutron activation measurements are between two and ten times higher than those given by the DS86 calculations. It now appears likely that actual neutron doses for the majority of survivors was between the old T65 and the revised DS86 values.

As a result of consideration of the impact of possible revisions in neutron dose, Jablon (1992) has given crude estimates (based on likely increases in air kerma) that the excess lifetime cancer risk per 10,000 person sievert (PSv) will fall by almost 50% from the risk estimates calculated in BEIR V. Straume (1992) has also implied that cancer risk estimates would be similarly reduced. On the other hand Preston and Pierce (1992) with access to the detailed RERF DS86 data, have argued that the decrease in excess relative risk per unit dose would decrease by only 3 - 22% assuming a RBE of between 1 and 20, respectively, for neutrons. No detailed bases for these somewhat disparate views were given.

Grimwood and Charles (1994) have used the LSS cancer mortality data (1950-85) to investigate the repercussions of upward revisions in neutron dose at Hiroshima. The extent of the predicted reduction in low LET radiation risk depends on the magnitude of the increases in neutron dose and the assumed RBE of neutrons which is assumed in the analysis. The magnitude of the increase in neutron dose depends on the distance of individual survivors from the hypocentre. In the absence of revised neutron doses for each individual survivor the impact has been explored of increasing the neutron doses for all survivors by various constant factors (the neutron revision factor, NRF). For survivor doses below about 4 Gy the increase for individuals is likely to be between 2-5. The most appropriate value of neutron RBE for survivors is about 20, the ICRP recommended value for neutrons of energy between 0.1 - 2 MeV. Using these estimates the likely reduction in low LET risk figure is given by Grimwood and Charles as 11 - 33%. A more definitive evaluation of the reduction will require the determination of the revised neutron doses for each individual survivor. The same analysis, using neutron RBE as a free parameter, provides support for current ICRP neutron radiation weighting factors.

Uncertainties in the low LET standard radiation

The ICRP use a radiation weighting factor W_R of 1 for all "low LET" radiations. Low LET radiations include photons and beta particles of all energies. However, it is well known that for a range of biological end-points, the biological effectiveness decreases with increasing energy for low LET radiations, reflecting a reduction in LET with increasing energy. Since the Hiroshima and Nagasaki gamma radiations were relatively high energy (mean kerma weighted energy about 4.5 MeV), it can be logically inferred that their biological effect would be significantly less than the lower energy radiations normally encountered in the workplace or used in radiobiology studies for the determination of RBEs etc. The general agreement between late stochastic risk estimates from the bomb and non-bomb data reported by UNSCEAR (1994) would indicate that the effect cannot be very great. Straume (1995) has used dicentric induction in human lymphocytes to infer that W_R values should logically range from 0.5 for 15 MeV electrons to 5 for tritium beta particles, with Co-60 gamma rays and conventional x-rays being somewhere in between. The ICRP had considered this issue (ICRP, 1991a, page 114, para. B68) but it has not been included in any modification of risk estimates from the Japanese data or in the provision of differing weighting factors for the range of low LET radiations.

Uncertainties in lifetime risk projection models

It has become clear in recent years that neither the absolute or time constant relative risk models can adequately fit the LSS cancer mortality data. While the relative risk model is better, it is possible to obtain more satisfactory fits using either of the models together with additional ad hoc modifying factors which essentially take account of the fact that the relative risk is not constant with time after follow up and is dependent upon age at exposure (Pierce et al., 1991). Projecting the health effects experience from the latest estimates (up to 1987) into the future to cover the whole life of the LSS cohort is probably the source of the greatest potential uncertainty in lifetime risk estimates from Japan.

Only BEIR V appears to have formally included such considerations in its final recommended risk figures. UNSCEAR (1994) includes illustrative examples of the effect on risk figures of allowing risk to fall with time after exposure, following an initial 40 year period of constant relative risk. The fall in risk is assumed to be linear with time and for the youngest age group it is assumed either to become zero at age 90 or alternatively at age 90 to fall to the value appropriate to a person aged 50 at exposure. The

method is used only for solid cancers for which a latent period of 5 years is assumed (although 10 years is assumed for this everywhere else in the report). The result is that the overall lifetime risk is reduced by about 40% and 20% for the two methods respectively (i.e., from 12% to 7.5% and 9.2% respectively). This large impact can be understood when it is realized that about 60% of the original survivors in the LSS cohort are still alive; that they were obviously mainly in the youngest age group at exposure; that only about half of the projected lifetime risk of 12% has so far been expressed; and that background cancer rates increase dramatically in old age where the relative risk is falling. The assumption of a fall in relative risk down to zero at age 90 clearly suppresses the majority of future cancers predicted by a constant relative risk model.

The basis for a fall in relative risk with time after exposure has been shown to be an expected feature of a multistage model of carcinogenesis (Little et al., 1990, 1991a,b, 1992 and 1993). Optimized multistage models have been used by Little et al. (1990) to evaluate lifetime risks for the Japanese bomb survivor data and for the Japanese data combined with several medically exposed groups. The results are in good agreement with the more stylized rather ad hoc assumptions of UNSCEAR (1994). For example, in Little and Charles (1993) the risk figures for lifetime cancer for Japanese and England and Wales populations are derived using the multistage model. The results are compared with UNSCEAR (1994) in Table 4.

Similar conclusions to those of Little et al. (1990) have been obtained by Kellerer and Barclay (1992) who have modeled the time course of cancers in the LSS population using a dependency of risk on attained age (age at exposure + time since exposure). Both approaches are essentially similar but the multistage model has a stronger foundation in the biologically based monoclonality and multistage nature of carcinogenesis, and is a statistically better fit to the data. It is becoming increasingly realized that the defensible projection of risk over the whole of life for incompletely ascertained cancer is dependent upon the use of an underlying biologically based model (Doll, 1994; Clarke, 1994) rather than the use of ad hoc modifications to fit existing data. Multistage models would seem to offer this route and it is only a matter of time before the ad hoc approaches followed by BEIR and UNSCEAR (1994) are treated more formally.

Uncertainties in transfer across populations

How does the experience of radiation cancer induction in the Japanese transfer to other populations? The excess lifetime radiation induced cancer in the Japanese is now believed to be predicted best by a relative risk model with appropriate age and sex specific background cancer rates and excess relative risk figures. It is clear however that the background cancer rates vary considerably for particular organs and between countries (Muir et al., 1987). Stomach cancer rates are an order of magnitude higher in Japan than the USA and the reverse is true of breast cancer. For a range of cancer types it is possible to find countries with background rates differing by almost two orders of magnitude (UNSCEAR, 1994, Annex A, Table 1). The question clearly arises as to whether an excess cancer rate seen for a particular organ in the Japanese, where that organ for example might have a high background cancer rate, is directly applicable to another country where the background rate is low. Apart from assuming that the Japanese data are directly relevant to all populations there are two obvious ways of transferring risks across populations (Table 5) and these have been considered by the ICRP (ICRP, 1991b):

1. Assume that the absolute excess seen in the Japanese to date is the same for all populations. The age specific background cancer rates for the country in question are used to derive the excess relative risk on the basis of a relative risk model. The lifetime risk is evaluated for the country in question using its national cancer rates and assuming that the excess relative risk is constant over life. This is often referred to as the NIH (National Institute of Health) model. For this procedure, the highest probabilities will arise for organs such as stomach, which have the highest background rates in Japan.

2. Assume that the excess relative risk figure is the same for all populations. The Japanese value can then be applied to the background rate in the particular country to give the lifetime excess using the multiplicative model. For this procedure the highest rates will arise for organs which have the highest rates in the country in question (e.g., lung and breast in the USA and UK). This is often termed the multiplicative transfer method.

These methods have been used by the ICRP (1991a,b). Table B-14A of ICRP Publication 60 (ICRP, 1991a) for example gives the results of applying the absolute and multiplicative methods to various populations, age 0-90, both sexes, to evaluate the lifetime cancer risk in various populations.

The difference between the Japanese figures for the two models is due to the use of contemporary demographic data for all the population projections. The differences between

different countries also reflect differences in demographic factors, primarily background cancer rates and mortality statistics. Apart from China the differences between the two projection models and the difference between countries is within about 25%. The UK values are about 30% and 10% higher than the average values for the absolute and NIH models respectively. While there are relatively small differences for all cancers combined, as expected, there are very large differences for specific organs.

There is no definitive support for an one particular procedure because of the paucity of parallel epidemiology studies across ethnic groups. The one series of studies which should have produced some useful comparison was in the case of breast cancer in the Japanese and in several US studies. Initial support from these data for the NIH method have however been removed since the results of several analyses have been contradictory. There has been no attempt to look to biological mechanisms for support for any particular procedure but the multiplicative method would seem to be in accord with a multi-stage model. UNSCEAR (1994) finds support for the multiplicative method from a comparison of stomach cancer risks in the LSS and three clinically exposed groups (one US and two UK) but because of the limited basis for such a general conclusion they have given risk estimates only for a Japanese population. The ICRP (1991a) has averaged risks supposedly not favoring either method. Its general average of 10% Sv^{-1} is however more in line with the multiplicative model. The NRPB (1993) has favored a multiplicative model as the basis of an estimate of cancer risks in a UK population on the basis of considerations of risk estimates for skin and stomach cancer in man and limited relevant animal studies.

Overall, it is unlikely in the foreseeable future that definitive information will become available to clarify the most appropriate method of transfer between populations. ICRP recommendations are for general international use so it is unlikely that the average of 10% Sv^{-1} which they have used will be significantly changed. For specific application in the UK or USA, the NIH method would produce results somewhat lower than the ICRP average value. A multiplicative model, as used by the NRPB, and used by Little in this elicitation exercise, would support a 10-30% higher value.

Table 4. Life time risk estimates at 1 Sv given by a multistage model and the UNSCEAR (1994) model using a fall in relative risk with time after exposure

Population	Little and Charles (1993)		UNSCEAR (1994) [1]
	Japan (1983)	England and Wales (1987)	Japan (1985)
Risk of exposure induced death REID % Sv^{-1}	7.2	9.0	9.2** (see assumptions below) 7.5*
Excess lifetime risk ELR % Sv^{-1}	6.0	7.7	Not given.
Years of life lost (average over whole population)	0.95	1.35	~1.2
Assumptions	Multistage model, total stages k, radiation acting at stages I and j. Non leukemia: k = 6, I = 2, j = 5, leukemia: k = 3, I = 1, j = 2,		Latent period 5 years. Fall in RR with time for solid cancers only. RR constant for 40 years then falling linearly to age 90 to zero* or the value for the group aged 50 at exposure**.

1. The UNSCEAR (1994) nominal lifetime risk at 1 Sv is 12% Sv^{-1}.

Table 5. Lifetime cancer mortality risk figures % Sv^{-1}

Transfer method	Japan	USA	Puerto Rico	UK	China	Average
NIH	9.7	8.7	10.2	9.7	6.0	8.9
Multiplicative	10.7	11.2	9.5	12.9	6.3	10.1

Uncertainties in extrapolation to low doses and low dose rates

The evaluation of risks of health effects in man for radiological protection purposes is based on information from man, animals, and cell systems. Studies to date have been largely at doses and dose rates considerably in excess of those incurred occupationally or received by the general public as a result of routine nuclear power generation. The broad body of human, animal and cell data show that, in general, the risks at high dose/dose rates are reduced at low dose rates by a certain factor. This reduction factor was previously known as the DREF but has more recently been referred to as the dose and DDREF to indicate the two important contributions made to the reduction factor by the shape of the dose response curve and/or by dose rate effects.

The DDREF depends on various parameters including; the particular values of dose and dose rate; the radiation type; the biological end point under consideration such as chromosome aberration, cell killing, cell transformation, cancer induction, life-shortening, etc.; the particular tumor type involved in cancer studies, and the species and strain of animal involved in animal studies; etc. It is therefore not surprising that there has been considerable debate and differences of opinion over several years regarding the choice of appropriate DDREF value. It has usually been thought that the DDREF was only significant for low LET radiations. Until recently the most authoritative, though not extensive, review of DDREF was given by the NCRP (1980). A range between 2-10 was given based primarily on animal carcinogenesis studies.

Various international bodies have given there own opinions on suitable values of DDREF. BEIR III (1980) used a DREF of 2.25 and BEIR V (1990) used a value of 2 for leukemia and 1 for other cancers. The ICRP Publication 26 (1977) followed the methodology of UNSCEAR (1977) and used a value between 2 - 2.5 for all cancer. The National Institute of Health (1985) radioepidemiological tables which were constructed for the assessment of probability of causation in compensation cases used a DREF of 2.5. In the 1990 revision of its basic recommendations, the ICRP (1991a) has used a DDREF value of 2. The ICRP rationale (publication 60, Annex B, Section 4) appears to have been influenced by the general use of low DDREF values by other groups and by the fact that "limited human information suggests a DDREF in the low region of the range." In the United States, the Nuclear Regulatory Commission, in documents predicting the health effects of reactor accidents, has moved from DDREF values of 2-10 (NUREG, 1989) to a narrower, lower range of 2-4 (NUREG, 1991) in the light of recent international reviews. The National Radiological Protection Board (NRPB, 1993) used a DDREF value of 2 in an evaluation of late radiation risks to the UK population. Although the NRPB review of animal and cell studies found DDREF values from 1 to greater than 10, they considered that the limited human data suggested values at the lower end of the range.

The view is sometimes expressed that the Japanese bomb survivor data do not support DDREF values much in excess of unity. However, Pierce and Væth (1991) have used the LSS data up to 1985 to estimate a linear extrapolation overestimation factor (LEOF) which is essentially the "dose" part of DDREF. They find that for all cancers other than leukemia, and for doses less than 4 Gy, the LEOF is 1.2 with a 90% confidence interval from less than 1 to 2.3. After allowing for random errors in dose estimates, the best estimate was 1.4 with a 90% CI of less than 1 to more than 3.1. The parallel results for leukemia were 1.6 (90% CI 1 - > 3.1) and after correction 2.0 (90% CI 1.1 - > 3.1). Thus while the Japanese bomb data for all cancers other than leukemia are best fitted by a linear dose response, they are compatible with a dose reduction factor up to about 3. The data for leukemia clearly support a dose reduction factor of at least 2 (it should be noted however that if the risk analysis procedure has already used a linear quadratic fit then no further subsequent application of an LEOF may be appropriate).

The most recent and thorough review of DDREFs, based on a very extensive range of data, has been carried out by UNSCEAR (1993) and is likely to remain the definitive view for some time. UNSCEAR reviewed cell, animal and epidemiological data. Cell and animal studies agreed in showing evidence for a wide range of DDREF values between 1 and 10. A "central value" (not defined) of 4 was given. These studies were over a similar dose range to those of the Japanese bomb survivors but with a very wide range of dose rates. DDREFs were very dependent on animal strain and tumor type. Some of the animal tumors had no counterpart in man. The DDREFs seen in cell transformation experiments were not as great as in some animal systems. Linear dose response relationships were observed for many systems which also showed dose rate effects. It was pointed out that the dose rate effects could originate from underlying non-linear dose response relationships that could not be differentiated statistically from a linear response. It was therefore concluded that, if the human response is similar to that in experimental animals, it could be envisaged that at lower dose rates than experienced by the Japanese survivors, a DDREF greater than that suggested by an analysis of the dose response

relationship in man could be obtained. Taken together the available data suggest that for tumor induction the DDREF adopted should, on cautious grounds, have a low value, probably no more than 3 (for low LET radiation). A DDREF of 1 was recommended for high LET radiation and a DDREF of 3 for hereditary effects was considered appropriate based on experimental data in male mice. Low dose rates were considered to be < 0.1 mGy/min (averaged over about an hour) or acute doses < 200 mGy.

Uncertainties in cancer ascertainment (under-reporting)

Since the LSS mortality data are based on death certificate ascertainment, the misclassification of causes of death can give rise to significant errors in radiation risk estimates when using an absolute risk model. The effect should not be important for a relative risk model providing the misclassification is the same for the study population and the controls, and providing there is no dose dependence of the misclassification.

It has been shown recently that there is a dose response relationship for non-cancer mortality in the LSS cohort at high doses and this has been explained in terms of an under reporting of cancer mortality. An analysis by Sposto et al. (1992) has shown that in order to explain the dose dependence for non-cancer deaths, it is necessary to assume a dose dependence on the extent of the misclassification. This leads, even using a relative risk model, to the conclusion that excess relative risk estimates could be subject to increases of about 13%. There is however no direct evidence for such a dose dependence of cancer misclassification in the autopsy data from the LSS, although the data are not adequate enough to dismiss the possibility. The autopsy data themselves may not be representative since a higher proportion of cancer deaths compared to non-cancer deaths were subject to autopsy. This may be due to cancer deaths preferentially occurring in hospitals where autopsies are more readily initiated, or a greater readiness of relatives of cancer patients agreeing to an autopsy if they considered radiation had been a contributory cause of death.

It may of course be that some at least of the of non-cancer deaths at high doses are in fact radiation induced. If this were to be substantiated then an increase in the low dose cancer mortality risk figure would be uncalled for, but it might then be necessary to take account of such non-cancer deaths when assessing the health impact of high dose exposures. Some evidence for radiation related increases in non-malignant diseases has recently been reported for Chernobyl emergency workers (the so called Liquidators) at the recent IAEA meeting on comprehending radiation risks in Paris (Ivanov et al., 1994). At this meeting several Russian workers expressed strong views regarding the importance of such effects and this may be a future area of considerable scientific and public concern.

It is interesting to note that a correction factor of 23% was used in the BEIR III (1980) derivation of risk figures for this effect but subsequent UNSCEAR and BEIR reports have not done so.

Summary

It can be seen from Table 1 that each of the potential revisions in risk estimates are of about the same magnitude.

The first three potential sources of change (time projection, neutron dose revision in Hiroshima, and dosimetry bias) are all firmly based and will almost certainly be taken into account in future international revisions of risk figures. The net effect would be to reduce risk figures by 30-60% below those currently used by the ICRP. The other sources of change are more conjectural but would all give rise to increases in risk estimates. The uncertainties in the low LET standard could give rise to large increases of perhaps 50% or more. Changes would probably have to be based on radiobiological rather than epidemiological evidence and such data are not yet consistent or extensive enough to provide a basis for this. The uncertainties arising from risk projection across populations and from misclassification in causes of death in the LSS could give rise to increases in risk estimates up to about 40%. They are less likely to be subject to a definitive treatment in the short term than the dosimetry related uncertainties. The treatment of the misclassification of causes of death raises a number of issues. The analysis is very complicated and it may not be possible to ever differentiate between a dose related misclassification and a real dose related non-cancer mortality risk. The range of uncertainties arising from various methods of projection across populations has already been evaluated and its impact can be said to have already been taken into account by the ICRP in arriving at its average risk value. Any definitive view on the most appropriate projection method must await more extensive parallel comparisons of cancer types across various ethnic groups. Few studies are capable of doing this, currently or in the near future. Finally the value of the DDREF, used by the ICRP to derive low dose/dose rate risk figures from high dose/dose rate data such as the Japanese bomb survivors, remains contentious. The ICRP has most recently used a DDREF value of 2. If a reduction for dose rate effects were not taken into account, this would obviously lead to an increase in low dose risk estimates by a factor of 2. Since

there is clearly evidence in man for some dose rate effects for some selected cancers such as leukemia, thyroid and breast, and extensive data from cellular and animal radiobiology, it is unlikely that the DDREF would be reduced to below 1.5. Other reductions would imply unwarranted precision in our knowledge of dose response and dose rate effects. Such a reduction would lead to a 33% increase in the low dose risk estimate. Clearly this issue will gradually subside as nuclear worker studies increase in statistical power as follow up is maintained. The confidence limits of the risk estimates from these studies are however unlikely to be reduced to levels comparable with those of the Japanese bomb survivor data for some considerable time. Overall my value judgement is that these various possible changes will approximately balance so that best estimates of radiation risk will not change dramatically. They will however contribute to the overall uncertainties associated with best estimates.

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Question 1. The number of radiation-induced cancer deaths up to 20 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone*	0	1.0×10^5	1.0×10^6
Colon	1.2×10^4	1.2×10^5	3.0×10^5
Breast	7.2×10^4	1.8×10^5	4.5×10^5
Leukemia	5.7×10^5	8.5×10^5	1.3×10^6
Liver	2.9×10^3	9.0×10^3	1.9×10^4
Lung	1.8×10^5	4.5×10^5	8.5×10^5
Pancreas*	0	2.6×10^4	1.3×10^5
Skin*	0	7.0×10^3	3.5×10^4
Stomach	4.0×10^3	2.1×10^4	5.3×10^4
Thyroid*	0	6.0×10^3	9.0×10^4
All other cancers	7.2×10^4	2.6×10^5	6.5×10^5
All cancers	1.2×10^6	2.0×10^6	3.3×10^6
* initial values, not subject to 25% changes			

Question 2. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone*	0	1.0×10^5	1.0×10^6
Colon	4.0×10^4	4.0×10^5	1.0×10^6
Breast	2.4×10^5	6.0×10^5	1.5×10^6
Leukemia	6.6×10^5	1.0×10^6	1.5×10^6
Liver	8.0×10^3	3.0×10^4	6.3×10^4
Lung	5.6×10^5	1.5×10^6	2.9×10^6
Pancreas*	0	8.0×10^4	4.0×10^5
Skin*	0	2.0×10^4	1.0×10^5
Stomach	1.36×10^4	7.0×10^4	1.8×10^5
Thyroid*	0	2.0×10^4	3.0×10^5
All other cancers	2.2×10^5	8.0×10^5	2.0×10^6
All cancers	2.8×10^6	4.5×10^6	7.5×10^6
* initial values, not subject to 25% changes			

Question 3. The number of radiation-induced cancer deaths over a lifetime (following the population up until it has become extinct) in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone*	0	1.0×10^5	1.0×10^6
Colon	1.6×10^5	9.2×10^5	2.25×10^6
Breast	4.4×10^5	1.1×10^6	2.8×10^6
Leukemia	6.4×10^5	1.0×10^6	1.5×10^6
Liver	1.8×10^4	5.5×10^4	1.2×10^5
Lung	1.4×10^4	3.4×10^6	6.4×10^6
Pancreas*	0	2.1×10^5	1.1×10^6
Skin*	0	5.6×10^4	2.8×10^5
Stomach	3.2×10^4	1.7×10^5	4.3×10^5
Thyroid*	0	4.1×10^4	6.2×10^6
All other cancers	4.8×10^5	1.8×10^6	4.5×10^6
All cancers	3.4×10^6	8.8×10^6	1.4×10^7
* initial values, not subject to 25% changes; based on long term changes of Table 1.			

Question 4. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 years) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Breast	1.8×10^5	4.6×10^5	1.2×10^6
Leukemia	3.2×10^5	5.0×10^5	7.5×10^5
Thyroid*	0	9.0×10^3	1.4×10^5
All cancers	1.4×10^6	2.4×10^6	3.9×10^6
* initial values, not subject to 25% changes; based on long term changes of Table 1.			

Question 5. The number of radiation-induced cancer deaths over a lifetime (following the population up until it has become extinct rather than up to 40 years following exposure) in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 years) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Breast	8.8×10^5	2.2×10^6	5.5×10^6
Leukemia	3.5×10^5	5.5×10^5	8.3×10^5
Thyroid*	0	7.2×10^4	1.1×10^6
All cancers	9.0×10^6	1.5×10^7	2.4×10^7
* initial values, not subject to 25% changes; based on long term changes of Table 1.			

Question 6. The number of radiation-induced cancer deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure of a dose of 1 Gy low LET (= gamma) radiation administered uniformly over their three trimesters (9 months) *in utero* and followed-up for 20 years after birth.

	Quantile		
	5%	50%	95%
Leukemia	8.0×10^5	1.7×10^6	3.4×10^6
All cancers	2.0×10^6	4.0×10^6	8.0×10^6

Question 7. The number of radiation-induced cancer deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure of a dose of 1 Gy low LET (= gamma) radiation administered uniformly over their three trimesters (9 months) *in utero* and followed over a lifetime (following the population up until it has become extinct rather than up to 20 years following exposure).

	Quantile		
	5%	50%	95%
Leukemia	1.0×10^6	2.0×10^6	4.0×10^6
All cancers	1.4×10^7	2.8×10^7	5.6×10^7

Question 8. The number of radiation-induced cancer cases (fatal and non-fatal) up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone*	0	1.4×10^5	1.4×10^6
Colon	2.2×10^5	7.0×10^5	1.8×10^6
Breast	1.0×10^6	1.8×10^6	3.2×10^6
Leukemia	9.0×10^5	1.4×10^6	2.1×10^6
Liver	8.6×10^3	2.7×10^4	5.7×10^4
Lung	7.2×10^5	1.8×10^6	3.4×10^6
Pancreas*	0	1.0×10^5	5.0×10^5
Skin	7.6×10^5	1.9×10^6	4.8×10^6
Stomach	4.0×10^4	1.0×10^5	2.5×10^5
Thyroid	9.0×10^4	2.2×10^5	4.1×10^6
All other cancers	4.0×10^5	1.5×10^6	3.8×10^6
All cancers	6.1×10^6	9.6×10^6	1.4×10^7
* initial values, not subject to 25% changes; based on long term changes of Table 1.			

Question 9. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 year (rather than 1 minute).

	Quantile		
	5%	50%	95%
Bone*	0	6.7×10^4	1.0×10^6
Colon	1.3×10^4	2.7×10^5	1.0×10^6
Breast	8.0×10^4	4.0×10^5	1.5×10^6
Leukemia	2.2×10^5	6.7×10^5	1.5×10^6
Liver	2.7×10^3	2.0×10^4	6.3×10^4
Lung	1.9×10^5	1.0×10^6	2.9×10^6
Pancreas*	0	5.3×10^4	4.0×10^5
Skin*	0	1.3×10^4	1.0×10^5
Stomach	4.5×10^3	4.7×10^4	1.8×10^5
Thyroid*	0	1.3×10^4	3.0×10^5
All other cancers	7.3×10^4	5.3×10^5	2.0×10^6
All cancers	9.3×10^5	3.0×10^6	7.5×10^6
* initial values, not subject to 25% changes; based on long term changes of Table 1.			

Question 10. The number of radiation-induced skin cancer cases (fatal and non-fatal) up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a uniform skin dose of 1 mGy high LET (= plutonium alpha particle) radiation at a uniform rate over 1 year.

	Quantile		
	5%	50%	95%
Skin	8.0×10^3	3.0×10^4	7.5×10^4

Question 11. Joint dosimetry/late effects question: The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each of whom inhales 10 K Bq of the radionuclides specified.

Nuclide	Physical Form	Chemical Form	Cancer Type	Number of Cancers Quantile		
				5%	50%	95%
Pu-239	1 μm AMAD	Oxide	Lung			
			Bone			
			Liver			
			Leukemia			
			All cancers			
Sr-90	1 μm AMAD	Oxide	Lung			
			Bone			
			Leukemia			
			All cancers			

Question 12. Given that radiation induced cancer death due to the specified cause has occurred as a result of a dose of radiation delivered over 1 minute, the average expected length of life lost in years, for a population followed up to extinction after exposure.

	Quantile		
	5%	50%	95%
Bone	22	40	58
Colon	11.7	13.0	14.3
Breast	16.2	18.0	19.8
Leukemia	20.3	21.3	22.3
Liver	14.5	16.0	17.5
Lung	13.5	15.0	16.5
Pancreas	12.1	13.5	14.9
Skin	11.2	12.5	13.8
Stomach	11.7	13.0	14.3
Thyroid	13.0	14.5	16.0
All other cancers	12.6	14.0	15.4
All cancers	14.0	15.5	17.0

Question 13. For each of the cancer sites listed, give the estimate of the threshold dose in Gy, for low LET (= gamma) radiation administered at a uniform rate over 1 minute, below which value there is no radiation-induced cancer risk.

	Quantile		
	5%	50%	95%
Bone	0	0	0
Colon	0	0	0
Breast	0	0	0
Leukemia	0	0	0
Liver	0	0	0
Lung	0	0	0
Pancreas	0	0	0
Skin	0	0	0
Stomach	0	0	0
Thyroid	0	0	0
All other cancers	0	0	0
All cancers	0	0	0

EXPERT C

General Introduction

For question (i) to (v), (viii) and (ix), and (xii), I rely primarily upon the experience of the Japanese survivors of the atomic bombings of Hiroshima and Nagasaki. The latest mortality data for the survivors during 1950–1985 has been presented by Shimizu et al. (1990) and discussed by the International Commission on Radiological Protection (ICRP, 1991), the BEIR V Committee (NAS/NRC, 1990), the UK National Radiological Protection Board (Muirhead et al., 1993), and the US National Council on Radiation Protection and Measurements (NCRP, 1993). Cancer incidence data for the Japanese survivors for solid tumours during 1958–1987 has been presented by Thompson et al. (1994) and for leukemia, lymphoma and multiple myeloma during 1950–1987 by Preston et al. (1994), and has been discussed by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 1994). The experience of the Japanese survivors is supplemented by the experience of other groups exposed to ionizing radiation, most of these groups being exposed for medical reasons, for example the British ankylosing spondylitis patients (Weiss et al., 1994), although evidence for the effects of chronic exposure can be gained from occupational exposure in the nuclear industry (for example Cardis et al., 1995), and, for exposure to radon decay products, from the study of underground miners (UNSCEAR, 1994).

Despite limitations, the principal one probably being the transfer of risks between different ethnic groups and different cultures, the experience of the Japanese survivors of the atomic bombings of Hiroshima and Nagasaki constitutes the most reliable source of information under the conditions outlined in these questions. The Japanese survivors were not selectively irradiated for any medical condition, and the dose and dose rate conditions during the atomic bombings were very similar to those outlined in all but questions (vi), (vii), and (ix) to (xi).

Several uncertainties in the dosimetry assessment for the Japanese survivors are outstanding: neutron doses in Hiroshima are likely to have been underestimated in the DS86 dosimetry, and certain shielding biases and random errors need to be taken into account. However, the overall influence of these remaining uncertainties may very well result in little change in the risk estimates, and are likely to be within ±30%. I assume that the low LET irradiation which is outlined in these questions is analogous to that experienced by the Japanese atomic bomb survivors and that, as a consequence, uncertainties associated with irradiation by low LET radiation of a different energy (Straume, 1995) are not relevant.

One of the greatest factors influencing risk, particularly many years after exposure, is the temporal expression of the excess risk. Since the Japanese atomic bomb survivors have not been followed to extinction (nor has any other reasonably sized irradiated group), risks must be projected over time using the best information available to date. There is no doubt that the excess relative risk of leukemia does not remain constant with time since exposure, although this is not clear for some forms of solid tumours. Various major datasets (in particular the Life Span Study, LSS, of the Japanese atomic bomb survivors, and the British ankylosing spondylitis study, ASS) do indicate that the excess relative risk of certain solid tumours falls away with time since exposure. Clearly, in particular for lifetime risk, the assumption of a particular temporal expression of excess risk plays a relatively important role in determining the overall excess risk. Some indication of this variation has been supplied by the various models fitted to the LSS data by Little*.

Owing to the different baseline cancer rates in Japan and in Western countries for particular types of cancer (notably stomach, breast, lung), the transfer of risks from a Japanese population to a Western population is going to carry with it additional uncertainties. Much discussion has occurred concerning how this transfer of risk should occur (see, e.g., Muirhead et al., 1993). Clearly, where data are directly available from irradiated Western populations, direct comparisons can be made between the risks transferred from the Japanese bomb survivors and those obtained directly from the Western populations. However, the overall shortcomings of both groups (for example, most Western populations will have been irradiated for medical reasons) must be borne in mind when making these comparisons.

Other factors influencing the uncertainty need to be considered, not least of which is that associated with the imprecision of estimates which are based upon limited numbers of deaths or cancer cases (e.g., in the LSS, the number of excess solid tumours is estimated to be 341 above a background of 4346, and the number of excess leukemias is estimated to be 86 above a background of 90). Added to this is the error associated with the model

* M. Little. 1996. Memorandum (January 23, 1996), "Scoping Cancer Risks," sent to all members of the CEC/US NRC Somatic Health Effects Panel. Little's memorandum has been included in Appendix B of this volume.

employed to derive risks. The influences of these various sources of uncertainty have been discussed by, among others, the BEIR V Committee in Annex 4F of the BEIR V report (NAS/NRC, 1990). The BEIR V report also introduces the useful concept of the "credibility interval," reflecting judgement as to likely uncertainty from various sources. I rely upon this discussion in my determination of uncertainties associated with particular cancer sites under the conditions outlined in the questions. I note that statistical uncertainties tend to dominate the overall uncertainty, which is not especially surprising given the above numbers of excess deaths in the LSS cohort.

Bone

Data relating to the risk of radiation-induced bone cancer arising from exposure to low LET radiation are not extensive. The published findings using LSS data do not show a statistically significant excess risk of bone cancer, although other datasets, notably the ASS data, do show an excess risk. Groups exposed to high LET radiation (specifically those exposed to radium and Thorotrast) do show an excess risk of bone cancer. There is little doubt that bone cancer can be induced by ionizing radiation, but the precise level of risk is uncertain because the data are limited. Certain other features of radiation-induced bone cancer risk are uncertain, for example the variation with age at exposure and the variation with time since exposure. The ^{224}Ra-injected patients indicate that the temporal expression of risk may be limited to the first 30 years or so following exposure, and this is supported, although not particularly strongly, by certain groups exposed to low LET radiation. However, the ASS data do appear to show the bone cancer risk persisting beyond 30 years after exposure, although this is based on just 4 cases occurring 31–33 years after exposure. My estimates reflect the uncertainty in the bone cancer risk arising from low LET irradiation, in particular whether the risk is higher for younger ages at exposure, and whether the risk persists much beyond 30 years.

Colon

There is a clear dose-related association for colon cancer in the LSS data. This is also seen in the ASS data, and is confirmed by other studies involving low LET irradiation. The LSS incidence data do show a statistically significant decline of relative risk with time since exposure; this decline is also seen in the ASS data.

Breast

There is clear evidence of a radiation-induced excess risk of cancer of the female breast from several studies. These studies indicate an increased risk at younger ages at exposure, and especially for childhood exposures. The excess risk would appear to be expressed over the attained age range during which breast cancer would normally be expected to occur. There is some evidence for a decrease in excess relative risk with time since exposure in the LSS data, the ASS data, and other datasets, although probably not as strong as suggested in the BEIR V report because of problems with the data used for that analysis (Muirhead et al., 1993). Transfer of risk between populations is particularly problematical for breast cancer, because of the wide variation in background rates. Given this problem, the NRPB prefer to use data from the North American studies to estimate the risk of radiation-induced breast cancer for Western populations (Muirhead et al., 1993).

Leukemia

The evidence that exposure to ionizing radiation materially increases the risk of leukemia is overwhelming. The excess risk is greatest for those exposed at young ages, and peaks within 10 years of exposure. The risk of acute leukemia would appear to be effectively exhausted within 25–30 years after exposure, although a small excess risk of chronic myeloid leukemia would seem to persist after this time. Cell killing becomes an issue for studies involving high bone marrow doses. Owing to this wide range of evidence for radiation-induced leukemia, and clear evidence of a diminution of excess relative risk with time since exposure, the radiation-induced risk of leukemia is one of the most secure of the risk estimates, at least for acute leukemia.

Liver

The evidence for cancer of the liver being induced by low LET radiation comes almost entirely from the LSS data. However, given the large and very highly significant excess of liver cancer among those patients injected with Thorotrast, it may be safely concluded that liver cancer may be induced by ionizing radiation. From the LSS incidence data, no effect with age at exposure, attained age, or time since exposure could be discerned.

Lung

There is clear evidence of cancer of the lung being induced by ionizing radiation. Evidence is particularly clear from the LSS data and the ASS data. A decrease in relative risk

with time since exposure was adopted by the BEIR V Committee on the basis of a statistically non-significant effect in the LSS mortality data, but a stronger effect in the ASS data. However, the LSS incidence data for lung cancer are not so persuasive that there is a fall-off of relative risk with time since exposure. The underground miners studies show clear evidence of a decrease in the relative risk of lung cancer with time since exposure, although this is for a predominantly alpha particle irradiation of the bronchial epithelium. A difficulty in determining the radiation risk for lung cancer is the interaction between radiation and cigarette smoking which is probably somewhat less than multiplicative. Since background rates of lung cancer are dominated by the risk of tobacco smoking, such an interaction will be important in transferring risks between populations.

Pancreas

The risk of pancreatic cancer arising from radiation exposure is somewhat equivocal, there being little evidence for a radiation-related excess of cancer of the pancreas among the Japanese atomic bomb survivors. The evidence is somewhat stronger from the ASS data. It would appear, however, from the available evidence that the pancreas is relatively insensitive to radiation-induced cancer.

Skin

For non-melanoma skin cancer, several studies, including the Japanese atomic bomb survivor data, have shown a radiation-related risk. There is a strong increase in the risk for young ages at exposure, and in general, skin is relatively sensitive to the induction of non-melanoma cancer by radiation. There is some indication of upward curvature in the dose-response relationship derived from LSS incidence data. These data also show no effect with time since exposure, although the children irradiated for ringworm of the scalp do indicate some decrease of relative risk after about 25 years following exposure. Of course, one might expect the transfer of risk across populations to be especially problematic for skin cancer, although the excess relative risk across the ethnic groups involved in the various studies has not demonstrated a particularly marked variation in the excess relative risk. Owing to the success of treatment for non-melanoma skin cancer, there will be a large difference between mortality and incidence.

Stomach

There is clear evidence from the LSS data for an excess risk of stomach cancer following exposure to low LET radiation. This is supported by other datasets, although not the ASS. There is evidence that the relative risk is greatest at young ages, but little evidence for a decrease in the relative risk with time since exposure. High baseline rates for stomach cancer in Japan, compared with those for Western populations, indicate that care is required in the transfer of risk. However, the data for stomach cancer in the LSS is the most extensive of any cancer site.

Thyroid

An excess risk of thyroid cancer is evident in many irradiated populations, and the thyroid would appear to be particularly sensitive to radiation-induced cancer. The pooled analysis of 7 studies by Ron et al. (1995) found that the excess risk was greatest for young ages at exposure, that the risk decreased significantly with increasing age at exposure, and that little risk was apparent after 20 years of age. The excess relative risk was found to decline about 30 years after exposure. Owing to the high treatment success for thyroid cancer, radiation-induced incidence rates will be much greater than comparable mortality rates.

All Other Cancers

Included in this grouping are cancers of the salivary gland, ovary and urinary bladder which have shown significant excess relative risks in the LSS incidence data, and cancer of the oesophagus which has shown a significant excess relative risk in the LSS mortality data. Apart from these, evidence does exist from other studies for radiation-related excess risk of brain and central nervous system cancers. The risk of radiation-induced cancers at other sites is weaker, and the evidence for certain cancers (chronic lymphoid leukemia, Hodgkin lymphoma and malignant melanoma of the skin) being insensitive to radiation is quite strong.

Question (i)

Each individual in the population of 100 million persons receives a whole body dose of 1 Gy low LET radiation at a uniform rate over 1 minute. Clearly these are high dose and high dose rate conditions. The excess risk under consideration is that expressed over the first 20 years.

Bone

From the ^{224}Ra studies, the radiation-induced bone cancer risk would appear to be expressed within about 30 years of exposure, with a peak incidence 6–8 years after exposure. The risk of fatal bone cancer derived from these studies

(Mays et al., 1986; UNSCEAR, 1994) is about 1% per Gy. A radiation-weighting factor of 20 would suggest a lifetime fatal bone cancer risk of 0.05% per Sv, appropriate for low dose/low dose rate conditions. The value for high dose/high dose rate conditions derived in Little's memorandum from the LSS mortality data using Model A for the period 20 years after exposure is 0.046% per Sv. Since some of the risk will be expressed beyond 20 years after exposure, I shall take the central estimate of the bone cancer mortality risk to be 0.075% per Sv. This gives the central estimate of the number of radiation-induced bone cancer deaths to be 75,000. A direct derivation of a risk estimate from low LET radiation data is not particularly robust, and I have increased the estimate on the basis of the ^{224}Ra evidence. Given that the ^{224}Ra data arise from high LET irradiation, some uncertainty must arise as a consequence, particularly over the appropriate value of the radiation-weighting factor under these circumstances. Therefore, my 5% quantile estimate of the risk coefficient is 0.0095% per Sv, giving 9,500 radiation-induced bone cancer deaths. Similarly, my 95% quantile estimate of the risk coefficient is 0.5% per Sv, giving 500,000 radiation-induced bone cancer deaths.

Colon

For my central estimate, I rely upon the LSS data. Model A in Little's memorandum gives a risk coefficient for colon cancer mortality within 20 years of exposure as 0.115% per Sv. I am inclined to reduce this to 0.1% per Sv from the actual LSS data for this period, giving a 50% quantile estimate of 100,000 radiation-induced colon cancer deaths. From the evidence of the sensitivity of the estimate provided by models B and C, and the uncertainties associated with the transfer of risk, I take the 5% quantile estimate to be 30,000 deaths, and the 95% quantile estimate to be 300,000 deaths.

Breast

Estimates provided by Model A correspond well with those given by the NRPB for risk up to 40 years following exposure and for lifetime projection from the North American irradiated patients. For my 50% quantile estimate, I have adopted 150,000 radiation-induced breast cancer deaths. My 5% quantile estimate is 60,000 deaths, and my 95% quantile estimate is 500,000 deaths.

Leukemia

A number of studies have demonstrated that much of the excess risk of radiation-induced leukemia is expressed within 20 years of exposure. Consequently uncertainties arising from time projection are relatively small, and the uncertainties arising for the risk of leukemia within 20 years of exposure are mainly those due to lack of data and modeling. For my central estimate, I use the LSS data as analyzed by Little to give 850,000 radiation-induced leukemia deaths. For the uncertainty on this figure, I am guided by the analysis carried out by the BEIR V Committee. I take the 5% quantile estimate to be 300,000 deaths, and the 95% quantile estimate to be 2,500,000 deaths.

Liver

My 50% quantile estimate is taken from the LSS data as analyzed by Little, and is 9,000 radiation-induced liver cancer deaths. Apart from the Thorotrast-injected patients, there is little other evidence of radiation-induced excess liver cancer risk, therefore taking this into account, together with the uncertainties associated with the LSS data, my 5% quantile estimate is 2,000 deaths, and my 95% quantile estimate is 30,000 deaths.

Lung

Adopting the LSS data provides a central estimate of 450,000 lung cancer deaths. Owing to the problems associated with the interaction between radiation and smoking, and the implications of this for the transfer of risk between populations, my 5% quantile estimate is 150,000 deaths, and my 95% quantile estimate is 1,100,000 deaths.

Pancreas

Owing to the epidemiological evidence indicating a comparatively low sensitivity of the pancreas to radiation-induced cancer, I take my central estimate from the LSS data, but the uncertainty is reflected in a wide credibility interval. My central estimate is 25,000 pancreatic cancer deaths, and the 5% and 95% quantile estimates are 5,000 and 100,000 deaths.

Skin

A major source of uncertainty in skin cancer mortality is that, according to ICRP, only 0.2% of non-melanoma skin cancers are fatal. NRPB gives this figure as 1%. Clearly, then, the assumed lethality fraction will have a large impact upon the risk of skin cancer mortality. For my central estimate, I rely upon the LSS data as Little analyzed to give 7,000 radiation-induced skin cancer deaths. When taking into account the additional uncertainty associated with the

lethality fraction, my 5% quantile estimate is 1,500 deaths, and my 95% quantile estimate is 35,000 deaths.

Stomach

I take my central estimate from the LSS data to obtain 20,000 radiation-induced stomach cancer deaths within 20 years of exposure. Uncertainties arise over the transfer of risk from a Japanese population, and reflecting this, my 5% quantile estimate is 7,000 deaths while my 95% quantile estimate is 65,000 deaths.

Thyroid

The lethality fraction for thyroid cancer is low, given as 0.10 by both ICRP and NRPB. Therefore, an additional uncertainty which will have a relatively large influence upon thyroid cancer mortality will be that related to the lethality fraction. For thyroid cancer mortality, I take from the LSS data a 50% quantile estimate of 6,000 deaths, with 5% and 95% quantile estimates of 1,000 deaths and 30,000 deaths.

All other cancers

My central estimate is taken from the LSS data and is 250,000 radiation-induced deaths. Given the uncertainties inherent in this pool of other cancers as outlined in the general introduction, my 5% quantile estimate is 50,000 deaths and my 95% quantile estimate is 1,000,000 deaths.

All cancers

Summing the above gives a 50% quantile estimate of 1,950,000 deaths. The 5% and 95% quantile estimates are 900,000 and 4,000,000 deaths respectively.

Question (ii)

Exposure circumstances are as in question (i). The risk is that apparent over the first 40 years.

Bone

For my central estimate, I assume from the ^{224}Ra data a lifetime risk of fatal bone cancer after high dose/high dose rate irradiation of 0.1% per Sv, which is expressed entirely within 40 years of exposure. Therefore, the 50% quantile estimate is 100,000 radiation-induced bone cancer deaths. The uncertainties in this estimate have been noted in my answer to question (i). My 5% quantile estimate is 12,000 bone cancer deaths. The ASS data suggest that the bone cancer excess risk might persist beyond 30 years after exposure, although data are sparse. Therefore, my 95% quantile estimate is 800,000 bone cancer deaths.

Colon

My 50% quantile estimate based upon Model A in Little's memorandum gives a central estimate of 350,000 deaths. The 5% and 95% quantile estimates are 100,000 and 1,200,000 deaths respectively. These estimates also take account of the uncertainty in the lethality fraction (ICRP gives 0.55 whereas NRPB gives 0.75) applied to the LSS incidence data.

Breast

Owing to the reasonable agreement between the LSS data as analyzed by Little, and the NRPB model based upon North American medical exposures, my 50% quantile estimate is 500,000 deaths. My 5% and 95% quantile estimates are 150,000 deaths and 1,800,000 deaths respectively.

Leukemia

Again, I take the central estimate from the LSS data as analyzed by Little to give 1,000,000 radiation-induced leukemia deaths. My 5% quantile estimate is 350,000 deaths, and my 95% quantile estimate is 3,000,000 deaths.

Liver

From the LSS data, my central estimate is 30,000 liver cancer deaths. Uncertainties are such that my 5% quantile estimate is 6,000 deaths, and my 95% quantile estimate is 120,000 deaths.

Lung

The LSS data provide a central estimate of 1,500,000 lung cancer deaths. My 5% quantile estimate is 500,000 deaths, and my 95% quantile estimate is 3,500,000 deaths.

Pancreas

My central estimate is from the LSS data and is 85,000 deaths. Again, evidence for radiation-induced pancreatic cancer is sparse, so that my 5% quantile estimate is 15,000 deaths, and my 95% quantile estimate is 300,000 deaths.

Skin

The LSS data, as analyzed by Little give the number of radiation-induced skin cancer deaths as 20,000 which I take

as my 50% quantile estimate. The lethality fraction for non-melanoma skin cancer presents additional uncertainty, and my 5% quantile estimate is 4,000 deaths while my 95% quantile estimate is 100,000 deaths.

Stomach

My central estimate is derived from the LSS data and is 70,000 deaths. Owing to the uncertainty arising over transfer of risk, my 5% and 95% quantile estimates are 20,000 and 250,000 deaths.

Thyroid

My central estimate is derived from the LSS data, and is 18,000 deaths. Reflecting the uncertainty in the lethality fraction, together with the generic uncertainties, gives a 5% quantile estimate of 3,000 deaths and a 95% quantile estimate of 90,000 deaths.

All other cancers

The LSS data as analyzed in Little's memorandum give a central estimate of 750,000 deaths, which I take as my 50% quantile estimate. The uncertainties inherent in this grouping are comparatively large, and therefore my 5% and 95% quantile estimates are 150,000 deaths and 3,000,000 deaths respectively.

All cancers

Summing the above gives a 50% quantile estimate of 4,400,000 deaths. The 5% and 95% quantile estimates are 2,000,000 and 9,000,000 deaths respectively.

Question (iii)

The exposure is as in question (i). The lifetime risk is required.

Bone

For my central estimate, I assume that the excess risk is expressed entirely within 40 years of exposure, and therefore the excess bone cancer deaths number 100,000. My 5% quantile estimate is, again, 12,000 deaths. Owing to the sparseness of the data for bone cancer after low LET irradiation, my 95% quantile estimate is 1,500,000 bone cancer deaths, reflecting the uncertainties in the bone cancer risk coefficient, particularly concerning projection in time.

Colon

The lifetime risk of colon cancer mortality is complicated by the issue of whether the excess relative risk decreases with time since exposure, which is not absolutely clear from the LSS data, but is certainly indicated by this dataset and the ASS data. Therefore, my 50% quantile estimate is 1,100,000 radiation-induced colon cancer deaths, with 5% and 95% quantile estimates as 250,000 and 4,000,000 deaths.

Breast

The lifetime projections provided by Little using the LSS data are not too far removed from the lifetime projection of the NRPB using the model of Gilbert (1985) using North American data. My central estimate is therefore 1,100,000 breast cancer deaths. My 5% quantile estimate reflects the uncertainty in the projection and is 200,000 deaths, while my 95% quantile estimate is 5,000,000 breast cancer deaths.

Leukemia

Although much of the risk of leukemia (particularly acute leukemia) is expressed within 20 years of exposure, some uncertainty exists as to the degree of excess risk of chronic myeloid leukemia which might persist over a lifetime. From the LSS data, my central estimate is 1,100,000 leukemia deaths. The 5% quantile estimate is 400,000 deaths, and the 95% quantile estimate is 3,500,000 deaths, reflecting the uncertainty arising over the level of risk which persists after irradiation at young ages.

Liver

Given the absence of direct evidence for factors modifying the risk of radiation-induced liver cancer, my central estimate is 65,000 liver cancer deaths, reflecting my belief that a time since exposure effect will be operating but perhaps not as strongly as for other solid tumours. My 5% quantile estimate is 18,000 deaths, and my 95% quantile estimate is 250,000 deaths, incorporating the comparative lack of knowledge of liver cancer risk.

Lung

The LSS data, assuming a decline in the excess relative risk with time since exposure, give a 50% quantile estimate of 3,500,000 lung cancer deaths. The uncertainty on this figure derives not only from the time projection required, but also the nature of the interaction between smoking and

radiation and the implications for the transfer of risk between populations. Therefore, my 5% quantile estimate is 1,000,000 deaths, and my 95% quantile estimate is 10,000,000 deaths.

Pancreas

Owing to the sparseness of relevant data, this estimate must be comparatively insecure. My central estimate is taken from the LSS data, and is 250,000 pancreatic cancer deaths. My 5% quantile estimate is 30,000 deaths, and my 95% quantile estimate is 1,000,000 deaths.

Skin

There is some evidence for a reduction in the risk of skin cancer with time since exposure, although this is not strong. Consequently, taking regard of the additional uncertainty arising from lethality fraction, my 50% quantile estimate is 80,000 deaths. Reflecting the uncertainty in the time projection and lethality fraction, my 5% quantile estimate is 12,000 deaths, while my 95% quantile estimate is 500,000 deaths.

Stomach

In addition to the difficulties associated with the transfer of risk from a Japanese population, there is little direct evidence for a decrease in the relative risk with time since exposure. Therefore, my 50% quantile estimate is 250,000 radiation-induced stomach cancer deaths. My 5% quantile estimate is 60,000 deaths, while my 95% quantile estimate is 750,000 deaths, reflecting the central estimate being close to the upper estimate expected from the time projection model.

Thyroid

Based upon the LSS data, my central estimate is 50,000 radiation-induced thyroid cancer deaths. As before, my upper and lower estimates reflect the uncertainty in the lethality fraction so that my 5% and 95% quantile estimates are 9,000 and 300,000 deaths respectively.

All other cancers

My 50% quantile estimate is based upon the LSS data as analyzed by Little which, given the uncertainty in time projection, leads to a central estimate of 2,250,000 deaths. My 5% and 95% quantile estimates reflect the comparatively large uncertainty for this group of cancers, so that these estimates are 500,000 and 10,000,000 respectively.

All cancers

Summing the above gives a 50% quantile estimate of 9,850,000 cancer deaths. The 5% and 95% quantile estimates are 3,000,000 and 30,000,000 deaths respectively.

Question (iv)

This question addresses the risk arising from high dose/high dose rate low LET irradiation of children. The risk is cancer mortality expressed within 40 years of exposure.

Breast

There is compelling evidence that the risk of radiation-induced breast cancer is significantly increased at young ages at exposure. I have taken Little's analysis of the LSS data to give a 50% quantile estimate of 500,000 radiation-induced breast cancer deaths. There is uncertainty over the transfer of risk between a Japanese and Western population, so my 5% quantile estimate is 120,000 deaths. Given some evidence of higher breast cancer risks for some groups irradiated in childhood, my 95% quantile estimate is 2,500,000 breast cancer deaths.

Leukemia

My 50% quantile estimate is taken from the LSS data as analyzed in Little's memorandum, giving 500,000 radiation-induced leukemia deaths. My 5% quantile estimate is 150,000 deaths, and my 95% quantile estimate is 2,000,000 deaths, reflecting the uncertainty on how much higher the leukemia risk is for children.

Thyroid

My 50% quantile estimate reflects the high risk estimates observed in some populations which have been studied and the lethality fraction for thyroid cancer at young ages, and is 12,000 radiation-induced thyroid cancer deaths. To encompass the greater uncertainties associated with irradiation at younger ages, my 5% and 95% quantile estimates are 1,500 and 100,000 deaths.

All cancers

From the models presented by Little from the LSS data, and the presentation of cancer risk arising from irradiation in childhood presented by Muirhead et al. (1993), my 50%

quantile estimate is 2,250,000 deaths. The 5% and 95% quantile estimates are 750,000 deaths and 10,000,000 deaths respectively, reflecting the additional uncertainties associated with exposures in childhood, in particular the temporal expression of risk.

Question (v)

The conditions of irradiation are as in question (iv), but the risk is of cancer mortality arising over a lifetime.

Breast

I take my central estimate from Little's memorandum for Model A because there is some evidence for a decrease in excess relative risk with time since exposure. Therefore, the 50% quantile estimate is 2,250,000 radiation-induced breast cancer deaths. Because of the uncertainties arising from transfer of risk between the Japanese and a Western population, the evidence of a higher risk coefficient in some studies and in the projection of risk, my 5% quantile estimate is 350,000 deaths, and my 95% quantile estimate is 15,000,000 deaths.

Leukemia

Lifetime risk from the LSS data gives 550,000 deaths. The 5% quantile estimate is 150,000 deaths, and the 95% quantile estimate is 2,500,000 deaths, to take account of the ignorance surrounding the persistence of the radiation-induced excess risk into later life.

Thyroid

My 50% quantile estimate is 100,000 radiation-induced thyroid cancer deaths reflecting the uncertainty in both the risk following irradiation at young ages, and the lethality fraction. The 5% and 95% quantile estimates are 20,000 and 800,000 deaths respectively, estimates which take into account these additional uncertainties.

All cancers

For my central estimate, I take the information presented by Little and Muirhead et al. (1993). My 50% quantile estimate is 17,500,000 deaths, somewhat greater than that presented by Little in Model A, reflecting my belief that the excess risk is probably maintained for slightly longer than that predicted by Model A. My 5% and 95% quantile estimates are 4,500,000 deaths and 50,000,000 deaths respectively, which [noting that Little's Model B gives 34,000,000 deaths, indicating the uncertainty due to modeling error alone] encompass the additional uncertainties associated with irradiation in childhood, both in the magnitude and time projection of the risk.

Question (vi)

The risk of cancer following irradiation *in utero* raises a number of difficult issues (Wakeford, 1995). The principal data source for the derivation of risk estimates is the Oxford Survey of Childhood Cancers (OSCC) which contains information on the risk of childhood cancer following diagnostic x-ray exposure *in utero*, principally for obstetric purposes (Mole, 1990). Consequently, doses per x-ray examination are low, of the order of 10 mGy. A statistically significant excess risk of childhood cancer has not been observed in the Japanese bomb survivors who were irradiated *in utero*. However, this is not necessarily inconsistent with the findings of the OSCC and other case-control studies of diagnostic x-ray exposures *in utero* (Wakeford, 1995). The current best estimate of the risk of cancer occurring before the age of 15 years after intrauterine exposure to doses of the order of 10 mGy is obtained from the OSCC data, together with dose estimates the Adrian Committee made in 1958 (Mole, 1990), which gives an excess absolute risk estimate of 8×10^{-2} per Gy.

Since we are being asked to consider a dose of 1 Gy, low-LET radiation administered uniformly throughout pregnancy (38 weeks), this gives a dose rate of about 2.5 μGy per minute which, for the purposes of applying a DDREF, is considered to be low (Muirhead et al., 1993). Therefore, this risk estimate may be applied directly to the situation outlined in question (vi). Since the evidence from the OSCC data suggests that the relative risks for all types of childhood cancer are equally raised following irradiation *in utero*, the overall excess risk of childhood cancer may be equally apportioned by the frequency of cancer type. Since childhood leukemia accounts for 30% of childhood cancers, the excess risk estimate for childhood leukemia becomes 2.5×10^{-2} per Gy.

The above estimates relate to childhood cancer and childhood leukemia incidence rather than mortality. Treatment of childhood cancers is progressing rapidly, but 50% of childhood cancers and 30% of childhood leukemias are fatal. Therefore, the risk of childhood cancer mortality is 4×10^{-2} per Gy, and of childhood leukemia mortality is 0.8×10^{-2} per Gy.

These risk estimates are for excess deaths up to 15 years of age. Therefore, the excess risk in the 15–19 year age group must be estimated. From the OSCC data, an excess is still

discernible at 15 years of age, although the excess relative risk is tending to fall away at this age (Muirhead and Kneale, 1989; Mole, 1990). I assume that some excess risk does exist at ages 15–19 years, but that this is smaller than for the 0–14 year age group: an excess relative risk of 25 per Gy (50% of the excess relative risk coefficient over the age group 0–14 years). This leads to an excess risk of cancer mortality in this age group of 1.0×10^{-2} per Gy and an excess risk of leukemia mortality in this age group of 0.2×10^{-2} per Gy.

The great majority of the x-ray examinations upon which the OSCC data are based were carried out late in the third trimester, and little hard evidence is available for exposures earlier in pregnancy. I assume, along with Muirhead et al. (1993) a uniform risk coefficient throughout pregnancy. Therefore the central estimates for question (vi) are 5,000,000 excess cancer deaths, of which 1,000,000 are leukemia deaths.

The uncertainties associated with the childhood cancer risk coefficient for intrauterine irradiation are substantial. Even though the OSCC data are currently based upon nearly 15,000 deaths, the 95% confidence interval associated with the point estimate of 8×10^{-2} per Gy is 4.5 to 12×10^{-2} per Gy. In addition to this statistical uncertainty are systematic uncertainties relating to the accuracy of fetal doses, the variation in the risk with fetal age at exposure, the variation in risk between cancer types, and whether the association between childhood cancer and intrauterine irradiation is indeed causal at all.

In order to provide a lower 5% quantile estimate, I have assumed that fetal doses have been underestimated by 50%, that the risk of childhood cancer arising from exposures in the first half of pregnancy are 50% lower than that arising from exposure in the second half of pregnancy, and that the risk of childhood solid tumours is 50% of that for childhood leukemia. Together with the statistical uncertainty in the risk estimate, these assumptions give a childhood cancer mortality risk coefficient of around 0.5×10^{-2} per Gy, and a childhood leukemia mortality risk coefficient of around 0.1×10^{-2} per Gy. Therefore, the 5% quantile estimates for question (vi) are 500,000 excess cancer deaths, of which 100,000 are leukemia deaths.

To calculate the upper 95% quantile estimate, I have assumed that fetal doses have been overestimated by 50%, and that the risk coefficient for the first half of pregnancy is twice that for the second half of pregnancy. Together with the statistical uncertainty, this gives a risk of childhood cancer mortality of around 20×10^{-2} per Gy, and of childhood leukemia mortality of around 4×10^{-2} per Gy. The upper 95% quantile estimates for question (vi) are, therefore, 20,000,000 excess cancer deaths, of which 4,000,000 are leukemia deaths.

Question (vii)

Exposure is as in question (vi), but the lifetime risk of cancer mortality is required.

The crux of this question is whether there is a substantial risk of adult cancer associated with intrauterine irradiation. Some rather weak evidence for this comes from the Japanese atomic bomb survivors irradiated *in utero*, but although a statistically significant excess risk was reported in this group for all ages followed up until 1984, the excess risk was not significant for the 15–39 year age group - RR = 2.44 (95% CI 0.71–9.49) (Yoshimoto et al., 1988). No further cases occurred in the period 1984–89 (Yoshimoto et al., 1994).

Data from the Oxford Survey of Childhood Cancers (OSCC) suggest that the risk of cancer following intrauterine exposure to diagnostic x-rays is decreasing by the age of 15 years, and this is also found in other case control studies. The question is whether this is a process of extinction of the excess risk associated with *in utero* irradiation, or whether the risk persists, and that small numbers do not allow this risk to be detected. A further consideration is whether irradiation of tissues *in utero* can produce an excess risk of adult cancers—many childhood cancers are thought to arise from sensitive cells which are present only *in utero* and early in postnatal life, and the excess of childhood cancers following intrauterine irradiation is a reflection of the exposure of the sensitive cells. The assumption of whether *in utero* exposure produces an excess risk of adult cancers is clearly central to the estimates produced for question (vii). In this respect, the excess of cancer in adulthood, notably breast cancer, following irradiation *in infancy* may be of relevance.

For the central estimates of the number of deaths, I assume that the risk of cancer associated with intrauterine irradiation does not extend far into adult life. I assume this because there is no hard evidence from the Japanese atomic bomb survivors irradiated *in utero* having an excess risk of adult cancer, and because the relative risk of cancer in the OSCC data is reducing at the age of 16 years. I assume this is a real phenomenon, and therefore I find it difficult to believe an excess risk would persist to any large extent in later life. Therefore, the central estimates for question (vi) are 12,000,000 excess cancer deaths, of which 1,250,000

are leukemia deaths. The leukemia risk is based on the assumption that the excess relative risk will attenuate with time since exposure, as at other ages at exposure.

Assuming that risk does not extend beyond 20 years of age, the 5% quantile estimates are the same as those given in question (vi), namely 500,000 excess cancer deaths, of which 100,000 are leukemia deaths.

For the 95% quantile estimates, I assume that the excess risk persists into adult life. I assume that the *in utero* irradiation leads to 60,000,000 radiation-induced cancer deaths, reflecting the very great uncertainty associated with the lifetime risk of cancer following irradiation *in utero*. Leukemia mortality will make only a relatively small contribution to this. Therefore, the 95% quantile estimates for question (vii) are 60,000,000 excess cancer deaths, of which 5,000,000 are leukemia deaths. The very wide interval between the 5% and 95% quantile estimates reflects the absence of data available to assess the excess risk directly.

Question (viii)

This question is as question (ii), except that the risk of fatal and non-fatal cancers over 40 years is required.

Until the recent publication of studies employing the LSS incidence data, most of the information on the risk of radiation-induced fatal and non-fatal cancer was obtained from mortality studies and a knowledge of the lethality fraction for a particular cancer site. For certain cancers with a high lethality fraction, such as liver cancer, lung cancer and stomach cancer, this produced reasonably accurate estimates of overall cancer incidence risks. However, for those cancer sites with low lethality fractions such as non-melanoma skin cancer and thyroid cancer, such a procedure could not be expected to have a high accuracy because the uncertainty was liable to be dominated by that associated with a lethality fraction. For example, for non-melanoma skin cancer, ICRP gives a lethality fraction as 0.002, whereas NRPB gives the lethality fraction as 5 times higher at 0.01. Clearly then, lethality fraction uncertainties must be taken into account in deriving incidence risks. When the lethality fraction is low, then it generally is the case that incidence data will provide the more reliable estimates. Even so, lethality fractions can provide a guide to risk estimates from mortality data and vice versa, although it must be borne in mind that the lethality fraction may have varied over the period of follow-up. These are additional considerations to those already outlined above for cancer mortality.

Bone

For bone cancer, for my central estimate I assume a lethality fraction of 0.75 which is halfway between the ICRP 60 value of 0.70 and the NRPB value of 0.80. Thus, taking into account Little's models and LSS incidence data, my central estimate of the number of radiation-induced bone cancer cases is 130,000. For my 5% quantile estimate, I use a lethality fraction of 0.85 to obtain 14,000 bone cancer cases, and for my 95% quantile, I use a lethality fraction of 0.6 to obtain an estimate of 1,300,000 bone cancer cases.

Colon

ICRP give a lethality fraction of 0.55 for colon cancer, whereas the NRPB give 0.75. My 50% quantile estimate is 650,000 colon cancer cases, which takes account of Little's Model A and corresponds to the ICRP lethality fraction, with 5% and 95% quantile estimates of 150,000 and 2,500,000 colon cancer cases. These estimates reflect the uncertainties in the time-projection model and in the lethality fraction.

Breast

Both ICRP and NRPB give the lethality fraction for breast cancer as 0.5. The LSS data, as analyzed by Little give a breast cancer incidence risk coefficient which is higher than expected for this lethality fraction from the mortality risk coefficient. For my central estimate, I adopt a figure of 1,750,000 radiation-induced breast cancer cases. The 5% quantile estimate is 400,000, and the 95% quantile estimate is 7,000,000 cases.

Leukemia

The lethality fraction for leukemia adopted by ICRP is 0.99, while that given by NRPB is 0.90. On the basis of these lethality fractions, the difference between the leukemia incidence and mortality risk coefficients as derived from the LSS data by Little is somewhat large. For the central estimate of leukemia incidence, I take a value of 1,400,000 cases, while for the 5% and 95% quantile estimates, I adopt values of 450,000 cases and 4,500,000 cases, to take account of the additional uncertainty arising over lethality fractions.

Liver

ICRP give a lethality fraction of 0.95 for liver, which is also the value adopted by NRPB. Consequently, my central estimate of the number of radiation-induced liver cancer

cases is 30,000, and the 5% and 95% quantile estimates are 6,000 and 120,000, respectively.

Lung

The lethality fraction for lung cancer is high, both ICRP and NRPB giving the value as 0.95. My central estimate becomes 1,600,000 cases, and my 5% and 95% quantile estimates are 550,000 and 3,750,000 cases respectively.

Pancreas

Pancreatic cancer is almost uniformly fatal. Therefore, my central estimate is 90,000 cases. My 5% and 95% quantile estimates are 15,000 and 350,000 cases, reflecting the uncertainties in the mortality data given in question (ii).

Skin

Given that only 1% or less of non-melanoma skin cancers are fatal, the number of cases of radiation-induced skin cancer is very much greater than the number of deaths. My central estimate is taken from the LSS data and is 1,800,000 radiation-induced skin cancer cases. Uncertainty arises primarily from the transfer of risks between populations and from the lethality fraction when extrapolating from mortality data, and my 5% quantile estimate is 450,000 cases, while my 95% quantile estimate is 7,000,000 cases.

Stomach

Stomach cancer has a high lethality fraction estimated at 0.90 by ICRP and 0.95 by NRPB. Consequently, there will not be much difference between stomach cancer incidence and stomach cancer mortality. My 50% quantile estimate is therefore 75,000 cases, and my 5% and 95% quantile estimates are 20,000 and 350,000 cases, respectively.

Thyroid

Owing to the comparatively small lethality fraction for thyroid cancer, the number of cases is much greater than the number of deaths. My 50% quantile estimate, derived from the LSS data is 220,000 cases. My 5% and 95% quantile estimates are 45,000 cases and 1,000,000 cases, respectively.

All other cancers

My central estimate is taken from the LSS data as analyzed in Little's memorandum and is 1,500,000 radiation-induced cancer cases. This is consistent with a lethality fraction of 0.50 adopted by ICRP. The 5% and 95% quantile estimates are 300,000 and 7,000,000 cancer cases.

All cancers

Summing the above, my 50% quantile estimate is 9,250,000 cases. My 5% and 95% quantile estimates are 4,250,000 cases and 20,000,000 cases, respectively.

Question (ix)

The risk is of cancer mortality over 40 years following a whole body dose of 1 Gy, low-LET radiation delivered uniformly over one year corresponds to a dose rate of around 2 μGy per minute; in other words the dose is delivered at a low dose rate (Muirhead et al., 1993). The question of the reduction of the risk per unit dose for doses delivered at low dose rates is a difficult and contentious one. The only cancer site to demonstrate definite sub-linearity is leukemia, with an indication of curvature also present for non-melanoma skin cancer. Solid tumours do not exhibit sub-linearity in the LSS data, and this has led to the questioning of the appropriateness of applying a reduction in the risk per unit dose for low dose rates for these cancer sites. Nevertheless, dose fractionation has been demonstrated to reduce the risk per unit dose in other studies, and experimental data do suggest that lower dose rates or dose fractionation does reduce the risk per unit dose, even though the dose response at each dose rate may not demonstrate significant sub-linearity. It is generally accepted that a dose and dose rate effectiveness factor (DDREF) of greater than unity should be applied to high dose/high dose rate data such as the LSS data to derive risk coefficients which may be applied to low dose/low dose rate conditions. How much larger than 1 the DDREF should be is another matter. The ICRP and NRPB have adopted a DDREF of 2. However, BEIR V and UNSCEAR 1994 do not recommend a specific value for the DDREF. It should also be noted that the recommended value of the DDREF has reduced over the past decade or so. On this basis, I am inclined to take a DDREF of 2 for my central estimates in the absence of alternative information, and apply this to the central estimates given for question (ii). I tend to take a DDREF of 3 as an upper estimate and a DDREF of 1 as a lower estimate, unless there is additional information for the particular cancer under consideration, to derive appropriate 5% and 95% quantile estimates. I judge that, in general, these values of the DDREF, while not themselves 5% and 95% quantile estimates of DDREF, will give upper and lower quantile estimates of deaths arising from this low dose rate irradiation.

Bone

For the central estimate of a DDREF, I select a value of 2, given that the ^{224}Ra data indicate that fractionation reduces the risk. Therefore, the 50% quantile estimate is 50,000 bone cancer deaths. Given the uncertainty in the DDREF and the sparseness of the data, my 5% quantile estimate is 3,000 deaths (applying a DDREF of 4), and my 95% quantile estimate is 800,000 bone cancer deaths (applying a DDREF of 1).

Colon

Adopting a central value of the DDREF as 2 gives a 50% quantile estimate of 180,000 deaths. For my 5% quantile, I take a higher DDREF of 3 to give 35,000 deaths, and for my 95% quantile estimates, I take a DDREF of 1 to give 1,200,000 colon cancer deaths.

Breast

The DDREF for breast cancer is somewhat uncertain, particularly given the evidence from the medical irradiation studies. For my central estimate, I take a DDREF of 1.5. This gives the 50% quantile value of 350,000 deaths. For my 5% quantile estimate, I take a DDREF of 3, and for my 95% quantile estimate, I take a DDREF of 1. This gives, respectively, values of 50,000 deaths and 1,800,000 deaths.

Leukemia

There is little doubt that the DDREF for leukemia is greater than 1. The best estimate of the DDREF is 2, giving the central estimate of the number of leukemia deaths as 500,000. For my 5% quantile estimate, I take a DDREF of 5, to give an estimate of 70,000 leukemia deaths. For my 95% quantile estimate, I take a DDREF of 1.5 to give an estimate of 2,000,000 leukemia deaths.

Liver

There is little, if any, direct evidence for a DDREF associated with liver cancer. Therefore I take a default option of a DDREF of 2 for my central estimate to give 15,000 liver cancer cases. For my 5% quantile estimate, I adopt a DDREF of 3 to give 2,000 liver cancer deaths, and for my 95% quantile estimate, I assume a DDREF of 1 to give 120,000 deaths.

Lung

For my 50% quantile estimate I take a DDREF of 2, giving 750,000 deaths. For my 5% and 95% quantile estimates, I take DDREFs of 3 and 1, giving 175,000 deaths and 3,500,000 deaths, respectively.

Pancreas

The DDREF for pancreatic cancer can be gained only from a knowledge of other solid tumours. For my central estimate, I take a DDREF of 2, giving 40,000 deaths. For my 5% quantile estimate, I take a DDREF of 3, to give 5,000 deaths; and for my 95% quantile estimate, I take a DDREF of 1, giving 300,000 deaths.

Skin

For non-melanoma skin cancer, for my central estimate I take a value of the DDREF as 2 to give 10,000 radiation-induced skin cancer deaths. Adopting a DDREF of 4 for my 5% quantile estimate gives 1,000 deaths, and adopting a DDREF of 1 for my 95% quantile estimate gives 100,000 deaths.

Stomach

Again, I take the central estimate of the DDREF to be 2, with the upper and lower estimates being 3 and 1, respectively. This gives a 50% quantile estimate of 35,000 radiation-induced stomach cancer deaths, with 5% and 95% quantile estimates of 7,000 and 250,000 deaths.

Thyroid

There is evidence from iodine-131 administration that the DDREF for the thyroid is greater than 1, although the interpretation of these findings is complicated by other factors, such as the distribution of dose. Adopting a DDREF of 2 for my central estimate gives a 50% quantile estimate of 9,000 deaths. I adopt a DDREF of 4 to obtain a 5% quantile estimate of 750 deaths, and a DDREF of 1 to obtain a 95% quantile estimate of 90,000 deaths.

All other cancers

I take a DDREF of 2 for my central estimate to give a 50% quantile estimate of 375,000 deaths. For my 5% quantile estimate, I adopt a DDREF of 3 to give 50,000 deaths and for my 95% quantile estimate I adopt a DDREF of 1 to give 3,000,000 deaths.

All cancers

Summing the above gives a 50% quantile estimate of 2,300,000 deaths. Reflecting the additional uncertainty associated with the DDREF, my 5% and 95% quantile estimates are 750,000 deaths and 7,000,000 deaths respectively.

Question (x)

This question deals with the number of incident skin cancer cases arising from 1 mGy of Pu alpha particles delivered over 1 year.

There has been a question raised in the past as to whether alpha particles from skin contamination can reach the cells which are sensitive to the induction of skin cancer through the layer of dead skin cells. Eatough and Henshaw (1992) have argued that alpha particles from radon decay products on the skin can affect the sensitive basal layer of the epidermis. There is little doubt that low LET radiation can induce non-melanoma skin cancer, but only one epidemiological study has reported an excess risk of skin cancer which might be attributable to alpha particle irradiation, that of Sevcova et al. (1978) who studied cancer incidence among uranium miners in the former Czechoslovakia. (The absence of evidence for an excess risk of skin cancer in other groups of miners may be due to an examination of cancer *mortality* in these groups, and the low lethality fraction for non-melanoma skin cancer.) There has been discussion whether this excess of skin cancer is attributable to alpha particle irradiation or to other carcinogens in the environment of the underground uranium mines. Taking the risks that have been derived from these miners by Albert and Shore (1986) gives a risk coefficient for 40 years after exposure of 7.6% per Gy of alpha particle radiation. This compares with the risk coefficient derived from the low LET radiation experience of the Japanese atomic bomb survivors of 1.8% per Gy over the period 40 years after exposure (Little's memorandum). Interpreted literally, an RBE of around 8 for skin cancer induced by alpha particle irradiation is suggested, assuming a DDREF of 2. If the direct estimate from the miners is taken, then 1 mGy plutonium alpha particle radiation will produce 8,000 skin cancer cases in the 40 years following exposure, and I take this as my 50% quantile estimate. Given the uncertainty in the estimates, taking the radiation-weighting factor for alpha particles of 20, and using the data from the Japanese atomic bomb survivors (transferring the relative risk), would give 18,000 excess skin cancer cases. However, given the uncertainties involved in these calculations, I am inclined to set the 5% quantile to 750 radiation-induced skin cancer cases, and the 95% quantile estimate to 100,000 radiation-induced skin cancer cases.

Question (xi)

No internal organ doses available to calculate risks.

Question (xii)

What is being assessed in this question is the average years of life lost per radiation-induced death. In other words, if an individual dies of cancer as a result of a particular exposure to radiation, what is the expected length of life lost. The average years of life lost per death is dependent upon the temporal expression of the risk after exposure. For leukemia, when the excess risk is expressed relatively soon after exposure, the average years of life lost per death is going to be greater than that for, for example, stomach cancer when the risk is more spread out over time since exposure. For a constant relative risk model, the average years of life lost per death will be least because most of the excess risk will be expressed when the background solid tumour risk is greatest at older ages. For models in which the excess relative risk decreases with increasing time since exposure (or increasing attained age) the average loss of life expectancy per death will be greater because proportionally more of the risk is experienced at younger ages.

The length of the latent period is also an important consideration. For leukemia, with a relatively short latency, the excess risk tends to be expressed closer to the time of exposure, and the average loss of life expectancy per death will be larger than for other cancers with a longer latency. The question appears to assume that the temporal expression of the excess risk is independent of the dose, but there is some evidence for latency being dose dependent—the latent period decreasing with increasing dose. (It is also possible that the period of expression of the excess risk might vary with the dose.) Latency and period of expression may also vary with age at exposure, being shorter at younger ages.

For the estimation of the average years of life lost per radiation-induced cancer death for the purposes of this question, I rely on the assumptions and uncertainties outlined in my treatment of question (iii). Principal results are obtained from the division of the loss of life expectancy for the population by the lifetime risk of radiation exposure induced death (to give the average years of life lost per radiation-induced death) given by Little.

Question (xiii)

This question asks about the threshold dose for low LET irradiation over 1 minute.

There is little direct epidemiological evidence for the presence or absence of an excess risk of cancer arising from exposure to very low doses of ionizing radiation. There is evidence of sub-linearity in the dose response curve for certain cancers (notably leukemia and skin cancer), but there is little evidence for a departure from linearity for most cancers. However, no significant excess risk is detectable in the LSS data below 0.2 Gy (Thompson et al., 1994), although a pooled analysis of thyroid cancer studies takes this figure down to 0.1 Gy (Ron et al., 1995). However, absence of evidence for an excess risk at low doses from these studies (due to low statistical power) is not evidence of absence of a risk.

Direct study of those irradiated under low dose/low dose rate conditions does indicate an excess risk of cancer associated with low dose irradiation, particularly for leukemia. Nuclear industry workforce studies suggest an excess risk of leukemia arising from protracted exposures at occupational levels (Cardis et al., 1995). A study of leukemia in Utah and exposure to fallout from nuclear weapons testing in Nevada found an association between childhood leukemia and fallout doses (Stevens et al., 1990), and a study of childhood leukemia in the Nordic countries found some evidence for a rise in incidence associated with atmospheric nuclear weapons testing fallout, consistent with predictions based upon the Japanese atomic bomb survivors (Darby et al., 1992). However, the strongest epidemiological evidence for cancer being induced by low doses of radiation is from studies of childhood cancer and *in utero* exposure to diagnostic x-ray examinations. An excess risk of childhood cancer has been reported from a number of case-control studies, and if a causal relationship is accepted, then this excess risk has been produced by doses of around 10 mGy.

The UK National Radiological Protection Board (1995) has recently re-examined the issue of the risk of cancer arising from low dose/low dose rate irradiation. The report concluded, principally on the basis of radiobiological evidence, that no threshold of dose exists below which there is no excess risk of cancer.

Consequently, for question (xiii), my 50%, 5% and 95% quantile estimates of the threshold dose are 0 Gy. I have set the 95% quantile estimates to 0 Gy because I do not believe that the probability of a non-zero threshold dose for any malignant disease that has been shown to be capable of being induced by ionizing radiation is as high as 5%.

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Question 1. The number of radiation-induced cancer deaths up to 20 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	9.5×10^3	7.5×10^4	5.0×10^5
Colon	3.0×10^4	1.0×10^5	3.0×10^5
Breast	6.0×10^4	1.5×10^5	5.0×10^5
Leukemia	3.0×10^5	8.5×10^5	2.5×10^6
Liver	2.0×10^3	9.0×10^3	3.0×10^4
Lung	1.5×10^5	4.5×10^5	1.1×10^6
Pancreas	5.0×10^3	2.5×10^4	1.0×10^5
Skin	1.5×10^3	7.0×10^3	3.5×10^4
Stomach	7.0×10^3	2.0×10^4	6.5×10^4
Thyroid	1.0×10^3	6.0×10^3	3.0×10^4
All other cancers	5.0×10^4	2.5×10^5	1.0×10^6
All cancers	9.0×10^5	1.95×10^6	4.0×10^6

Question 2. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	1.2×10^4	1.0×10^5	8.0×10^5
Colon	1.0×10^5	3.5×10^5	1.2×10^6
Breast	1.5×10^5	5.0×10^5	1.8×10^6
Leukemia	3.5×10^5	1.0×10^6	3.0×10^6
Liver	6.0×10^3	3.0×10^4	1.2×10^5
Lung	5.0×10^5	1.5×10^6	3.5×10^6
Pancreas	1.5×10^4	8.5×10^4	3.0×10^5
Skin	4.0×10^3	2.0×10^4	1.0×10^5
Stomach	2.0×10^4	7.0×10^4	2.5×10^5
Thyroid	3.0×10^3	1.8×10^4	9.0×10^4
All other cancers	1.5×10^5	7.5×10^5	3.0×10^6
All cancers	2.0×10^6	4.4×10^6	9.0×10^6

Question 3. The number of radiation-induced cancer deaths over a lifetime (following the population up until it has become extinct) in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	1.2×10^4	1.0×10^5	1.5×10^6
Colon	2.5×10^5	1.1×10^6	4.0×10^6
Breast	2.0×10^5	1.1×10^6	5.0×10^6
Leukemia	4.0×10^5	1.1×10^6	3.5×10^6
Liver	1.8×10^4	6.5×10^4	2.5×10^5
Lung	1.0×10^6	3.5×10^6	1.0×10^7
Pancreas	3.0×10^4	2.5×10^5	1.0×10^6
Skin	1.2×10^4	8.0×10^4	5.0×10^5
Stomach	6.0×10^4	2.5×10^5	7.5×10^5
Thyroid	9.0×10^3	5.0×10^4	3.0×10^5
All other cancers	5.0×10^5	2.25×10^6	1.0×10^7
All cancers	3.0×10^6	9.85×10^6	3.0×10^7

Question 4. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 years) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Breast	1.2×10^5	5.0×10^5	2.5×10^6
Leukemia	1.5×10^5	5.0×10^5	2.0×10^6
Thyroid	1.5×10^3	1.2×10^4	1.0×10^5
All cancers	7.5×10^5	2.25×10^6	1.0×10^7

Question 5. The number of radiation-induced cancer deaths over a lifetime (following the population up until it has become extinct rather than up to 40 years following exposure) in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 years) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Breast	3.5×10^5	2.25×10^6	1.5×10^7
Leukemia	1.5×10^5	5.5×10^5	2.5×10^6
Thyroid	2.0×10^4	1.0×10^5	8.0×10^5
All cancers	4.5×10^6	1.75×10^7	5.0×10^7

Question 6. The number of radiation-induced cancer deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure of a dose of 1 Gy low LET (= gamma) radiation administered uniformly over their three trimesters (9 months) *in utero* and followed-up for 20 years after birth.

	Quantile		
	5%	50%	95%
Leukemia	1.0×10^5	1.0×10^6	3.0×10^6
All cancers	5.0×10^5	5.0×10^6	2.0×10^7

Question 7. The number of radiation-induced cancer deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure of a dose of 1 Gy low LET (= gamma) radiation administered uniformly over their three trimesters (9 months) *in utero* and followed over a lifetime (following the population up until it has become extinct rather than up to 20 years following exposure).

	Quantile		
	5%	50%	95%
Leukemia	1.0×10^5	1.25×10^6	5.0×10^6
All cancers	5.0×10^5	1.2×10^7	6.0×10^7

Question 8. The number of radiation-induced cancer cases (fatal and non-fatal) up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	1.4×10^4	1.3×10^5	1.3×10^6
Colon	1.5×10^5	6.5×10^5	2.5×10^6
Breast	4.0×10^5	1.75×10^6	7.0×10^6
Leukemia	4.5×10^5	1.4×10^6	4.5×10^6
Liver	6.0×10^3	3.0×10^4	1.2×10^5
Lung	5.5×10^5	1.6×10^6	3.75×10^6
Pancreas	1.5×10^4	9.0×10^4	3.5×10^5
Skin	4.5×10^5	1.8×10^6	7.0×10^6
Stomach	2.0×10^4	7.5×10^4	3.5×10^5
Thyroid	4.5×10^4	2.2×10^5	1.0×10^6
All other cancers	3.0×10^5	1.5×10^6	70×10^6
All cancers	4.25×10^6	9.25×10^6	2.0×10^7

Question 9. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 year (rather than 1 minute).

	Quantile		
	5%	50%	95%
Bone	3.0×10^3	5.0×10^4	8.0×10^5
Colon	3.5×10^4	1.8×10^5	1.2×10^6
Breast	5.0×10^4	3.5×10^5	1.8×10^6
Leukemia	7.0×10^4	5.0×10^5	2.0×10^6
Liver	2.0×10^3	1.5×10^4	1.2×10^5
Lung	1.75×10^5	7.5×10^5	3.5×10^6
Pancreas	5.0×10^3	4.0×10^4	3.0×10^5
Skin	1.0×10^3	1.0×10^4	1.0×10^5
Stomach	7.0×10^3	3.5×10^4	2.5×10^5
Thyroid	7.5×10^2	9.0×10^3	9.0×10^4
All other cancers	5.0×10^4	3.75×10^5	3.0×10^6
All cancers	7.5×10^5	2.3×10^6	7.0×10^6

Question 10. The number of radiation-induced skin cancer cases (fatal and non-fatal) up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a uniform skin dose of 1 mGy high LET (= plutonium alpha particle) radiation at a uniform rate over 1 year.

	Quantile		
	5%	50%	95%
Skin	7.5×10^2	8.0×10^3	1.0×10^5

Question 11. Joint dosimetry/late effects question: The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each of whom inhales 10 K Bq of the radionuclides specified.

Nuclide	Physical Form	Chemical Form	Cancer Type	Number of Cancers Quantile		
				5%	50%	95%
Pu-239	1 μm AMAD	Oxide	Lung	N/A	N/A	N/A
			Bone	N/A	N/A	N/A
			Liver	N/A	N/A	N/A
			Leukemia	N/A	N/A	N/A
			All cancers	N/A	N/A	N/A
Sr-90	1 μm AMAD	Oxide	Lung	N/A	N/A	N/A
			Bone	N/A	N/A	N/A
			Leukemia	N/A	N/A	N/A
			All cancers	N/A	N/A	N/A

Question 12. Given that radiation induced cancer death due to the specified cause has occurred as a result of a dose of radiation delivered over 1 minute, the average expected length of life lost in years, for a population followed up to extinction after exposure.

	Quantile		
	5%	50%	95%
Bone	1.2×10^1	2.0×10^1	2.4×10^1
Colon	1.1×10^1	1.3×10^1	1.5×10^1
Breast	1.4×10^1	1.9×10^1	2.1×10^1
Leukemia	1.9×10^1	2.2×10^1	2.4×10^1
Liver	1.2×10^1	1.6×10^1	1.9×10^1
Lung	1.3×10^1	1.5×10^1	1.7×10^1
Pancreas	1.0×10^1	1.4×10^1	1.7×10^1
Skin	1.0×10^1	1.2×10^1	1.4×10^1
Stomach	1.0×10^1	1.2×10^1	1.5×10^1
Thyroid	1.0×10^1	1.2×10^1	1.4×10^1
All other cancers	1.2×10^1	1.4×10^1	1.6×10^1
All cancers	1.4×10^1	1.6×10^1	1.8×10^1

Question 13. For each of the cancer sites listed, give the estimate of the threshold dose in Gy, for low LET (= gamma) radiation administered at a uniform rate over 1 minute, below which value there is no radiation-induced cancer risk.

	Quantile		
	5%	50%	95%
Bone	0	0	0
Colon	0	0	0
Breast	0	0	0
Leukemia	0	0	0
Liver	0	0	0
Lung	0	0	0
Pancreas	0	0	0
Skin	0	0	0
Stomach	0	0	0
Thyroid	0	0	0
All other cancers	0	0	0
All cancers	0	0	0

EXPERT D

Introduction

The assessments to be described have two parts: (1) a determination of a "best" estimate (the median number of events in question) for the various endpoints and (2) estimation of upper and lower bounds (95% and 5% quantiles) to describe the uncertainty associated with the assessment. In the approach to uncertainty assessments briefly outlined in this introduction and explained in detail on the following pages some precision in the derivation of "best" estimates has deliberately been sacrificed to facilitate a systematic approach to assessment of the uncertainty.

My knowledge about late health effects after radiation exposure derives almost entirely from experiences with analysis of the cancer mortality data from the follow-up of the Japanese atomic bomb survivors in the Life Span Study (LSS). I have therefore decided to use results from this cohort as the main data source for the uncertainty assessment. The basic idea behind the present approach has been to obtain estimates of excess lifetime risk, measured as risk of exposure-induced death (*REID*, see Thomas et al., 1992 for a discussion of this and other measures of lifetime risk), by applying a simple approximation for *REID* valid for excess relative risk (ERR) models. The ERR model considered here gives an adequate description of the excess mortality seen in the Japanese mortality data for the first 40 years of follow-up. The approximation does not require extensive calculations, since it uses only the site-specific lifetime risk of dying of cancer in the EU/USA standard population for which the assessment is to be applied. Once these estimates were obtained, estimates for different endpoints (e.g., 40 years instead of lifetime risks) and other scenarios (e.g., incidence instead of mortality) were computed by applying various correction factors. These factors were calibrated by more detailed computations for a few sites and also by comparing the results to those of Mark Little (pers. comm. from M. Little, 1996). The spreadsheet Microsoft® EXCEL was used for all computations.

The various steps in the calculation of the risk estimates include aspects which are not well understood and therefore contribute to the uncertainty of the estimates. In statistics, such uncertainties are usually handled by associating a component of variance to each contributing factor. An estimate of the total uncertainty can then be derived as the sum of these variance components. In the present context a multiplicative error structure seems most appropriate. The uncertainty bounds were therefore obtained by computing an uncertainty factor for each endpoint. Upper and lower bounds were then derived from the medians by multiplying or dividing the median by this uncertainty factor. Multiplicative uncertainty structures are conveniently handled by considering the effect measures on a log-scale. Once the potential sources of uncertainty are identified and assigned a variance component the total uncertainty for a given endpoint can be described by the sum of the relevant components of variance. Uncertainty bounds on the log-scale are proportional to the square root of the total variance. Such bounds translate into the desired uncertainty factors when transforming back to the original, linear scale. This approach ensures a high degree of consistency between the uncertainty bounds computed for different endpoints and moreover allows a straightforward quantification of dependencies between endpoints. Such dependencies are rather large with the present approach since all results are essentially derived from the same data source.

The basic models for radiation-induced cancer mortality following acute radiation exposure

A risk assessment has three main components: a description of the population exposed, a description of the type and size of exposure, and a model for the magnitude and duration of the effect. The first two components are described in the case structure document* and further specified in the individual questions. The basic models used to describe the effect of exposure are presented in this section. Before turning to a description of the last component let me briefly clarify how a whole body exposure of 1 Gy has been interpreted in the risk assessment. I have assumed that when an individual is exposed to a whole body dose of 1 Gy gamma radiation all potential target cells have received this dose. I have also assumed that the dose is exact, i.e., determined without error. Moreover, when assessing the risk of radiation-induced death for a given organ, allowance has been made for the fact that the individual may die of radiation-induced cancer in some other organ.

When modeling excess cancer mortality due to radiation, leukemia is traditionally considered separately, partly because the effect of radiation is much larger for this site, and partly because the temporal pattern of the excess risk differs markedly from what is found for other cancer sites. The variation in time and age of the excess leukemia risk is

* M. Little and C. Muirhead. 1995. Case structure document for EC/USNRC Project on Expert Judgment for Uncertainty Analysis of ACA Codes: Expert Panel on Somatic Health Effects.

rather complex, and no simple model gives a satisfactory description of the pattern. For present purposes, I have simply based the assessment of leukemia risks on the results derived by Mark Little (pers. comm. from M. Little, 1996) and not tried to derive alternative estimates based on different models. Note, however, that all risk estimates presented in Tables 2, 3 and 4 of (pers. comm. from M. Little, 1996) are derived using a test dose of 0.001 Sv. A dose of 1 Sv is considered in the assessments, and results for this dose will become too large if obtained simply by multiplying the results in (pers. comm. from M. Little, 1996) by 1000. The risk of exposure-induced death is non-linear in dose. Investigations further described below indicate that a reduction on the order of 15% is needed to allow for the non-linearity of *REID*, and this reduction has therefore been applied to all the leukemia results in (pers. comm. from M. Little, 1996) before using them in the present assessments.

For the Japanese solid tumor mortality data, the excess risk for the current follow-up period is described fairly well by a simple linear ERR model for which the ERR per unit dose depends on sex and age at exposure, but not on time since exposure (allowing for a 5-year latency period) or attained age. Model B in (pers. comm. from M. Little, 1996) is one such model; I will consider a slightly different model. Usually, site specific risk coefficients are estimated from such a model, but the variations of these coefficients between sites are not substantially larger than what could result merely from sampling variation (e.g., Pierce and Preston, 1993). To avoid relying on poorly determined risk coefficients for some sites and also to simplify the calculations, it was decided *to apply the same risk coefficients for all sites*. In the model used here the ERR per unit dose was allowed to depend on sex and age at exposure with the latter factor categorized as 0-19, 20-39, and 40 and above (Table 1).

Table 1. ERR per unit dose for the model used in the assessment of solid tumor risks.

Age at exposure	Sex	
	male	female
0-19	0.75	1.5
20-39	0.50	1.0
40-	0.25	0.5

This model has previously been used in Væth and Pierce (1990) and is also very similar to the models for non-leukemia cancer mortality considered in Pierce et al. (1991). The estimates allow for the effect on risk coefficients of a 35% uncertainty in the LSS dose estimates.

A simple approximation to *REID* is available for *ERR* models for which the *ERR* is assumed independent of follow-up time and attained age. Letting a, s, and d denote age at exposure, sex and dose we have

$$REID(a,s,d) \approx p(a,s) \cdot ERR(a,s,d) \cdot LTR(a,s) \quad (1)$$

where $p(a,s)$ the probability of surviving the 5 year latency period and $LTR(a,s)$ is the lifetime risk of dying from the cancer in question for an individual in the (unexposed) population of sex s and alive at age a. The population *REID* can then obtained by averaging over the sex- and age distribution in the exposed population.

The relation (1) may be derived in the same way as similar relations for excess lifetime risks (see Væth and Pierce [1990] for details). The right side of (1) actually gives an upper bound and direct calculations for all cancer combined, and a few selected sites showed that the over-estimation was on the order of 17% for males and 13% for females. To improve the approximation it was therefore decided to consider the following approximation

$$REID(d) \approx \sum_{a,s} f(s) \cdot p(a,s) \cdot w(a,s) \cdot ERR(a,s,d) \cdot LTR(a,s) \quad (2)$$

where $f(s)$ is 0.83 for males and 0.87 for females and $w(a,s)$ gives the sex and age distribution in the population. In some calculations an average value of 0.85 was used for $f(s)$.

The main problem with risk projections based on the model summarized in Table 1 is the extrapolation to old ages for individuals exposed as children or young adults. In the Japanese data there are some indications of a decreasing *ERR* with time since exposure in these groups, and it seems prudent to allow for such a time trend when projecting the model beyond the current follow-up. To quantify the impact of a likely time trend the following procedure was adopted. For those exposed under age 20 the risk coefficient was changed after 40 years of follow-up to that specified for the subsequent age group (i.e., for males 0.75 was replaced by 0.5). A similar procedure was used for those exposed at age 20-39. The impact of this change was determined by life table-based calculations of 40 years and lifetime *REID* for selected sites. For males below age 20 at exposure the consequence of this change was then assessed by comparing the lifetime *REID*, assuming constant *ERR* of 0.75, with a modified lifetime *REID* obtained as the sum of the 40 years *REID* using *ERR* = 0.75 plus the difference between the

lifetime *REID* and the 40 years *REID*, assuming *ERR* = 0.5. Similar calculations were carried out for the three other age and sex groups for which a modification was considered relevant. The calculations where carried out for all cancers combined and separately for lung, liver and bone cancer. The modification resulted in a decrease of the lifetime *REID* by 11-15%.

Similar considerations led Mark Little (pers. comm. from M. Little, 1996) to Model C which was derived from Model B by introduction of a decreasing time trend after 40 years of follow-up for those exposed as children. His modification is somewhat larger; the ratio of *REID* from Model C to that from model B being in the 0.61 – 0.76 range.

A final consideration has to do with the distinction between medians and means. The *REID* gives the expected number (i.e., the mean) of deaths associated with radiation exposure, but in the assessment a 50% quantile (i.e., a median) is requested. The sampling variation in the risk estimates is skewed, so the mean will be slightly larger than the median. Some preliminary calculations suggested that the difference was expected to be around 5%. This is only a minor correction compared to the one above, so it was decided to account for both aspects by using a combined correction factor, *c*, equal to 0.85 to the population *REID* in (2)

$$REID(d) \approx c \cdot \sum_{a,s} f(s) \cdot p(a,s) \cdot w(a,s) \cdot ERR(a,s,d) \cdot LTR(a,s) \quad (3)$$

Some further investigations revealed that the following simplified approximation was sufficiently accurate for the present purposes

$$REID = REID(1) = c \cdot \sum_{a,s} f(s) \cdot p(s) \cdot ERR(s) \cdot LTR(s) \quad (4)$$

where $p(s)$, $ERR(s)$, and $LTR(s)$ are averages of the corresponding age-specific values for each sex using the age distributions in the total population as weights. The values of $p(s)$ and $ERR(s)$ are shown in Table 2.

Table 2. Values of $p(s)$ and $ERR(s)$ used in the assessments

	males	females
average probability of surviving 5 years	0.939	0.941
average ERR at 1 Gy	0.451	0.886

Table 3 contains the values of $LTR(s)$ and the *REID* estimates for each of the sites considered in the assessments.

Table 3. Average lifetime risks and estimates of average *REID* for the total population obtained from (4).

Cancer site	Average lifetime risk in the total population[a]		Estimate of average REID in the total population[b]
	males	females	
Bone	0.03	0.02	0.012
Colon	2.13	1.84	0.886
Female Breast	0.00	3.23	0.994
Leukemia[c]	0.66	0.45	0.851
Liver	0.22	0.13	0.073
Lung	7.72	2.93	2.057
Pancreas	1.03	0.87	0.421
Skin	0.11	0.07	0.038
Stomach	1.29	0.69	0.405
Thyroid	0.03	0.07	0.024
All other	11.82	7.14	3.964
All cancer[d]	24.86	17.33	9.726

a Values are multiplied by 100.
b Values are given in units of 10^{-2} Sv^{-1}.
c Leukemia REID taken from (pers. comm. from M. Little, 1996) but modified as explained in the text.
d Lifetime risk estimates are based on all cancer mortality rates, these differ slightly from the sum of the site-specific cancer rates so the site-specific lifetime risks do not sum exactly to the lifetime risk for all cancers. For REID the value is obtained as the sum of the site-specific values.

The approach outlined above was used to obtain estimates of radiation-induced deaths in the total population. The corresponding estimates for selected sites in a population of children and for *in utero* exposure (Questions 5 and 7) were obtained by direct life-table calculations based on the constant relative risk model in Table 1. Here the results were further modified to allow for a time trend in the ERR after 40 years of follow up. The same approach as the one described above was used for this modification (i.e., the risk coefficient was changed after 40 years of follow-up to that specified for the subsequent age group).

Risk of exposure-induced deaths up to 20 and 40 years after exposure

I decided to estimate the risk of radiation-related deaths during the first 20 years of follow-up by multiplying the lifetime *REID* obtained above by an estimate of the fraction

of radiation-induced cancer deaths in first 20 years among all radiation-induced cancer deaths, i.e.,

$$REID_{20} = k_{20} \cdot REID \quad (5)$$

This approach is computationally very attractive once the relevant fractions are determined, but may seem rather indirect since 20 years (and 40 years) of follow-up are covered by the current follow-up period in the LSS. A more direct approach, however, was considered too time-consuming to be feasible. Similarly, the risk of radiation-related deaths during the first 40 years of follow-up was computed as

$$REID_{40} = k_{40} \cdot REID \quad (6)$$

The method requires that the coefficients k_{20} and k_{40} are determined for each site. To this end, the detailed life-table calculations of $REID_{40}$ and lifetime *REID* for lung, liver, bone and all cancers carried out in connection with the evaluation of the impact of the time trend were expanded to include an estimate of $REID_{20}$. This allowed a direct estimation of k_{20} and k_{40} for these sites. Based on a visual inspection of the degree of age dependence of the site-specific cancer rates, the cancer sites were then divided into three groups and the following values of k_{20} and k_{40} were assigned to each group (the calibration was done using a lifetime *REID* not corrected for time trend; the coefficients below were then obtained as 85% of the initial coefficients):

Table 4. Values for k_{20} and k_{40} used in formula (5) and (6).

Cancer site	20 years period	40 years period
Bone	0.21	0.425
Breast, Liver, Thyroid	0.13	0.34
All other sites	0.085	0.30

These coefficients were then applied to population average lifetime *REID* to obtain estimates of population average $REID_{20}$ and $REID_{40}$. For leukemia Little's calculations (pers. comm. from M. Little, 1996) were used, again with a 15% reduction to allow for non-linearity in dose (see the discussion above). For the all cancers combined category $REID_{20}$ and $REID_{40}$ were determined as sums of all site-specific estimates. The site-specific values of $REID_{20}$ and $REID_{40}$ are shown in Table 5, together with the results for cancer incidence to be described in the next section.

For comparison, the ratio of $REID_{20}$ to *REID* and of $REID_{40}$ to *REID* were computed for Little's Models A and B. For all sites the coefficients above were smaller than the Model A ratio, but larger than the Model B ratio.

The coefficients in Table 4 were used to derive estimates of the average risk of radiation-induced deaths in the population for the specified period from average lifetime *REID* in the population. For children and *in utero* exposed (Questions 4 and 6) a similar approach was considered too imprecise, and risk estimates for selected sites were obtained by direct life-table calculations based on the constant relative risk model in Table 1.

Assessment of radiation-induced cancer incidence

The approach used to estimate the risk of radiation-induced cancer (fatal or non-fatal), here denoted *REIC*, is very similar to the one used to obtain estimates of $REID_{20}$ and $REID_{40}$. In the unexposed population the lifetime risk of dying of cancer and the lifetime risk of developing cancer as a function of sex and age were obtained from a detailed life-table calculation for each site. The ratio of these two numbers is an estimate of the lethality of the disease. For all cancer sites the lethality varied little with age or between males and females. To reduce the complexity of the calculations a single value of the lethality for each site was obtained as a population average of the age- and sex-specific lethality. The risk of radiation-induced cancer was then estimated from *REID* as

$$REIC = REID / lethality \quad (7)$$

The risk of radiation-induced cancer up to 40 years following exposure was determined from $REID_{40}$ in a similar way.

Some problems with the approach used to derive *REIC* should be noted. The derivation of the lethality estimates implicitly assumes that each individual will at most get one cancer. Occurrence of multiple primaries are therefore ignored. Also, a few sites have incidence rates of zero in the first age group, but the corresponding mortality rates are positive, indicating that cancers initiated *in utero* and present at birth may not be accounted for in the population rates. These are both minor problems and will have only minimal impact on the *REIC* estimation. More seriously, the analyses of data from the LSS cohort have indicated that the decreasing time trend in the ERR is somewhat stronger in the incidence data (Thompson et al., 1994). Moreover, the approach to estimation of a 40-year risk of radiation-induced cancers does not allow for the fact that some individuals who have developed a fatal cancer will still be alive 40 years after exposure. These problems have,

however, not been considered further since the biases do to some extent counterbalance each other.

Estimates of the inverse lethality parameter and average $REID_{40}$ in the total population for each site are listed in Table 5.

Other types of exposure

The calculations above all relate to acute gamma-ray exposures. Some of the elicitation questions concern other types of exposure and therefore require additional modifications.

Results for prolonged exposure to low LET radiation (Questions 6, 7 and 9) were obtained by dividing the corresponding results for acute exposure with a dose rate effectiveness factor (DREF). For leukemia a DREF of 2 was assumed; for all other sites a value of 1.5 was used. These choices were based on results reported in Pierce and Væth (1991) on the size of the low-dose extrapolation factor for the LSS mortality data.

The assessment for extended exposure of the skin to high LET radiation (Question 10) was derived from the corresponding result for acute exposure by applying an relative biological effectiveness (RBE) of 20 for alpha particles. This value was taken from UNSCEAR 1994, p. 164. No DREF was used for high LET exposure, i.e., a DREF of 1 was assumed, but since the result for acute exposure was derived for a dose of 1 Gy, an adjustment for non-linearity of *REIC* in dose was applied (division by 0.85, see earlier discussion of "basic models for radiation-induced cancer mortality"). For Question 10 it was assumed that the specified dose was the dose delivered to the target cells.

The joint question to the dosimetry and late health effects panels (Question 11) describes a problem that is definitely outside my range of expertise. The extent of exposure is specified in KBq and I have no idea of how such an exposure can be translated to an absorbed dose in Gy (or Sv). I have therefore decided not to return any estimates for this question.

Additional considerations

Estimates of radiation-induced deaths for a population exposed *in utero* (Questions 6 and 7) were derived by assuming that the effect was identical to that observed in children. However, a DREF of 1.5 or 2 (see above) was applied to account for the fact that the exposure period was 9 months.

Table 5. Estimates of radiation-induced deaths up to 20 years and 40 years after acute exposure of the total population, the factor used to obtain incidence estimates from mortality estimates, and 40 years risk of radiation-induced cancer (fatal or non-fatal) in the total population.

Cancer site	20 years *REID*[a]	40 years *REID*[a]	*1/lethality*	40 years *REIC*[a]
Bone	0.004	0.007	1.94	0.014
Colon	0.104	0.365	1.80	0.656
Female Breast	0.175	0.468	2.58	1.207
Leukemia[b]	0.717	0.832	--	1.222
Liver	0.013	0.034	1.18	0.041
Lung	0.242	0.847	1.12	0.949
Pancreas	0.050	0.174	1.11	0.193
Skin	0.005	0.016	55.7	0.877
Stomach	0.048	0.167	1.39	0.232
Thyroid	0.004	0.012	3.87	0.045
All other	0.466	1.632	1.58	2.579
All cancer[c]	1.827	4.553	--	8.014

a In unit of 10^{-2} Sv^{-1}.
b Leukemia estimates taken from (pers. comm. from M. Little, 1996), but modified as explained in the text.
c Estimates for all cancers are obtained by summing sites-specific estimates.

Question 12 concerns assessment of the expected length of life lost in years for individuals dying of the cancer in question. For each sex- and age-at-exposure category the value of years of life lost is equal to the expected remaining lifetime for an unexposed computed at the average age at radiation-induced cancer death (see Thomas et al., 1992 for a discussion of loss of life expectancy among exposure-induced deaths). The population value is obtained as the average, weighted according to the age and sex distribution in the population, of these expected remaining lifetimes. Life-table calculations were used for the estimation, which was based on a constant relative risk model (Table 1), but the results were further modified by a 10% increase to allow for the effect on the time to cancer distribution of a time trend in the excess rates. The dose is not specified in Question 12, so for the calculations a whole body dose of 1 Gy low LET radiation at a uniform rate over 1 minute was assumed. The results are, however, rather robust to changes in the dose level. Using a dose of 0.001 Gy reduces the years of life lost by 3-5%; therefore, for leukemia the result obtained from (pers. comm. from M. Little, 1996) was increased by 4%.

The final question concerns the existence of a *threshold dose*. I strongly believe that there is no threshold dose for exposure to radiation, but the existence of an extremely small dose below which no effect from radiation occurs cannot be completely ruled out.

Components of uncertainty

Each step in the calculation of the risk estimates includes aspects that are not completely understood and therefore contribute to the uncertainty of the estimates. In the present context a multiplicative error structure seems most appropriate. The uncertainty bounds were therefore obtained by computing an uncertainty factor for each endpoint. Upper and lower bounds were then derived from the medians by multiplying or dividing the median by this uncertainty factor.

Multiplicative uncertainty structures are most easily handled by considering the effect measures on a log-scale. The uncertainties then become additive and may be combined by adding the variances for the different components of the uncertainty. This is the standard statistical approach to quantification of uncertainty from several independent sources. Thus, in this approach each factor contributing to the uncertainty in the risk assessment for a given endpoint is assigned a component of variance. The total uncertainty is then represented by a variance obtained as the sum of the relevant variance components. Uncertainty described by a variance component for the log-transformed effect may seem a rather elusive quantity, but for a single source of uncertainty this variance is essentially equal to the squared relative standard error.

Uncertainty bounds on the log-scale are proportional to the square root of the total variance. Such bounds translate into the desired uncertainty factors when transforming back to the original, linear scale. This approach ensures a high degree of consistency between the uncertainty bounds computed for different endpoints and, moreover, allows a straightforward quantification of dependencies between endpoints. Such dependencies are rather large with the present approach since all results are essentially derived from the same data source.

To implement the approach to uncertainty assessment outlined above, the first step consists of identification of all possible sources of uncertainty. This problem has been discussed in several papers including Thomas et al. (1992) and Pierce and Væth (1989). For the analysis presented here, the following factors were identified:

1. *ERR estimates:* Statistical uncertainty in the risk estimates. This is the statistical uncertainty in the risk estimates in Table 1 and reflects the sampling variation in these estimates assuming that the model is correct.
2. *Model selection:* Variation between models that all give an adequate fit to the data for the current follow-up of LSS cohort. Uncertainty arising from uncertainty in the LSS dose estimates is included here.
3. *Risk projection:* Uncertainty introduced by extrapolating the model beyond the current follow-up of the LSS cohort. The size of this uncertainty depends critically on the age at exposure.
4. *Transportation:* Uncertainty introduced by transporting risk estimates to populations at other times and places. Two models that give essentially the same fit to the Japanese data may lead to very different results when applied to the EU/USA population.
5. *20 years calculation:* Uncertainty related to the particular method used here to derive estimates of radiation-induced deaths within 20 years following exposure.
6. *40 years calculation:* Uncertainty related to the particular method used here to derive estimates of radiation-induced deaths within 40 years following exposure.
7. *Incidence calculation:* Uncertainty related to the particular method used here to derive estimates of lifetime risk of radiation-induced cancers from lifetime risk of radiation-induced deaths.

8. *In utero extrapolation:* Uncertainty introduced by assuming that the effects of *in utero* exposure are identical to the effects seen in children.
9. *RBE:* The uncertainty in the estimate of the RBE for alpha particles.
10. *Dose-rate extrapolation:* The uncertainty in the estimate of DREF.
11. *Internal exposure:* Uncertainties arising from estimation of absorbed dose.
12. *Other sources:* This is included to account for what one may call "inter-assessor variation." The presence of this source of uncertainty was discovered in the workshop which eventually led to the publication of Thomas et al. (1992). Two experts who agree on all modeling aspects may get slightly different results simply because they implement the assumptions in different ways. The main part of this source of uncertainty comes from calculations of excess risk for old people (in the present setting this means older than 85 years).

The first three sources of uncertainty are those that would be present even if the risk assessment were to be carried out for the LSS cohort. Note that the size of these uncertainties must be determined both at a population level (when estimating excess deaths/cases in the total population) and at an individual level (when estimating excess deaths/cases for special sub-populations). Item 5, 6 and 7 reflect uncertainties that are highly dependent on the particular approach adopted here.

The uncertainties associated with leukemia risks and calculation of years of life lost require special considerations since different approaches were used for these assessments.

The next step in the uncertainty assessment consists of assigning a component of variance to each source of uncertainty. Table 6 gives the values used for the variance components in the uncertainty assessment of *REID* and *REIC*. A few comments on the rationale for selecting these particular values seem appropriate.

Table 6. The components of variance used in the uncertainty assessments for REID and REIC. The shared fraction is used to determine dependencies between sites within the same endpoint, see the explanation in the text below.

Source of uncertainty	All sites except leukemia		Leukemia Variance
	Variance	Shared fraction	
ERR estimates, individual estimate	0.10	0.50	0.15
ERR estimates, population average	0.02	0.50	0.03
Model selection, children/*in utero*	0.10	0.50	0.15
Model selection, population average	0.02	0.50	0.03
Projection, age at exposure 0-19 years	0.45	0.50	0.20
Projection, age at exposure 20-39 years	0.10	0.50	0.05
Projection, age at exposure 40 or more years	0.02	0.50	0.01
Projection, population average	0.05	0.50	0.02
Transportation	0.25	0.50	0.20
20 years calculation, population average	0.05	0.25	--
40 years calculation, population average	0.05	0.25	--
Incidence calculation	0.10	0.25	--
In utero extrapolation	0.20	0.50	0.20
RBE of alpha particles	0.20	0.50	0.20
Dose-rate extrapolation	0.20	0.50	0.20
Internal exposure	0.20	0.50	0.20
Other sources	0.01	1.00	0.01
Note: The shared fraction is used to determine dependencies between sites within the same endpoint, see the explanation in the text below.			

The relative standard error of the individual *ERR estimates* in Table 1 is on the order of 30%, and this corresponds to a variance of 0.1 (on a log-scale). For population predictions the sampling variance is reduced by averaging over age and sex categories, resulting in a variance of 0.02. The *model selection* uncertainty is believed to be of the same order of magnitude, and variance components of 0.1 and 0.02 were therefore used for individual and population predictions, respectively. The uncertainty associated with *risk projection* concerns prediction of the future pattern of the excess risks assuming that the model for the current follow-up is correctly specified. For individuals exposed at old ages the remaining lifetime is (almost) completely covered by the current follow-up and no or very little uncertainty is present. For children, on the other hand, the prediction is highly uncertain, since most of the excess deaths may appear in the coming years. These considerations are reflected in the chosen values for the variance components for the individual age-at-exposure categories. The *transportation* uncertainty is difficult to assess. A crude idea of the size of the uncertainty introduced by transporting the LSS risk estimates to the EU/USA population can be obtained from Little's analyses (pers. comm. from M. Little, 1996). Models A and B both describe the current follow-up adequately, but lead to rather different predictions of the risk of radiation-induced death in the EU/USA population. Differences in the lifetime predictions may also result from uncertainty related to extrapolation in time, but the between-methods variation in the estimates of 20 years and 40 years risk of radiation-induced death is primarily a consequence of the transportation problem. The average relative standard error (computed as the square root of the pooled site-specific variances of the log-transformed estimates) was here 0.31 (range 0.13–0.59) and 0.16 (range 0.07–0.33) suggesting a variance component of at least 0.05. Models A and B are, however, both relative risk models and are therefore in some respects very similar. Thus this estimate is definitely too small. I therefore used a variance of 0.25 for the transportation uncertainty. The variance components associated with the *20 years, 40 years and incidence calculations* reflect the uncertainty in the correction factors. The values are here are based on a general judgment. The chosen values are relatively large, reflecting the rather crude approach used for these aspects of the assessment. For *other sources* I believe that a value of 0.01 is fairly reasonable. The *remaining variance components* describe aspects with which I am less familiar; and an uncertainty factor on the order of 2 seemed appropriate for each source when considered separately. This corresponds roughly to a variance component of 0.2.

For leukemia a different approach was used and the components of variance are therefore different. The estimates and the model are believed to be somewhat more uncertain. The risk projections are probably more precise, since excess leukemia mortality rates in the LSS cohort are quite small after 40 years of follow-up, suggesting that most of the excess mortality appears within this time interval. There are no additional uncertainty terms for the 20 years, 40 years, and incidence calculations, since these results are derived directly from the model. The remaining variance components are believed to be similar to those for other cancer forms.

For each elicitation question the total uncertainty can now be obtained as the sum of the relevant variance components. The uncertainty factor F for endpoint X is then derived as

$$F = \exp\left(1.645 \cdot \sqrt{\mathrm{Var}_{Tot}(X)}\right), \qquad (8)$$

where 1.645 is the upper 95% quantile of the standard normal distribution. The upper (lower) uncertainty bound is derived by multiplying (dividing) the median by the uncertainty factor. Table 7 gives the total variance and the uncertainty factor for each of the questions for which this method was applied.

If the same approach is used for years of life lost (Question 12) an uncertainty factor of 2.7 is obtained. This endpoint is, however, believed to be less sensitive to misspecification of the different components of the assessment. It is primarily uncertainty in the timing of the events, rather than uncertainty in the number of events, that introduces uncertainty in the assessment of the years of life lost. The uncertainty factor was therefore reduced to 2.

Table 7. Total variance an uncertainty factor for the questions concerning radiation-induced death and radiation-induced cancer.

Question		1	2	3	4	5	6	7	8	9	10
All sites except leukemia	tot. var.	0.40	0.40	0.35	0.46	0.91	0.86	1.31	0.50	0.60	0.90
	factor *F*	2.8	2.8	2.6	3.1	4.8	4.6	6.6	3.2	3.6	4.8
leukemia	tot. var.	0.27	0.27	0.29	0.51	0.71	0.91	1.11	0.27	0.47	-
	factor *F*	2.4	2.4	2.4	3.2	4.0	4.8	5.7	2.4	3.1	-

Dependencies among outcome measures

Dependencies between two endpoints result from shared components of variance appearing in the total variance of both endpoints. The covariance is obtained as the sum of the shared variance components. Usually, the full common component was included in this sum, but in the following two instances only the "shared fraction" (Table 6) of a common component was used:

- Dependencies among different cancer sites for the same endpoint (Questions 3 and 3). The shared fraction was used for all relevant variance components.

- Dependencies between assessments for the same site at different follow-up times (Questions 1 and 2, 2 and 3, 4 and 5 and 6 and 7). The shared fraction of the model uncertainty component was used to avoid a model autocorrelation of 1, which seemed unreasonable.

For dependencies between assessments for the total population and for a population of children (Questions 3 and 5) the population component of uncertainty of the *ERR* estimates and the model was included to account, rather crudely, for the fact that children are a part of the total population.

For two endpoints X and Y a correlation between log-transformed effects can now be computed as

$$\rho_{XY} = \frac{\text{Sum of shared variance components}}{\sqrt{Var_{Total}(X) \cdot Var_{Total}(Y)}}$$

In the elicitation questionnaire dependencies are not quantified in terms of correlation, but as the conditional probability, z. However, applying a standard result for the two-dimensional Gaussian distribution (see e.g., Stuart and Ord, 1994, p. 516) this probability can be derived from the correlation coefficient as

$$z = P[X > median(X) \mid Y > median(Y)]$$
$$= 0.5 + \arcsin(\rho_{XY})/\pi$$

Note that this probability is unchanged when the effects are transformed back to the original, linear scale. Correlations and conditional probabilities are given in Table 8.

A conditional probability of 0.67 was used to quantify all dependencies between assessments of years of life lost for different cancer types. The existence and size of a threshold dose is believed to be essentially independent of the other questions being assessed. The conditional probabilities describing for each cancer site the dependency between Questions 3 and 13 are therefore all set to 0.5.

Assessments of elicitation questions and dependencies

My assessments are included in the table section that follows. As explained above there are no assessments for Question 11. Assessment of the seed variables is at the end of the table section.

Table 8. Dependency expressed as a correlation and a conditional probability for pairs of questions concerning radiation-induced death and radiation-induced cancer.

Questions		1&2	2&3	2&8	4&5	6&7	3&5	5&7	3	2&9	9&10
all sites except leukemia	shared var.	0.34	0.34	0.40	0.41	0.81	0.30	0.91	0.18	0.60	0.60
	prob. *z*	0.82	0.86	0.85	0.72	0.78	0.68	0.81	0.67	0.80	0.80
leukemia or leukemia and other[a]	shared var.	0.26	0.26	0.24	0.44	0.84	0.27	0.71	0.10	0.27	-
	prob. *z*	0.89	0.86	0.85	0.76	0.81	0.70	0.80	0.60	0.77	-

[a] For dependencies among sites (Question 3) the shared variance and the conditional probability *z* for the dependency between leukemia and any other site is given.

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Question 1. The number of radiation-induced cancer deaths up to 20 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	1.0×10^3	4.0×10^3	1.0×10^4
Colon	3.7×10^4	1.04×10^5	2.92×10^5
Breast	6.3×10^4	1.75×10^5	4.91×10^5
Leukemia	2.99×10^5	7.17×10^5	1.72×10^6
Liver	5.0×10^3	1.3×10^4	3.6×10^4
Lung	8.6×10^4	2.42×10^5	6.78×10^5
Pancreas	1.8×10^4	5.0×10^4	1.39×10^5
Skin	2.0×10^3	5.0×10^3	1.3×10^4
Stomach	1.7×10^4	4.8×10^4	1.34×10^5
Thyroid	2.0×10^3	4.0×10^3	1.2×10^4
All other cancers	1.67×10^5	4.66×10^5	1.306×10^6
All cancers	6.53×10^5	1.827×10^6	5.116×10^6

Question 2. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	3.0×10^3	7.0×10^3	2.0×10^4
Colon	1.3×10^5	3.65×10^5	1.021×10^6
Breast	1.67×10^5	4.68×10^5	1.31×10^6
Leukemia	3.47×10^5	8.32×10^5	1.997×10^6
Liver	1.2×10^4	3.4×10^4	9.6×10^4
Lung	3.03×10^5	8.47×10^5	2.372×10^6
Pancreas	6.2×10^4	1.74×10^5	4.86×10^5
Skin	6.0×10^3	1.6×10^4	4.4×10^4
Stomach	6.0×10^4	1.67×10^5	4.68×10^5
Thyroid	4.0×10^3	1.2×10^4	3.2×10^4
All other cancers	5.83×10^5	1.632×10^6	4.57×10^6
All cancers	1.626×10^6	4.553×10^6	1.275×10^7

Question 3. The number of radiation-induced cancer deaths over a lifetime (following the population up until it has become extinct) in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	5.0×10^3	1.2×10^4	3.1×10^4
Colon	3.41×10^5	8.86×10^5	2.303×10^6
Breast	3.82×10^5	9.94×10^5	2.585×10^6
Leukemia	3.55×10^5	8.51×10^5	2.042×10^6
Liver	2.8×10^4	7.3×10^4	1.9×10^5
Lung	7.91×10^5	2.057×10^6	5.349×10^6
Pancreas	1.62×10^5	4.21×10^5	1.096×10^6
Skin	1.5×10^4	3.8×10^4	9.9×10^4
Stomach	1.56×10^5	4.05×10^5	1.054×10^6
Thyroid	9.0×10^3	2.4×10^4	6.4×10^4
All other cancers	1.524×10^6	3.964×10^6	1.031×10^7
All cancers	3.741×10^6	9.726×10^6	2.529×10^7

Question 4. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 years) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Breast	6.2×10^4	1.91×10^5	5.93×10^5
Leukemia	1.36×10^5	4.36×10^5	1.395×10^6
Thyroid	1.0×10^3	2.0×10^3	6.0×10^3
All cancers	4.05×10^5	1.256×10^6	3.893×10^6

Question 5. The number of radiation-induced cancer deaths over a lifetime (following the population up until it has become extinct rather than up to 40 years following exposure) in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 years) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Breast	3.44×10^5	1.65×10^6	7.918×10^6
Leukemia	1.16×10^5	4.63×10^5	1.853×10^6
Thyroid	8.0×10^3	3.7×10^4	1.76×10^5
All cancers	2.944×10^6	1.413×10^7	6.782×10^7

Question 6. The number of radiation-induced cancer deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure of a dose of 1 Gy low LET (= gamma) radiation administered uniformly over their three trimesters (9 months) *in utero* and followed-up for 20 years after birth.

	Quantile		
	5%	50%	95%
Leukemia	3.7×10^4	1.79×10^5	8.6×10^5
All cancers	4.8×10^4	2.21×10^5	1.015×10^6

Question 7. The number of radiation-induced cancer deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure of a dose of 1 Gy low LET (= gamma) radiation administered uniformly over their three trimesters (9 months) *in utero* and followed over a lifetime (following the population up until it has become extinct rather than up to 20 years following exposure).

	Quantile		
	5%	50%	95%
Leukemia	4.1×10^4	2.32×10^5	1.32×10^6
All cancers	1.416×10^6	9.343×10^6	6.166×10^7

Question 8. The number of radiation-induced cancer cases (fatal and non-fatal) up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	4.0×10^3	1.4×10^4	4.4×10^4
Colon	2.05×10^5	6.56×10^5	2.1×10^6
Breast	3.77×10^5	1.207×10^6	3.862×10^6
Leukemia	5.09×10^5	1.22×10^6	2.934×10^6
Liver	1.3×10^4	4.1×10^4	1.3×10^5
Lung	2.97×10^5	9.49×10^5	3.036×10^6
Pancreas	6.0×10^4	1.93×10^5	6.16×10^5
Skin	2.74×10^5	8.77×10^5	2.808×10^6
Stomach	7.3×10^4	2.32×10^5	7.43×10^5
Thyroid	1.4×10^4	4.5×10^4	1.43×10^5
All other cancers	8.06×10^5	2.579×10^6	8.252×10^6
All cancers	2.504×10^6	8.014×10^6	2.565×10^7

Question 9. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 year (rather than 1 minute).

	Quantile		
	5%	50%	95%
Bone	1.0×10^3	5.0×10^3	1.7×10^4
Colon	6.8×10^4	2.43×10^5	8.75×10^5
Breast	8.7×10^4	3.12×10^5	1.123×10^6
Leukemia	1.6×10^4	4.9×10^4	1.52×10^5
Liver	6.0×10^3	2.3×10^4	8.3×10^4
Lung	1.57×10^5	5.65×10^5	2.033×10^6
Pancreas	3.2×10^4	1.16×10^5	4.16×10^5
Skin	3.0×10^3	1.1×10^4	3.8×10^4
Stomach	3.1×10^4	1.11×10^5	4.01×10^5
Thyroid	2.0×10^3	8.0×10^3	2.8×10^4
All other cancers	3.02×10^5	1.088×10^6	3.917×10^6
All cancers	8.05×10^5	2.897×10^6	1.043×10^7

Question 10. The number of radiation-induced skin cancer cases (fatal and non-fatal) up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a uniform skin dose of 1 mGy high LET (= plutonium alpha particle) radiation at a uniform rate over 1 year.

	Quantile		
	5%	50%	95%
Skin	4.0×10^3	2.1×10^4	9.9×10^4

Question 11. Joint dosimetry/late effects question: The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each of whom inhales 10 K Bq of the radionuclides specified.

Nuclide	Physical Form	Chemical Form	Cancer Type	Number of Cancers Quantile		
				5%	50%	95%
Pu-239	1 μm AMAD	Oxide	Lung			
			Bone			
			Liver			
			Leukemia			
			All cancers			
Sr-90	1 μm AMAD	Oxide	Lung			
			Bone			
			Leukemia			
			All cancers			

Question 12. Given that radiation induced cancer death due to the specified cause has occurred as a result of a dose of radiation delivered over 1 minute, the average expected length of life lost in years, for a population followed up to extinction after exposure.

	Quantile		
	5%	50%	95%
Bone	8.0	1.6×10^{1}	3.2×10^{1}
Colon	5.7	1.13×10^{1}	2.26×10^{1}
Breast	7.0	1.39×10^{1}	2.79×10^{1}
Leukemia	1.11×10^{1}	2.21×10^{1}	4.43×10^{1}
Liver	6.3	1.26×10^{1}	2.52×10^{1}
Lung	6.3	1.26×10^{1}	2.51×10^{1}
Pancreas	5.8	1.16×10^{1}	2.32×10^{1}
Skin	4.9	9.7	1.95×10^{1}
Stomach	5.5	1.11×10^{1}	2.21×10^{1}
Thyroid	6.2	1.24×10^{1}	2.47×10^{1}
All other cancers	5.9	1.18×10^{1}	2.36×10^{1}
All cancers	6.5	1.3×10^{1}	2.6×10^{1}

Question 13. For each of the cancer sites listed, give the estimate of the threshold dose in Gy, for low LET (= gamma) radiation administered at a uniform rate over 1 minute, below which value there is no radiation-induced cancer risk.

	Quantile		
	5%	50%	95%
Bone	1.0×10^{-8}	1.0×10^{-7}	1.0×10^{-6}
Colon	1.0×10^{-8}	1.0×10^{-7}	1.0×10^{-6}
Breast	1.0×10^{-8}	1.0×10^{-7}	1.0×10^{-6}
Leukemia	1.0×10^{-8}	1.0×10^{-7}	1.0×10^{-6}
Liver	1.0×10^{-8}	1.0×10^{-7}	1.0×10^{-6}
Lung	1.0×10^{-8}	1.0×10^{-7}	1.0×10^{-6}
Pancreas	1.0×10^{-8}	1.0×10^{-7}	1.0×10^{-6}
Skin	1.0×10^{-8}	1.0×10^{-7}	1.0×10^{-6}
Stomach	1.0×10^{-8}	1.0×10^{-7}	1.0×10^{-6}
Thyroid	1.0×10^{-8}	1.0×10^{-7}	1.0×10^{-6}
All other cancers	1.0×10^{-8}	1.0×10^{-7}	1.0×10^{-6}
All cancers	1.0×10^{-8}	1.0×10^{-7}	1.0×10^{-6}

Assessment of Seed Variables

Assessments of aggregated ERR coefficient pr Sv (neutron RBE = 20) to the colon (bone-marrow for leukemia) averaged over both sexes, both cities (Hiroshima and Nagasaki), all age at exposure groups and all dose groups, and associated uncertainty intervals, for cancer mortality in the Japanese atomic bomb survivor LSS cohort followed up from January 1, 1991 to the end of 1995.

Cancer Site	Quantile		
	5%	50%	95%
Colon	-0.02	0.60	1.60
Breast	0.11	1.20	3.36
Leukemia	0.60	2.50	6.64
Liver	-0.48	0.20	1.79
Lung	0.07	0.50	1.11
Pancreas	-0.47	0.00	0.90
Stomach	-0.20	0.20	0.80
Solid tumors	0.18	0.40	0.66

EXPERT E

After some calculations using the three models given, I have chosen to respond to the questions primarily on the basis of my empirical background knowledge and information; I have included a single mathematical approach.

This choice was made because

- in publications to which I have access, I did not find any information concerning the covariances between the model parameters.
- in the absence of such information, I think that establishing calculations only with variances would lead to important errors because the covariances between parameters of each of the three models are necessarily strong.
- even had I had useful information concerning these covariances, I would have been unable to establish the formulation of the variance of the number of radioinduced cancers or fatal cancers. This is true even in absence of variation of the baseline rate and more so in the presence of such a variation.

There are two sources of uncertainty—synergistic effects and an average population with varying health—that would be important, but poorly quantifiable, for the estimation of the uncertainty of the probability of causation by radiation of a given cancer in a given individual. These sources of uncertainty are not relevant for questions concerning the number of radioinduced events in a population of 1,000,000 persons. These sources of variability are included in the estimations of average risks and of intervals of confidence of the average risk within each study.

I emphasize the information from pooled studies that combined different studies varying two or more of the nine sources of uncertainties taken into account for the late effects exercise. When possible in using these pooled studies, I have considered individual results from each study rather than results from the pooled analysis. Indeed, I think the variation of the estimation of the mean ERR/Sv in each study provides better information on the role of sources of uncertainty which are not directly estimable: length of follow-up, transport across populations, synergistic effects and dosimetric errors. Obviously, in this approach, I excluded studies which are not credible or which address exposures to different from those dictated in this case structure.

Because the ERR/Sv rather than the EAR/PYR Sv model was to model risk, theoretically, results from mortality studies have to be similar to those concerning incidence studies. Survival from a give type of cancer is, from my own knowledge, not modified by the radiogenic origin of the cancer. Because of that, I considered that differences in ERR/Sv between mortality and incidence studies do not provide information concerning, respectively, mortality and incidence, but rather information concerning ERR/Sv, whatever the event. Hence, I considered that results from mortality and incidence studies have to be combined in order to obtain a global approach to uncertainties for ERR/Sv.

I was not able to establish and explain a difference in 95% confidence intervals (CI) for uncertainties between incidence/mortality (see above), and years of life lost. In the same way, I failed to established variation of the uncertainties according to the length of follow-up.

1. Choice of the model

Mark Little [2] utilized a pool of six studies, including Japanese atomic bomb survivors.

- He found a decrease in the relative risk of solid cancer with time since exposure. He found that the speed of the reductions in relative risk with time since exposure was not significantly different after childhood and adulthood. Nevertheless, due to lower initial excess relative risks, adult populations are less informative than populations of children when considering the speed of reduction of the relative risk. Hence, the power of the test for interaction between the speed of the reduction of the relative risk with time and the age at irradiation is probably low. As an example, the reduction of risk per years of follow-up was found to be 5.7% (95%CI: 2.6%-8.7%) after irradiation in childhood and 3.4% (95% CI: 1.4%-, 5.4%) for the whole set of cohorts.
- He found also that there were no indications for inter-cohort heterogeneity in the speed of the reduction of the relative risk.
- Within the Japanese cohort, he did not find significant heterogeneity due to the type of second cancer in speed of the reduction of relative risk. Nevertheless, the results of his analysis taken study by study showed that results for breast cancers seemed more homogeneous, between Japanese and others, than results for skin cancers and thyroid tumours or cancers.

Because of these results, and even if there are not incompatible with that of Tompson [4], I will consider the results of the Model A, rather than those of Model B, as a base for the calculation of the expected mean numbers of events.

As a base for the calculation of the expected mean numbers of events, I prefer to use model A rather than model C because of the question concerning the risk for the 0 to 20 years period.

I have, nevertheless, some difficulty in understanding why the total number of events obtained with Model A is higher than the number obtained with Models B or C, although the observed period of follow-up (42 years) use to fit the models is the same.

The three models proposed by Mark Little [3], assume:

- a similar coefficient for risk reduction according to age at irradiation, whatever the type of the solid cancers.
- a similar coefficient for risk reduction according to the delay after irradiation, whatever the type of solid cancer.

Although these assumptions are based on the fact that variations of likelihood for such sources of uncertainty were not statistically significant in Little's analyses, these sources of variations have to be taken into account for the present exercise.

The differences in results site by site for the period 0 to 40 years between Model A and Model B or C give us an indication of the influence of the modeling of cancer risk upon the uncertainties.

2. Bone

Table II shows that estimation of bone cancer risk is quite dependent on the type of modeling: a factor of 1/2 for 0-20 years estimation and a factor of 1/3 for the 0 to 40 years estimation.

As noted in the UNSCEAR 1994 report [9, p. 107], three main published studies provided estimation of ERR/Sv of bone cancer after low LET exposure.

From my personal experience, I know that results from the LESG study [12] cannot be used for the present study because of the strong role some drugs play in the bone cancer risk; these drugs have not been not taken into account in this study because they are not alkylating agents. Moreover, the scoring system established by the authors to account for the role of chemotherapy is very poor. Because the drugs not only play a direct role in bone cancer risk, but also interact with the risk due to radiation, I think the LESG study does not provide reliable information on bone cancer risk after childhood exposure to radiation. In fact, even if the LESG study did not have these problems with chemotherapy, it could not be used for this exercise because the doses are too local, and this problem is not taken into account in the analysis.

The risk for incidence of bone and connective tissue cancers estimated from the atomic bomb was 1.4 (95%CI <-0.2 - 4.5). The risk from a skin hemangioma study [11] was 4.33 (95%CI 0.9 - 9.8. As noted in the UNSCEAR report [9, p. 107], the mean bone dose in that study was 0.4 Gy. In fact, 0.4 Gy is a value for average mean dose to all bones of the body; the dose due to radium is very low at no more than a few centimeters from radium needles or tubes. Although this study is better analysed that the LESG one, I think that the estimated ERR/Sv of 4.33 cannot be used in our exercise because it is based on doses that are too heterogeneous.

Hence, for the question concerning 1 Gy of low LET irradiation at high dose rate, only the A-bomb study results can be used. In the absence of other possibilities, I used the 95%CI for ERR/Sv from A-bomb study and considered that, for 1 Gy, the 95%CI includes zero to three times the median value.

3. Colon

Table II shows that colon cancer risk estimation is quite dependent on the type of modeling: a factor about 1/2 for 0-20 years estimation, and 1/4 for 0 to 40 years estimation.

According to UNSCEAR 1994 [9, p. 106], five studies published estimations of ERR/Sv for colon cancer after low LET exposure. The risk for incidence of colon cancer estimated from the A-bomb was 0.67 (95%CI 0.1–1.3). The risk for cervical cancer [13] (ERR/Sv = 0: 95%CI from 0 to 0.01) was established from patients who received too high local doses (24 Gy as a mean). Hence, I considered that this risk estimation is not useful for the present estimation.

Another study concerns patients treated with radium for uterine bleeding who were given lower local doses [15]. In this study, the estimated dose to the colon is due to photons emitted by radium and not to alpha particles, which have very low trajectories. Hence this study can be used in the present estimation. The two other studies concern local

doses of Ra and can be included in an estimation of the uncertainties concerning colon cancer.

From these studies, I considered that an ERR/Sv 12 times lower than that estimated from the A-bomb study has to be included in a 95%CI (0.47/0.04). The ERR/Sv estimated from A-bomb survivors is the higher one. Hence I considered the upper limit of the 95%CI for this population (two times the mean value) as an upper limit for the confidence interval in my estimation.

4. Breast

Table II shows that estimation female breast cancer risk is not very dependent on the type of modeling.

According to UNSCEAR 1994 [9, p. 109], 10 studies published useful estimation of ERR/Sv for breast cancer after low LET exposure. The study on cervical cancers is excluded because of the effects of castration on breast cancer risk and the two studies of contralateral breast cancer are excluded because extension of the first cancer cannot be ruled out.

When the age at irradiation is taken into account, variation in ERR/Sv for cause of death by breast cancer ranged from a factor 2 to 3, according to the study and the type of dose rate. For example:

- 0 to 4 years at irradiation: 4.6 from A-bomb survivors, 2.8 from thymus treatment, and 4.2 from skin hemangiomas treatment
- 30 to 40 years at irradiation: 1.2 from A-bomb survivors, 0.3 and 0.4 from repeated fluoroscopies, 0.6 from postpartum study

From these results, I concluded that, for the question concerning 1 Gy of low LET Ra delivered in one minute, a range of 2 is acceptable for the 95%CI uncertainties range, for all ages.

5. Leukemias

The UNSCEAR 1994 report [9, page 112] notes that 11 major studies published useful estimates of ERR/Sv for leukemia after low LET exposure. The childhood cancer study of the LESG [16] was excluded because the statistical analysis of this study did not take into account the high heterogeneity of the doses (the opposite of what the authors of the cervical cancer study did), and was unable to adjust correctly for alkylating agents.

Of the 11 major studies, three (A-bomb survivors, cervical cancer, and ankylosing spondylitis studies) provide better information than the others because of their size and because of the authors' detailed estimations of maximum risk and its value (if observable) and the duration of the excess risk. These parameters are important because the ERR/Sv and the mean AER/PYR Sv are too dependent on the length of the follow-up and decrease as length of follow-up increases.

The three major studies (A-bombs survivors, cervix cancer study, and ankylosing spondylitis [19] studies) lead to a radiation risk at 1 S of from 1.7 to 7, i.e., an ERR/Sv from 0.7 to 6. The conclusions concerning the period of risk and the duration of risk were quite similar in the three studies.

From these results, I retained the range from median 1/3 to median 2.

6. Liver

According to UNSCEAR 1994 [9, p. 106], six major studies published useful estimates of ERR/Sv for liver cancer after low LET exposure.

With the exception of the A-bomb study, all the published studies lead to very small ERR/Sv or to the absence of risk, but these studies use a small number of cases. Despite the small numbers, I think it is not possible to ignore the fact that four studies led to null or negative ERR/Sv. Thus, I retained 0 as a possible value for ERR/Sv.

From the results of A-bomb analysis, which leads to the higher estimate, I considered that twice the median value is an acceptable value for the upper part of the 95%CI for uncertainties.

7. Lung

After excluding the Massachusetts TB fluoroscopy study [17] because it concerns low dose rate, the UNSCEAR (1994) [9, p. 107] report notes that three major studies published useful estimates of ERR/Sv for lung cancer after low LET exposure.

Because of the size of this organ (compared with the thyroid, for example), the role of heterogeneity of the dose could be important: a higher ERR/Sv was found for the A-bomb studies, which are also those that involve a a uniform dose.

In the absence of information about the heterogeneity of dose in ankylosing spondylitis patients, I think the ERR/Sv (0.12) from this study must be multiplied by at least 3 in order to be applicable to uniform doses.

From these studies, the ERR/Sv values range from 1/3 of the median value to 1.5 times the median value.

8. Pancreas

According to Tompson [4, p. 30]) and UNSCEAR [9, pp. 103, 134, and 138), only three published studies have detailed this localization. The most important risk (ERR/Sv = 4.18, 95%CI 1.34–9.63) has been estimated from a study of 592 workers in a thorium processing plant [10]. The two other studies concern A-bomb survivors and 1761 women treated at the Massachusetts General Hospital with ^{131}I for hyperthyroidism.

I do not know why the study concerning ^{131}I focuses on the pancreas; ^{131}I is neither passively nor actively concentrated in the pancreas; the doses delivered to the pancreas are particularly low. This study leads to a not significantly negative ERR / Sv and is absolutely uninformative.

Hence, only the A-bomb study is available concerning ERR/ Sv after high dose rate, low LET irradiation. The 95% confidence interval of the ERR/Sv includes the value of zero both for the incidence and for the mortality [9, p. 5]. When the estimated value is positive (incidence data,) the 95% upper part of the ERR/Sv confidence interval is 4 times the mean estimate (0.8 vs. 0.2).

In all questions concerning low LET high doses at a high dose rate, I have considered a 95%CI from 0–4 times the median number.

9. Skin

Seven major studies published useful estimates (UNSCEAR, 1994 [9, p. 108]) of ERR/Sv for nonmelanoma skin cancers after low LET exposure, excluding the Massachusetts TB fluoroscopy study [18] which concerns low dose rate.

Owing to the important size of this organ, I think that it is impossible to use the studies concerning local high doses to estimate risk for uniform whole-body irradiation. However, these studies might be used if the authors had stated an estimate of the proportion of the skin that received the mentioned dose. Curiously, this was never done. Hence, the A-bomb study is the only study available.

From ERR/Sv of this study (0.9, 95%CI: 0.4-1 .9), I considered the range of 4 to be approximately the median value.

10. Stomach

Table II shows that estimation of stomach cancer risk is not dependent on the type of modeling. As noted in the UNSCEAR 1994 report [9, p. 105], six studies published estimates of ERR/Sv for stomach cancer after low LET exposure.

Concerning incidence, the ERR/Sv values from the cervical cancer and A-bomb studies are similar: 0.54 and 0.3. Mortality of A-bomb survivors provides a lower result: 0.2. However, I do not know how to resolve the problem of the extremely low risk (ERR/Sv=0.01, 95%CI: –0.1 to 0.2) estimated form the ankylosing spondylitis study. Therefore, I cannot exclude this study.

Based on the studies cited in the UNSCEAR 1994 report [9, p. 105], I consider the range to be from 0 to 2 times the median risk.

11. Thyroid

Table II shows that within the follow-up period of observation, the type of cancer modeling has little influence on the estimated risks.

Concerning all other uncertainties except DDREF and RBEF, I reviewed two publications about thyroid cancer after childhood exposure:

1. the Ron pool [1] because this pool dealt with large variation in dose and mixed different populations (Asian and Occidental).

2. the skin hemangioma study [2], which is not included in the Ron pool.

From the Ron pool:

- I excluded the study from the LESG (childhood cancer study), because this study, in fact, was a case control study in which all cases received radiotherapy, and because the doses are too high.
- concerning the *Tinea capitis* study, I kept the analysis with an initial intercept (ERR/Sv=6.6), which seems to me more conclusive than that without an initial intercept (ERR/Sv=32.5).

The following mean values for constant ERR/Sv were found: 9.1, 4.7, 6.6, 2.5, and 4.9. On the basis of the Ron pool, the skin hemangioma study, and the fact that estimation for A-bomb children (ERR/Sv 4.7) was done in the middle of the observed interval, I retained a range from half to twice the median value.

The Ron pool includes two adult populations: A-bomb and cervical cancer cases. The ERR/Sv was 0.4 in the adult A-bomb study and 34.9 in the cervical cancer study. I will not use the cervical cancer study because the estimate of 34.9 does not seem credible and because both thyroid and cervical cancer are linked to women's hormonal status. Hence, in the absence of other information, I used the same range of uncertainties for adults as for children.

In the absence of other available methods, I will use this range of 4 (half of the median to twice the median) for questions (i), (ii), (iii), (iv), and (v).

12. All other cancers

There is no proof of radiation effect on this set of cancers. In the absence of reliable information, I will assume that the uncertainties for this set of cancers are at least equal to those estimated for the above cancers. Hence, I retained a range from 0 to 4 times the median value.

13. All cancers

From UNSCEAR 1994 [9], 95%CI for all cancer ERR/Sv values from A-bomb survivors range from 0.32–0.46 [9, p. 129]. No estimate of ERR/Sv for all solid cancers or all cancers was published from the cervical cancer study, nor from the ankylosing spondylitis study.

Because solid cancers are more frequent than leukemia, the ERR/Sv for these cancers is better known. Nevertheless, variations in incidence among populations are much more important for solid cancers than for leukemias, and many studies have shown that ERR/Sv models provide better fits for solid cancers than EAR/Sv models. Hence variations in baseline cancer incidence may strongly influence the predicted numbers of radioinduced cancer.

For these reasons, I estimated that the range I took for leukemia can be extrapolated to all cancers, after limitation for the upper value of the 95%CI: one third to twice the median value. The choice of 2 and not 3 times the median value is due to the ERR/Sv estimated from A-bomb survivors, which in most cases is higher than that estimated with other studies. ERR/Sv values three-fold higher than those from A-bombs are improbable.

14. *In utero* irradiation

I have no information about *in utero* irradiation.

From the UNSECEAR report [9], the Oxford study on childhood cancer [20] and the study about cancer in children exposed *in utero* to A-bomb radiations [21], it seems that uncertainties are very high, mainly because the doses in most of the studies are very low. The only study concerning nonmedical irradiation, the study of A-bomb survivors [21], did not conclude that there was an excess risk in childhood, in contrast to the conclusions reached by other studies, particularly the Oxford study [20]. The A-bomb study leads to an ERR/Sv value of 2.77 (95%CI, 0.14–12.48), with a follow up of about 40 years and a mean dose of 0.18 Gy, but deals with only 920 children who received more than 0.01 Sv and with 11 cases of solid cancers, and 2 leukemias.

From all these studies, and because of my opinion about the role of DDREF (see above), the absence of a carcinogenic effect of 1 Gy of LET irradiation uniformly delivered over 9 months cannot be excluded. Nevertheless, DDREF studies in humans will never be possible, and it is possible that the extremely high grow the rate *in utero* counterbalances the role of DDREF. Because it has been found [21] that ERR/Sv after exposure *in utero* is on the same order of magnitude as that after exposure from 0 to 5 years, I believe that an ERR/Sv estimated with a high dose rate and low LET irradiation in childhood could be possible after irradiation at a low dose rate *in utero*, but is improbable. I retained this possibility in the upper part of the confidence interval.

Because I think the total absence of effect of *in utero* low dose rate irradiation is not the most probable issue, I considered half of the upper part of the 95%C CI as a median value.

15. DDREFs

Concerning the effect of DDREF in Question ix, I will not take a statistical point of view. I know that, at this time, no study has established the role of the DDREF. This could be due in great part to the problem of the lack of power of such studies and to the fact that this type of study necessarily deals with both low dose and of low dose rate.

Nevertheless, from a biological point of view, I considered that, for each category of cancer, the lower part of the

5%-95% confidence interval of the number of events after an irradiation of 1 Gy over 1 year, have to include the possibility of a total absence of radioinduced events.

This point of view is supported by the results of the high natural background study in China [5], that of the studies of ^{131}I by Hall and Holm [6,7], and that of the workers' pool by Cardiz [8]. For the pool studied by Cardiz, I think that the lower value of the confidence interval she found for ERR/Sv for leukemias, excluding CLL (95%CI: 0.1 to 5.7, p = 0,046), is not far enough from zero to change my proposition about the possible absence of radioinduced events.

For leukemia [8, Cardiz pool] and breast cancer [17, fluoroscopy studies], I believe that the estimate for the median number cannot be 0, and hence I took a value equal to a third of the value estimated from high dose rate studies.

Owing to the low power of previous studies and Cardiz' results for leukemias, I think that there is still not enough information to assess a decrease in the upper part of the confidence interval of risk established with irradiation during 1 minute for extrapolation to irradiation during 1 year, after applying a DDREF of 3.

16. RBEs

I have no knowledge or experience of RBE, but I think the RBE probably depends on the type of tissue exposed. I was not able to find a study specifically dealing with plutonium and skin cancer. I did not find additional information from studies about radon. In the same way, studies of cancers occurring in personnel working in a thorium processing plant provide very little information. Hence, I have no way to respond to Question x, so I retained the RBE of 20 proposed by IRCP for the upper part of the 95%CI. I think that half of this value is a more probable median value than 0, which, nevertheless, cannot be excluded.

17. Thresholds (Question xiii)

Because this question concerns low LET at high dose rate, and because the threshold question states "there is no radio-induced cancer risk," I think the more probable hypothesis (median value) is the absence of such a threshold, as opposed to a possible practical threshold. Concerning breast and thyroid cancers, I think that a threshold higher than 0.01 Gy in 1 minute is very improbable. Thus, I retained the value of 0.01 Gy as the upper part of the 95%CI for breast, thyroid, and all sites together.

For pancreas, the ERR/Sv from the A-bomb incidence study was positive in the latest report [4], but the ERR/Sv for mortality was negative [4]. Hence, the dose to colon received by A-bomb survivors included in the incidence study (0.23 Gy) could be lower than that of a threshold dose for pancreas. Hence, I chose 0.3 Gy as a median value for the threshold for the pancreas.

Bone, colon, liver, and stomach seem less sensitive to low doses than the other cancers. Hence, I retained 0.3 Gy as the upper part of the 95%CI for these cancers, as well as for "all other cancers."

Concerning other cancers, including leukemias, I think that a value of 0.1 Gy can be taken for the 0.95 quantile.

18. Seed variables

From UNSCEAR [9], I obtained the 95%CI confidence interval for the ERR/Sv established for the 1950–1985 follow-up. Empirically, I think that the confidence interval has to be in proportion, multiplied by 2: It will be estimated for a period seven-fold smaller that for 1950–1985, but the mean expected baseline per survivor will be about two-fold higher.

The ERR/Sv for leukemia would be much lower, because the 1991–1995 follow-up does not take into account the first 20 years of follow-up, as opposed to the 1950–1985 follow-up. The ERR/Sv for other cancers will probably slowly decrease with time since exposure and attained age.

19. Rationale for reply to the dependencies questions

I was not able to establish a rationale for response to the dependencies questions.

19.1 Questions (i) and (ii)

Because the number of deaths for the period 0 to 20 were estimated by fitting the model for the period 0–40 and applying the estimated coefficients for the 20 first years, the risk for 0–20 years is strongly linked with that for 0–40 years. Thus, there is a strong correlation between the risk 0–40 and the risk 0–20; a value above the median value for the 0 to 40 years period will lead very frequently to a value above the median for the 0 to 20 years period: (p=0.95).

19.2 Questions (ii) and (iii)

Because it concerns projection, the two numbers are less linked than in the response to Questions (I) and (ii), but the link is important, nevertheless, because it concerns the same condition and same cancers: (p=0.85).

19.3 Questions (ii) and (viii)

Because it concerns the same period and same types of cancers, the two numbers are linked. Nevertheless, the problem of the public health system causes uncertainties about the link between the two estimated numbers: (p=0.9).

19.4 Questions (iv) and (v)

Concerning this question, I think that links have to be lower than those estimated from mixed adult and children populations, because the uncertainties about projection are greater: (p=0.75).

19.5 Questions (vi) and (vii)

Because of my lack of knowledge about *in utero* irradiation and because for this question I estimated the median value myself, I think the links are lower than in similar questions for after *in utero* irradiation: (p=0.7).

19.6 Questions (iii) and (v)

To me, the link seems important—the child population is included in the general population. The uncertainties concerning projection of lifetime risk of irradiated children are important and are not dependent on the risk for irradiation in adulthood: (p=0.75).

19.7 Questions (iii) and (v)

On the basis of my limited knowledge about *in utero* irradiation and because I think the link is weak: (p=0.65).

19.8 Among cancer sites in Question (iii)

I think the numbers are independent of each other: (p=0.5).

19.9 Among cancer sites in Question (xxi)

I think the numbers are independent of each other: (p=0.5).

19.10 Questions (iii) and (ix)

Because of my empirical response to Question ix and because of the very important uncertainties concerning cancers after low dose irradiation, I think there is no relationship between estimates for low dose rate and those for high dose rate. The two variables are absolutely independent: (p=0.5).

19.11 Questions (ix) and (x)

Because of my empirical response to Question ix and because of the very important uncertainties concerning cancers after low dose irradiation, I think the two numbers are independent of each other: (p=0.5).

19.12 Questions (ix) and (xi)

I was not able to reply to Question xi.

19.13 Among cancer sites in Question (iii)

Because of my empirical response to Question ix and because of the very important uncertainties concerning cancers after low dose irradiation, I think these two variables independent: (p=0.5).

19.14 Among cancer sites in Question (iii)

I think that the numbers are independent of each other (p=0.5).

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Question 1. The number of radiation-induced cancer deaths up to 20 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile (incidence in thousands)		
	5%	50%	95%
Bone	0	46	138
Colon	10	115	230
Breast	134	778	268
Leukemia	281	843	1686
Liver	0	9	18
Lung	150	451	677
Pancreas	0	26	704
Skin	3.5	7	14
Stomach	0	21	42
Thyroid	3	6	12
All other cancers	0	261	1044
All cancers	654	1963	3536

Question 2. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile (incidence in thousands)		
	5%	50%	95%
Bone	0	67	201
Colon	31	374	748
Breast	428	570	855
Leukemia	326	979	1958
Liver	0	27	54
Lung	405	1484	2226
Pancreas	0	84	336
Skin	11	21	42
Stomach	0	68	136
Thyroid	9	18	36
All other cancers	0	785	3140
All cancers	1493	4478	8956

Question 3. The number of radiation-induced cancer deaths over a lifetime (following the population up until it has become extinct) in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile (incidence in thousands)		
	5%	50%	95%
Bone	0	87	261
Colon	8	920	1840
Breast	851	1135	1703
Leukemia	336	1001	2002
Liver	0	55	110
Lung	1124	3373	5060
Pancreas	0	205	820
Skin	28	56	112
Stomach	0	172	344
Thyroid	20	41	82
All other cancers	0	1787	7148
All cancers	2944	8832	17664

Question 4. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 years) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile (incidence in thousands)		
	5%	50%	95%
Breast	346	461	695
Leukemia	171	513	1026
Thyroid	3	9	18
All cancers	795	2384	4768

Question 5. The number of radiation-induced cancer deaths over a lifetime (following the population up until it has become extinct rather than up to 40 years following exposure) in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 years) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile (incidence in thousands)		
	5%	50%	95%
Breast	1628	2171	3257
Leukemia	182	545	1090
Thyroid	36	72	144
All cancers	472	14714	28348

Question 6. The number of radiation-induced cancer deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure of a dose of 1 Gy low LET (= gamma) radiation administered uniformly over their three trimesters (9 months) *in utero* and followed-up for 20 years after birth.

	Quantile (incidence in thousands)		
	5%	50%	95%
Leukemia	0	421	843
All cancers	0	982	1963

Question 7. The number of radiation-induced cancer deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure of a dose of 1 Gy low LET (= gamma) radiation administered uniformly over their three trimesters (9 months) *in utero* and followed over a lifetime (following the population up until it has become extinct rather than up to 20 years following exposure).

	Quantile (incidence in thousands)		
	5%	50%	95%
Leukemia	0	500	1001
All cancers	0	4416	8832

Question 8. The number of radiation-induced cancer cases (fatal and non-fatal) up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile (incidence in thousands)		
	5%	50%	95%
Bone	0	155	465
Colon	57	684	1368
Breast	1347	1796	2694
Leukemia	479	1438	2876
Liver	0	27	54
Lung	582	1745	2618
Pancreas	0	97	388
Skin	935	1869	3738
Stomach	0	96	192
Thyroid	107	215	430
All other cancers	0	1518	6072
All cancers	3214	9642	19284

Question 9. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 year (rather than 1 minute).

	Quantile (incidence in thousands)		
	5%	50%	95%
Bone	0	0	670
Colon	0	0	243
Breast	0	190	285
Leukemia	0	326	653
Liver	0	0	18
Lung	0	0	742
Pancreas	0	0	112
Skin	0	0	14
Stomach	0	0	45
Thyroid	0	0	12
All other cancers	0	0	105
All cancers	0	516	2985

Question 10. The number of radiation-induced skin cancer cases (fatal and non-fatal) up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a uniform skin dose of 1 mGy high LET (= plutonium alpha particle) radiation at a uniform rate over 1 year.

	Quantile × 1000		
	5%	50%	95%
Skin	0	140	280

Question 11. Joint dosimetry/late effects question: The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each of whom inhales 10 K Bq of the radionuclides specified.

Nuclide	Physical Form	Chemical Form	Cancer Type	Number of Cancers Quantile		
				5%	50%	95%
Pu-239	1 μm AMAD	Oxide	Lung			
			Bone			
			Liver			
			Leukemia			
			All cancers			
Sr-90	1 μm AMAD	Oxide	Lung			
			Bone			
			Leukemia			
			All cancers			

Question 12. Given that radiation induced cancer death due to the specified cause has occurred as a result of a dose of radiation delivered over 1 minute, the average expected length of life lost in years, for a population followed up to extinction after exposure.

	Quantile (incidence in thousands)		
	5%	50%	95%
Bone	0	32.5	97.5
Colon	11	126.2	252
Breast	161	214.9	322
Leukemia	71	212.8	416
Liver	0	9.5	19
Lung	173	519.4	779
Pancreas	0	28.6	114
Skin	3.75	7.5	15
Stomach	0	23.3	466
Thyroid	3.1	6.3	72.6
All other cancers	0	268.9	1076
All cancers	483	1450	2900

Question 13. For each of the cancer sites listed, give the estimate of the threshold dose in Gy, for low LET (= gamma) radiation administered at a uniform rate over 1 minute, below which value there is no radiation-induced cancer risk.

	Quantile (incidence in thousands)		
	5%	50%	95%
Bone	0	0	0.3
Colon	0	0	0.3
Breast	0	0	0.01
Leukemia	0	0	0.1
Liver	0	0	0.3
Lung	0	0	0.1
Pancreas	0	0.3	1
Skin	0	0	0.1
Stomach	0	0	0.3
Thyroid	0	0	0.01
All other cancers	0	0.1	0.3
All cancers	0	0	0.01

EXPERT F

Risk Evaluation Procedures

Leukemia

I. Estimation of Risks

A – absolute risks.

Two primary sources were used.

1) Shimizu et al., 1988 A-bomb data, Life Span Study (LSS), for 1950-1985 (Table 4, vs. organ dose)

   Excess absolute risk 2.94×10^4 PY Gy for 35 years at risk, this is $2.94 \times 35 = 103$ in 10^4 person per Gy (acute) or 1.03×10^6 in 10^8 person per Gy (not clear how the first years 1945 to 1950 were handled).

2) Preston et al., 1994. A-bomb data (LSS) for 1950-1987, with correction for the missing 5 years to 1950.

   Average excess absolute risk is 0.6 (ALL) + 1.1 (AML) + 0.9 (CML) per 10^4 PY Sv = 2.60 per 10^4 PY Sv for 40 years (42 y – 2 y latency) this is 1.04×10^6 per 10^8 people per Sv (Sv is with Dosimetry System of 1986 (DS86) and relative biological effectiveness (RBE) = 10).

   The result is quite similar from both sources (and this is for 40 years).

Modifications

For lifetime. Mark Little,* Table II data set A, B or C gives a ratio of

$$\frac{1.001}{0.979} = 1.022$$

for lifetime/40 y.

For 20 years. Little, 1996, Table II for data set A, B or C gives a ratio of

$$\frac{0.843}{0.979} = 0.86$$

compared with 40 years. These ratios will be applied where appropriate.

For incidence. (# cases vs. # deaths). Little, 1996, Table IV model set A or B gives leukemia

$$\frac{1.438}{0.979} = 1.47 \cdot$$

(This seems suspiciously high to me – ICRP gives a lethality ratio for acute leukemia of 0.99! (ICRP, 1991, Table B-19, page 135, ICRP 60). Chronic leukemia will be less fatal, but that much less? Anyway, I don't have a better figure so I will use it.

For children. Little, 1996, Table III for model set A, B or C gives

$$\frac{0.513}{0.979}$$

or 0.52 for 40 years and

$$\frac{0.545}{1.001} = 0.54$$

for lifetime.

For chronic exposure. It is necessary to divide by a dose and dose rate effectiveness factor (DDREF). Instead of using the range for total cancer given in NCRP 1996, we have specific values derived from the leukemia data by Vaeth et al., 1992 ranging from 1.3 to 7 (95% confidence limits) with an optimum value of 2.0 (unadjusted doses – the range for these seems preferable to adjusted doses, see Figure VIII of UNSCEAR, 1994, Annex A (1994).

B. Relative Risk

An alternative approach, not one I favor for leukemia, is to use relative risk and the data for the EU/US population. (Supplied to panel members.) I don't care much for this population by the way – (a) the death rates seem out by a factor of 10, (b) all the cancer deaths seem too low at 8,950,000 males per 50×10^6 and 6,220,000 females per 50×10^6 for a total of 15,170,000 per 100,000,000. Modern U.S. data is now 20-23%, I understand. Also, urinary tract (bladder) tumors were not listed separately and this amazes me – why have the pancreas instead of the urinary tract tumors.

* M. Little. 1996. Memorandum (January 23, 1996), "Scoping Cancer Risks," sent to all members of the CEC/US NRC Somatic Health Effects Panel. Little's memorandum has been included in Appendix B of this volume.

Anyway, Shimizu, et al., 1988 gives an excess relative risk of 5.2/Gy (Table 4). Preston et al., 1994) gives excess relative risks/Sv of 9.1, 3.3 and 6.2 for ALL, AML and CML respectively, with deaths in the ratio 32, 103 and 57. Thus, a weighted ERR/Sv is 5.1, very similar to Shimizu, et al.)

The number of natural leukemia deaths in the EU/US population is 397,000 per 100×10^6 (both sexes and all ages) which, multiplied by 5.1, yields 2.0×10^6 induced deaths at 1 Sv. This is a little beyond the high end of the absolute risk estimate. It is not to be preferred in my view, but at least its almost in the ballpark.

C. ICRP risk estimates, 1990.

It is useful to check any detailed result obtained as above with the estimates made by ICRP, 1990 (publication 60) since they considered the UNSCEAR, 1988 report, the BEIR V report, the RERF reports and their own (Land and Sinclair, 1991) transfers in five populations.

ICRP would have estimated an average risk of $0.096 \times 9.5 \times 10^{-2}$ Sv^{-1} or 912,000 per 10^8 people (Table B-15) (rounded, 1.0×10^6 per 10^8, Table B-17 with DDREF = 2). Thus, their result would agree well with the absolute estimates of risk here.

II. Uncertainty in risk estimates

The starting point here, for this expert, is the very recent NCRP Report on "Uncertainties in Fatal Cancer Risk Estimates Used in Radiation Protection" which considers total cancer risk derived from the A-bomb data of 1950-1985 (NCRP, 1997).

One may note that this broadly finds 90% confidence limits (i.e., 5-95% confidence interval) of very close to a factor of 2, the 5% value being about 1/2 of the 50% value and the 95% being about 2 times it. The result was based on an analysis of the five principal components of uncertainty in the risk, viz. epidemiological, dosimetrical, transfer between populations, projection of the observation period to lifetime and the application of a DDREF for low dose, low dose rate risk.

These components have distribution types, and 5%, 95% and 50% values as shown in Table 1 for total cancer.

For each organ site of cancer the possible deviation of values from the total cancer value especially for R_{HN} the range of sampling variation, will be considered and a new overall range developed. These range values for the organ sites will be summarized later.

If we consider these items in relation to leukemia, it seems that leukemia could have a narrower range than that estimated for total cancers.

1) Epidemiological. Shimizu et al., gives a slightly narrower range for leukemia against organ dose (Table 4) 2.94 (2.43 – 3.49) is from 0.83 to 1.19 vs. solid tumors 10.13 (7.96 – 12.44) or 0.79 to 1.23.

2) Dosimetrical. There is no reason to suppose the estimate of dose for leukemia is better or worse than for the collection of individual solid tumors when the irradiation is uniform. It will be considered the same.

3) The transfer between populations for leukemia in the ICRP analysis (publication 60, Annex B or Land and Sinclair, 1991) is quite similar by relative or absolute risk. The ratio to total risk being 0.089 and 0.104 respectively, Tables B-14A and B-14B. Total cancer varies by about the same amount 10.1 to 8.9 so leukemia will have about the same transfer uncertainty as for total cancer.

4) Projection. There is virtually no projection to lifetime for leukemia and, therefore, an uncertainty involving a lifetime value of 1.0 and a 90% confidence interval from 0.62 to 1.05 is not needed.

5) The DDREF is a major uncertainty in the NCRP analysis. It should be noted that in all estimates involving acute exposure the DDREF does NOT apply and thus the result does not include this uncertainty. When the DDREF is applied, the uncertainty allotted in the NCRP analysis (from 1 to 5) could be used, or in the case of leukemia there are specific analyses ranging from 1.3 to 7 with a 50% value of 2.0 (Vaeth et al., 1992).

   Overall, leukemia is somewhat more certain rather than less than the uncertainties for solid tumors. One could use something like 1/1.5 to 1.5 × for no DDREF and

   $\frac{1}{1.75}$ for a DDREF. I prefer to be more conservative because uncertainties are always underestimated and I will use

Table 1. Uncertainties in Fatal Cancer Risk Estimates used in Radiation Protection[a]

Summary of Uncertainties				
	Distribution	5%	95%	50%
F (RHN) Statistical Uncertainty	N	0.75	1.25	1.00
F(R) Bias due to underreporting of cancer deaths	N	1.02	1.18	1.10
F(D) Dosimetrical Uncertainty (all sources)	N	0.69	1.0	0.89
F(T) Population Transfer Uncertainty	LN	0.57	1.81	1.00
F(P) Projection Uncertainty	Triangular	0.62	1.05	1.00
F(E) Uncertainty in DDREF	Trunc. Triangle	1.1	4.5	2.00
Combined Uncertainty (Risk $\times 10^{-2}$ Sv^{-1})		1.5	8.2	4.00

[a] NCRP (1997). Note: The final table in NCRP 1997 has some slightly different values.

$\frac{1}{1.75}$ and $\times$ 1.75 for no DDREF and 1/2 to 2 (the same as NCRP for solid tumors) when a DDREF is to be applied.

Bone

For bone there are no distinct data from the A-bomb survivors although excess bone tumors (ICD 170) are included in "other and ill defined sites." Thompson et al., 1994. No estimate is derivable from this. (*†but see later).

Instead, risks must be derived from the results of exposure to α emitters such as radium, which is more or less uniformly distributed in bone (eventually) or bone surface seekers such as plutonium which is considered separately later.

An estimate of the lifetime risk of induced bone tumors is available from BEIR IV (NAS/NRC, 1988) derived from ^{224}Ra studies, of 133×10^4 Gy^{-1}. With a lethality fraction of 0.70 (ICRP 1991, Table B-19) this yields a mortality risk of 93×10^{-4} Gy^{-1} or 4.7×10^{-4} Sv^{-1} with RBE = 20, i.e., a risk estimate of 0.05×10^{-2} Sv^{-1} which would apply to both high and low dose rate – no DDREF for alpha particles with an assumed linear response.

Thus, expect 50,000 deaths in 10^8 people as the central estimate, lifetime. For 40 years Little (1996), Table 2

$\frac{40\ y}{lifetime}$

$$\text{model} = \frac{0.067}{0.087} = 0.77$$

$$\text{model B} = \frac{0.044}{0.103} = 0.43$$

$$\text{model C} = \frac{0.044}{0.078} = 0.56$$

I am not comfortable about applying these values. First because I am not sure the BEIR IV value is truly lifetime, although life tables were used, second because the time relationship for a induced bone cancer shows no increment beyond 40 years (NIH, 1985, Figure V-I) included here as Figure 1. Consequently, I would take 40 y and lifetime to be essentially the same.

20 years. This is different and should be less. Little, 1996, Table II gives,

$$\text{model A} = \frac{0.046}{0.067} = 0.69$$

$$\text{models B \& C} = \frac{0.021}{0.044} = 0.48$$

The NIH time relationship (Figure 1) shown in Figure 1,would give about 0.90 for the area under the curve. Thus, I would use a value of 0.7.

For incidence (40 y) Little, 1996, Table IV gives

$$\text{model A} = \frac{0.155}{0.067} = 2.3$$

$$\text{model B} = \frac{0.090}{0.044} = 2.04$$

But ICRP 1991, Table B-19 gives a ratio of only 1.4. I propose to use 2.0 in order not to underestimate the incidence.

For chronic exposure (40 y) no DDREF since the result is based on acute/chronic α response. Use the same values as for 40 y.

For the uncertainty in the bone risk estimates we cannot use the uncertainty analysis for the A-bomb data.

We have to make a judgement about the initial value 133×10^{-4} Gy^{-1} for incidence. Depending, as it does, on both epidemiological and difficult dosimetric factors, the value cannot be considered to be closer than 1/2 to 2 × for the 5% and 95% confidence levels. There is, in addition, the lethality value of 0.70 probably not better than about 0.5 to 0.8 or 0.9, and the larger uncertainty in the RBE of 20 probably ranging from 5 (1/4) to about 40 (x2). Combining these uncertainties just very roughly, a refined (Bouville type) calculation does not seem to be indicated, yields a range of about 1/5 to 5x $(2^2 + 1.4^2 + 4^2 = 22)^{1/2} \approx 5$.

Thus, the results will be presented by dividing the central estimates for each case by 1/5 for 5% and multiplying by 5 for 95%.

(Note: ICRP 1991 gives the same estimate of risk for bone as given here).

There is, of course, nominally at least, additional uncertainty in 20 years because of the application of uncertain factors and models – even though 20 year data is actually available. I have not increased the uncertainty in the 20 year estimates. Note that NIH (1985) Figure 1 has the major part of the effect expressed in 20 years.

* Note: While there is no risk estimate given for bone in the 1994 A-bomb data (1950-1987), Shimizu et al., 1988, did give a value of the EAR for bone of 0.02 (- , 0.16) for kerma, about

$$\frac{2.94}{2.29}$$

x or 0.025 for organ dose x 35 y - 0.9 per 10^4 PGy, i.e., 9,000 deaths per 10^8 people. Thus, does not agree well with the 50,000 deaths central estimate derived from α particles – but the value is extremely uncertain and not given by Thompson et al. or Ron et al., 1994.

† I learned at the conference that there is an estimate of bone risk from the A-bomb survivors which is not discussed in any of the 1994 papers or in UNSCEAR, 1994 as bone alone, but the data is on the RERF disk for bone alone (ICD 170), without connective tissue. It was said the result was in very good agreement with the alpha derived value. Assuming this is so, I would reduce the range for bone from 1/5 to 5 to perhaps 1/3 to 3 for two good estimates in agreement. See summary Table 3.

Note 1: Relative Risk Estimate

$$\text{EU / US population has } \left.\begin{matrix}1449\\1138\end{matrix}\right\}\text{x10}$$
$$25870 \quad 26000 \text{ deaths} / 10^8$$

Shimizu et al. give ERR/Sv of 0.22. Thus, expect 6,000 bone cancer deaths lifetime. This is very poor agreement with 50,000 by EAR and reflects mostly the very weak estimates from the A-bomb source. Later data, see above, agrees better.

Note 2: ICRP estimate

Bone 5 per 10^4 is the same for acute and chronic. Thus, 50,000 per 10^8 people agrees exactly with the EAR estimate – not surprisingly since it was done the same way.

Colon

Mortality data for the LSS for 1950-1987 (Ron et al., 1994) give colon risk 0.51 per 10^4 PY Gy with range from 0.06 to 1.1. For example, 40 y risk is $0.51 \times 37 = 18.9$ per 10^4 or 189,000 (190,000) deaths per 10^8 people. From the statistics alone, this value ranges from 20,000 to 410,000 deaths.

Considering all the other uncertainty factors involved in A-bomb derivations (NCRP, 1996) which yield 1/2 to 2x for all combined sources for all other cancers, and will still apply in the case of colon, this uncertainty range could be rounded and extended from 10,000 (5%) to 200,000 (50%) and 800,000 (95%) for 40 y.

For lifetime. Little, 1996, Table II gives

$$\text{model A} = \frac{0.920}{0.374} = 2.46$$

$$\text{model B} = \frac{1.432}{0.297} = 4.82$$

$$\text{model C} = \frac{0.922}{0.297} = 3.10 \qquad \text{Average} = 3.5$$

I prefer to use the average value. Thus, lifetime has values 35,000 – 700,000 – 2,800,000.

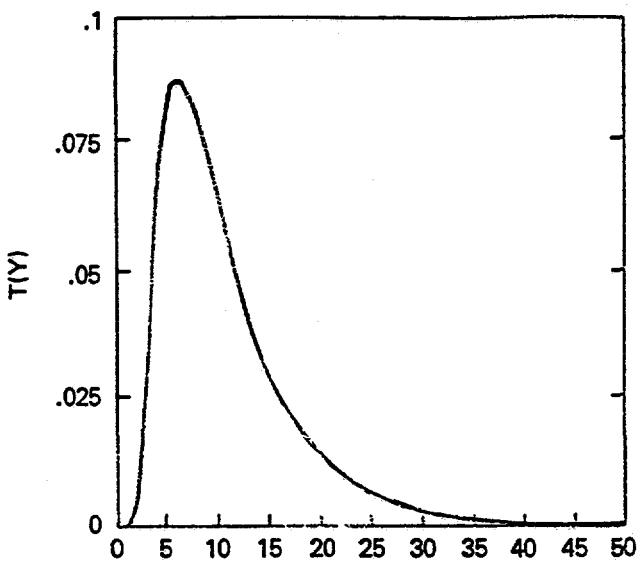

Figure 1. Fitted time-to-tumor model for bone sarcoma induced by a brief exposure to radium-224. T(Y) is the probability of diagnosis within one year after time Y. (NIH, 1985)

For 20 years. Little, Table II, gives

$$\text{model A} = \frac{0.115}{0.374} = 0.31$$

$$\text{model B} = \frac{0.076}{0.297} = 0.26$$

model C same as B. Average = 0.28

Thus, 20 year values are: 3,000 – 56,000 – 220,000.

For incidence. Little, Table IV vs. Table II

$$\text{model A} = \frac{0.684}{0.374} = 1.82$$

$$\text{model B} = \frac{0.547}{0.297} = 1.84$$

(ICRP, 1991 gives colon lethality as 0.55 = 1.82, very good agreement) thus, take incidence as 1.82 × __. For example, 18,000 – 360,000 – 1,500,000 for 40 y.

For chronic exposure. (40 y) divide by DDREF of 2. No evidence for any other value.

Note 1: Estimate by relative risk

$$\text{EU / US population has } \begin{array}{r} 76{,}677 \text{ male} \\ +63{,}450 \text{ female} \\ \hline 140{,}127 \text{ (*10)} \end{array}$$

1,400,000 colon deaths in 10^8 people. ERR/Sv (Ron et al., 1994) is 0.52 (0.06-1.2) thus 84,000 – 730,000 – 1,700,000. This is very close to the lifetime values derived from the absolute risks and, thus, is quite reassuring.

Note 2: Estimate by ICRP 60 (ICRP 1991)

Colon lifetime risk Table B-17 is 85 × 2 per 10^4 for each acute exposure, i.e., 1,700,000 central value for 10^8 people. This is at the high end of the colon risk estimates – but it is based on Shimizu et al., who had a 60% higher EAR (0.82 vs. 0.51) than Ron et al. and ERR/Sv – 0.85 vs. 0.52 for colon. Thus, the degree of agreement is not unreasonable.

Female Breast

Mortality data for the LSS for 1950-1987 (Ron et al., 1994) gives 1.3 (0.64-2.1) per 10^4 PYGy.

40 y risk is 37 × 1.3 = 48 per 10^4 PGy i.e., central value is $48 \times 50 \times 10^6 \times 10^{-4} = 240{,}000$ in 50 million women or 100 million people.

Note range of uncertainty in the statistics is about 1/2 to 2, considerably more than for all cancers. The uncertainty analysis for all sources of uncertainty for all cancers gives also 1/2 to 2. Thus, combination is $(2^2 + 2^2)^{1/2} = 3$ and range is 1/3 to 3, approximately. 40 y risk is 80,000 – 240,000 – 720,000.

Lifetime risk. Little, 1996

$$\text{model A} = \frac{1.135}{0.570} = 1.99$$

$$\text{model B} = \frac{1.747}{0.515} = 3.39$$

$$\text{model C} = \frac{1.226}{0.515} = 2.38 \qquad \text{Average} = 2.6$$

Lifetime risk is 207,000 – 620,000 – 1,870,000.

20 year risk. Little, 1996

$$\text{model A} = \frac{0.178}{0.570} = 0.31$$

$$\text{model B} = \frac{0.134}{0.515} = 0.26$$

model C same as B. Average = 0.28

22,000 – 67,000 – 200,000.

Incidence. Little, 1996

$$\text{model A} = \frac{1.796}{0.570} = 3.15$$

$$\text{model B} = \frac{1.630}{0.515} = 3.16$$

[ICRP 60, (ICRP, 1991) gives lethality 0.50 or 2.0x for incidence, not very good agreement].

Take 3.0 as ratio incidence/mortality

Children – 40 y, Little, 1996

$$\text{model A} = \frac{0.461}{0.570} = 0.81$$

$$\text{model B} = \frac{0.456}{0.515} = 0.89$$

model C same as B. Average = 0.86

Thus, values are 69,000 – 206,000 – 618,000.

Children – Lifetime. Little, 1996

$$\text{model A} = \frac{2.171}{1.135} = 1.91$$

$$\text{model B} = \frac{4.761}{1.747} = 2.72$$

$$\text{model C} = \frac{2.137}{1.226} = 1.74 \qquad \text{Average} = 2.12$$

Multiply lifetime values by 2.1: 435,000 – 1,300,000 – 3,900,000.

For chronic exposure, 40 y use DDREF of 2, since no sound evidence for another value. (Fractionation produces little effect for breast, however.)

Note 1. Estimate by relative risk

EU/US population has 1,200,000 deaths in females due to breast cancer.

ERR/Sv (Ron et al., 1994) is 1.3 then expect 1,550,000.

Agreement is not very good (but within the range) indicating relative risk is not a good transfer method.

Note 2. ICRP estimate

20 per $10^4 \times 2$ for acute = 40 per 10^4 or 400,000 per 10^8 for both sources agrees reasonably well with EAR result.

Note 3.

Other sources of breast information could also be used – see Summary in Table VIII of UNSCEAR, 1994. However, the average of these estimates of breast cancer risk is very close to the LSS value.

Liver

Risk Estimate

EAR for the LSS for 1950-1987 (Ron et al., 1994) is 1.3 (0.52 - 2.2) per 10^4 PYGy multiply by 37 y $\rightarrow$ 48 per 10^4 PGy = 480,000 in 10^8 people

Uncertainty

Statistical range is a little more than 1/2 to 2. Other factors for liver should not differ much from all cancers, i.e., 1/2 to 2 combination is 1/3 to 3x i.e., 160,000 – 480,000 – 1,400,000 for 40 y.

For Lifetime. Little, Table II

$$\text{model A} = \frac{0.055}{0.027} = 2.0$$

$$\text{model B} = \frac{0.075}{0.021} = 3.6$$

$$\text{model C} = \frac{0.052}{0.021} = 2.5 \qquad \text{Average} = 2.7$$

For 20 years. Little, Table II

$$\text{model A} = \frac{0.009}{0.027} = 0.33$$

$$\text{model B} = \frac{0.006}{0.021} = 0.29$$

model C same as B. Average = 0.30

For incidence. Little, Table IV

$$\text{model A} = \frac{0.027}{0.009} = 3.0$$

$$\text{model B} = \frac{0.022}{0.006} = 3.6 \qquad \text{Average} = 3.3$$

For chronic exposure. Divide by DDREF of 2 – no evidence for any other value.

[Note: This applies to all organs. We are using 40 y values – which is the period of observation – thus, strictly there is not a projection error as in lifetime estimates. But we have used 1/2 to 2 for total cancer uncertainty and I think it's a bit too narrow – so I am not unhappy to use 1/2 to 2 for 40 y even though projection error isn't involved.]

Note 1. Estimate by relative risk.

Ron et al., 1994.

$$0.46\,(0.18 - 0.8)$$

$$\text{EU / US population} \begin{matrix} 78,665 \text{ male} \\ +46,610 \text{ female} \end{matrix} \Big\} = 1,250,000$$

$$\times 10$$

which lies between the central estimate for 40 y, 480,000 and for lifetime 1,300,000. It should be closer to the latter but probably indicates a transfer problem by ERR to the new EU/US population.

Note 2. Estimate by ICRP

Central estimate is (ICRP Publication 60, Table B-17) 15×2 per 10^4 per Sv = 300,000 per 10^8 people.

This is low by about 1/4. The ICRP value was derived from α data (thorotrast) using an RBE of 20, which may be in error. But the low LET value from the A-bomb survivors still has the difficult problem of whether the tumor is primary or not. This level of agreement is not very good. The ICRP value is almost certainly low, but note that the EAR for liver in report 12 draft is lower (1.14×10^4 PYGy) than for 1987 (1.3×10^4 PYGy, so the agreement will improve when report 12 is published (Pierce et al., 1996).

Lung

Absolute risk estimate for the LSS for 1950-1987 is 1.9 (1.0-2.9) per 10^4 PYG (Ron et al., 1994) $\times$ 37 y = 70 per 10^4 PGy.

40 y. 700,000 per 10^8 people

Statistical range is 1/2 to 2 and again with other factors also 1/2 to 2, these combine to 1/3 to 3. Thus, 230,000 – 700,000 – 2,100,000.

For lifetime. Little, Table II

$$\text{model A} = \frac{3.373}{1.484} = 2.27$$

$$\text{model B} = \frac{5.183}{1.278} = 4.05$$

$$\text{model C} = \frac{3.495}{1.278} = 2.73 \qquad \text{Average of A \& C} = 2.5$$

I reject the model B value. It's too high, especially for an endpoint in which there is some (not significant) evidence of a drop from constant relative risk. Use 2.5.

For 20 years. Little, Table II

$$\text{model A} = \frac{0.451}{1.484} = 0.30$$

$$\text{model B} = \frac{0.325}{1.278} = 0.25$$

model C same as model B. Average A, B, C = 0.27

For incidence. Little, Table IV, 40 y

$$\text{model A} = \frac{1.745}{1.484} = 1.18$$

$$\text{model B} = \frac{1.518}{1.278} = 1.19$$

ICRP lethality fraction (ICRP 60, Table B-19) 0.95, i.e., 1.05. Will take 1.18 which may be generous – I don't know where the Little figures really come from.

For chronic exposure. 40 y

Divide by DDREF of 2. Actually there is some evidence that for lung the DDREF may be much greater than breast for example, and thus, higher than 2. We will use 2, nevertheless, and the values will be conservative.

Note 1. Estimate of lifetime risk by ERR and number of cancers in EU/US population, which are

$$\left.\begin{array}{c}278,706 \text{ male} \\ +106,267 \text{ female} \\ \text{x10}\end{array}\right\} = 3.849730 = 3,850,000$$

Ron et al., 1994, ERR/Sv = 0.65 (0.34-1.0) thus excess deaths, lifetime = 2,500,000 which is within the range given for lifetime by the EAR method 1.2×10^6 (50%) – 5.25×10^6 (95%).

Note 2. Estimate based on ICRP. – lifetime

ICRP 60, Table B-17, gives lung 85 (x2 for acute) per 10^4 i.e., 1,700,00 in 10^8 people – which again is within the absolute estimates 1,200,000 to 5,250,000.

Pancreas

Absolute risk, for mortality in the LSS is not given by Ron et al., 1994 – presumably because the risk is very small and nonsignificant. For incidence in the LSS Thompson et al. discuss the pancreas and give an EAR of 0.24 (–0.36, 1.05) (p. S41-S43). This is 0.24×37 y = 8.9, i.e., 90,000 per 10^8 people. The statistics suggest from below 0 to $4.4 \times$ this value. Other uncertainties would increase the overall uncertainty from below 0 to $((4.4)^2 + 2^2)^{1/2} = 5$. Thus, range is 0 – 90,000 – 450,000. But this is incidence, mortality is 1/1.15 times less → 78,000 or 80,000. Again, incidence/mortality is given by Little, Tables IV and II as

$$\frac{0.097}{0.084} = 1.15$$

but where does this come from? Pancreatic tumors are 99% fatal in less than 5 y.

For lifetime. Little, Table II

$$\text{model A} = \frac{0.205}{0.084} = 2.4$$

$$\text{model B} = \frac{0.407}{0.086} = 4.7$$

$$\text{model C} = \frac{0.264}{0.086} = 3.1 \quad \text{Average of models} = 3.4$$

$80,000 \rightarrow 270,000$

For 20 years. Little, Table II

$$\text{model A} = \frac{0.026}{0.084} = 0.31$$

$$\text{model B} = \frac{0.022}{0.086} = 0.26$$

model C same as B. Average = 0.28

Thus, 0 – 25,000 – 110,000.

For incidence. Little, Table IV

$$\text{model A} = \frac{0.097}{0.084} = 1.15$$

$$\text{model B} = \frac{0.120}{0.086} = 1.16$$

Thus, 80,000 – 90,000 – 450,000.

Note: Lethality, given by ICRP is 0.99.

For chronic exposure.

Divide 40 y absolute acute value by DDREF of 2 – no reason to use any other value.

Note 1. Estimate based on relative risk

EU / US population has 368,570 male
272,500 female
640,000 pancreatic tumors

Thompson et al. ERR 0.18 (–0.25 to 0.82) $0.18 \times 640,000 =$ 115,000 central value compares reasonably well with lifetime value 270,000.

Note 2. Estimate based on ICRP – None

Pancreas is not significantly at risk, so ICRP has no value. I question the value of including this nonsignificant tumor here – also, even the ratio of incidence to mortality seems nonsense. The 5 year survival for pancreas is less than 1%. This is especially nonsense when urinary tumors, of much greater importance, are left out!

Skin

Absolute risk, mortality in the LSS 1950-1987 (Ron et al., 1994) is 0.034 (< –0.019 - 0.16) per 10^4 PYGy × 37 y = 1.26 per 10^4 PGy i.e., 12,600 fatal skin tumors per 10^8 people. Range statistically is about x5 on the positive side and below zero on the negative side. The 1/2 to 2 raises the overall uncertainty from below zero to 5.4x, thus, the numbers are 0 to 12,500 to 68,000 (40 y).

For lifetime. Little, Table II

$$\text{model A} = \frac{0.056}{0.021} = 2.7$$

$$\text{model B} = \frac{0.117}{0.020} = 5.8$$

$$\text{model C} = \frac{0.071}{0.020} = 3.6 \qquad \text{Average} = 4.0$$

Thus, 0 – 50,000 – 270,000.

For 20 years. Little, Table II

$$\text{model A} = \frac{0.027}{0.021} = 0.33$$

$$\text{model B} = \frac{0.005}{0.020} = 0.25$$

model C same as B. Average = 0.28

Thus, 0 – 3,500 – 19,000.

For incidence. Little, Table IV, 40 y

$$\text{model A} = \frac{1.869}{0.021} = 93.4$$

$$\text{model B} = \frac{1.853}{0.020} = 93$$

i.e., incidence is 93x or 0 – 1,200,000 – 6,300,000.

For chronic exposure. Apply a DDREF of 2 – no other value presents itself.

Note 1. Estimate by relative risk

EU / US population	39,820 male
	23,250 female (x10 used)
	63,000 deaths

Ron et al., 1994 mortality ERR/Sv = 0.31 (<–0.15-1.8) 0.31 × 63,000 = 20,000 deaths. This compares with 50,000 lifetime and seems reasonable given uncertainty of lethality factors (about 0.01 to 0.03).

Note 2. Estimate of ICRP 60, Table B-17

2 × 2 (for acute) and 10^4 PYGy or 40,000 per 10^8 people. This agrees very well with the 50,000 lifetime central estimate.

Stomach

Absolute risk mortality in the LSS 1950-1987 (Ron et al., 1994) is 1.9 (0.51 - 3.5) per 10^4 PYGy. For 37 y = 70.3 × 10^4 i.e., 700,000 central estimate in 10^8 people. Statistical range is 1/4 to 2x. Combined with other uncertainties of 1/2 to 2, this is

$\frac{1}{4.4}$ to 3x overall.

160,000 – 700,000 – 2,100,000

For lifetime. Little, Table II

$$\text{model A} = \frac{0.172}{0.068} = 2.5$$

$$\text{model B} = \frac{0.325}{0.063} = 5.1$$

$$\text{model C} = \frac{0.206}{0.063} = 3.3 \qquad \text{Average} = 3.6$$

For 20 years. Little, Table II

$$\text{model A} = \frac{0.021}{0.068} = 0.31$$

$$\text{model B} = \frac{0.016}{0.063} = 0.25$$

model C same as B. Average = 0.27

For incidence. Little, Table IV

$$\text{model A} = \frac{0.098}{0.068} = 1.44$$

$$\text{model B} = \frac{0.091}{0.063} = 1.44$$

ICRP gives 0.90 or 1.11 which is probably better but I will use 1.4 to be conservative. (Again, I am dubious about Little's incidence/mortality values.)

For chronic exposure. 40 y

Divide the 40 y acute value by 2 for an assumed DDREF of 2.

Note 1. Estimate by relative risk

Natural stomach cancers, EU / US	45,794 male
	23,570 female (x10)
	694,000 per 10^8 people

ERR/sv (Ron et al., 1994) is 0.22 (0.057-0.40), yielding 150,000 central estimate.

This should compare with lifetime risk estimate of 2,500,000 – a very poor comparison and reflects the difficulty of transferring by relative risk from a high incidence population (Japan) to a low incidence population. (EU/US).

Note 2. Estimate by ICRP

Lifetime is 110 per $10^4 \times 2$ for acute or 2,200,000 per 10^8 people. This is very close to the lifetime absolute risk.

Thyroid

Absolute risk, mortality in the LSS 1950-1987 (Ron et al., 1994) 0.016 (–0.04 to 0.24) × 37 years = 0.6 per 10^4 6,000 deaths in 10^8 people.

The statistics give 0 for lower bound and 15x higher for upper – thus we can ignore other errors which are relatively, minor, and within the uncertainty of the statistical range.

Thus, 0 – 6,000 – 90,000 (40 y values)

(I think the 15x is quite unrealistic but what can one do? Use an overriding judgement? NO! Leave it as it is and wait for the future to solve these problems.)

For lifetime. Little, Table II

$$\text{model A} = \frac{0.041}{0.018} = 2.28$$

$$\text{model B} = \frac{0.079}{0.018} = 4.39$$

$$\text{model C} = \frac{0.053}{0.018} = 2.94 \qquad \text{Average} = 3.2$$

i.e., 0 – 19,000 – 290,000.

For 20 years. Little, Table II

$$\text{model A} = \frac{0.006}{0.018} = 0.33$$

$$\text{model B} = \frac{0.005}{0.018} = 0.28$$

model C same as B. Average = 0.30

i.e., 0 – 1,800 – 27,000.

For children. (40 y) Little, Table III

$$\text{model A} = \frac{0.009}{0.018} = 0.5$$

$$\text{model B} = \frac{0.008}{0.018} = 0.44$$

model C same as B. Average = 0.46

i.e., 0 – 2,800 – 41,000.

For children. Lifetime, Little, Table III

$$\text{model A} = \frac{0.072}{0.041} = 1.76$$

$$\text{model B} = \frac{0.214}{0.079} = 2.70$$

$$\text{model C} = \frac{0.078}{0.053} = 2.47 \qquad \text{Average} = 2.0$$

0 – 12,000 – 18,000.

For incidence. Little, Table IV

$$\text{model A} = \frac{0.215}{0.018} = 11.9$$

$$\text{model B} = \frac{0.185}{0.018} = 10.3$$

ICRP uses a lethality ratio of 0.10 or 10. Use 11 as the average here.

For chronic exposure. Divide by DDREF of 2.

Note 1. Estimate by relative risk

EU / US population has	23,180 female
	10,090 male
	33,000 deaths

ERR/sv (Ron et al., 1994) 0.094 is (–0.23 to 1.7) = 3,100 deaths lifetime which compares with 19,000 by EAR. Again, transfer problems are considerable. See below 40,000 deaths.

Note 2. ICRP estimate

8 per 10^4 PYSv × 2 for acute = 16 or 160,000 per 10^8.

This should compare with 19,000 but checks fail to reveal the discrepancy – but see below.

Note 3. Estimates of thyroid risk using incidence in the LSS (Ron et al., 1994).

(a) ERR/Sv is 1.2 (0.48 - 2.1) with 33,000 deaths in the EU/US population this implies 40,000 deaths per Sv. [33,000 deaths in EU/US imply 330,000 cases, × 1.2 - 400,000 cases/Sv x mortality 0.10 = 40,000 deaths]

(b) EAR is 1.6 (0.78 - 2.5), which is 100x mortality, and 10x, so obviously will lead to 10x as many cancers. This approach looks much better for thyroid. It should yield a 40 y value of 1.6 × 37 = 59 per 10^4 for incidence, 5.9×10^4 for mortality, or 59,000 per 10^8 people central.

The range should be (0.78 to 2.5) or 1/2 to 2 for statistics and 1/2 to 2 for other uncertainties which are equivalent to those for all cancers. There is one other problem, viz. the lethality ratio, which is also an additional uncertainty, but the 0.10 is probably not more uncertain than 0.06 to 0.15 (ICRP 60, 1991) or say another

$$\frac{1}{1.5}$$

to $1.5\sqrt{2^2 + 2^2 + \left(1.5^2\right)} = 3.1$ say 1 / 3 to 3x still.

Lifetime risk estimate $59{,}000 \times 3.2 = 189{,}000$ which compares well with ICRP 160,000.

I changed all the thyroid risk numbers to conform to the incidence estimate (note 3b above) using the ratios outlined above. Note: This changes the central and lower values greatly (x10) but not so much the upper 95% value which was already 15x the central.

Note 4. The values taken from Ron et al., 1994 for incidence in the LSS are for both children and adults. In a recent paper involving a pooled analysis of all thyroid results (Ron et al., 1995) children and adults were separated for the LSS data. The EAR for adults only is about 1/4 of the value used here and 1/6th of the value for children. These differences seem very large for those <15 vs. those >15. Earlier estimates (NCRP, 1985) give only a factor of about 2. I will use a factor of 2 for children, but the thyroid estimate is probably too high for adults and too low for children. I will increase the range from 1/3 to 3x to 1/4 to 4x.

All Other Cancer

All other cancers include important groups like urinary tract cancer, ovary, oesophagus etc. included in the ICRP list of significant tumors (given weighting factors) but not listed in the lists we were given.

It is not obvious what the best way to approach this is but I think the following is a good way. What I have done (below) is to take the EAR for all solid tumors for the LSS from Ron et al., 1994 and subtract from it the EAR for all those tumors that have already been treated singly above.

All solid tumors	11.1 (8.4 - 14.0) per 10^4 PYSv
Bone	0.02 (– , 0.16) per 10^4 (Shimizu et al.)
Colon	0.51 (0.06, 1.1)
Breast	1.3 (0.64, 2.1)
Liver	1.3 (0.52, 2.2)
Lung	1.9 (1.0, 2.9)
Pancreas	0.24 (–0.36, 1.05) (Thompson et al.)
Skin	0.034 (–0.019, 0.16)
Stomach	1.9 (0.51, 3.5)

Thyroid 0.016 (–0.04, 0.24)

Sum (bone to thyroid) = 7.22 [note: assumption is that for breast, the 11.1 included only the EAR for females]. All solid tumors 11.1 – sum (bone to thyroid) = 3.88.

Note, of this 3.88, oesophagus 0.45, ovary, 0.69 and urinary tract 0.67, make up 1.81 leaving about 2.07 for all other tumors – this is probably quite reasonable.

Sophisticated methods probably could be used to obtain a statistical range. Given the uncertainties anyway I prefer to use a simple method. The larger the EAR the smaller the statistical range, thus let's take the range proportional to

$$\frac{1}{\text{EAR}}.$$

For all solid tumors 11.1 (8.4 - 14.0) the range is very close to ± 25%. For EAR = 3.88 lets assume range is ± 25% ×

$$\frac{11.1}{3.88} = 71.5\%$$

thus, range is 3.88 (1.10 - 6.65).

The central value (40 y) is $3.88 \times 37\text{ y} = 144$ per 10^4/y or 1,440,000 per 10^8 people. Range, statistically, is less than 1/3 to about twice [this may not be unreasonable by comparing with the ranges for EARs about 1.9 or so, in Ron et al., 1994.]

The other factors of uncertainty for total cancer are about 1/2 to 2 (NCRP, 1997). Thus, full range of uncertainty will be taken as 1/4 to 3x using the combination of the two uncertainties. For example, 360,000 – 1,440,000 – 4,300,000.

For lifetime. Little, 1996, Table II

$$\text{model A} = \frac{1.787}{0.785} = 2.28$$

$$\text{model B} = \frac{3.096}{0.709} = 4.37$$

$$\text{model C} = \frac{2.034}{0.709} = 2.87 \qquad \text{Average} = 3.2$$

For 20 years. Little, 1996, Table II

$$\text{model A} = \frac{0.261}{0.785} = 0.33$$

$$\text{model B} = \frac{0.188}{0.709} = 0.27$$

model C same as B. Average = 0.29

For incidence. Little, 1996, Table IV

$$\text{model A} = \frac{1.518}{0.785} = 1.9$$

$$\text{model B} = \frac{1.333}{0.709} = 1.88 \qquad \text{Average} = 1.89$$

This particular ratio of incidence/mortality may not be bad.

For chronic exposure. Divide by DDREF of 2.

Note: Another way the evaluation of "all other tumors" might have been handled would have been to take its ratio to some of the other solid tumors given in Little, Table II because these are nominal REID values according to him. However, brief examination of the Table II shows that for each of the organ sites, such as colon, liver, lung, stomach, there is a huge range of ratios of REIDs for "all other tumors" from about 0.5 to 3.0.

$$\text{vs colon} \quad \frac{0.785}{0.374} = 2.1\,(\text{model A})$$

$$\text{vs liver} \quad \frac{0.755}{0.027} = 29.1\,(\text{model A})$$

$$\text{vs lung} \quad \frac{0.785}{1.484} = 0.53\,(\text{model A})$$

$$\text{vs stomach} \quad \frac{0.785}{0.068} = 11.5\,(\text{model A})$$

I don't know how Little's Table II was obtained but this approach is not attractive to me.

Note 1. Estimate by ERR.

EU / US population has 417,090 males
251,591 females (x10)
6,686,000 deaths due to all other cancers

But no ERR is derivable for this group of cancers – at least not by me.

Note 2.

ICRP does not consider this group but the group could be similar to ICRP's oesophagus, ovary, urinary tract plus the remainder. These would have a risk, from ICRP 60, Table B-17 of $(30 + 10 + 30 + 50) = 120$ per 10^4 PYGy $\times 2$ for acute vs. chronic i.e., 240×10^4 or 2,400,000 per 10^8 people for lifetime, central estimate. This is a little more than half the estimate I have made – but the ratio Lifetime 40 y of 3.2 was high and maybe too high. Anyway, within a factor of 2 isn't bad.

All Cancers

Absolute risk, EARs are available for the LSS from (Ron et al., 1994) for solid tumors and (Preston et al., 1994) for leukemia.

These are 11.1 (8.4-14.0) and 2.6 (2.15 - 3.1) using Shimizu derived levels i.e. (.83 - 1.19). For example, 13.7 (10.3 - 17.1), 13.7×37 y = 507 per 10^4 PGy i.e., 5,070,000 per 10^8 PGy central for 40 y.

The range of uncertainty should be the same as that derived by NCRP in NCRP, 1997 viz. 1/2 to 2 yielding 2,500,000 – 5,000,000 – 10,000,000.

In Little, 1996, the total for each model is given and presumably corresponds to the designation "all cancers". However, these include leukemia and projections should be done separately – thus, the total of all cancer less leukemia is

$$\text{model A} = \frac{7.831}{3.499} = 2.24$$

$$\text{model B} = \frac{8.001}{3.053} = 2.62$$

$$\text{model C} = \frac{12.565}{3.053} = 4.11 \qquad \text{Average} = 3.0$$

$11.1 \times 37 = 4{,}100{,}000$ per 10^8 people, x3 $\rightarrow$ lifetime 12,300,00 per 10^8 people plus leukemia 1,050,000

6,800,000 – 13,300,000 per 10^8 – 27,000,000

For 20 years. Again do separately, Little, 1996.

$$\text{model A} = \frac{1.120}{3.499} = 0.3$$

$$\text{model B} = \frac{0.799}{3.053} = 0.26$$

model C same as B. Average = 0.27

For children. (40 y) Little, 1996, Table III. This time, didn't separate leukemia and all solid tumors.

$$\text{model A} = \frac{2.383}{4.478} = 0.53$$

$$\text{model B} = \frac{2.151}{3.053} = 0.70$$

model C same as B. Average = 0.62

For children lifetime. Little, 1996, Table III

$$\text{model A} = \frac{14.714}{8.832} = 1.67$$

$$\text{model B} = \frac{34.410}{13.566} = 2.53$$

$$\text{model C} = \frac{34.885}{9.402} = 3.66$$ Average = 2.60 times the lifetime adult value

For incidence. Little, 1996, Table IV

$$\text{model A} = \frac{9.642}{4.478} = 2.15$$

$$\text{model B} = \frac{8.808}{4.032} = 2.18 \qquad \text{Average} = 2.16$$

For chronic exposure. Divide by DDREF = 2.

Note 1. Estimate by relative risk

EU / US population has 8,950,00 male
6,220,000 female
15,200,000 deaths due to all other cancers

This includes leukemia 400,000 deaths. Thus, solid tumors are 14,800,000. For all solid tumors (Ron et al., 1994) give an ERR of 0.45 (0.34-0.57).

or	6,700,000 deaths/Sv lifetime
+	1,050,000
Total	7,750,000

This compares with 13,300,00 deaths estimated by absolute risk and is within a factor of 2.

Note 2. Estimate of all cancer by ICRP, 10×10^{-2} Sv^{-1} for acute.

10,000,000 in 10^8 people for 1 Sv exposure

This is quite good agreement especially since it is based on data to 1985 and the EAR estimates are based on data to 1987 and yield higher risk estimates.

Question (XII)

The average years of life lost by a population (not by the individual with the cancer) due to induced cancers after one sievert, is given by Little 1996 in the last column of Table II.

In line with my practice of averaging the model sets, from these averages I have the 50% values for the table of question 12. To obtain the 5% and 95% values I use the same range as for risk estimates since the same models etc. are involved. These vary by organ site and are as follows:

Table 2. Values for 5% - 95% relative to the central risk estimate

Bone	1/5 to 5x (revised 1/3 to 3)
Colon	1/20 to 4x
Breast	1/3 to 3x
Leukemia	$\frac{1}{1.75}$ to 1.75x
Liver	1/3 to 3x
Lung	1/3 to 3x
Pancreas	0 to 5x
Skin	0 to 5.4x
Stomach	$\frac{1}{4.4}$ to 3x
Thyroid	1/3 to 3x (revised to 4x)
All other Cancer	1/4 to 3x
All Cancer	1/2 to 2x

Question (XI) Joint Dosimetry /Late

(Consultation between three experts 02/02/96)

A. Plutonium 239 as oxide (type S is ok)

Lung

For adult, the conversion factor (ICRP 71, December 1995 – not available to most people yet) is 8.7×10^{-5} Sv/Bq. For younger persons it increases from 9.6×10^{-5} Sv/Bq at 15 y to 1.1×10^{-4} at 10, 1.7×10^{-4} at 5, 2.7×10^{-4} at 1 and 3.0×10^{-4} at 3 months. Use 1.0×10^{-4} Sv/Bq for an "average" age person. For an amount of 10 kBq this is a dose of 1.0 Sv. Lung cancer has a risk (ICRP 60, Table B-17) of 0.85×10^{-2} Sv^{-1} and for 1 Sv this is $0.85 \times 10^{-2} \times 10^8$ people, i.e., 850,000 fatal lung tumors - lifetime in 10^8 people.

For 40 y use Little, Table II model B, and fraction of lifetime is

$$\frac{1.278}{5.183}$$

for lung or .247 i.e., 210,000 in 40 y.

$$\left(\text{model A is } \frac{1.484}{3.373} = 0.44 \quad \text{model C is } \frac{1.278}{3.495} - 0.36\right)$$

The three experts then multiplied this by 0.7 being the geometric mean of something – I do not now recall what, so I will not use it.

Also, there was talk about partitioning the dose in the respiratory tract to 0.33/0.33 and 0.33 and making allowance for that. I have made no allowance.

The uncertainties were based on

1) the dose conversion from the amount of plutonium inhaled. This was considered to be 1/2 to 2 for the lung.

2) RBE for plutonium in lung – taken as 20 in the calculation but possibly ranging from 5 to 40, i.e., 1/4 to 2.

3) risk per unit dose for lung derived from A-bomb is ~ 1/3 to 3 (see earlier).

The total range by combining $\sqrt{3^2 + 4^2 + 3^2} = 6$ or 1/6 to 6x.

Note: This is considered to be the risk for an average member of the population. For children, the conversion for dose/Bq is higher, about 1.5x, the risk/dose would be higher also (could be taken x 2) but all of this is within the high end of the range given.

Note: The three experts reduced the 210,000 to 130,000 somehow and used 1/4 to 4 for the full range, i.e., 32,000 to 560,000.

Bone

Value for adult (children are a little smaller) is 1.8×10^{-4} Sv/Bq. Risk conversion is 0.05×10^{-2} Sv^{-1} lifetime for uniformly distributed bone seekers. For surface seekers it is about 1/5 or 0.01×10^{-2} Sv^{-1} (one expert). Thus, for 10 kBq we have $10^4 \times 1.8 \times 10^{-4} \times 0.01 \times 10^{-2} \times 10^8$ people = 18,000 bone deaths lifetime.

For 40 y. Little, 1996, Table II gives a reduction factor of

$$\frac{0.067}{0.087} = 0.77$$

but since the bone risk is all expressed in 25-30 years (see bone earlier) 40 y is the same as lifetime and I will not reduce this value for those coefficients. But numbers in ICRP are 50 y doses and in the case of bone, 25 y is the expression time. The three experts multiplied by 1/2 for this – but on reflection I think the conversion factor for amount to dose may already include it. Anyway, I am not using it.

For the uncertainties

1) amount → dose is more uncertain for bone than lung, 0.2 to 5x
2) RBE is not at issue because the bone risk was derived from alpha exposure
3) Risk to dose is, nevertheless, uncertain by at least 1/2 to 2.

Thus, overall range is ~ 0.1 to 6. The three experts suggested 900 – 8,200 – 73,000.

I propose: 1,800 – 18,000 – 108,000.

Liver

Conversion factor amount/dose 3.9×10^{-5} Sv/Bq
Dose for 10 kBq is 3.9×10^{-1} Sv

Risk, using ICRP 60, 15×10^{-4} Sv^{-1}
$5.9 \times 10^{-4} \times 10^8$ people
6×10^4 deaths lifetime

For 40 y. Little, 1996, Table II has for model set B.

Thus, $6 \times 10^4 \rightarrow 1.7 \times 10^4$ deaths in 40 y. Dose takes ~15 y to arrive in liver and thus, only 25-30 y of the 40 is relevant – thus, divide by 2 said the three experts. I don't want to do this now until I understand better the way in which the dose conversion factors are derived.

Uncertainty in dose taken to be 1/3 to 3 in RBE, because risk is alpha derived.

Risk/dose 1/3 to 3

Thus, combined uncertainty about $\sqrt{3^2 + 3^2} \sim 4$ take it as 1/4 to 4.
Thus, 4,000 – 17,000 – 68,000 (different from the three experts) at 1,900 – 9,000 – 43,000

$$\left(\frac{1}{4.7} \times 4.7\right)$$

Leukemia

Conversion, amount/dose 9.1×10^{-6} Sv/Bq, amount 10 kBq, dose 9.1×10^{-2} Sv, risk 0.50×10^{-2} Sv^{-1} lifetime for low LET but high LET RBE for leukemia (thorotrast data – Danish studies 1993-1994 see UNSCEAR, 1994) is only about 1-3 instead of 20. Say 2 for RBE or 10x less than for other endpoints.

Thus, risk is not 0.5×10^{-2} Sv^{-1} but 0.05×10^{-2} Sv^{-1}, $9.1 \times 10^{-2} \times 0.05 \times 10^{-2} \times 10^8$ people 4.5×10^4 or 4,500 deaths. The three experts said, no correction for lifetime to 40 y (correct!) but in dose vs. time, latency is shorter and thus, divide by 2. I don't understand this now, so I won't divide by 2.

Central estimate stands at 4,500 deaths.

Uncertainties

Dose	1/3 to 3
RBE	1/3 to 3
Risk/dose	1/2 to 2 but no projection and transfer good thus, instead of 1/2 to 2, 1/1.75 to 1.75

Combine all three to roughly 1/5 to 5.

900 – 4,500 – 22,500

(The three experts had 360, 1800, and 6900.)

All Cancer

Since lung, bone, liver and leukemia are the only sites of cancer induced by plutonium α's, simply add these up for all cancers!

41,000 – 249,500 – 1,420,000

(The three experts had 34,000 – 150,000 – 650,000)

B. Strontium 90

Lung

Amount/dose, ICRP 71, 2.1×10^{-7} Sv/Bq
Dose for 10 kBq = 2.1×10^{-3} Sv
Risk per Sv = 0.85×10^{-2}
Risk for amount administered = 1.8×10^{-5} in 10^8 people, i.e., 1,800 cancer deaths.

This is a lifetime result, for 40 y use Little 1996 Table II for model set B

$$\frac{1.278}{5.183} = 0.247$$

450 cancer deaths in 40 y

Uncertainties

1.	Dose	$\frac{1}{2.5}$ to 2.5x after discussion
2.	RBE	1 no uncertainty
3.	Risk/dose	1/2 to 2

overall $\frac{1}{3.2}$ to 3.2x

for lung, 140 – 445 – 1400 (same as the three experts).

Bone

Conversion, amount to dose (ICRP 71) 1.6×10^{-7} Sv/Bq
Amount 10 kBq, dose 1.6×10^{-3} Sv
Risk, for isotope uniformly distributed in bone, is 0.05×10^{-2} Sv^{-1}
Risk is 0.08×10^{-5} for 10^8 people 80 cancer deaths – central

Uncertainties

1.	Dose/amount	1/2 to 2
2.	RBE = 1	1 to 1
3.	Risk/dose	1/3 to 3 given risk is from a β emitter overall 1/4 to 4

Thus, 20 – 80 – 320 compared with (the three experts) = 20 – 80 – 280

Leukemia

Conversion, amount to dose (ICRP 71) 7.1×10^{-8} Sv/Bq
Dose, for amount 10 kBq, = 7.1×10^{-4} Sv
Risk/unit dose, 0.5×10^{-2} Sv^{-1}
Risk 3.6×10^{-6}
Number of deaths in 10^8 people = 360

Uncertainty factors

1.	Dose/amount	1/2 to 2
2.	RBE	1
3.	Risk/dose	$\frac{1}{1.75}$ to 1.75
	combination	$\frac{1}{2.6}$ to 2.6

140 – 360 – 940 (the three experts have 160 – 360 – 800)

All Cancer

Sum of lung, bone, leukemia – no other Sr^{90} sites.

Result 300 – 900 – 2,700 (the three experts have 320 – 880 – 2,500).

Question VI

UNSCEAR 1994, Annex A, discusses the question of prenatal exposure (paras. 139-145) page 36-37. They give only one risk estimate, viz. 5×10^{-2} Sv^{-1} for all childhood cancers in the first 14 years. They do not give a separate figure for childhood leukemia but somewhere I seem to remember that about half of childhood cancers are leukemias. Furthermore, the relative risks for solid tumors and for leukemia are about the same, 1.4. Thus, of the 5×10^{-2} Sv^{-1} risk, half is due to leukemias and half due to solid tumors. This enables us to get 50% values of $5 \times 10^{-2} \times 10^8$ persons = 5,000,000 cancers total = 2,500,000 leukemias.

Uncertainty? It is certainly doubtful whether there is actually a significant risk and, thus, the 5% level is 0. As for the 95% end, if indeed there were a large factor, like 5 over the central value yielding a very large risk of 25×10^{-2} Sv^{-1} which would surely be very detectable – it hasn't been. Thus, I think a factor of 2 is as much as one can put on the high end.

So all cancer	0 – 5,000,000 – 10,000,000
leukemia	0 – 2,500,000 – 5,000,000

Reasonable only in that we know very little – this is one of the least known of all exposure problems – the risk to the fetus.

Question VII

This is a very vexing problem because the most recent information on prenatal exposure (UNSCEAR 1994 and other references therein) do not show excesses of adult cancers for those exposed in utero. They may still do so but not for adult leukemia, for example, where I suppose we must consider the risk over by now. For solid tumors there is still a possibility of cancer rates as great as those in the youngest group of postnatal individuals. These are often said to be, again really believed to be, because the evidence is very poor, twice the average population risk of 5×10^{-2} Sv^{-1}, i.e., 10×10^{-2} Sv^{-1}. If so, the central estimate would be 10,000,000 cancers after 1 Sv in 10^8 people. The 5% could still be 0 – since we haven't seen any. On the high end, again, the high value of the risk already, although perhaps with a long latent period, makes me hesitate to increase the high end by more than a factor of 2. It is unreasonable, in my view, to expect to see such a high rash of cancers after more than 40 years when we don't have an excess yet.

Thus, 0 – 10,000,000 – 20,000,000
add childhood leukemia 0 – 2,500,000 – 5,000,000
and childhood solid cancers 0 – 2,500,000 – 5,000,000

0 – 15,000,000 – 30,000,000

Question X

There are no cancers induced by 1 mGy (or any other dose) of plutonium alpha particles over 1 year or any other time because Pu alphas do not reach the basal cell layer and cause skin cancer.

Question XIII

In my opinion, the most important dose response relationships show a fairly clear continuum in almost all cases, so whether the response is actually linear or not at low doses, I think it is very likely to be non-threshold. Indeed, it is up to threshold proponents to say where they think the threshold is. Almost in variably they do not do so. I think there are no threshold values to go in this table.

Furthermore, at the lowest doses, if one believes in a biophysical mechanism involving only 1 ionizing cluster and one cellular change, no matter what follows thereafter, there should initially be a linear response, because when the dose is increased from very low values the only thing that happens is that more cells are at risk for a single event and thus, a cancer is more likely and proportionally more likely.

The last question requests estimates of excess relative risk for the number of tumors at different sites to be expected in 1991-1995!

The range is taken from my summary of the ranges used for all organ sites in the answer to Question (XII).

Note: The question requests estimated ERR values for the period 1991 to 1995 rather than 1950-1995. But I do not have specific time period information in that form even for the draft of report 12. What I do have suggests that the ERRs for the time period 1986-90 are not sensibly different from those for 1950-1990. This is borne out by Table 3 above for ERRs 1950-1985, ERRs 1950-1987 and ERRs 1950-1990 which, allowing for variations here and there in organ site, show rather little change. This can only be so if the ERR during the latest period is about the same as before it.

Consequently, I have "guesstimated" the value of ERR_e as applying either to 1950-1995 or 1991 to 1995. In this "guesstimation" I have rounded the 50% values from what goes before – and not increased them, because although ERRs have tended still to rise a little with time up to now, we have used a constant ERR model mainly. However, I think we can expect that to begin to fall off a little – thus, I would tend to make the expected ERR about the same or a little lower than before.

Table 3. Estimates of ERR/Sv Over Recent Times

	ERR_a	ERR_b	ERR_c	ERR_d	ERR_e	Range
Colon	0.72	0.85	0.52	0.65	0.6	$\frac{1}{20}$ to 4x
Breast	1.24	1.19	1.3	1.4	1.2	$\frac{1}{3}$ to 3x
Leukemia	4.00	5.2	5.1	4.6	4.6	$\frac{1}{1.75}$ to 1.75
Liver	0.14	0.12	0.46	0.29	0.3	$\frac{1}{3}$ to 3
Lung	0.48	0.63	0.60	0.53	0.5	$\frac{1}{3}$ to 3
Pancreas	-0.15	-0.11	--	-0.07	-0.1	0 to 5x
Stomach	0.28	0.27	0.22	0.24	0.25	$\frac{1}{4.4}$ to 3x
Solid Tumors	0.36	0.41	0.45	0.40	0.40	$\frac{1}{2}$ to 2x

ERR_a given on page 13 as nominally from Shimizu et al., 1988
ERR_b, Shimizu et al., 1988, Table 4
ERR_c, Ron et al., 1994, Table VII
ERR_d, 1994 draft of report 12 (Pierce et al., 1996)
ERR_e, my estimate of ERR to be expected for 1950-1995

Summary

It is useful to compare the central estimates of risk that have been derived here for each organ by absolute risk, relative risk and the ICRP estimates. These are given for lifetime estimates for each organ in Table 4. Lifetime is the only real comparison that can be made with the ICRP values widely used in radiation protection.

In general agreement is quite good between absolute risk values (greatly preferred by me) and relative risk values. The worst cases (e.g., stomach) are those in which transfers from high incidence populations to a low incidence population.

Agreement between the absolute risk and the ICRP values is very good, indeed in about all cases and well within the ranges given.

An important agreement also is that by absolute risk the sum of all the (separate organ and all other cancer) is very close to the result obtained for all cancer. This would argue against any correlations or dependencies between individual tumor site estimates.

Table 4. Summary – Number of Deaths – Lifetime (per Sv) in 10^8 people

Site	Absolute Risk	Relative Risk	ICRP	Range
Bone	50,000	6,000	50,000	1/5 to 5x 1/3 to 3x (revised)
Colon	700,000	730,000	1,700,000	1/20 to 4x
Breast	620,000	1,550,000	400,000	1/3 to 3x
Leukemia	1,050,000	2,000,000	1,000,000	$\frac{1}{1.75}$ to 1.75x
Liver	1,300,000	575,000	300,000	1/3 to 3x
Lung	1,200,000	2,500,000	1,700,000	1/3 to 3x
Pancreas	270,000	115,000	---	0 to 5x
Skin	50,000	20,000	40,000	0 to 5.4x
Stomach	2,500,000	150,000	2,200,000	$\frac{1}{4.4}$ to 3x
Thyroid	190,000	40,000	160,000	1/3 to 3 1/4 to 4x (revised)
All other	4,600,000	6,700,000	2,400,000	1/4 to 3
All cancer	13,300,000	7,750,000	10,000,000	1/2 to 2
(Sum of bone to all other)	12,530,000			

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Question 1. The number of radiation-induced cancer deaths up to 20 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	12,000	35,000	105,000
Colon	3,000	56,000	220,000
Breast	22,000	67,000	200,000
Leukemia	480,000	850,000	1,500,000
Liver	48,000	144,000	430,000
Lung	62,000	190,000	570,000
Pancreas	0	22,000	110,000
Skin	0	3,500	19,000
Stomach	40,000	190,000	570,000
Thyroid	4,500	18,000	72,000
All other cancers	100,000	520,000	1,200,000
All cancers	680,000	1,350,000	2,700,000

Question 2. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	17,000	50,000	150,000
Colon	10,000	200,000	800,000
Breast	80,000	240,000	720,000
Leukemia	570,000	1,000,000	1,800,000
Liver	160,000	480,000	1,400,000
Lung	230,000	700,000	2,100,000
Pancreas	0	80,000	400,000
Skin	0	12,500	68,000
Stomach	160,000	700,000	2,100,000
Thyroid	15,000	60,000	240,000
All other cancers	360,000	1,440,000	4,300,000
All cancers	2,500,000	5,000,000	10,000,000

Question 3. The number of radiation-induced cancer deaths over a lifetime (following the population up until it has become extinct) in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	17,000	50,000	150,000
Colon	35,000	700,000	2,800,000
Breast	207,000	620,000	1,870,000
Leukemia	600,000	1,050,000	1,850,000
Liver	430,000	1,300,000	3,800,000
Lung	580,000	1,800,000	5.250,000
Pancreas	0	270,000	1,400,000
Skin	0	50,000	270,000
Stomach	580,000	2,500,000	7,600,000
Thyroid	47,500	190,000	760,000
All other cancers	1,150,000	4,600,000	13,800,000
All cancers	6,800,000	13,300,000	27,000,000

Question 4. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 years) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Breast	69,000	206,000	618,000
Leukemia	300,000	500,000	940,000
Thyroid	30,000	120,000	220,000
All cancers	1,550,000	3,100,000	6,200,000

Question 5. The number of radiation-induced cancer deaths over a lifetime (following the population up until it has become extinct rather than up to 40 years following exposure) in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 years) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Breast	435,000	1,300,000	3,900,000
Leukemia	320,000	570,000	1,000,000
Thyroid	95,000	380,000	1,500,000
All cancers	17,500,000	34,600,000	70,000,000

Question 6. The number of radiation-induced cancer deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure of a dose of 1 Gy low LET (= gamma) radiation administered uniformly over their three trimesters (9 months) *in utero* and followed-up for 20 years after birth.

	Quantile		
	5%	50%	95%
Leukemia	0	2,500,000	5,000,000
All cancers	0	5,000,000	10,000,000

Question 7. The number of radiation-induced cancer deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure of a dose of 1 Gy low LET (= gamma) radiation administered uniformly over their three trimesters (9 months) *in utero* and followed over a lifetime (following the population up until it has become extinct rather than up to 20 years following exposure).

	Quantile		
	5%	50%	95%
Leukemia	0	2,500,000	5,000,000
All cancers	0	15,000,000	30,000,000

Question 8. The number of radiation-induced cancer cases (fatal and non-fatal) up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	33,000	100,000	300,000
Colon	18,000	360,000	1,500,000
Breast	240,000	720,000	2,160,000
Leukemia	840,000	1,500,000	2,600,000
Liver	530,000	1,000,000	4,600,000
Lung	270,000	830,000	2,480,000
Pancreas	0	90,000	450,000
Skin	0	1,200,000	6,300,000
Stomach	220,000	980,000	2,900,000
Thyroid	150,000	600,000	2,400,000
All other cancers	680,000	2,700,000	8,100,000
All cancers	5,400,000	10,800,000	21,600,000

Question 9. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 year (rather than 1 minute).

	Quantile		
	5%	50%	95%
Bone	17,000	50,000	150,000
Colon	5,000	100,000	400,000
Breast	40,000	120,000	360,000
Leukemia	82,000	500,000	1,400,000
Liver	80,000	240,000	700,000
Lung	120,000	350,000	1,050,000
Pancreas	0	40,000	200,000
Skin	0	6,000	34,000
Stomach	80,000	350,000	1,050,000
Thyroid	7,500	30,000	120,000
All other cancers	180,000	720,000	2,150,000
All cancers	1,250,000	2,500,000	5,000,000

Question 10. The number of radiation-induced skin cancer cases (fatal and non-fatal) up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a uniform skin dose of 1 mGy high LET (= plutonium alpha particle) radiation at a uniform rate over 1 year.

	Quantile		
	5%	50%	95%
Skin	0	0	0

Question 11. Joint dosimetry/late effects question: The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each of whom inhales 10 K Bq of the radionuclides specified.

Nuclide	Physical Form	Chemical Form	Cancer Type	Number of Cancers Quantile		
				5%	50%	95%
Pu-239	1 μm AMAD	Oxide	Lung	35,000	210,000	1,220,000
			Bone	1,800	18,000	110,000
			Liver	4,000	17,000	68,000
			Leukemia	900	4,500	22,500
			All cancers	42,000	250,000	1,400,000
Sr-90	1 μm AMAD	Oxide	Lung	140	450	1,400
			Bone	20	80	320
			Leukemia	140	360	940
			All cancers	300	900	2,700

Question 12. Given that radiation induced cancer death due to the specified cause has occurred as a result of a dose of radiation delivered over 1 minute, the average expected length of life lost in years, for a population followed up to extinction after exposure.

	Quantile		
	5%	50%	95%
Bone	0.008	0.025	0.075
Colon	0.007	0.143	0.57
Breast	0.081	0.243	0.73
Leukemia	0.122	0.213	0.37
Liver	0.003	0.010	0.03
Lung	0.200	0.600	1.800
Pancreas	0	0.039	0.117
Skin	0	0.010	0.03
Stomach	0.007	0.030	0.09
Thyroid	0.002	0.008	0.032
All other cancers	0.08	0.32	0.96
All cancers	0.82	1.64	3.28

Question 13. For each of the cancer sites listed, give the estimate of the threshold dose in Gy, for low LET (= gamma) radiation administered at a uniform rate over 1 minute, below which value there is no radiation-induced cancer risk.

	Quantile		
	5%	50%	95%
Bone	There are no threshold values for any of the cancers.		
Colon			
Breast			
Leukemia			
Liver			
Lung			
Pancreas			
Skin			
Stomach			
Thyroid			
All other cancers			
All cancers			

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Uncertainties In Radiogenic Cancer Risk Estimates

Nominal estimates of risk were calculated based on model assumptions and risk coefficients derived from epidemiological studies of radiation exposed populations. For most cancer types (bone, breast, leukemia, stomach, colon, skin, and all cancers) the nominal estimate of lifetime mortality risk for the general population, at an acute dose of 1 Gy, was taken from an EPA report (EPA, 1994). The basis for the bone and skin risk models used in that report were studies of medically irradiated populations. The basis for most of the others was data from the Life Span Study (LSS) of the Japanese atomic bomb survivors. The thyroid and breast cancer models were derived primarily from data on medically irradiated cohorts, but supplemented with data on the atomic bomb survivors. For liver, pancreas, and "all other cancers," the nominal estimate for lifetime mortality was taken from tables provided by Dr. Mark Little* that he derived from LSS data. For this purpose, Little's constant relative risk model projections (Model B) were selected.

Unless otherwise specified, to obtain nominal site-specific estimates of general population risk for the periods 20 years and 40 years after exposure the respective nominal risk estimates were scaled using Little's Model B tables. For example, to obtain the nominal estimate of colon cancer mortality risk to the general population for the 40 year period after exposure, the nominal estimate for lifetime mortality risk from the EPA report was multiplied by the ratio of Little's Model B projection of colon cancer mortality risk for 40 years following exposure to his corresponding lifetime projection.

The uncertainty in each nominal estimate was then treated as arising from various sources, such as sampling errors in the epidemiological data, the temporal projection of epidemiological results beyond the period of follow-up, the "transport" of risk estimates from the bomb survivors to the Western population of interest, errors in the estimates of dose for the epidemiological studies, and the extrapolation to low doses and dose rates. For each source of uncertainty, a probability distribution was assigned that reflected the possible multiplicative error in the nominal estimate due to that source. The assignment of these distributions often involved subjective judgment. The various sources of uncertainty were then treated as mathematically independent and combined through a Monte Carlo procedure to obtain a distribution of the overall uncertainty in each risk estimate. It is recognized that the assumption of independence is not always valid; e.g., the error due to sampling and the uncertainty in temporal projection are correlated, both being enhanced for childhood exposures. Some adjustments have been made to reflect these correlations.

Colon, Lung, and Stomach

The procedure for estimating uncertainty for these three organs was identical. Each of the nominal estimates reflects the result of a life table calculation based on the "GMC model" projection and 1980 U.S. vital statistics (EPA, 1994). The GMC model makes use of relative risk coefficients derived from the LSS, adopting a geometric mean of age specific coefficients for ICRP's "multiplicative" and "NIH" projection models (Land and Sinclair, 1991; EPA, 1994; Puskin and Nelson, 1995).

To estimate the uncertainty distribution in lifetime mortality for each site, four sources of uncertainty were considered: (1) sampling errors; (2) temporal projection; (3) transportation uncertainty; and (4) dosimetric uncertainty.

(1) Sampling Errors

Ninety percent confidence bounds on the age-averaged relative risk coefficient for each site are provided in RERF's LSS Report 11 (Shimizu et al., 1987). For each of the organs, a normal distribution was constructed that produced the same relative widths as given by the RERF report. This approach is likely to understate the uncertainty in lifetime risk due to sampling errors since it does not reflect the larger uncertainties in age-specific risk coefficients. In particular, the sampling errors are generally larger for those exposed as children, a subgroup accounting for a disproportionate share of the population risk. However, for childhood exposures, temporal projection generally constitutes the dominant source of uncertainty. As noted below, the uncertainty due to temporal projection has been widened slightly to reflect the relatively large sampling error associated with estimated childhood exposure risk coefficients.

(2) Temporal Projection

The LSS data show evidence of a decrease in relative risk with time after exposure. Little et al. (1991) have found that

* M. Little. 1996. Memorandum (January 23, 1996), "Scoping Cancer Risks," sent to all members of the CEC/US NRC Somatic Health Effects Panel. Little's memorandum has been included in Appendix B of this volume.

a model reflecting this apparent fall-off produces a lifetime risk estimate about 40% lower than a constant relative risk model. Reflecting also the rather large sampling errors associated with childhood exposures, an uncertainty range of 0.5 to 1.2 has been adopted for this source of uncertainty in the lifetime risk estimate. The shape of the distribution has been taken to be uniform in this interval: U(0.5, 1.2).

(3) Transportation Uncertainty

An upper (lower) bound on the "transportation uncertainty" for each site was obtained by choosing the respective multiplicative or NIH projection, whichever is higher (lower). The shape of the uncertainty distribution was taken to be loguniform over the range calculated in this way. For example, in the case of stomach, the risk model projections are: 29.3 (mult.), 274 (NIH), and 88.7 (GMC). The lower and upper bounds in the uncertainty distribution are then 29.3/88.7 and 274/88.7, respectively. Thus to account for the uncertainty due to transportation of the risk estimates from the LSS to the U.S. population, the nominal estimate is multiplied by the loguniform distribution LU(0.33, 3.1).

(4) Dosimetric Uncertainties

Uncertainties in the Hiroshima/Nagasaki dose estimates provided in Dosimetry System of 1986 (DS86) arise in several ways: random errors in dose estimation, possible bias in DS86 gamma ray estimates, uncertainty in survivor shielding characterization, uncertainty in neutron relative biological effectiveness (RBE), and possible bias due to the apparent presence of thermal neutrons at Hiroshima in excess of those predicted by DS86 (NCRP, 1997). It has been estimated that the combined uncertainty due to these factors results in a correction factor of about 0.84 with a standard deviation of 0.11 (NCRP, 1997). Accordingly, the distribution N(0.84, 0.11) has been assigned to this source of uncertainty.

Table 1 lists the nominal lifetime risks and the uncertainty factors that multiply the nominal estimate for each site.

Following *ICRP Publication 60* recommendations (ICRP, 1990), the distributions for cancer incidence were obtained assuming cancer lethalities of 50%, 100%, and 100%, respectively, for colon, stomach and lung. Possible errors in these values were neglected in the analysis. The uncertainty distribution for the dose and dose rate effectiveness factor (DDREF) was taken to be trapezoidal, with a probability constant over the interval $1 \leq \text{DDREF} \leq 2$, decreasing linearly to zero over the interval $2 < \text{DDREF} \leq 4$, and zero elsewhere. This distribution will be denoted as T*(1, 1, 2, 4).

Liver, Pancreas, and "All Other Cancers"

The analyses for liver, pancreas, and "all other cancers" were handled very similarly to stomach, colon, and lung, with the exceptions and special considerations described below.

The nominal estimates of lifetime mortality were taken directly from Little's (Model B) tables.

Sampling errors were estimated from a cancer incidence study of the atomic bomb survivors (Thompson et al., 1994). Based on the 90% confidence intervals published by those authors, the uncertainty distributions due to sampling were approximated by lognormal distributions: LN(geometric mean (GM) = 0.78, geometric standard deviation (GSD) = 1.55) for liver and LN(1.0, 2.1) for pancreas. The stated distribution for pancreas is not appropriate at the low end, however. The excess of pancreatic cancer is not statistically significant; accordingly, the 5% value on the risk is judged to be zero for pancreatic cancer. We were unable to find an estimate of the sampling uncertainty in the estimate for the class of "all other cancers," as defined by the list of specified cancers. However, since the projected number of these cancers is similar to that projected for colon, it seems reasonable to suppose that the sampling error would also be similar. Thus the same uncertainty distribution due to sampling errors for colon has been applied to the pancreas, i.e., N(1.08, 0.35).

According to SEER data (Ries et al., 1997) pancreatic cancer accounts for 5.0% for all cancer deaths in the U.S., as compared with 3.6% in the LSS (Shimizu et al., 1987). The corresponding figures for liver are 2.2% and 3.6%. Based on these figures, the transportation uncertainties are taken to be: LU(0.7, 1) for pancreas and LU(1, 1.6) for liver. Based on an examination of the tables in the EPA report (EPA, 1994), the multiplicative model is likely to project somewhat more cancers for the "all other" category than the NIH model. The transportation uncertainty for this category is assumed to be distributed as LU(0.67, 1.2).

For liver or pancreas, incidence was taken to be equal to mortality. For "all other," the incidence/mortality was treated as an uncertain quantity with a triangular distribution, T(1.3, 1.5, 2.0), confined to the interval between 1.3 and 2.0, and peaked at 1.5.

Table 1.

Organ	Nominal Risk	Sampling	Transport	Dosimetry	Temporal
Stomach	8.87×10^{-3}/Gy	N(1.07, 0.31)	LU(0.33, 3.1)	N(0.84, 0.11)	U(0.5, 1.2)
Lung	1.43×10^{-2}/Gy	N(1.05, 0.29)	LU(0.55, 1.9)	N(0.84, 0.11)	U(0.5, 1.2)
Colon	1.04×10^{-3}/Gy	N(1.08, 0.35)	LU(0.55, 1.94)	N(0.84, 0.11)	U(0.5, 1.2)

Leukemia

The nominal leukemia mortality risk estimate for an acute high dose of low-LET radiation is 9.9×10^{-3}/Gy (EPA, 1994). According to Little's tables, the leukemia risk from childhood exposures is 54.4% of the general population risk. Scaling the EPA nominal risk estimate by this factor, a nominal estimate of 5.4×10^{-3}/Gy for childhood exposures is obtained.

From the LSS (Shimizu et al., 1987), sampling uncertainty can be approximated by the normal distribution, N(1.0, 0.11). Based on incidence data published by Preston et al. (1994), a larger standard deviation (sigma = 0.2) was used for the case of childhood exposures. Although the multiplicative and NIH projection models yield similar quantitative results, there is significant transportation uncertainty in light of differences in rates of specific types of leukemia between the U.S. and Japan. A normal distribution N(1.0, 0.15) has been assigned to the transportation uncertainty. The relatively low neutron shielding of the bone marrow implies a slightly greater possible bias in dose estimates for bone marrow compared to most other organs. In view of this difference, the distribution for dosimetric uncertainties, N(0.8, 0.15), is shifted downward and broadened compared to that for the organs above. Although we have essentially complete follow-up for leukemia in the LSS, beginning in 1950, there is uncertainty in the extrapolation of model projections back to the first five years after exposure. A temporal uncertainty factor N(1.0, 0.07) has been introduced to account for this uncertainty.

It is often assumed for risk assessment purposes that leukemias are essentially 100% fatal. This may have been true for the period before 1970 in which the LSS leukemias were concentrated. However, an appreciable fraction of leukemias are now curable—perhaps about 60% for children, and 15% for the general population. For general population risk, therefore, an uncertainty factor of U(0.8, 0.9) was applied for estimating mortality risk. (This factor was omitted when calculating the distribution of uncertainty for incidence). Noting that a sizeable fraction of the leukemias induced by childhood exposures will actually appear in early adulthood, when they would presumably be less curable, the uncertainty distribution associated with lethality for leukemias induced through childhood exposures is assumed to be N(0.65, 0.1).

Based on Little's tables, the 20-yr and 40-yr leukemia projections were equated to 100% and 85% of the lifetime projection, respectively. LSS leukemia data show upward curvature in the dose response function, indicative of a DDREF of about 2. The probability distribution for the DDREF was assumed to be lognormally distributed with a GM of 2.0 and a GSD of 1.4.

Breast

Using the "multiplicative projection model" derived from the LSS data (Land and Sinclair, 1991), for an acute dose of 1 Gy, the lifetime breast cancer mortality risk in the 1980 U.S. life table population is 1.16×10^{-2} (EPA, 1994). Given the higher rates of breast cancer in the U.S. compared to Japan, the "NIH projection" is considerably lower, 3.3×10^{-3} (EPA, 1994). Epidemiological studies of medically irradiated women suggest that the NIH projection is probably more accurate in this case. These studies also seem to indicate that little or no reduction in risk occurs when doses are fractionated. However, the sampling errors associated with these studies are considerably higher than for the LSS.

The EPA estimate of general population lifetime breast cancer risk was derived using a model developed by Gilbert, primarily based on a Canadian fluoroscopy study (EPA, 1994; Gilbert, 1991; Miller et al., 1989). The calculated risk was 4.6×10^{-3} per person-Gy, which was employed here as the nominal estimate for lifetime mortality. In view of the reasonable agreement between studies of breast cancer induction by radiation—including the agreement between studies of the atomic bomb survivors and medically irradiated populations—the overall uncertainty associated with the epidemiological data is judged to be about a factor

of 2, up or down. We have reflected this uncertainty by a multiplicative uncertainty factor LN(1.0, 1.4).
In projecting lifetime risk for the general population, we have also incorporated an uncertainty factor U(0.5, 1.0) to reflect the possible fall-off in relative risk with time after exposure. The nominal 40-yr and 20-yr mortality estimates were obtained by scaling the lifetime estimates, using the tables supplied by Little. These values were, respectively, 1.4×10^{-3} and 3.5×10^{-4} per person-Gy. The uncertainties in these values were obtained through application of the epidemiological uncertainty factor LN(1.0, 1.4), given above. The temporal projection uncertainty for the 40- and 20-yr estimates is presumed to be small since the Canadian fluoroscopy study and the LSS reflect about 40 years of follow-up.

Again using Little's tables for scaling purposes, the nominal estimates of risk (per person-Gy) for childhood exposures are 1.3×10^{-3} (40-yr projection) and 1.25×10^{-2} (lifetime projection). In calculating the uncertainty in these values, an additional uncertainty factor LN(1.0, 1.2) was incorporated to reflect the higher degree of epidemiological uncertainty associated with childhood exposures. The overestimation in temporal projection is also potentially greater, and the factor U(0.45, 1.0) was used to reflect the uncertainty in temporal projection for the lifetime estimate of risk due to childhood exposures.

The nominal estimate of 40-yr incidence was set equal to twice the 40-yr mortality estimate. A triangular distribution T(0.8, 1.0, 1.2) was applied, in addition to the epidemiological uncertainty distribution, to reflect uncertainty in the lethality of breast cancer.

The nominal estimates were derived assuming a DDREF = 1. The model employed was primarily developed from data on highly fractionated exposures (fluoroscopy studies), but supported by data on acute exposures (LSS studies). Thus, it is difficult to separate the DDREF uncertainty from what has been referred to above as epidemiological uncertainty. As noted above, there appears to be little difference in low dose rate and high dose rate risks, but the estimates generated here are possibly more reliable for the low dose rate exposure case.

Thyroid

Ron et al. (1995) have published a pooled analysis of epidemiological studies of thyroid cancer by external radiation. For childhood exposures the excess relative risk per gray (ERR/Gy) was 7.7. Based on the 95% confidence interval given by Ron et al., the uncertainty distribution on this value is approximated by a lognormal with a GSD of 1.92. The width of the distribution reflects not only sampling errors, but also differences in the study populations and possible biases in the epidemiological studies. Thus, for example, although we shall treat this uncertainty analogously to the sampling errors for other sites, it reflects the transportation uncertainty, and perhaps other uncertainties as well.

Included among the cohorts analyzed by Ron et al. were the atomic bomb survivors. The ERR/Gy for this cohort was 61% of the pooled estimate. To obtain nominal estimates of thyroid cancer mortality risk, we have used the values given in Little's (Model B) tables, which were derived from LSS mortality data, but have divided each of them by 0.61 to reflect the somewhat lower ERR/Gy seen in the atomic bomb survivor incidence data compared with the pooled estimate from all studies.

For the 20-yr and 40-yr high dose rate mortality estimates, the uncertainty distribution was assumed to be lognormally distributed about the nominal estimate with a GSD = 1.92. [It might be questioned whether the scaling factor and GSD derived from data on childhood exposures is appropriate for the general population. A justification for this procedure is that thyroid risk decreases rapidly with age at exposure, so childhood exposures account for a substantial fraction of the population risk.]

For the lifetime estimates of risk, an additional uncertainty factor was incorporated to account for the uncertainty in temporal projection. Based on the range of thyroid model projections computed by Little, an uncertainty factor of U(0.5, 1) was assigned to the temporal projection for the general population; for children, this uncertainty factor was U(0.35, 1).

It is expected that about 10% of all radiation-induced thyroid cancers will be fatal (NCRP, 1985). The 5%, 50%, and 95% probability points on the cumulative distribution for 40-yr incidence were obtained by multiplying the corresponding values on the 40-yr mortality distribution by 10.

To estimate the uncertainty in mortality through 40 years following a chronically delivered dose of 1 Gy, an additional uncertainty factor was introduced for the DDREF, which divides the nominal estimate. This source of uncertainty was assigned a triangular distribution, T(1, 1,

3), which is maximal at a DDREF of 1 and decreases linearly to zero at a DDREF of 3.

Bone

The basis for bone cancer risk estimates are epidemiological studies of patients injected with the alpha-emitter, radium-224. Based on a nominal alpha-particle RBE of 10 relative to acute low-LET exposures, the nominal estimates of lifetime incidence and mortality risk are 2.6×10^{-4} and 1.8×10^{-4}, respectively, for an acute gamma ray dose of 1 Gy (EPA, 1994). Since bone cancer risk has a limited expression period, we can equate the 40-yr estimates to the lifetime estimates; the 20-yr estimates were taken to be 20% lower.

In addition to usual sampling errors in the epidemiological data, estimates of the ERR/Gy for bone cancer induction by low dose rate alpha-irradiation are subject to uncertainties in dosimetry and in the magnitude of the inverse dose rate effect for high-LET radiation, which are difficult to quantify. In this analysis, the combined uncertainty due to these factors was assigned a GSD of 2.3.

Also to be considered is the uncertainty in alpha-particle RBE. Relative to acute, high dose, low-LET radiation, the uncertainty distribution for the RBE was assumed to be lognormally distributed about a geometric mean of 8, with a GSD = $2^{1/2}$, corresponding to a 95% uncertainty range of 4 - 16. Relative to chronic, low dose, low-LET radiation the 95% uncertainty range is judged to be 5 - 40. The uncertainty distribution for the RBE applied to chronic low-LET case was taken to be lognormal with a GM = $(200)^{1/2}$ = 14.14 and a GSD = $(40/5)^{1/4}$ = 1.682.

Since the risk for low-LET is inversely related to the alpha-particle RBE, it follows from the figures above that, for high dose rates, the nominal estimate is multiplied by an uncertainty factor LN(GM = 1.25, GSD = 2.46). For low dose rates the combined uncertainty distribution has a GM = 0.707 and a GSD = 2.67.

Skin

The nominal estimate of lifetime skin cancer mortality, 2×10^{-4}/Gy, is taken from *ICRP Publication 59* (ICRP, 1992). This estimate is predicated on: a constant relative risk model, with the risk coefficient derived from studies of young irradiated populations, and an assumed 0.002 lethality for radiation-induced skin cancers. Using Little's tables as a guide, nominal estimates for 40 years and 20 years, respectively, were obtained by dividing the nominal lifetime estimate by factors of 6 and 20, yielding a 40-yr estimate of 3×10^{-5}/Gy and a 20-yr estimate of 1×10^{-5}/Gy. The nominal 40-yr incidence estimate was assigned a value 500 times the 40-yr mortality estimate.

The assumption of 0.2% mortality is probably an overestimate since it presumes that, like UV-induced skin carcinomas, about 20% of those induced by ionizing radiation are squamous cell (SCC) rather than basal cell (BCC), whereas the epidemiological data suggest that only about 5% are SCC (ICRP, 1992). To reflect this uncertainty, each estimate of mortality was multiplied by the lognormal distribution LN(GM = 0.25, GSD = 2.0).

The use of an ERR coefficient derived from data on irradiated children might bias risk estimates upward by a factor of roughly 2. To reflect this uncertainty, the 20- and 40-yr estimates of mortality (or incidence) were multiplied by the loguniform distribution LU(0.5, 1.0). The lifetime projection also neglects any fall-off in relative risk with time after exposure, which could produce about another factor of 2 overestimate in risk. Consequently, in the case of lifetime expression, an uncertainty distribution of the form LU(0.25, 1.0) was employed to account for age and temporal uncertainties.

Finally, for chronic exposures, it was assumed that the probability for the DDREF is distributed according to the same trapezoidal function T*(1, 1, 2, 4) applied to most other cancer sites.

All Cancers

In the case of an acute exposure of 1 Gy to the general population, the nominal estimate for the lifetime mortality risk from all cancers combined is 9.7×10^{-2} (EPA, 1994). From Shimizu et al. (1987), the standard error in the age-average relative risk coefficient for all solid tumors is about 15% of the mean; consequently, to account for sampling errors, the uncertainty factor N(1.0, 0.15) was applied. An uncertainty factor U(0.5, 1) was applied to reflect the possible fall-off in relative risk with time after exposure, which would imply an upward bias in the constant relative risk models used to generate the nominal estimate for most sites. For some cancer sites, the baseline rates are higher in the U.S. than in Japan; for others, the reverse is true. As a result, the transportation error for all cancers combined is unlikely to be large. Based on some calculations made under differing sets of assumptions regarding the relative applicability of the multiplicative and NIH projection models, it was concluded that the distribution N(1.1, 0.2) provides a reasonable representation of this source of

uncertainty. The uncertainty in the atomic bomb dosimetry again contributes a factor N(0.84, 0.11). Finally, autopsy studies indicate that the relative risk for cancer mortality in the LSS is biased low by about 13% due to errors in medical diagnosis; a fixed multiplicative factor of 1.13 was applied to account for this bias (Sposto et al., 1992).

Using Little's Model B tables to scale from the lifetime mortality estimate, the nominal estimates for 40-yr and 20-yr mortality were determined to be 2.9×10^{-2}/Gy and 1.2×10^{-2}/Gy, respectively. Omitting the uncertainty in temporal projection, the uncertainties in these estimates were calculated in the same way as the lifetime mortality projection described in the previous paragraph.

Scaling once again from the Model B tables, the nominal estimates of mortality risk for those exposed before age 15 are: 1.5×10^{-2}/Gy (40-yr projection) and 2.4×10^{-1}/Gy (lifetime projection). The uncertainties in these values were calculated in the same way as for the general population, except that a larger sampling error was incorporated. From the LSS data, the relative standard error in the estimated ERR/Gy for all solid tumors is about 22% for the 0-19 year age-at-exposure cohort (Preston et al., 1987). An uncertainty factor of N(1.0, 0.22) has been employed here to reflect the sampling errors for childhood exposures (age<15 yr).

A nominal estimate for 40-yr incidence (4.3×10^{-2}/Gy) can be obtained by scaling the EPA (EPA, 1994) high dose rate estimate for incidence of all cancers except nonfatal skin cancers (1.43×10^{-3}/Gy) by the ratio of Model B 40-yr to lifetime mortality projections (3.892/12.988). The uncertainty distribution for this 40-yr incidence was then calculated in the same way as for the 40-yr mortality. The median, 5%, and 95% points on this distribution were then simply added to the corresponding points on the distribution for skin cancer to obtain points on the cumulative distribution for the incidence of all cancers.

The uncertainty in the 40-yr all-cancer mortality at low dose rate was calculated in the same way as for an acute dose, except that the trapezoidal DDREF uncertainty distribution T*(1, 1, 2, 4) was incorporated.

Prenatal Exposure Risk

The nominal estimates of fatal cancer induction over the first 20 years of life due to a chronic *in utero* exposure were derived from an NRPB report (NRPB, 1993). The NRPB estimates that the risk of fatal cancer induction by age 15 is 1.25×10^{-2}/Gy for leukemia and 3.0×10^{-2}/Gy for all cancers combined. These estimates were based on case control studies of the correlation between childhood cancer cases and prenatal x-rays. Although the exposures were generally delivered acutely, the fetal doses were usually very low; consequently, the results are believed to be applicable to the chronic dose case. Presumably, slightly more would be expected over the first twenty years of life; on the other hand, the assumption of a 50% *fatality rate for* childhood cancers appears to be a little high. Consequently, the NRPB values have been adopted here as the median estimates of the 20-yr fatality risks. Noting that the data on exposures during the first trimester of gestation are very sparse, but suggestive of a substantially higher risk, the median values were doubled to obtain the respective 95% values.

The medical x-ray data remains controversial: some epidemiologists believe that the apparent high sensitivity of the fetus results from some sort of subtle confounding. Thus, to construct a 5% risk estimate for leukemia, it was assumed that this data is invalid, and that the actual risk is the same as the median fatal leukemia risk in children. Factoring in a DDREF of 2, a lower bound estimate for the prenatal exposure case is found to be 2.7×10^{-3}/Gy. Leukemias account for more than 1/3 of childhood cancer mortality. If the medical x-ray results are rejected and assuming that the ERR/Gy for solid tumor induction by prenatal exposures is similar to that for childhood exposures, then the risk of radiation-induced solid tumor appearing before age 20 is very small. Therefore, a 5% value of 3×10^{-3}/Gy has been adopted for all cancers combined.

Nearly all of the leukemia risk should be expressed in the first 20 years of life. Hence, the lifetime estimates for leukemia were equated to the 20-yr estimates. It is expected that most of the lifetime risk for solid tumors, and for all cancers combined, will be expressed in adulthood. To obtain the 5% point on the distribution for lifetime mortality from all cancers due to a prenatal exposure, the 5% point on the derived distribution for lifetime risk from all cancers due to an acute childhood exposure was divided by an assumed DDREF of 3. Similarly, the median (95%) point on the childhood exposure distribution was used in conjunction with an assumed DDREF of 2 to obtain the median (95%) estimate for prenatal exposure.

Skin Cancer Risk from Plutonium

One question asked for estimates of risk due to a uniform skin dose of 1 mGy plutonium alpha particle radiation. This poses an unrealistic scenario. Alpha particles emitted by Pu

atoms deposited on the skin will not irradiate the skin uniformly: in fact, the alpha particles will generally not have sufficient range to reach the target cells beneath the outer layer of skin. There may be the possibility of some irradiation of target cells due to penetration of the deposited Pu into pores or breaks in the skin, but the doses should be extremely low. Consequently, I believe that the risk is negligible and have set it equal to zero – even at the lower 5% confidence level.

Years of Life Lost

For most of the cancer types, the radiogenic mortality risk is expected to increase sharply with age at death, roughly in proportion to the increase in baseline rate with age. In particular, it can be deduced from Little's tables that, even if the relative risk coefficient falls off with time after irradiation (Models A and C), the average number of years lost per cancer death increases only slightly from the constant relative risk projection (Model B). The 50% estimate for years of life lost was taken to be the mean of the Model A, B, and C projections (rounded to the nearest 0.5 years). The upper and lower bounds were obtained by slightly broadening the range defined by Little's three model projections.

Bone cancer and leukemia risks fall off dramatically within about 25 years after exposure. Moreover, the baseline mortality rates for these cancers do not rise rapidly with age. As a consequence, the years of life lost per cancer death is expected to be greater for these cancers. Crudely taking into account the temporal pattern of the risk and the somewhat lower (absolute) risk for leukemia mortality associated with childhood, compared to adult, exposures, the years of life lost per cancer death were estimated to be 29 yr for bone cancer and 27 yr for leukemia; the 90% confidence intervals were estimated to be 21-37 yr (bone cancer) and 22-32 yr (leukemia).

Thresholds

In view of the evidence that, even at the lowest doses, radiation produces damage to the DNA which is not correctly repaired, a strict threshold for carcinogenesis appears to be very unlikely. However, from the epidemiological evidence, it remains unclear whether radiation can induce all types of cancers. Specifically, the evidence for radiation induced pancreatic cancer is very weak. Since, in my mind, there is a 5% chance that pancreatic cancer does not arise from radiation, I have ascribed a 5% probability of a "threshold" of infinity for pancreatic cancer. There is compelling evidence for radiogenic cancers at all other sites listed; for these other sites, I have judged that the probability for a nonzero threshold is less than 5%.

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Question 1. The number of radiation-induced cancer deaths up to 20 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	3.30×10^3	1.70×10^4	9.00×10^4
Colon	4.50×10^4	1.20×10^5	2.80×10^5
Breast	2.00×10^4	3.50×10^4	6.10×10^4
Leukemia	3.40×10^5	5.63×10^5	8.60×10^5
Liver	2.00×10^3	4.50×10^3	9.90×10^3
Lung	4.10×10^4	9.70×10^4	2.10×10^5
Pancreas	0	1.40×10^4	5.00×10^4
Skin	3.50×10^2	1.80×10^2	9.20×10^2
Stomach	1.20×10^4	4.00×10^4	1.30×10^5
Thyroid	2.80×10^3	8.20×10^3	2.40×10^4
All other cancers	7.60×10^4	1.80×10^5	3.20×10^5
All cancers	7.50×10^5	1.20×10^6	1.90×10^6

Question 2. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	4.40×10^3	2.20×10^4	1.20×10^5
Colon	1.60×10^5	4.20×10^5	4.50×10^5
Breast	8.00×10^4	1.40×10^5	2.90×10^5
Leukemia	4.00×10^5	6.60×10^5	1.00×10^6
Liver	8.70×10^3	1.90×10^4	4.30×10^4
Lung	1.50×10^5	3.30×10^5	7.20×10^5
Pancreas	0	5.70×10^4	2.00×10^5
Skin	1.00×10^2	5.30×10^2	2.80×10^3
Stomach	4.40×10^4	1.50×10^5	4.70×10^5
Thyroid	1.00×10^4	3.00×10^4	8.60×10^4
All other cancers	2.60×10^5	5.90×10^5	1.10×10^6
All cancers	1.80×10^6	2.90×10^6	4.50×10^6

Question 3. The number of radiation-induced cancer deaths over a lifetime (following the population up until it has become extinct) in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	4.40×10^3	2.20×10^4	1.20×10^5
Colon	5.10×10^5	1.50×10^6	3.60×10^6
Breast	1.80×10^5	3.40×10^5	6.40×10^5
Leukemia	4.00×10^5	6.60×10^5	1.00×10^6
Liver	2.00×10^4	4.90×10^4	1.20×10^3
Lung	4.10×10^5	1.00×10^6	2.40×10^6
Pancreas	0	2.20×10^5	8.20×10^5
Skin	4.30×10^2	2.50×10^3	1.50×10^4
Stomach	1.80×10^5	6.30×10^5	2.20×10^6
Thyroid	3.00×10^4	9.20×10^4	2.80×10^5
All other cancers	7.70×10^5	1.90×10^6	3.90×10^6
All cancers	4.00×10^6	7.30×10^6	1.20×10^7

Question 4. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 years) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Breast	6.00×10^4	1.30×10^5	2.80×10^5
Leukemia	1.40×10^5	2.70×10^5	4.60×10^5
Thyroid	4.50×10^3	1.30×10^4	3.80×10^4
All cancers	7.40×10^5	1.30×10^6	2.20×10^6

Question 5. The number of radiation-induced cancer deaths over a lifetime (following the population up until it has become extinct rather than up to 40 years following exposure) in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 years) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Breast	3.80×10^5	8.90×10^5	2.10×10^6
Leukemia	1.40×10^5	2.70×10^5	4.60×10^5
Thyroid	6.50×10^4	2.10×10^5	6.90×10^5
All cancers	9.10×10^6	1.80×10^7	3.20×10^7

Question 6. The number of radiation-induced cancer deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure of a dose of 1 Gy low LET (= gamma) radiation administered uniformly over their three trimesters (9 months) *in utero* and followed-up for 20 years after birth.

	Quantile		
	5%	50%	95%
Leukemia	2.70×10^5	1.00×10^6	2.00×10^6
All cancers	3.00×10^5	2.40×10^6	4.80×10^6

Question 7. The number of radiation-induced cancer deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure of a dose of 1 Gy low LET (= gamma) radiation administered uniformly over their three trimesters (9 months) *in utero* and followed over a lifetime (following the population up until it has become extinct rather than up to 20 years following exposure).

	Quantile		
	5%	50%	95%
Leukemia	2.70×10^5	1.00×10^6	2.00×10^6
All cancers	3.00×10^6	1.00×10^7	2.00×10^7

Question 8. The number of radiation-induced cancer cases (fatal and non-fatal) up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	6.30×10^3	3.20×10^4	1.70×10^5
Colon	3.20×10^5	8.40×10^5	1.90×10^6
Breast	1.60×10^5	2.80×10^5	4.90×10^5
Leukemia	4.70×10^5	7.70×10^5	1.20×10^6
Liver	8.70×10^3	1.90×10^4	4.30×10^4
Lung	1.50×10^5	3.30×10^5	7.20×10^5
Pancreas	0	5.70×10^4	2.00×10^5
Skin	3.30×10^8	1.10×10^6	3.50×10^6
Stomach	4.40×10^4	1.50×10^5	4.70×10^5
Thyroid	1.00×10^5	3.00×10^5	8.60×10^5
All other cancers	4.10×10^5	9.40×10^5	1.70×10^6
All cancers	2.10×10^6	4.30×10^6	8.90×10^6

Question 9. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 year (rather than 1 minute).

	Quantile		
	5%	50%	95%
Bone	2.30×10^3	1.30×10^4	7.10×10^4
Colon	7.10×10^4	2.10×10^5	5.90×10^5
Breast	8.00×10^4	1.40×10^5	2.40×10^5
Leukemia	1.60×10^5	3.20×10^5	6.60×10^5
Liver	3.70×10^3	9.80×10^3	2.60×10^4
Lung	6.20×10^4	1.70×10^5	4.40×10^5
Pancreas	0	2.90×10^4	1.10×10^5
Skin	4.80×10^1	2.70×10^2	1.50×10^3
Stomach	1.90×10^4	7.50×10^4	2.80×10^5
Thyroid	5.80×10^3	1.80×10^4	5.90×10^4
All other cancers	1.10×10^5	2.90×10^5	6.80×10^5
All cancers	7.20×10^5	1.50×10^6	3.10×10^6

Question 10. The number of radiation-induced skin cancer cases (fatal and non-fatal) up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a uniform skin dose of 1 mGy high LET (= plutonium alpha particle) radiation at a uniform rate over 1 year.

	Quantile		
	5%	50%	95%
Skin	0	0	0

Question 11. Joint dosimetry/late effects question: The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each of whom inhales 10 K Bq of the radionuclides specified.

Nuclide	Physical Form	Chemical Form	Cancer Type	Number of Cancers Quantile		
				5%	50%	95%
Pu-239	1 μm AMAD	Oxide	Lung	3.10×10^4	1.30×10^5	5.20×10^5
			Bone	9.00×10^2	8.20×10^3	7.30×10^4
			Liver	1.90×10^3	9.00×10^3	4.30×10^4
			Leukemia	3.60×10^2	1.80×10^3	9.00×10^3
			All cancers	3.40×10^4	1.50×10^5	6.50×10^5
Sr-90	1 μm AMAD	Oxide	Lung	1.40×10^2	4.40×10^2	1.40×10^3
			Bone	2.20×10^1	8.00×10^1	2.90×10^2
			Leukemia	1.60×10^2	3.60×10^2	8.00×10^2
			All cancers			

Question 12. Given that radiation induced cancer death due to the specified cause has occurred as a result of a dose of radiation delivered over 1 minute, the average expected length of life lost in years, for a population followed up to extinction after exposure.

	Quantile		
	5%	50%	95%
Bone	2.10×10^1	2.70×10^1	3.70×10^1
Colon	1.20×10^1	1.30×10^1	1.40×10^1
Breast	1.60×10^1	1.80×10^1	1.95×10^1
Leukemia	2.20×10^1	2.70×10^1	3.20×10^1
Liver	1.35×10^1	1.60×10^1	1.85×10^1
Lung	1.40×10^1	1.50×10^1	1.60×10^1
Pancreas	1.25×10^1	1.35×10^1	1.45×10^1
Skin	1.10×10^1	1.20×10^1	1.30×10^1
Stomach	1.20×10^1	1.30×10^1	1.40×10^1
Thyroid	1.30×10^1	1.40×10^1	1.50×10^1
All other cancers	1.25×10^1	1.40×10^1	1.55×10^1
All cancers	1.40×10^1	1.55×10^1	1.70×10^1

Question 13. For each of the cancer sites listed, give the estimate of the threshold dose in Gy, for low LET (= gamma) radiation administered at a uniform rate over 1 minute, below which value there is no radiation-induced cancer risk.

	Quantile		
	5%	50%	95%
Bone	0	0	0
Colon	0	0	0
Breast	0	0	0
Leukemia	0	0	0
Liver	0	0	0
Lung	0	0	0
Pancreas	∞	0	0
Skin	0	0	0
Stomach	0	0	0
Thyroid	0	0	0
All other cancers	0	0	0
All cancers	0	0	0

EXPERT H

Introduction

The overall aim of a joint study is to assess the uncertainties associated with consequence calculations for accidental releases of radionuclides from nuclear power plants. One part of the uncertainty analysis is risk calculation and unnecessary change assessment of radiation-induced cancers following the exposure of a given dose.

Committees like the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) or that on the Biological Effects of Ionizing Radiation (BEIR) publish regular reports in which they examine studies on the health effects of radiation and summarize the combined knowledge by creating special risk models for each cancer site. These model and modifications of them are used to assess radiation-induced cancers. New risk calculations are not performed.

General description of life-table calculations

To calculate the additional number of cancer deaths in a population following an instantaneous exposure to ionizing radiation, standard life-table techniques are used that are based on risk models presented by the UNSCEAR and the BEIR committees (see e.g., BEIR V, 1990). The age distribution, size and baseline mortality rates of the population for all causes and for the cancer site of interest are needed, as well as the length of follow-up, the dose of radiation exposure and a risk model predicting the risk due to the exposure.

The life-table analysis proceeds as described by the BEIR V committee (BEIR, 1990). Starting with a first age stratum of people exposed to a specific radiation dose, the first column in the life table gives the number of persons that are expected to survive to each age. The second column gives the cancer rate predicted by the exposure-time-response model. The third column gives the number of deaths from cancers that would result; this is determined from the product of the first two columns. The fourth column gives the number of deaths from other causes, based on current mortality rates, which are not assumed to be a result of radiation.

The number of survivors at the beginning of the next age stratum is therefore the number at the start of the interval minus the number of radiogenic and non-radiogenic deaths, and the process continues until the entire cohort is dead (for practical reasons, the calculations are terminated at age 100). The total number of excess deaths from cancer is estimated by subtracting the number of deaths obtained from a similar table for persons with no radiation exposure.

Basic risk models

In order to calculate additional cancer deaths in a population, different risk models were used as a basis for calculation.

Risk models of the UNSCEAR 1994 committee

The UNSCEAR 94 (UNSCEAR, 1994) committee preferred only two different risk models, one for leukemia and one for cancer sites other than leukemia. The last model is applied to different specific cancer sites by estimating its parameters separately. Therefore, the following detailed presentation of the models needs only two sections, and the parameters are summarized in tables.

UNSCEAR 1994 risk model for leukemia

The model for leukemia chosen by the UNSCEAR 94 committee (UNSCEAR, 1994)* is

$$EAR(D,T) = \alpha(SEX,E)\left(D + \vartheta D^2\right)\exp\left[\beta(T-25)\right]$$

where EAR is the excess absolute risk, T is time since exposure, E is age at exposure and D is weighted dose in bone marrow. The excess absolute risk is the difference between the mortality rate under exposure and the baseline mortality rate for leukemia.

The parameter estimates are based on the Life Span Study (LSS) of the Atomic Bomb survivors data, so that ϑ = 0.79 Sv^{-1}, and the sex- and age-at-exposure-specific parameters, α and β are presented in Table 1.

Table 1. Parameter values for the UNSCEAR 94* leukemia model.

Age at Exposure (years)	α (Sv^{-1})		β ($years^{-1}$)	
	Males	Females	Males	Females
0 - 19	0.33	0.66	0.17	0.07
20 - 39	0.48	0.66	0.13	0.03
≥40	1.31	2.64	0.07	0.03

* In UNSCEAR 1994 there is a printing error in the given formula.

UNSCEAR 1994 risk model for non-leukemia

The non-leukemia model for all cancers except leukemia differs from the preceding leukemia model and is given by

$$ERR(D,E) = \alpha\, D \exp[\beta(E-25)]$$

where *ERR* is the excess relative risk, D is weighted dose and E is age at exposure.

The parameter values for the different non-leukemia cancer sites based on the LSS data are presented in Table 2.

Table 2. Parameter values for the UNSCEAR 94 model for non-leukemia cancer sites.

Site	Males		Females	
	α (Sv^{-1})	β	α (Sv^{-1})	β
Stomach	0.16	-0.035	0.62	-0.035
Colon	0.54	-0.033	1.00	-0.033
Liver	0.97	-0.027	0.32	-0.027
Lung	0.37	0.021	1.06	0.021
Breast	--	--	1.95	--
All solid tumours	0.45	-0.026	0.77	-0.026

Risk models of the BEIR V committee

All models of the BEIR V committee for risk assessment of ionizing radiation have the following general structure,

$$\gamma(d) = \gamma_0[1 + f(d)g(\beta)]$$

where $\gamma(d)$ is the individual's age-specific mortality rate for a specific cancer and a given radiation dose equivalent d in Sv, γ_0 denotes the corresponding baseline mortality rate for an individual at a given age, and the functions $f(d)$ and $g(\beta)$ represent functions of the dose d and a vector of additional parameters β, respectively.

BEIR V risk model for leukemia (ICD 204-207)

For leukemia the committee chose the following model:

$$f(d) = \alpha_2 d + \alpha_3 d^2$$

$$g(\beta) = \exp\left[\beta_1 I_{[0,15]}(T) + \beta_2 I_{[15,25]}(T)\right] \quad \text{if } E \le 20$$

$$g(\beta) = \exp\left[\beta_3 I_{[0,25]}(T) + \beta_4 I_{[25,30]}(T)\right] \quad \text{if } E > 20$$

where T is time since exposure in years and E is age at exposure. The LSS data without information prior to five years post exposure yield the following parameter estimates with standard errors in parentheses:

$$\alpha_2 = 0.243\,(0.291),\ \alpha_3 = 0.271\,(0.314)$$
$$\beta_1 = 4.885\,(1.349),\ \beta_2 = 2.380\,(1.311),$$
$$\beta_3 = 2.367\,(1.121),\ \beta_4 = 1.638\,(1.321).$$

BEIR V risk model for respiratory cancer (ICD 160-163)

For respiratory cancer the committee chose the following model:

$$f(d) = \alpha_1 d$$

$$g(\beta) = \exp\left[\beta_1 \log\frac{T}{20} + \beta_2 I_{(female)}(sex)\right]$$

where T is time since exposure in years. The LSS data without deaths at age 75 and older yield the following parameter estimates with standard errors in parentheses:

$$\alpha_1 = 0.636\,(0.291)$$
$$\beta_1 = -1.437\,(0.910),\ \beta_2 = 0.711\,(0.610)$$

BEIR V risk model for breast cancer (ICD 174)

The committee's model for breast cancer age specific mortality (female only) is

$$f(d) = \alpha_1 d$$

$$g(\beta) = \exp\left[\beta_1 + \beta_2 \ln(T/20) + \beta_3 \ln^2(T/20)\right] \quad \text{if } E \le 15$$

$$g(\beta) = \exp\left[\beta_2 \ln(T/20) + \beta_3 \ln^2(T/20) + \beta_4(E-15)\right] \quad \text{if } E > 15$$

where E is age at exposure and T is years after exposure. The parameters were estimated by the combined LSS/non-Nova Scotia CAN-TB data and are (standard error in parentheses)

$$\alpha_1 = 1.220\,(0.610)$$
$$\beta_1 = 1.385\,(0.554),\ \beta_2 = -0.104\,(0.804),$$
$$\beta_3 = -2.212\,(1.376),\ \beta_4 = -0.0628\,(0.0321)$$

BEIR V risk model for other cancers (ICD 140-209 less those listed above)

The preferred model is

$$f(d) = \alpha_1 d$$
$$g(\beta) = 1 \qquad \text{if } E \le 10$$
$$g(\beta) = \exp\left[\beta_1 (E-10)\right] \qquad \text{if } E > 10$$

where E is age at exposure. The estimated parameters are

$$\alpha_1 = 1.220\,(0.519)$$
$$\beta_1 = -0.0464\,(0.0234)$$

Little's risk models

Mark Little* presented risk models in the following way. The first sort of model fitted assumed that the excess relative risk, *ERR*, varied with time since exposure, *TSE*, and age at exposure, *AAE*, so that the expected number of cases of whichever cancer is under consideration in stratum j and average dose, d, in Sv is given by

$$PYR_{jd} \cdot \lambda_j \cdot \left[1 + \beta_s \cdot d \cdot \exp^{(\delta \cdot t + \mu \cdot a)}\right]$$

where PYR_{jd} is the number of person-years in stratum j, and average dose d, λ_j is the base cancer rate in stratum j, β_j is a scaling factor for the *ERR* in sex, s, δ is the factor determining the exponential adjustment for *TSE*, t, in the *ERR*, and μ is the factor determining the exponential adjustment for *AAE*, a, in the *ERR*.

In addition, models are fitted which incorporate power adjustments for *TSE*, *AAE*, and attained age (*AA*). An overview of all models used and parameters calculated by Little (1996) is given in Appendix B.

Basic calculation set

Population age distribution

For this report, age classes of one year from age 0 to 1 in the first class to age 100 to 101 in the last stratum are used. The given size of the population, 50,000,000 males and the same number of females, was distributed among the 101 age groups according to the EU/USA population (see Appendix A). To construct one-year age groups, the number of people was pro-rated from the corresponding five year classes of the population. The last age group, 85+, was pro-rated among the last 16 one-year class.

Baseline cancer mortality rates

For baseline cancer mortality rates the EU/USA population was used. It provides sex- and age-specific mortality rates for 12 cancer sites (bone, colon, breast, leukemia, chronic lymphatic leukemia, liver, lung, pancreas, skin, stomach, thyroid gland, all other cancers) and the same age groups. Since the mortality rates are expressed per year, there were no difficulties with the matching of age classes.

Population size

The population size was fixed to a population of 50,000,000 males and 50,000,000 females.

Length of follow-up

The length of follow-up was varied in the categories 20 years, 40 years, and 100 years as a proxy for lifetime.

Radiation dose

In all the previous models the dose must be given as equivalent dose, a quantity obtained by multiplying the average absorbed dose in a tissue or organ by a radiation-weighting factor to compensate for the effectiveness of the various ionizing radiations in causing harm to tissue. The unit is sievert (Sv), and the factor for gamma radiation is usually 1.

* M. Little. 1996. Memorandum (January 23, 1996), "Scoping Cancer Risks," sent to all members of the CEC/US NRC Somatic Health Effects Panel. Little's memorandum has been included in Appendix B of this volume.

Calculations

The calculations were performed by a program consisting of two macros, one calculating the number of cancer deaths in an exposed population and another doing the same for an unexposed population. A third macro combines the previous two and runs each of them twice, once for males and once females. The variables the macros require are cancer site, model, dose, population size, and length of follow-up. Although the population itself with its age distribution and baseline mortality rates can be varied, this is not routinely done because of the large amount of data that must be input.

Uncertainties

The life-table method described to calculate the number of additional cancer deaths from exposure to ionizing radiation as predicted by a risk model contains various uncertainties. Not only the estimated parameter values but also the models used to predict exposure-, age-, sex-, AAE- and TSS-specific mortality rates are subject to variation; second, predictions made for values of covariates out of the range of the original data.

Thomas et al. (1992) distinguish three types of uncertainties:

- pure sampling variation in the epidemiologic data used for fitting the model;
- the form of the model;
- nonstatistical concerns such as systematic and random errors in the source data, the influence of unmeasured confounding and interaction effects, and the assumptions for transportation and extrapolation.

A fourth, possibly small, uncertainty could be added, namely the random process of developing cancer, but this may be negligible in a population of 1 million people.

Uncertainties of the models

Linear risk models seem to be accepted for all cancer sites, but still are not certain. Therefore, mixed models with both linear and squared terms would yield different values, mainly for high doses.

In all models the age-dependencies of the risk factors are rather crude. In the current models, more specific risk factors seem to be realistic, but may not change the overall picture too much.

The sex-dependency of the risk factors is an additional factor of uncertainty. For example, the relative excess risk for leukemia seems to be the same for men and women while the absolute risk is higher for men. This is true because leukemia risk is higher in men, but what happens if leukemia risk is the same in some population or in combination with other life-style factors?

For the time since exposure, the models make rather simple assumptions. Only for some cancer sites like lung cancer is additional information available to provide a better understanding of the decrease of risk with time since exposure.

Statistical uncertainties

The standard (random) error of the parameter estimates in the models was given by the committees. For some cancer sites, these errors are quite large and this will increase the uncertainty. This is true even for possible systematic errors in data collection, which may cause a selection bias because not all deaths were included in the analysis.

The changes in the estimated doses from T65D to Dosimetry System of 1986 (DS86) for the Japanese atomic-bomb survivors document the new knowledge in calculations of neutron and gamma transport through weapon materials. This may indicate additional uncertainties in the dose estimates in the cohorts. If we assume that some misclassification errors were still present in the individual dose estimates, the parameters are biased (in general toward 0).

Uncertainties by extrapolation after the time of observation

Only 50 years of observations are available for the Japanese atomic-bomb survivors. Whether radiation exposure in very young ages results in higher risk of cancer in the older age (where cancer is more common) is yet unclear. As was seen for female breast cancer, the risk is elevated for women in their 50s if they have been exposed as children. This may also be true for other cancers and would result in changes in the models.

Uncertainties of extrapolation to other populations

The extrapolation from the Japanese to other populations can result in uncertainties of radio-sensitivity of populations. In addition, if in Hiroshima and Nagasaki only very healthy people survived, they are also less vulnerable

to radiation exposure, and the risk is therefore underestimated.

In extrapolation to other populations, different baseline cancer rates cause additional uncertainty. For instance, breast cancer is low in Japan. Therefore a relative risk model may be correct, but interpolation to European breast cancer rates yields an enormous excess factor. The opposite trend is true for stomach cancer risk.
Finally it has to be mentioned that social factors and effects of life style are missed in all risk calculations.

Modification of UNSCEAR, BEIR V and Little's models

Thomas et al. (1992) provide some ideas about how all types of uncertainties could be investigated by Monte-Carlo simulations, but they do not actually perform these simulations.

We estimated expected number of deaths for several models taking into account the listed uncertainties. The UNSCEAR, BEIR V and Little's 1996 models were taken as "basic" models and parameter modifications were calculated. As we still believe that not all uncertainties are included in these calculations, we use our lowest value times 0.8 for the 5% and the highest times 1.2 as the 95% estimate of the asked distribution.

This type of modification was used to estimate the numbers in Tables (i) to (v). For table (viii) the calculations for table (ii) were used as a basis and modified with the estimates of Ron et al. (1994). Table (xii) was calculated as a direct consequence of the results of Table (iii). For all other tables answers are not available.

Validation of the results

At first it was guaranteed that any submitted calculation yielded no additional cancer deaths for a zero dose. For natural doses on the order of 1 – 4 mSv, the number of additional cancers should be less than a few percent of all cancers in the underlying population. This was indeed true for all 50% estimates.

Another possibility to validate the calculations is provided in the report of the BEIR V committee:

> "In this report it is estimated that if 100 000 persons of all ages received a whole body dose of 0.1 Gy of gamma radiation in a single brief exposure, about 800 extra cancer deaths would be expected to occur during their remaining lifetimes in addition to the nearly 20 000 cancer deaths that would occur in the absence of the radiation."

The same calculations performed by the written program with a follow-up of 100 years and the age distribution and baseline mortality rates of the EU/USA population for 50,000,000 males and 50,000,000 females yielded 1,832 extra cancer deaths in addition to 20,385 cancer deaths in an unexposed population for the models preferred by the BEIR V committee. For the UNSCEAR 94 committee's models, the corresponding results based on the cancer sites for which baseline mortality rates are available are 1,412 extra cancer deaths in addition to 20,560 "normal" cancer deaths.

Results

The results in this rationale are presented in the tables section relating to questions (i) to (xiii) of the case-structure document.* Questions which we could not answer with additional efforts are noted as not available (NA) in this document.

The results presented in these tables are not discussed in detail. For those tables, where additional commentary seems necessary, comments are given as footnotes to the tables.

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Question 1. The number of radiation-induced cancer deaths up to 20 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	980	25 000	57 000
Colon	35 000	110 000	480 000
Breast	5 000	138 000	460 000
Leukemia	10 000	750 000	1 200 000
Liver	1 000	15 000	85 000
Lung	150 000	1 700 000	4 200 000
Pancreas	0	22 000	120 000
Skin	2 500	6 500	15 000
Stomach	12 000	23 000	140 000
Thyroid	500	5 500	18 000
All other cancers	350 000	710 000	5 600 000
All cancers	500 000	2 500 000	12 400 000

Question 2. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	1 700	58 000	79 000
Colon	47 000	340 000	1 000 000
Breast	75 000	590 000	1 300 000
Leukemia	15 000	940 000	1 500 000
Liver	2 000	40 000	120 000
Lung	600 000	2 800 000	8 400 000
Pancreas	0	62 000	360 000
Skin	4 000	20 000	110 000
Stomach	25 000	65 000	385 000
Thyroid	2 000	18 000	62 000
All other cancers	560 000	1 100 000	8 600 000
All cancers	2 000 000	6 300 000	21 000 000

Question 3. The number of radiation-induced cancer deaths over a lifetime (following the population up until it has become extinct) in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	2 700	100 000	150 000
Colon	65 000	1 100 000	2 000 000
Breast	100 000	1 400 000	4 200 000
Leukemia	20 000	1 500 000	1 800 000
Liver	3 000	80 000	170 000
Lung	800 000	3 800 000	8 600 000
Pancreas	0	165 000	840 000
Skin	4 000	55 000	340 000
Stomach	30 000	100 000	480 000
Thyroid	5 000	60 000	192 000
All other cancers	1 200 000	2 200 000	14 000 000
All cancers	3 500 000	7 500 000	35 000 000

Question 4. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 years) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Breast	80 000	440 000	1 400 000
Leukemia	10 000	92 000	1 500 000
Thyroid	1 000	8 500	30 000
All cancers	NA	NA	NA

Question 5. The number of radiation-induced cancer deaths over a lifetime (following the population up until it has become extinct rather than up to 40 years following exposure) in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 years) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Breast	310 000	2 600 000	11 600 000
Leukemia	72 000	860 000	5 000 000
Thyroid	20 000	170 000	460 000
All cancers	NA	NA	NA

Question 6. The number of radiation-induced cancer deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure of a dose of 1 Gy low LET (= gamma) radiation administered uniformly over their three trimesters (9 months) *in utero* and followed-up for 20 years after birth.

	Quantile		
	5%	50%	95%
Leukemia			
All cancers			

Question 7. The number of radiation-induced cancer deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure of a dose of 1 Gy low LET (= gamma) radiation administered uniformly over their three trimesters (9 months) *in utero* and followed over a lifetime (following the population up until it has become extinct rather than up to 20 years following exposure).

	Quantile		
	5%	50%	95%
Leukemia			
All cancers			

Question 8. The number of radiation-induced cancer cases (fatal and non-fatal) up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	NA	NA	NA
Colon	59 000	428 000	1 260 000
Breast	80 000	630 000	1 400 000
Leukemia	NA	NA	NA
Liver	NA	NA	NA
Lung	600 000	2 800 000	8 400 000
Pancreas	NA	NA	NA
Skin	NA	NA	NA
Stomach	38 000	98 000	585 000
Thyroid	NA	NA	NA
All other cancers	NA	NA	NA
All cancers	NA	NA	NA

All numbers are based on table (ii) by applying a mortality-incidence ratio from Ron et al. (1994). For lung cancer the same settings as in table (ii) were used.

Question 9. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 year (rather than 1 minute).

	Quantile		
	5%	50%	95%
Bone			
Colon			
Breast			
Leukemia			
Liver			
Lung			
Pancreas			
Skin			
Stomach			
Thyroid			
All other cancers			
All cancers			

Question 10. The number of radiation-induced skin cancer cases (fatal and non-fatal) up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a uniform skin dose of 1 mGy high LET (= plutonium alpha particle) radiation at a uniform rate over 1 year.

	Quantile		
	5%	50%	95%
Skin			

Question 11. Joint dosimetry/late effects question: The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each of whom inhales 10 K Bq of the radionuclides specified.

Nuclide	Physical Form	Chemical Form	Cancer Type	Number of Cancers Quantile		
				5%	50%	95%
Pu-239	1 μm AMAD	Oxide	Lung			
			Bone			
			Liver			
			Leukemia			
			All cancers			
Sr-90	1 μm AMAD	Oxide	Lung			
			Bone			
			Leukemia			
			All cancers			

Question 12. Given that radiation induced cancer death due to the specified cause has occurred as a result of a dose of radiation delivered over 1 minute, the average expected length of life lost in years, for a population followed up to extinction after exposure.

	Quantile		
	5%	50%	95%
Bone			
Colon			
Breast			
Leukemia			
Liver			
Lung			
Pancreas			
Skin			
Stomach			
Thyroid			
All other cancers			
All cancers			

Question 13. For each of the cancer sites listed, give the estimate of the threshold dose in Gy, for low LET (= gamma) radiation administered at a uniform rate over 1 minute, below which value there is no radiation-induced cancer risk.

	Quantile		
	5%	50%	95%
Bone			
Colon			
Breast			
Leukemia			
Liver			
Lung			
Pancreas			
Skin			
Stomach			
Thyroid			
All other cancers			
All cancers			

Seed Variables

Estimated aggregate excess relative risk coefficient per Sv (neutron RBE = 20) (averaged over both sexes, all age of exposure groups, all dose groups) for cancer mortality in the Japanese atomic bomb survivor Life Span Study cohort for the follow-up from 1991 to 1995.

	Quantile		
	5%	50%	95%
Colon	0.05	0.7	2.8
Breast	0.5	1.7	6.0
Leukemia	NA	1.5	NA
Liver	0.2	0.5	1.0
Lung	0.1	0.4	1.1
Pancreas	0	0	n.a.
Stomach	0.05	0.3	1.5
Solid tumors	0.05	0.4	1.0

EXPERT I

Rationale

General Considerations

The purpose of the joint study was to assess uncertainties associated with cancer risk in an exposed population representative of the EU/USA. As part of this assessment, population risk calculations were provided using three models fitted to the Japanese atomic bomb survivor cancer incidence data sets analyzed by Thompson et al. (1994) for solid tumors and Preston et al. (1994) for leukemia and lymphoma. From these fitted models, cancer mortality risks were derived for a series of cancer sites and expressed as risk of exposure-induced deaths (REID) in units of 10^{-2} Sv^{-1}. Analogous measures for cancer incidence were also provided. Three models were used to derive these risk calculations which were referred to as Models A, B, and C. These three models yielded essentially similar estimates of risk at 20 and 40 years after exposure. However, when projections of lifetime cancer risks were calculated, the choice of model made a substantial difference. In particular, the lifetime risks obtained using Model B were much higher than with either Models A or C, and much higher than those estimated by other groups who have made similar estimates. The lifetime estimates obtained using model A, the simplest model, appeared to provide estimates in line with those derived by other groups such as ICRP (1991) and UNSCEAR (1994); therefore, it was decided that the estimates obtained using model A would serve as the basis for the 50th percentile estimates of radiation risks in this study. The decision to use these calculated risks rather than independently derived risks based on my own calculations was a matter of convenience and the fact that computer programs to accomplish these calculations were not readily available. Since the primary goal of this study was to assess the degree of uncertainty associated with radiation cancer risk, most of the effort was placed on selection of appropriate 5th and 95th percentiles for these estimates.

Range in Estimates of Uncertainties

Introduction

The uncertainties associated with estimates of cancer risk are a result of the fact that these estimates are derived essentially exclusively from the population of Japanese survivors of the atomic bombings (UNSCEAR, 1994). Even though this represents a very large population, the number of cancers attributable to the radiation exposure is relatively small. This creates relatively large uncertainties when the data are analyzed according to individual cancers types. In addition to statistical uncertainties in risk coefficients, which are expected in any epidemiological study, there are a number of other factors that also contribute to the overall uncertainty of these estimates (UNSCEAR, 1994). Those factors which have been considered in all calculations include: errors in reporting of cancer deaths; errors in dosimetry, including uncertainty errors in dose estimation, quality and quantity of gamma ray and neutron components, and neutron relative biological effectiveness (RBE); and uncertainties associated with the transfer of risk coefficients from the Japanese population of 1945 to current western populations. For specific questions related to lifetime risks, exposure of children, in utero exposure, low dose rate exposures, and effects of high LET radiation, additional considerations are necessary. For estimates of lifetime risks, there are considerable uncertainties in the projection of current observed risks over the lifetime of the population due to cancers that are still to occur in the population that is living. This is exacerbated when considering effects of in utero exposures and exposures of populations of children because information on solid tumors occurring in adulthood are only now becoming available. Information on effects at low dose rates in human populations is quite limited, and in general, there are insufficient data available to determine the shapes of dose-response relationships. Such data would be useful for determining whether dose rate effects might be expected and the potential magnitude of such an effect. As a result, additional uncertainties must be considered when projecting risks from the Japanese population which was irradiated at very high dose rates to a population exposed at low dose rates. The lack of direct data creates additional problems in evaluation of risks from exposure to high LET radiations. As a result, estimates of quality factors have relied on experimental endpoints such as tumor induction in animals or cancer related endpoints in cellular systems, including human cell systems.

Specific elicitation questions

Unless otherwise specified, the population consists of 100 million persons (half male and half female) exposed to a whole body dose of 1 Gy gamma radiation in 1 minute.

(i) The number of radiation-induced cancer deaths 20 years following exposure.

(ii) The number of radiation-induced cancer deaths 40 years following exposure.

For both questions, the considerations were essentially the same. Since information is available for the Japanese population over this time period, the principle considerations, in addition to statistical uncertainties, were errors in dosimetry, errors in reporting cancer deaths, and the transfer of the Japanese data to a modern western population. For solid tumors, except those discussed below, the errors associated with statistical uncertainties were judged to be approximately 40 percent, those associated with dosimetric uncertainties 30 percent, and uncertainties in reporting and transfer 15 percent. Propagation of these errors used a multiplicative independent error model. Information on leukemia and the category of all cancers were considered to be the most reliable and, therefore, have the smallest range of associated statistical uncertainties. This was judged to be approximately 25 percent. This assumption was carried through all elicited questions. The estimates of uncertainty for cancer of the bone were skewed to the left to take into account the data from animal studies which suggests a low apparent risk at low doses of low LET radiation. The estimates for frequency of pancreatic cancers were also skewed strongly to the left to take into account the very weak non-significant association with radiation exposure that has been observed in studies to date. The distributions of uncertainties for these two cancer types were similarly skewed to the left in the other elicitation questions below. Estimates for stomach cancer were widened to account for broader uncertainties for transfer of data from the Japanese population to the western population in all elicited questions. For breast cancer, this was not considered necessary since estimates of risk for western populations are available which tend to support the adequacy of the risks derived using the Japanese data.

(iii) The number of radiation-induced cancer deaths over a lifetime.

When considering lifetime risks, the uncertainties associated with the projection of current observations to estimates of cancer deaths that will occur in the population still living was added to the uncertainties (UNSCEAR, 1994). This tended to widen the ranges of uncertainties from those estimated for Questions i and ii. The degree of increased uncertainty varied for each tumor type depending upon several factors including but not limited to current perceptions of patterns of individual cancer development as a function of attained age and current estimates of attributable cancers.

(iv) and (v) The number of radiation-induced cancer deaths in a population of children up to 40 years following exposure.

Since the children exposed to the A-bomb have lived over 40 years at the present time, uncertainties are limited to those of statistics, dose, and transfer. However, when lifetime risks are projected, however, there is a considerable range to uncertainties for solid cancers since that age group in the surviving population is only now reaching the age at which they are developing solid tumors. As a result, the range of uncertainties associated with all cancers is very wide. The range of uncertainties associated with leukemia was kept the same in Questions iv and v, assuming all leukemias have developed at this time.

(vi) and (vii) The number of radiation-induced cancer deaths following in utero exposure.

The 50 percentile values were estimated based on the Oxford study as recently discussed by Wakeford (1995). The rationale for the ranges of uncertainty for in utero exposure where essentially the same as for childhood exposure. Uncertainties at 40 years post exposure have narrower ranges than for lifetime exposure for the category of all cancers but were similar for leukemia. The upper bound (95 percentile) estimate for all cancers assumed a similar radiation sensitivity to that for exposure during childhood (as in Questions iv and v).

(viii) The number of radiation-induced cancer cases (fatal and non-fatal) up to 40 years following irradiation.

Because the difficulties in obtaining reliable estimates of total cancer cases are greater than obtaining data on cancer deaths, the ranges of uncertainties associated with the these estimates are slightly greater than those associated with cancer deaths in Question ii (1).

(ix) Cancer deaths following low dose rate gamma ray exposure, i.e. 1 Gy over 1 year rather than 1 minute.

Uncertainties associated with a dose rate effect are complex. While in general it has been suggested that the risk be reduced by a factor of two, there are data for individual tumors, such as breast, which suggest no effect of dose rate (UNSCEAR, 1994). Further, the dose response data for most solid tumors appears linear. While not excluding a dose rate effect, the data to date suggests that a factor of

greater than two is not likely. Another factor that should be taken into account when considering the degree of reduction of risk is the total dose. At high total doses, the dose rate reduction factor may be larger than at lower doses. Considering, for example, the risk of lung cancer in Balb/c mice at high and low dose rates (Ullrich et al., 1987), the overall data suggests a dose rate effect in the range of 2-3. However, the alpha-beta ratio for the dose response is in the range of 1 Gy, which suggests that at doses of 1 Gy or less the effect of dose rate would not be large (~1.1). These data were significant in the present consideration of the impact of dose rate on cancer risks. The estimates for the 50 percentile frequencies for this question were reduced by a factor of only 1.1 compared to the equivalent high dose rate estimates in Question ii. The 95 percentile frequencies were made equal to those of the high dose rate group in Question ii, while the 5 percentiles uncertainties were expanded to accommodate a dose rate effect of 2.

(x) number of fatal and non-fatal skin cancers 40 years following alpha particle (plutonium) irradiation.

It was assumed for this question that the dose stated was that received by the target cells. While it is recommended that the quality factor for alpha particles be considered as 20, the uncertainties associated with this number are large, particularly at the upper end. Experimental RBE data for tumor induction with high LET radiations are more consistent with a factor of 30, with a high range of about 60 and a low range of 15 (NCRP, 1989).

(xi)

Not Done.

(xii) Life lost in years in the population as a result of radiation-induced cancer.

A relatively wide range of uncertainties similar to those used for lifetime cancer estimates in Question iii was used for this elicitation question.

(xiii) Question of Threshold

There is no evidence in any experimental or human studies for a threshold for the initiation of cancer by radiation. On the basis of current understanding of mechanisms of carcinogenesis, especially radiation carcinogenesis, a threshold is highly unlikely. There are specific tumors in experimental systems where an apparent threshold for cancer development has been observed, but the data suggest these are instances in which initiated cells require promotion for their expression as tumors (Fry et al.). Considering the exposure of humans to many factors that could promote radiation-initiated cells, it is not likely that a dose could be chosen at which there is no risk for cancer following radiation exposure.

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Question 1. The number of radiation-induced cancer deaths up to 20 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	2.00×10^3	4.60×10^4	7.36×10^4
Colon	5.75×10^4	1.15×10^5	1.84×10^5
Breast	4.45×10^4	8.90×10^4	1.42×10^5
Leukemia	3.46×10^5	8.43×10^5	9.61×10^5
Liver	9.00×10^2	9.00×10^3	1.44×10^4
Lung	2.25×10^5	4.51×10^5	7.22×10^5
Pancreas	1.30×10^3	2.60×10^4	4.16×10^4
Skin	7.00×10^2	7.00×10^3	1.10×10^4
Stomach	2.10×10^3	2.10×10^4	3.80×10^4
Thyroid	6.00×10^2	6.00×10^3	9.60×10^3
All other cancers	2.61×10^4	2.61×10^5	4.18×10^5
All cancers	1.16×10^6	1.96×10^6	2.24×10^6

Question 2. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	6.00×10^3	6.70×10^4	1.07×10^5
Colon	1.87×10^5	3.74×10^5	5.98×10^5
Breast	1.42×10^5	2.85×10^5	4.56×10^5
Leukemia	5.78×10^5	9.79×10^5	1.41×10^5
Liver	2.90×10^3	2.70×10^4	4.32×10^4
Lung	7.42×10^5	1.48×10^6	2.37×10^6
Pancreas	4.20×10^3	8.40×10^4	1.34×10^5
Skin	2.10×10^3	2.10×10^4	3.36×10^5
Stomach	6.80×10^3	6.80×10^4	1.22×10^5
Thyroid	1.80×10^3	1.80×10^4	2.88×10^4
All other cancers	7.85×10^4	7.85×10^5	1.26×10^6
All cancers	2.60×10^6	4.48×10^6	6.50×10^6

Question 3. The number of radiation-induced cancer deaths over a lifetime (following the population up until it has become extinct) in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	7.00×10^3	8.70×10^4	1.39×10^6
Colon	3.50×10^5	9.20×10^5	2.02×10^6
Breast	2.20×10^5	5.68×10^5	1.25×10^6
Leukemia	5.90×10^5	1.00×10^6	1.44×10^6
Liver	5.00×10^3	5.50×10^4	1.21×10^6
Lung	1.30×10^6	3.37×10^6	7.42×10^6
Pancreas	1.00×10^4	2.05×10^4	3.90×10^4
Skin	5.60×10^3	5.60×10^4	1.23×10^5
Stomach	1.72×10^4	1.72×10^5	4.30×10^5
Thyroid	4.10×10^3	4.10×10^4	7.79×10^4
All other cancers	7.00×10^5	1.79×10^6	3.93×10^6
All cancers	3.50×10^6	8.83×10^6	1.94×10^6

Question 4. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 years) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Breast	1.15×10^5	2.31×10^5	4.37×10^5
Leukemia	3.02×10^5	5.13×10^5	8.72×10^5
Thyroid	9.00×10^2	9.00×10^3	1.70×10^4
All cancers	1.41×10^6	2.38×10^6	4.05×10^6

Question 5. The number of radiation-induced cancer deaths over a lifetime (following the population up until it has become extinct rather than up to 40 years following exposure) in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 years) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Breast	4.30×10^5	1.09×10^6	2.72×10^6
Leukemia	3.20×10^5	5.45×10^5	9.27×10^5
Thyroid	7.20×10^3	7.20×10^4	1.80×10^5
All cancers	5.80×10^6	1.47×10^7	3.70×10^7

Question 6. The number of radiation-induced cancer deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure of a dose of 1 Gy low LET (= gamma) radiation administered uniformly over their three trimesters (9 months) *in utero* and followed-up for 20 years after birth.

	Quantile		
	5%	50%	95%
Leukemia	6.25×10^5	1.25×10^6	2.50×10^6
All cancers	1.25×10^6	2.50×10^6	5.00×10^6

Question 7. The number of radiation-induced cancer deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure of a dose of 1 Gy low LET (= gamma) radiation administered uniformly over their three trimesters (9 months) *in utero* and followed over a lifetime (following the population up until it has become extinct rather than up to 20 years following exposure).

	Quantile		
	5%	50%	95%
Leukemia	6.25×10^5	1.25×10^6	2.50×10^6
All cancers	1.25×10^6	1.50×10^7	3.7×10^7

Question 8. The number of radiation-induced cancer cases (fatal and non-fatal) up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 minute.

	Quantile		
	5%	50%	95%
Bone	1.35×10^4	1.55×10^5	3.10×10^5
Colon	3.40×10^5	6.84×10^5	1.37×10^6
Breast	3.50×10^5	8.98×10^5	1.80×10^6
Leukemia	7.10×10^5	1.44×10^6	2.80×10^6
Liver	2.70×10^3	2.70×10^4	5.40×10^4
Lung	7.00×10^5	1.75×10^6	3.50×10^6
Pancreas	4.20×10^3	9.70×10^4	1.94×10^5
Skin	1.87×10^5	1.87×10^6	3.80×10^6
Stomach	9.80×10^3	9.80×10^4	1.96×10^5
Thyroid	2.10×10^4	2.15×10^5	4.30×10^5
All other cancers	1.52×10^5	1.52×10^6	3.04×10^6
All cancers	3.80×10^6	9.64×10^6	1.93×10^7

Question 9. The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a whole body dose of 1 Gy low LET (= gamma) radiation at a uniform rate over 1 year (rather than 1 minute).

	Quantile		
	5%	50%	95%
Bone	3.50×10^3	6.10×10^4	1.27×10^5
Colon	9.35×10^4	3.40×10^4	7.10×10^5
Breast	7.10×10^4	2.60×10^5	5.41×10^5
Leukemia	2.89×10^5	8.90×10^5	1.66×10^6
Liver	1.35×10^3	2.50×10^4	5.10×10^4
Lung	3.71×10^5	1.35×10^6	2.82×10^6
Pancreas	2.10×10^3	7.60×10^4	1.59×10^5
Skin	1.05×10^3	2.00×10^4	3.40×10^4
Stomach	3.40×10^3	6.20×10^4	1.29×10^5
Thyroid	9.00×10^2	1.64×10^4	3.40×10^4
All other cancers	3.90×10^4	7.14×10^5	1.49×10^6
All cancers	1.30×10^6	4.07×10^6	7.61×10^6

Question 10. The number of radiation-induced skin cancer cases (fatal and non-fatal) up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each receiving a uniform skin dose of 1 mGy high LET (= plutonium alpha particle) radiation at a uniform rate over 1 year.

	Quantile		
	5%	50%	95%
Skin			

Question 11. Joint dosimetry/late effects question: The number of radiation-induced cancer deaths up to 40 years following exposure in a population of a hundred million persons (5×10^7 male, 5×10^7 female) each of whom inhales 10 K Bq of the radionuclides specified.

Nuclide	Physical Form	Chemical Form	Cancer Type	Number of Cancers Quantile		
				5%	50%	95%
Pu-239	1 μm AMAD	Oxide	Lung			
			Bone			
			Liver			
			Leukemia			
			All cancers			
Sr-90	1 μm AMAD	Oxide	Lung			
			Bone			
			Leukemia			
			All cancers			

Question 12. Given that radiation induced cancer death due to the specified cause has occurred as a result of a dose of radiation delivered over 1 minute, the average expected length of life lost in years, for a population followed up to extinction after exposure.

	Quantile		
	5%	50%	95%
Bone	3.30×10^{5}	3.25×10^{6}	7.20×10^{6}
Colon	5.0	1.26×10^{7}	3.20×10^{1}
Breast	4.0	1.08×10^{7}	2.70×10^{1}
Leukemia	1.20×10^{1}	2.13×10^{7}	3.62×10^{1}
Liver	9.50×10^{-2}	9.50×10^{5}	2.10
Lung	2.00×10^{1}	5.19×10^{7}	1.30×10^{2}
Pancreas	1.00×10^{-1}	2.86×10^{6}	6.40
Skin	7.00×10^{-2}	7.50×10^{5}	1.70
Stomach	2.30×10^{-1}	2.33×10^{6}	5.80
Thyroid	6.00×10^{-2}	6.30×10^{5}	1.40
All other cancers	1.00×10^{1}	2.69×10^{7}	6.80×10^{1}
All cancers	6.50×10^{1}	1.45×10^{8}	3.20×10^{2}

Question 13. For each of the cancer sites listed, give the estimate of the threshold dose in Gy, for low LET (= gamma) radiation administered at a uniform rate over 1 minute, below which value there is no radiation-induced cancer risk.

	Quantile		
	5%	50%	95%
Bone	No Threshold		
Colon			
Breast			
Leukemia			
Liver			
Lung			
Pancreas			
Skin			
Stomach			
Thyroid			
All other cancers			
All cancers			
Solid Tumors			

APPENDIX D

Short Biographies of the Late Health Effects Experts

Short Biographies of the Late Health Effects Experts

Maria Blettner*, Germany

Dr. Blettner received her Ph.D. in Statistics at the University of Dortmund in 1987. Since 1989 she has worked as a statistician and epidemiologist at the Division of Epidemiology of the German Cancer Research Centre. Before that she was an expert statistician, functioning as guest researcher for the Radiation Epidemiology Branch of the National Cancer Institute in the USA and as lecturer in Medical Statistics at the University of Liverpool in the UK. Dr. Blettner is associate editor of the *International Journal of Epidemiology* and elected member of council of the German Region of the Biometric Society.

Monty W. Charles, UK

Dr. Charles obtained his Ph.D. in Physics (X-ray spectrometry) in 1968 and DSc (Physics and Biology) in 1989 from the University of Leicester. He is now a Reader in Radiation Physics at the School of Physics and Space Research in the University of Birmingham. In parallel with research on dosimetry Dr. Charles carried out work in the radiobiology field. He designed and coordinated a large radiobiology study which showed that spatially non-uniform radiation fields were less carcinogenic than uniform exposures at a given average dose. His interest in dosimetry and radiobiology led naturally to involvement in the area of radiation epidemiology. He is the elected president of the Society for Radiological Protection.

Florent de Vathaire, France

Dr. de Vathaire received his Ph.D. in Ecology at the École Pratique des Hautes Études and his Ph.D. in Biomathematics and Biostatistics at the University of Paris in 1984. Currently he is a Senior Researcher at the Unit of Research in Cancer Epidemiology of the National Institute of Health and Medical Research and he works as a statistician consultant at the French Agence du Médicament. He is also a member of the Scientific Committee of the Office de Protection Contre les Radiations Ionisantes (OPRI). He has experience in epidemiology of carcinogenic and teratogenic effects of low-dose radiation (cohort and case control studies, geographical studies) statistical analysis (survival and Poisson regression and general epidemiology of cancer, in particular childhood cancer).

Ethel S. Gilbert, USA

Dr. Gilbert earned an A.B. degree in mathematics from Oberlin College and the M.P.H. and Ph.D. degrees in biostatistics from the University of Michigan. She spent several years as a biostatistician and senior staff scientist at Battelle, Pacific Northwest Laboratories, but recently joined the Radiation Epidemiology Branch of the National Cancer Institute as a special expert. Focusing on epidemiologic studies of nuclear workers, Dr. Gilbert's research has included combined analyses of national and international data and the development of statistical methods for examining the relationship of health effects and low-level chronic exposures. She has also analyzed data on experimental animals exposed to radon and inhaled plutonium. Dr. Gilbert was a member of the working group responsible for revising the health effects model in the NRC Reactor Safety Study, where she provided and updated a model for estimating cancer risks. Dr. Gilbert is a fellow of the American Statistical Association, a member of the National Council on Radiation Protection and Measurements, and a member of the BEIR VI Committee on Health Risks of Exposure to Radon.

Lothar Kreienbrock*, Germany

Dr. Kreienbrock graduated in Statistics and Operations Research at the University of Dortmund in 1983, where he received his Ph.D. in Statistics in 1987. After being a research and teaching assistant at the University of Dortmund and oberingenieur at the Department of Safety Technology of the University of Wuppertal, he became head of the Research Group "Epidemiological Methods" of the GSF-Forschungszentrum für Umwelt und Gesundheit. Dr. Kreienbrock has research experience in sampling techniques, multivariate statistical analysis, environmental medicine and epidemiological methods, epidemiology of lung cancer and effects of residential radon.

Jerome S. Puskin, USA

Dr. Puskin received his Ph.D. in Physics from Harvard University in 1970. From 1970 to 1982 he was in the Department of Radiation Biology and Biophysics at the University of Rochester, teaching and conducting research

* Blettner and Kreienbrock worked jointly.

on the transport and binding of ions by biological membranes. In 1982 he moved to the US Nuclear Regulatory Commission, where he provided advice regarding the health risks from ionizing radiation. Since 1985, he has been employed at the US Environmental Protection Agency as leader of the group responsible for developing and implementing models to assess radiation exposure, dose, and risk. He has been especially involved in estimating the carcinogenic risks from low-level ionizing radiation, including residential radon, and in quantifying the uncertainties in these estimates.

Warren Keith Sinclair, USA

Dr. Sinclair was President of the National Council on Radiation Protection and Measurements from 1977–1991 and is now President Emeritus at NCRP. He is a biophysicist with publications in radiological physics, radiobiology and radiation protection. He was born in New Zealand and educated in New Zealand and England before coming to the USA in 1954. He has a Ph.D. in physics from the University of London and served as physicist at the Royal Marsden Hospital, London 1947–1954. He was Chairman of the Department of Physics at the MD Anderson Hospital and Professor of Physics at the University of Texas 1954–1960. He then became Senior Biophysicist, (1960–1983), Division Director and Associate Laboratory Director at Argonne National Laboratory in Chicago. He is Emeritus Professor of Radiology at the University of Chicago. He is a member of the International Commission on Radiological Protection and a former member of the International Commission on Radiation Units and Measurements. He serves on the US delegation to the United Nations Scientific Committee on the Effects of Atomic Radiation and is presently Chairman of the Board on Radiation Effects Research at the National Academy of Sciences. He continues to undertake research in radiation risk assessment on behalf of NCRP and others.

Robert L. Ullrich, USA

Robert L. Ullrich received his Ph.D. from the University of Rochester and joined the Biology Division of Oak Ridge National Laboratory. Initial research focused on quantitative analysis of dose-response relationships for the induction of cancer in mice following radiation exposure and the influence of dose rate and radiation quality of these dose-response relationships. Subsequent research focused on mechanisms of radiation-induced mammary cancer at the cell and molecular level. He has continued this research since joining the University of Texas Medical Branch where he is a Professor in the Departments of Radiation Oncology and of Human Biological Chemistry and Genetics, Director of the Biology Division and Vice-Chairman of the Department of Radiation Oncology. Dr. Ullrich is a member of council, and member of the Board of Directors of the National Council for Radiation Protection and Measurements and has served as consultant on advisory committees for the National Cancer Institute (NCI), National Academy of Sciences (NAS/NRC), National Institute for Environmental Health Sciences (NIEHS), and the National Aeronautics and Space Administration (NASA).

Michael Væth, Denmark

Prof. Væth, who earned his Ph.D. in Statistics at the University of Aarhus in 1979, works as a professor in Biostatistics at the same university. His fields of interest are statistical analysis of survival data and statistical methods in epidemiology, but he also spends time as statistical consultant on research projects from almost any branch of medicine. In 1987 he went to Japan to work for 26 months as a research scientist in the Department of Statistics at the Radiation Effects Research Foundation in Hiroshima. There he worked with statistical aspects of the analysis of the cancer mortality and cancer incidence in the Life Span Study (LSS) cohort. This work has given Prof. Væth a detailed knowledge about late health effects after acute radiation exposures to gamma rays.

Richard Wakeford, UK

Dr. Wakeford earned a Ph.D. in Physics from the University of Liverpool in 1978. Since 1981, he has been employed by British Nuclear Fuels plc. in work concerning radiological protection. Since 1986, he has been involved in epidemiological studies of the effects of low levels of ionizing radiation, particularly the risk of childhood leukemia around nuclear installations and in the offspring of men exposed to radiation, and the statistical analysis of the spatial distribution of childhood leukemia cases. In 1994, Dr. Wakeford was awarded the Founder's Prize of the Society for Radiological Protection for contributions of distinction to radiological protection. His main area of expertise is radiation epidemiology and the risk to health from exposure to ionizing radiation, particularly at low doses.

APPENDIX E

Aggregated Results of Expert Responses

Table 1. Aggregated results of Late Health Effects Panel expert responses for *Probabilistic Accident Consequence Uncertainty Analysis*

	Quantiles		
	5%	50%	95%
Question 1 radiation-induced ***bone cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 20 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	2.23E+01	2.27E+04	4.79E+05
Question 1 radiation-induced ***colon cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 20 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	3.41E+03	9.84E+04	3.27E+05
Question 1 radiation-induced ***breast cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 20 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	5.79E+03	1.01E+05	4.21E+05
Question 1 radiation-induced ***leukemia*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 20 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	1.34E+04	7.46E+05	1.76E+06
Question 1 radiation-induced ***liver cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 20 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	4.151633	1.13E+04	2.25E+05
Question 1 radiation-induced ***lung cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 20 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	4.20E+04	3.80E+05	2.49E+06
Question 1 radiation-induced ***pancreatic cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 20 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	1.13E+01	2.36E+04	1.14E+05
Question 1 radiation-induced ***skin cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 20 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	1.77E+01	5.09E+03	2.45E+04
Question 1 radiation-induced ***stomach cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 20 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	5.39E+01	2.95E+04	3.09E+05
Question 1 radiation-induced ***thyroid cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 20 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	3.50045	6.37E+03	5.07E+04
Question 1 radiation-induced deaths from ***all other cancers*** in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 20 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	1.11E+02	2.85E+05	2.22E+06
Question 1 radiation-induced deaths from ***all cancers*** in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 20 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	5.08E+05	1.72E+06	6.42E+06
Question 2 radiation-induced ***bone cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	2.40E+01	3.24E+04	5.06E+05
Question 2 radiation-induced ***colon cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	1.13E+04	3.39E+05	1.01E+06
Question 2 radiation-induced ***breast cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	7.71E+04	3.30E+05	1.32E+06

Table 1. Aggregated results of Late Health Effects Panel expert responses for *Probabilistic Accident Consequence Uncertainty Analysis (Continued)*

Question 2 radiation-induced ***leukemia*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	1.92E+04	8.81E+05	2.10E+06
Question 2 radiation-induced ***liver cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	5.66E+01	3.63E+04	7.41E+05
Question 2 radiation-induced ***lung cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	1.53E+05	1.21E+06	5.00E+06
Question 2 radiation-induced ***pancreatic cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	1.16E+01	8.23E+04	3.80E+05
Question 2 radiation-induced ***skin cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	2.04E+01	1.56E+04	1.28E+05
Question 2 radiation-induced ***stomach cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	7.65E+01	1.01E+05	1.13E+06
Question 2 radiation-induced ***thyroid cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	4.85E+01	2.01E+04	1.68E+05
Question 2 radiation-induced deaths from ***all other cancers*** in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	1.60E+02	9.00E+05	4.48E+06
Question 2 radiation-induced deaths from ***all cancers*** in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	1.80E+06	4.38E+06	1.51E+07
Question 3 radiation-induced ***bone cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) over a lifetime (following population until it becomes extinct) after receiving whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min	2.45E+01	3.51E+04	8.80E+05
Question 3 radiation-induced ***colon cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) over a lifetime (following population until it becomes extinct) after receiving whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min	1.06E+04	9.76E+05	3.35E+06
Question 3 radiation-induced ***breast cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) over a lifetime (following population until it becomes extinct) after receiving whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min	1.06E+05	7.76E+05	3.78E+06
Question 3 radiation-induced ***leukemia*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) over a lifetime (following population until it becomes extinct) after receiving whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min	2.58E+04	9.11E+05	2.33E+06
Question 3 radiation-induced ***liver cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) over a lifetime (following population until it becomes extinct) after receiving whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min	7.09336	8.64E+04	2.02E+06

Table 1. Aggregated results of Late Health Effects Panel expert responses for *Probabilistic Accident Consequence Uncertainty Analysis (Continued)*

Question 3 radiation-induced ***lung cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) over a lifetime (following population until it becomes extinct) after receiving whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min	5.91E+05	2.76E+06	8.77E+06
Question 3 radiation-induced ***pancreatic cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) over a lifetime (following population until it becomes extinct) after receiving whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min	1.19E+01	1.73E+05	1.26E+06
Question 3 radiation-induced ***skin cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) over a lifetime (following population until it becomes extinct) after receiving whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min	2.43E+01	3.91E+04	3.73E+05
Question 3 radiation-induced ***stomach cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) over a lifetime (following population until it becomes extinct) after receiving whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min	10.40E+01	3.02E+05	4.01E+06
Question 3 radiation-induced ***thyroid cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) over a lifetime (following population until it becomes extinct) after receiving whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min	6.94E+01	5.86E+04	7.08E+05
Question 3 radiation-induced deaths from ***all other cancers*** in a population of a hundred million persons (5×10^7 male, 5×10^7 female) over a lifetime (following population until it becomes extinct) after receiving whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min	2.26E+02	2.60E+06	1.08E+07
Question 3 radiation-induced deaths from ***all cancers*** in a population of a hundred million persons (5×10^7 male, 5×10^7 female) over a lifetime (following population until it becomes extinct) after receiving whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min	3.48E+06	1.02E+07	2.85E+07
Question 4 radiation-induced ***breast cancer*** deaths in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 yrs) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	6.03E+04	2.54E+05	1.35E+06
Question 4 radiation-induced ***leukemia*** deaths in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 yrs) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	1.31E+04	5.05E+05	1.64E+06
Question 4 radiation-induced ***thyroid cancer*** deaths in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 yrs) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	3.90E+01	9.89E+03	8.53E+04
Question 4 radiation-induced deaths from ***all cancers*** in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 yrs) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	4.13E+05	2.09E+06	6.29E+06
Question 5 radiation-induced ***breast cancer*** deaths in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 yrs) over a lifetime (following population until it becomes extinct) after receiving whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min	2.34E+05	1.48E+06	9.05E+06

Table 1. Aggregated results of Late Health Effects Panel expert responses for *Probabilistic Accident Consequence Uncertainty Analysis (Continued)*

Question 5 radiation-induced ***leukemia*** deaths in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 yrs) over a lifetime (following population until it becomes extinct) after receiving whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min	7.63E+04	5.55E+05	2.55E+06
Question 5 radiation-induced ***thyroid cancer*** deaths in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 yrs) over a lifetime (following population until it becomes extinct) after receiving whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min	7.48E+01	9.89E+04	6.92E+05
Question 5 radiation-induced deaths from ***all cancers*** in a population of a hundred million children (5×10^7 male, 5×10^7 female, each under the age of 15 yrs) over a lifetime (following population until it becomes extinct) after receiving whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min	5.48E+05	1.78E+07	5.77E+07
Question 6 radiation-induced ***leukemia*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure [dose of 1 Gy low LET (= gamma) radiation] administered uniformly over three trimesters (9 months) *in utero* and followed up for 20 yrs after birth	3.37E+01	8.77E+05	3.76E+06
Question 6 radiation-induced deaths from ***all cancers*** in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure [dose of 1 Gy low LET (= gamma) radiation] administered uniformly over three trimesters (9 months) *in utero* and followed up for 20 yrs after birth	3.80E+01	2.17E+06	1.15E+07
Question 7 radiation-induced ***leukemia*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure [dose of 1 Gy low LET (= gamma) radiation] administered uniformly over three trimesters (9 months) *in utero* and followed over a lifetime (following population until it becomes extinct)	3.41E+01	1.00E+06	4.21E+06
Question 7 radiation-induced deaths from ***all cancers*** in a population of a hundred million persons (5×10^7 male, 5×10^7 female) who survive to term an exposure [dose of 1 Gy low LET (= gamma) radiation] administered uniformly over three trimesters (9 months) *in utero* and followed over a lifetime (following population until it becomes extinct)	4.60E+01	9.30E+06	5.00E+07
Question 8 radiation-induced ***bone cancer*** cases (fatal and non-fatal) in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	2.34E+01	5.38E+04	9.73E+05
Question 8 radiation-induced ***colon cancer*** cases (fatal and non-fatal) in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	2.04E+04	6.03E+05	2.01E+06
Question 8 radiation-induced ***breast cancer*** cases (fatal and non-fatal) in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	8.54E+04	8.84E+05	4.01E+06
Question 8 radiation-induced ***leukemia*** cases (fatal and non-fatal) in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	4.99E+05	1.27E+06	3.49E+06
Question 8 radiation-induced ***liver cancer*** cases (fatal and non-fatal) in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	5.00E+01	3.88E+04	1.95E+06

Table 1. Aggregated results of Late Health Effects Panel expert responses for *Probabilistic Accident Consequence Uncertainty Analysis (Continued)*

Question 8 radiation-induced ***lung cancer*** cases (fatal and non-fatal) in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	1.53E+05	1.37E+06	5.20E+06
Question 8 radiation-induced ***pancreatic cancer*** cases (fatal and non-fatal) in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	1.20E+01	9.21E+04	4.62E+05
Question 8 radiation-induced ***skin cancer*** cases (fatal and non-fatal) in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	1.38E+02	1.41E+06	5.27E+06
Question 8 radiation-induced ***stomach cancer*** cases (fatal and non-fatal) in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	8.38E+01	1.45E+05	1.73E+06
Question 8 radiation-induced ***thyroid cancer*** cases (fatal and non-fatal) in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	1.45E+04	2.15E+05	1.92E+06
Question 8 radiation-induced cases (fatal and non-fatal) from ***all other cancers*** in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	1.44E+02	1.59E+06	6.79E+06
Question 8 radiation-induced cases (fatal and non-fatal) from ***all cancers*** in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 min]	2.63E+06	8.66E+06	2.14E+07
Question 9 radiation-induced ***bone cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 yr]	1.09E+01	1.60E+04	5.35E+05
Question 9 radiation-induced ***colon cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 yr]	1.14E+01	1.60E+05	9.38E+05
Question 9 radiation-induced ***breast cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 yr]	7.79E+01	1.82E+05	1.20E+06
Question 9 radiation-induced ***leukemia*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 yr]	9.16E+01	3.87E+05	1.54E+06
Question 9 radiation-induced ***liver cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 yr]	1.12E+01	2.13E+04	4.72E+05
Question 9 radiation-induced ***lung cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 yr]	1.16E+01	4.38E+05	2.80E+06
Question 9 radiation-induced ***pancreatic cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 yr]	1.04E+01	3.64E+04	3.14E+05

Table 1. Aggregated results of Late Health Effects Panel expert responses for *Probabilistic Accident Consequence Uncertainty Analysis (Continued)*

Question 9 radiation-induced ***skin cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 yr]	1.06E+01	4.95E+03	6.46E+04
Question 9 radiation-induced ***stomach cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 yr]	1.13E+01	6.45E+04	6.53E+05
Question 9 radiation-induced ***thyroid cancer*** deaths in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 yr]	1.09E+01	1.07E+04	1.19E+05
Question 9 radiation-induced deaths from ***all other cancers*** in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 yr]	1.16E+01	4.17E+05	2.67E+06
Question 9 radiation-induced deaths from ***all cancers*** in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [whole body dose of 1 Gy low LET (= gamma) radiation at uniform rate over 1 yr]	1.35E+02	2.17E+06	7.66E+06
Question 10 radiation-induced ***skin cancer*** cases (fatal and non-fatal) in a population of a hundred million persons (5×10^7 male, 5×10^7 female) up to 40 yrs following exposure [uniform skin dose of 1 mGy high LET (= plutonium alpha particle) radiation] at uniform rate over 1 yr	1.03E+01	1.15E+04	2.15E+05
Question 11 radiation-induced ***lung cancer*** deaths up to 40 yrs following exposure in population of a hundred million persons (5×10^7 male, 5×10^7 female), each of whom inhales 10 K Bq of ^{239}Pu	1.06E+01	1.52E+05	1.64E+06
Question 11 radiation-induced ***bone cancer*** deaths up to 40 yrs following exposure in population of a hundred million persons (5×10^7 male, 5×10^7 female), each of whom inhales 10 K Bq of ^{239}Pu	1.05E+01	6.97E+03	7.70E+04
Question 11 radiation-induced ***liver cancer*** deaths up to 40 yrs following exposure in population of a hundred million persons (5×10^7 male, 5×10^7 female), each of whom inhales 10 K Bq of ^{239}Pu	1.05E+01	1.18E+04	6.37E+04
Question 11 radiation-induced ***leukemia*** deaths up to 40 yrs following exposure in population of a hundred million persons (5×10^7 male, 5×10^7 female), each of whom inhales 10 K Bq of ^{239}Pu	1.05E+01	2.75E+03	1.62E+05
Question 11 radiation-induced deaths from ***all other cancers*** up to 40 yrs following exposure in population of a hundred million persons (5×10^7 male, 5×10^7 female), each of whom inhales 10 K Bq of ^{239}Pu	1.18E+02	1.79E+05	1.87E+06
Question 11 radiation-induced ***lung cancer*** deaths up to 40 yrs following exposure in population of a hundred million persons (5×10^7 male, 5×10^7 female), each of whom inhales 10 K Bq of ^{90}Sr	8.09E+02	8.87E+02	8.57E+03
Question 11 radiation-induced ***bone cancer*** deaths up to 40 yrs following exposure in population of a hundred million persons (5×10^7 male, 5×10^7 female), each of whom inhales 10 K Bq of ^{90}Sr	1.03E+01	78.33715	1.11E+03
Question 11 radiation-induced ***leukemia*** deaths up to 40 yrs following exposure in population of a hundred million persons (5×10^7 male, 5×10^7 female), each of whom inhales 10 K Bq of ^{90}Sr	3.95E+01	3.82E+02	1.02E+04
Question 11 radiation-induced deaths from ***all cancers*** up to 40 yrs following exposure in population of a hundred million persons (5×10^7 male, 5×10^7 female), each of whom inhales 10 K Bq of ^{90}Sr	1.70E+02	2.23E+03	2.24E+04
Question 12 given radiation-induced ***bone cancer*** death has occurred as result of dose of radiation delivered over 1 min, avg. expected length of life lost (yrs), for population followed up to extinction after exposure	8.87E+01	21.63132	51.36387

Table 1. Aggregated results of Late Health Effects Panel expert responses for *Probabilistic Accident Consequence Uncertainty Analysis (Continued)*

Question 12 given radiation-induced ***colon cancer*** death has occurred as result of dose of radiation delivered over 1 min, avg. expected length of life lost (yrs), for population followed up to extinction after exposure	6.66E+01	12.95595	19.22026
Question 12 given radiation-induced ***breast cancer*** death has occurred as result of dose of radiation delivered over 1 min, avg. expected length of life lost (yrs), for population followed up to extinction after exposure	8.25E+01	17.75931	24.25093
Question 12 given radiation-induced ***leukemia*** death has occurred as result of dose of radiation delivered over 1 min, avg. expected length of life lost (yrs), for population followed up to extinction after exposure	1.28E+02	21.99805	37.108
Question 12 given radiation-induced ***liver cancer*** death has occurred as result of dose of radiation delivered over 1 min, avg. expected length of life lost (yrs), for population followed up to extinction after exposure	7.40E+01	15.51555	21.86152
Question 12 given radiation-induced ***lung cancer*** death has occurred as result of dose of radiation delivered over 1 min, avg. expected length of life lost (yrs), for population followed up to extinction after exposure	7.38E+01	14.62413	21.3309
Question 12 given radiation-induced ***pancreatic cancer*** death has occurred as result of dose of radiation delivered over 1 min, avg. expected length of life lost (yrs) for population followed up to extinction after exposure	6.77E+01	13.43632	19.85559
Question 12 given radiation-induced ***skin cancer*** death has occurred as result of dose of radiation delivered over 1 min, avg. expected length of life lost (yrs), for population followed up to extinction after exposure	5.75E+01	11.83512	16.74834
Question 12 given radiation-induced ***stomach cancer*** death has occurred as result of dose of radiation delivered over 1 min, avg. expected length of life lost (yrs), for population followed up to extinction after exposure	6.45E+01	12.78877	18.88019
Question 12 given radiation-induced ***thyroid cancer*** death has occurred as result of dose of radiation delivered over 1 min, avg. expected length of life lost (yrs), for population followed up to extinction after exposure	7.22E+01	13.74617	20.91362
Question 12 given radiation-induced death due to ***all other cancers*** has occurred as result of dose of radiation delivered over 1 min, avg. expected length of life lost (yrs) for population followed up to extinction after exposure	6.92E+01	13.83935	20.15825
Question 12 given radiation-induced death due to ***all cancers*** has occurred as result of dose of radiation delivered over 1 min, avg. expected length of life lost (yrs) for population followed up to extinction after exposure	7.63E+01	15.31114	22.18089
Question 13 threshold dose in Gy for low LET (= gamma) radiation (administered at uniform rate over 1 min) below which value there is no radiation-induced ***bone cancer*** risk	1.00E-08	1.39E-07	0.000304
Question 13 threshold dose in Gy for low LET (= gamma) radiation (administered at uniform rate over 1 min) below which value there is no radiation-induced ***colon cancer*** risk	1.00E-08	1.39E-07	0.000304
Question 13 threshold dose in Gy for low LET (= gamma) radiation (administered at uniform rate over 1 min) below which value there is no radiation-induced ***breast cancer*** risk	1.00E-08	1.39E-07	0.000108
Question 13 threshold dose in Gy for low LET (= gamma) radiation (administered at uniform rate over 1 min) below which value there is no radiation-induced ***leukemia*** risk	1.00E-08	1.39E-07	0.000108
Question 13 threshold dose in Gy for low LET (= gamma) radiation (administered at uniform rate over 1 min) below which value there is no radiation-induced ***liver cancer*** risk	1.00E-08	1.39E-07	0.000304

Table 1. Aggregated results of Late Health Effects Panel expert responses for *Probabilistic Accident Consequence Uncertainty Analysis (Continued)*

Question 13 threshold dose in Gy for low LET (= gamma) radiation (administered at uniform rate over 1 min) below which value there is no radiation-induced ***lung cancer*** risk	1.00E-08	1.39E-07	0.000304
Question 13 threshold dose in Gy for low LET (= gamma) radiation (administered at uniform rate over 1 min) below which value there is no radiation-induced ***pancreatic cancer*** risk	1.00E-08	1.39E-07	0.000304
Question 13 threshold dose in Gy for low LET (= gamma) radiation (administered at uniform rate over 1 min) below which value there is no radiation-induced ***skin cancer*** risk	1.00E-08	1.39E-07	0.000108
Question 13 threshold dose in Gy for low LET (= gamma) radiation (administered at uniform rate over 1 min) below which value there is no radiation-induced ***stomach cancer*** risk	1.00E-08	1.39E-07	0.000304
Question 13 threshold dose in Gy for low LET (= gamma) radiation (administered at uniform rate over 1 min) below which value there is no radiation-induced ***thyroid cancer*** risk	1.00E-08	1.39E-07	0.000108
Question 13 threshold dose in Gy for low LET (= gamma) radiation (administered at uniform rate over 1 min) below which value there is no radiation-induced risk from ***all other cancers***	1.00E-08	1.39E-07	0.000304
Question 13 threshold dose in Gy for low LET (= gamma) radiation (administered at uniform rate over 1 min) below which value there is no radiation-induced risk from ***all cancers***	1.00E-08	1.39E-07	0.000108

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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 developed in 1990. These codes estimate the consequence from the accidental releases of radiological material from hypothesized accidents at nuclear installations. In 1991, the U.S. Nuclear Regulatory Commission and the Commission of the European Communities began cosponsoring a joint uncertainty analysis of the two codes. The ultimate objective of this joint effort was to systematically develop credible and traceable uncertainty distributions for the respective code input variables. A formal expert judgment elicitation and evaluation process was identified as the best technology available for developing a library of uncertainty distributions for these consequence parameters. This report focuses on the results of the study to develop distribution for variables related to the MACCS and COSYMA late health effects models.

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

uncertainty analysis, radiological health effects, late health effects, stochastic health effects, ingestion pathways, accident consequence analysis, nuclear accident analysis, probabilistic analysis, expert elicitation, MACCS, COSYMA, consequence uncertainty analysis

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