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INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION

ASSESSING DOSE OF THE REPRESENTATIVE INDIVIDUAL FOR THE PURPOSE OF RADIATION PROTECTION OF THE PUBLIC

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PREFACE

On October 20, 2001 the Main Commission of the International Commission on Radiological Protection (ICRP) approved the formation of a new Task Group, reporting to Committee 4, on the Definition of the Individual. As stated in the terms of reference, the objective of the Task Group was to develop principles that assist in defining the individual to be used for determining exposures in the ICRP system of protection. These principles were expected to be important as the Commission's draft 2005 Recommendations evolved because they give more emphasis to the individual rather than to society as a whole. Examples of areas to be covered by the Task Group included how the individual is defined in the context of exposure in prospective and retrospective situations, as well as in avoidable and unavoidable situations. Demonstration of compliance was also to be addressed. Issues related to the critical group and concepts of uncertainty as related to the individual were to be considered. It was anticipated that the document produced as a result of the Task Group's work would form one of the supporting documents for the 2005 Recommendations.

This report is the outcome of the Task Group's efforts. It addresses the areas mentioned above and also several other issues that became evident during the course of the Task Group's work. The guidance in this report builds upon the concept of the critical group previously implemented by ICRP and defines the representative individual to be used for determining compliance with the dose constraint.

The membership of the Task Group was as follows:

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The Task Group would like to thank those organizations and staff that made facilities and support available for its meetings. These include the National Institute of Radiation Hygiene in Denmark; the Ministry of Housing, Spatial Planning, and Environment in The Netherlands; the National Radiological Protection Board in the United Kingdom; the Research Centre for Engineering, Environment, and Technology (CIEMAT) in Spain; the Nuclear Energy Agency in France; and the Department of Energy, the Nuclear Regulatory Commission, and the Centers for Disease Control and Prevention in the United States of America.

The report was adopted by the Main Commission at its meeting in (????????) on (?????), 2005.

ABSTRACT

Abstract— The Commission concluded that its 2005 Recommendations should be based on a simple, but widely applicable, general system of protection that would clarify its objectives and would provide a basis for the more formal systems needed by operating managers and regulators. The recommendations would establish quantified limits and constraints on individual dose from specified sources. The dose constraint provided in the recommendations applies to actual or representative individuals who encounter occupational, medical, and public exposures. Recommendations in this report update and revise the previous guidance for estimating dose to the public. Doses to the public cannot be measured directly. Therefore, for the purpose of protection of the public, it is necessary to characterise an individual, either hypothetical or specific, whose dose can be used for determining compliance with the dose constraint. This individual is defined as the representative individual. If the dose constraint for this individual is met, then the Commission's goal of protecting the public is considered to be achieved.

The report explains the process of estimating annual dose and recognises that a number of different methods are available for estimating dose to the representative individual. These methods range from simple deterministic calculations to more complex Monte Carlo techniques. In addition, a mixture of these may be applied. In selecting characteristics for the representative individual, three important concepts must be borne in mind: reasonableness, sustainability, and homogeneity. Each concept is explained and examples are provided to illustrate its role in defining characteristics of the representative individual. It is important to distinguish between doses to the public that are either prospective (may occur in the future), or retrospective (occurred in the past). Prospective doses are for hypothetical individuals who may or may not exist in the future while retrospective doses are to specific (real) individuals.

The Commission recognises that the level of detail afforded by its recommendations of dose coefficients for seven age categories are not necessary in making prospective assessments of dose for hypothetical individuals, given the inherently large uncertainties associated with estimating dose to the public and identification of the representative individual. Therefore, the Commission now recommends the use of three age categories for estimating annual dose to the representative individual in prospective assessments. These categories are 0 to <6 years (infant), 6 to <16 years (child) and 16 to 70 years (adult). For practical implementation of this recommendation, dose coefficients and habit data for the 1-year-old infant, 10-year-old child, and the adult should be used as representing the three age categories.

Compliance with the Commission's quantitative recommendations exists when the dose to the representative individual is less than the corresponding constraint. Overall compliance with the Commission's recommendations also requires optimisation to achieve further levels of protection. With deterministic methods, compliance exists when dose to the representative individual is less than the dose constraint.

In a prospective probabilistic assessment of dose to hypothetical individuals, whether from a planned facility or an existing situation, the Commission recommends that the representative individual be identified such that the probability is less than about 5% that a person drawn at random from the hypothetical population will receive an annual dose exceeding the dose constraint. If this dose to the representative individual is below the dose constraint set by ICRP, then the design and planned operations are determined to be in compliance.

The Commission recognises the role that stakeholders can play in identifying characteristics of the representative individual. Collaboration with stakeholders can significantly improve the quality, understanding, and acceptability of the characteristics of the representative individual and the resulting estimated dose.

EXECUTIVE SUMMARY

(S1) On October 20, 2001 the Main Commission of the International Commission on Radiological Protection approved the formation of a new Task Group on the Definition of the Individual. The objective of the Task Group was to develop principles that assist in defining the individual whose dose is to be used as the basis for determining compliance with the dose constraint for the public in the draft 2005 Recommendations.

(S2) In practices and existing situations, the dose constraint for the public is specified as an annual dose for regulatory and administrative purposes. This dose does not include exposure received from medicine or occupational sources. In setting it's the dose constraint for the public, the Commission recognises the inherent variability in estimated annual effective dose to members of the public and the transient nature of many extreme exposure situations. As a result, the Commission believes there should be a small probability that some individual may exceed the dose constraint.

(S3) The Commission's constraint for the public is set, in part, on the basis of exposure situations for individuals that are assumed to continue to occur for a number of years into the future. Since the population being exposed at any given time is made up of a spectrum of individuals composed of a range of ages, the same individual will progress in age over the time that exposures are expected to occur.

(S4) The Commission recognises three types of exposure situations: practices, existing situations, and emergency situations. Furthermore, dose assessments may be prospective or retrospective. Prospective doses are for hypothetical individuals who may receive the dose in the future. Retrospective doses are for doses that have occurred in the past and are for specific (real) individuals.

(S5) Dose assessment can be thought of as a multi-stage process. The first stage is to obtain information about the source, including data on the types and quantities of radionuclides and radiations emitted. The second stage is to obtain information about the environment, specifically the concentrations of radionuclides in environmental media arising from the source in question. The third stage of the process is to combine concentrations with habit data that are defined by an exposure scenario. The fourth stage is to use coefficients that either relate concentrations in air or soil to external dose rates (external doses), or that convert a unit of intake into dose (internal doses). Dose coefficients are estimated using models of radionuclide behaviour and radiation absorption in the body and have been derived and published by ICRP. The final stage is to sum the contributions from external and internal dose as appropriate. As an aid to clarification, and for intakes of radionuclides in particular, it is useful to consider the stages separately.

(S6) It is recognised that uncertainties are inherent in any process of defining individual characteristics and in estimating doses. Whether doses are estimated using measurement data, by applying models, or through a combination of measurements and calculations, the uncertainty for a given annual dose estimate is represented by a distribution of possible values. Uncertainty in dose assessment is a result of the inherent variability of some of the processes involved or a lack of knowledge about specific data that are needed for evaluating the process.

(S7) The Commission draws a distinction between quantities having values that are measured or estimated and quantities that have values that are selected, either by the Commission or by other organizations. For example, dose constraints, weighting factors, and dose coefficients—when used in the process of assessing compliance and in decision making—are assumed not to be uncertain. They are assumed to be point values. The Commission recognises uncertainties in the models linking detriment to dose. These uncertainties are considered in establishing selected values of quantities, such as limits and constraints. The Commission believes that the regulatory authority should make the final decision on how to include uncertainties in the estimation of dose for compliance purposes.

(S8) The Commission recognises that the level of detail afforded by its recommendations of dose coefficients for seven age categories are not necessary with the large uncertainties associated with estimating dose to the public and identification of the representative individual. Therefore, for the purpose of prospective assessments of continuing exposure, the Commission now recommends that three age categories are sufficient for estimating annual dose to the representative individual in prospective assessments. These categories are 0 to <6 years (infant), 6 to <16 years (child), and 16 to 70 years (adult). The shorter time period (5 years) is selected for the 0-to-<6-year age category, when dosimetric characteristics are changing most rapidly, to avoid any unwarranted reduction in the importance attached to doses to younger age groups. Use of these three age categories is sufficient to characterise the radiological impact of a source and assure consideration of younger, more sensitive populations. For practical implementation of this recommendation, dose coefficients and habit data for the 1-year-old infant, 10-year-old child, and the adult should be used as representing the three age ranges.

(S9) It is not possible to monitor dose directly to all members of the public; rather monitoring must be focused on environmental pathways such as radon in homes or concentrations of radionuclides in air or water that may lead to exposure of individuals. Since dose to the public cannot be measured directly, it must be estimated using environmental concentrations and appropriate habit data. Therefore, for the purpose of protection of the public, it is necessary to define a hypothetical exposed person to be used for determining compliance with the dose constraint and for introduction of a practice. This is the representative individual. The representative individual is the hypothetical individual receiving a dose that is representative of the most highly exposed individuals in the population.

(S10) If the value of dose to the representative individual meets the dose constraint established by the Commission, then the Commission’s goal is achieved.

(S11) In considering dose to the representative individual, a number of factors must be taken into account: (1) the dose must account for all pathways of exposure; (2) habit data should be based on the group or population exposed; (3) habit data must be reasonable, sustainable, and homogeneous; (3) dose coefficients must be applied according to specific age categories; (4) the dose must consider spatial distribution of radionuclides to be assured that the group receiving the highest dose is included in the assessment. Once these factors are taken into account and depending on the assessment approach employed (deterministic or probabilistic or a mixture of these), the representative individual can be identified and used to determine compliance.

(S12) If specific habit data for a local population are not available, values may be derived from national or regional population data. A distribution of these data may be used in probabilistic assessments, or a value on the distribution may be selected for deterministic calculations. Established databases suggest that the 95th percentile of consumption rates for many staple foods tend to exceed the mean values by approximately a factor of 3. Therefore, using the 95th percentile of behaviour may be considered to represent a cautious, but acceptable assumption, for defining a reasonable and sustainable intake rate using the deterministic approach. However, care must be exercised to avoid selecting extreme percentile values for every variable, in order to avoid excessive conservatism in the assessment. Taken together, the selection of parameter values must represent a reasonable and sustainable exposure scenario.

(S13) Dose to the representative individual may be calculated using several different approaches that range from simple deterministic to probabilistic (Monte Carlo) methods.

(S14) Deterministic methods involve the direct multiplication of selected point values of parameters and environmental concentrations. The simplest form of deterministic method is screening, where very conservative assumptions are made to estimate dose using concentrations of radionuclides at the point of discharge to the environment. In another form of the deterministic method, a general assessment of the involved populations, pathways, and radionuclides is made. This could be done by simplified screening methods or by expert opinion. In some situations, people receiving the highest dose are easily identified because site-specific exposure data are readily available and habit information is known. In other situations, identifying these individuals is an iterative process that considers key pathways of exposure and populations receiving doses from the source. The iterative process will usually indicate the areas that are likely to receive the greatest exposure from each pathway. It addresses the transport of radionuclides in the environment and accounts for the ultimate spatial and temporal disposition of the materials and the exposure of the population. The greater exposure areas should be investigated in more detail. Ultimately, a group is identified that is expected to receive the highest exposure. The average characteristics of this group are used to estimate dose to the representative individual.

(S15) It is now possible to use probabilistic methods to estimate dose. Probabilistic methods combine distributions of parameters into a composite distribution that present a range of possible doses based on their probability of occurrence. The distribution of dose incorporates (1) the uncertainty and natural variability in the estimated environmental media concentration (i.e., radionuclide concentration in air, water, soil, and food) and (2) uncertainty in the habit data (i.e., breathing rate, food and water ingestion rates, time spent at various activities).

(S16) For some prospective probabilistic assessments of dose, it is possible that essentially all doses on the distribution will be predicted to be less than the dose constraint set by ICRP. In this case, compliance is readily met. In a prospective probabilistic assessment of dose to hypothetical individuals, whether from a planned facility or an existing situation, the Commission recommends that the representative individual be identified such that the probability is less than about 5% that a person drawn at random from the hypothetical population will receive an annual effective dose exceeding the dose constraint. This hypothetical individual should be representative of, at most, a few tens of people who are the most highly exposed. If this dose to the representative individual is below the dose constraint

set by the Commission, then the design and planned operations are determined to be in compliance.

(S17) In probabilistic assessments, particular attention must be given to the region and accompanying population where the assessment is being conducted to define the representative individual. Care must be used to include all hypothetical individuals whose dose could possibly be representative of persons receiving the highest dose, including extremes.

(S18) For retrospective assessments of dose to specific individuals, either for the purpose of determining compliance for a past period of operation of a practice or an existing situation, the Commission recognises that estimated doses above the dose constraint must be evaluated on a case by case basis. In most cases it may be expected that the extremes represented by these individuals will continue for only a short time or may actually never be realised. However, if doses to specific individuals exceeded the dose constraint and these doses are expected to continue for a protracted period of time, a decision must be made by the operator and the regulator whether a reduction in the source is required or whether changes in habits of the individuals exposed might be proposed and supported. Such a situation might warrant additional monitoring to reduce uncertainty in the dose estimate or verify the magnitude of dose. The above considerations should be separate from any decision regarding whether the previous design or operations were in compliance with their basis of authorisation.

(S19) The Commission recognises the role that the public can play in helping to identify and characterise the representative individual for radiological protection purposes. The extent of stakeholder involvement will vary between countries and situations. Stakeholders can provide input regarding habit data that are specific to their location. In particular, stakeholders can be helpful in determining reasonableness, sustainability, and homogeneity of data. Collaboration with stakeholders can significantly improve the quality, defensibility, and acceptability of characteristics of the representative individual and also strengthen support from stakeholders in the compliance and decision-making process.

(S20) Regardless of the approach taken to determine compliance, the Commission stresses that application of the total system of protection, utilising both compliance with quantitative constraints and optimisation of protection, is necessary for radiological protection.

1. INTRODUCTION

(1) The Commission's system of protection is based upon the principles of quantitative standards of protection, complemented by the requirement to optimise the level of protection achieved. The system is intended to provide an appropriate degree of protection for individuals from the risks associated with exposure to ionising radiation.

(2) The Commission concluded that its 2005 Recommendations (ICRP, 2005a) should be based on a simple, but widely applicable, general system of protection that would clarify its objectives and provide a basis for the more formal systems needed by operating managers and regulators. The recommendations establish quantified limits and constraints on an individual's annual dose from specified sources. These restrictions are applied to the exposure of actual or representative individuals. Within this scope, the Commission includes numerical restrictions on the exposure of members of the public.

(3) The Commission has previously used the concept of the critical group for defining those persons who receive the highest exposures from a particular source or set of sources of radiation for the purposes of applying its recommendations. The recommendations in this report update and revise the previous guidance for estimating annual dose to the public. Although emphasis in this report is on the prospective exposure situation (that is dose to the public in the future), some guidance is also provided on retrospective dose (that is dose that has already been received).

(4) The dose[1] from a source received by any particular individual depends upon a number of factors, such as time, location, transport of radionuclides through the environment, and the characteristics of the individual. These characteristics include physiological parameters (e.g., breathing rate), dietary information (e.g., consumption rate of various foods), residence data (e.g., type of dwelling), use of local resources (e.g., agricultural resources), recreational activities (e.g., swimming), and any other individual-specific information that is necessary to estimate annual dose. In the assessment on doses, a specific set of these characteristics is referred to as an *exposure scenario*. In general, the Commission refers to diet, residence, and other information needed to estimate exposure as *habit data.*

(5) Section 1 of the report addresses the objective of this report and provides background information on the historical development of the Commission's approach to identifying and using the critical group for the purpose of assessing dose to an exposed population. Section 2 reviews the process for estimating doses to members of the public arising from sources. Section 3 discusses the selection of characteristics for the representative individual. Section 4 presents other considerations relevant to the representative individuals. Section 5 is a summary of the recommendations provided in the report.

1.1. Objective

(6) The objective of this report is to provide guidance on how to assess dose to the individual for the purposes of establishing compliance with the Commission's recommendations for the protection of the public. Since radiation dose to individual members of the public cannot generally be monitored, it is necessary to provide guidance on how these doses are estimated and how compliance is determined.

[1] in this report, "dose" is taken to mean "effective dose"

(7) This updated guidance is needed since the ICRP system of protection has continued to evolve and recommendations of the Commission have become a basic element of regulations in many countries. In addition to this evolution within ICRP, the ability to carry out assessments using more sophisticated computer and software tools has improved significantly over the past two decades. Doses can now be estimated probabilistically, so that a distribution of doses can be developed that includes uncertainties rather than a single point estimate of dose. The objective of this report is to update principles necessary to implement the ICRP system of protection so that it is consistent with methods that are being used to estimate doses to individuals. The report also clarifies and elaborates on methods for estimating dose to the public in order to compare individual the dose constraint, optimise protection, and aid in the planning and decision making for emergency situations.

(8) The source and the exposed individual are fundamental elements in each category of exposure, whether occupational, medical, or public. There must be a clear understanding and characterisation of the individual for whom the dose is being assessed. For occupational exposure, which is exposure incurred at work and principally as a result of work, characterisation of the exposed individuals and the sources is generally straightforward in that there are records for these individuals and their exposures are monitored or individually assessed. Likewise, in medical exposure, which is principally the exposure of persons as a part of their own medical diagnosis or treatment, the source and exposure to individuals is usually obvious. Occupational and medical exposures, therefore, are not considered further in this report.

(9) Guidance for the protection of future individuals in the case of disposal of long-lived radioactive waste is provided in ICRP Publication 81 (ICRP, 2000a).

(10) Exposure situations are classified in the 2005 Recommendations (ICRP, 2005a) in three broad groups: practices, existing situations, and emergency situations. The Commission uses practices to address those parts of its scope corresponding to any human activity deliberately introduced or maintained that causes, or potentially causes, radiation exposures. Existing situations are those in which sources already exist and may have been introduced unintentionally, inappropriately, or as a result of past human activities that have then been abandoned. In many circumstances, existing situations can be controlled only by action to modify exposure pathways. Emergency situations relate to unintended or unexpected events that could result in exposures sufficient to warrant consideration of the introduction of countermeasures. Guidance is provided in Chapter 2 of this report for each of the three groups of exposure of the public described above.

(11) When protection of the public against expected exposure situations is being assessed for the future, doses may be estimated either deterministically or probabilistically. In either case, parameters involved are uncertain and these uncertainties must be addressed. In the deterministic approach, a single point estimate of dose is generated. Uncertainties are addressed by selecting parameter values that will reasonably assure that the dose is not underestimated. In the probabilistic approach, uncertainties are taken into account by including the range of possible values of each of the parameters and developing a distribution of doses.

(12) For exposure determination in an existing situation it may be possible to use measurement data and other habit data that are specific to the location. These site-specific data may significantly reduce the uncertainties in estimated doses. However, it is also likely that in the case of retrospective dose assessment for public exposure a distribution of possible doses will result due to the inherent variability of measurement and habit data.

1.2. Background

(13) The concept of critical group was first introduced by ICRP in Publication 7 (ICRP, 1965) to provide a means for evaluating compliance with the Commission's recommendations. Paragraph 15 of that publication states:

> 'The presence of a critical nuclide in some critical pathways will not cause the same exposure of each member of the population outside an installation, and preoperational investigations […] will usually establish the existence of one or two groups of people whose characteristics, e.g. habits, location, or age, cause them to receive doses higher than those received by the rest of the population outside the installation and this requires them to be considered separately, i.e., to be designated as critical. Great judgement is necessary in defining such a group in practice and the following aspects will have to be considered. Some of these are the same as the factors influencing the design of routine surveys and only those concerned with the critical group itself are listed below:
>
> - The location and age distribution of the potentially exposed group
> - Dietary habits (e.g., special foodstuffs and amounts consumed)
> - Special occupational habits (e.g., the handling of fishing gear)
> - The type of dwelling (e.g., shielding characteristics)
> - Domestic habits (e.g., time spent indoors, frequency of personal washing and laundering of clothes)
> - Hobbies (e.g., sport fishing or sunbathing).
>
> Such groups in the population may be in the vicinity of the installation or at some distant location; they may include adult males, adult females, pregnant women, and children; they may be individuals who eat foodstuffs prepared in a special way or produced in a particular location; or they may be people in a particular industry…The concept of critical group provides a sound and practical way of complying with the Commission's recommendations concerning members of the public….'

(14) Paragraph 16 continues:

> 'The critical group should be identified in such a way that it is representative of the more highly exposed individuals in the population and is as homogeneous as practicable with respect to radiation dose, that is, with respect to those factors in paragraph 15 which affect the dose in the specific case considered.'

(15) Paragraph 17 states:

> ‘Once the critical group has been identified in this way, a suitably representative sample of the group should be selected and studied so as to assess their [sic] actual or potential exposure. The average exposure of such a sample should then be regarded as typical of that of the highly exposed individuals and the Commission’s recommendations for the maximum permissible doses for individual members of the public applied to the average. The spread of values in the sample will give some measure of its homogeneity with respect to the characteristics of the individual (such as metabolic rates) which may influence the dose received and which are not measured. These individual differences may tend to increase the spread of the individual doses received within the critical group. It must also be recognised that, outside the critical group, there may be a few individuals whose habits and characteristics are dramatically unconventional. Such peculiarities may sometimes mean that these individuals receive doses somewhat higher than those in the critical group.’

(16) The concept of critical group has continued to be used in ICRP publications and has been widely applied in radiation protection. In paragraph 67 of Publication 43 (ICRP, 1985) it is noted:

> ‘In an extreme case it may be convenient to define the critical group in terms of a single hypothetical individual, for example when dealing with conditions well in the future which cannot be characterised in detail. Usually, however, the critical group would not consist of one individual nor would it be very large for then homogeneity would be lost. The size of a critical group will usually be up to a few tens of persons. In a few cases, where large populations are uniformly exposed, the critical group may be much larger. This guidance on size has certain implications; for example, in habit surveys it is not necessary to search for the most exposed individual within a critical group in order to base controls on that one person. The results of a habit survey at a particular point in time should be regarded as an indicator of an underlying distribution and the value adopted for the mean should not be unduly influenced by the discovery of one or two individuals with extreme habits.’

(17) The 1990 recommendations in ICRP Publication 60 (ICRP, 1991) state:

> ‘These groups are chosen to be representative of the individuals most highly exposed as a result of the source under review. They are required to be reasonably homogeneous with respect to the characteristics that influence their doses from that source. When this is achieved any individual constraints should be applied to the mean values for the critical group. It is implicit that some members of the critical group will receive doses both above and below the group average.’

(18) The Commission continues to endorse the principles developed in Publications 7, 43, and 60 relating to the selection of the individuals for the purpose of assessing compliance

with the dose constraint. However, in the 2005 Recommendations, more emphasis is being placed on source-related individual doses. The purpose of this report is to clarify and elaborate on the application of this concept by taking into account recent experience and advances in assessing doses to members of the public.

1.3. Fundamental principles and concepts

(19) In practices and existing situations, the dose constraint for the public is specified in the form of an annual effective dose for regulatory and administrative purposes. This dose does not include exposure received from medical or occupational sources. In setting its dose constraint for the public, the Commission recognises the inherent variability in estimated annual effective dose to members of the public and the transient nature of many extreme exposure situations. As a result, the Commission believes there should be a small probability that some individual may exceed the dose constraint.

(20) The Commission's constraint for the public is set, in part, on the basis of exposure situations for individuals that are assumed to continue to occur for a number of years into the future. (ICRP, 2005a). The population being exposed at any given time is made up of a spectrum of individuals composed of a range of ages, and individuals within the population must be afforded protection as they progress in age over the time that exposures are expected to occur.

(21) In most cases it is not possible to monitor dose directly to all members of the public; rather, monitoring must be focused on environmental pathways such as radon in homes or concentrations of radionuclides in air or water that may lead to exposure of individuals. Since dose to the public is not being measured directly, it must be estimated using environmental concentrations and appropriate habit data. Methods used to calculate dose range between point value estimates (deterministic) to a distribution of doses (probabilistic). In either case, or with the application of a mixture of these methods, decision makers need guidance on how to determine when compliance exists.

(22) In some situations, such as those existing from an accident or earlier practice, exposure to the public can be directly measured or at least inferred using environmental concentrations and specific habit data. An example of this is reconstructed doses from the Chernobyl accident (IAEA, 1991). In this case, a distribution of doses was developed that could be related to individuals in the population. Generally, these distributions include a number of doses that lie well beyond those received by most of the population and arise from some extreme values in habit data.

(23) Therefore, for the purpose of protection of the public, it is necessary to characterise an individual, either hypothetical or specific, who receives the highest dose which can be used for determining compliance with the dose constraint. This individual is defined as the *representative individual*.

(24) The sections that follow describe fundamental elements of the process of dose assessment and explain how the representative individual is characterised and identified for making decisions about compliance, design of a practice, planning for emergencies, and other aspects of radiation protection for members of the public.

2. ASSESSMENT OF DOSE

2.1. Purpose of dose assessment

(25) Assessment of annual dose to the public can be made to determine compliance with the dose constraint, to guide decisions on the level of control of exposure, and to help identify actions to be taken to reduce exposure. For example, in the case of controlled discharges to the environment, the results of the comparison with a dose criterion may determine whether additional effluent control is required. Doses are also estimated to allow for planning in accident situations and to determine the conditions under which countermeasures may be taken in the event of an accident. In addition, doses are estimated in the process of optimisation, where it is not merely sufficient to meet dose the dose constraint, but also necessary to show that doses below the recommended constraint have been reduced to "as low as reasonable achievable, social and economic considerations being taken into account" (ICRP, 2005a).

(26) The type of assessment conducted, and the degree to which specific information is incorporated, will depend on the purpose. In many circumstances, assessments for planning, optimisation, and compliance will require different types of assessment. Planning and optimisation, for example, must consider a variety of exposure circumstances and evaluate where there are opportunities for further protective measures. Compliance assessments, in contrast, are usually designed to specifically demonstrate that predetermined conditions either are, or are not, being met. The remainder of this report focuses on demonstrations of compliance with a pre-selected constraint, which may be the quantitative values recommended by the Commission, but may also be the more specific constraint derived for a particular situation through constrained optimisation as recommended by the Commission.

2.2. Types of dose assessment

(27) The Commission recognises three types of exposure situations: practices, existing situations, and emergency situations. Furthermore, dose assessments may be prospective, or retrospective (see Table 1). Assessments of dose for the current year can be categorised in either of these two types depending on whether the dose is estimated for the upcoming year (prospective) or the past year (retrospective).

(28) Prospective dose is estimated for hypothetical individuals while retrospective dose is generally estimated for specific individuals. The Commission emphasizes that by "hypothetical" it implies that exposures have not yet occurred and that persons who may receive prospective exposures are assumed to exist and to possess certain habit characteristics whether or not these can be related to specific individuals. In retrospective assessments it is possible to estimate exposure to specific individuals.

Table 1. Examples of dose assessment in different exposure situations

SITUATION	TYPE OF ASSESSMENT		
	Prospective		**Retrospective**
Practice	Design of new facility or compliance with the dose constraint for an upcoming year		Dose to the public from past operations or compliance with dose the dose constraint for past year
Existing	Future prolonged exposures (e.g., after remediation)		Earlier exposures
Emergency	Emergency planning		Actual impacts after emergency

(29) For practices, prospective assessments are undertaken to estimate future exposures and to show whether a proposed course of action (e.g., the introduction of a new source or the continuation of an existing source) is indicated or optimised. These assessments will necessarily have to make assumptions about future conditions. Such prospective assessments provide the basis for determining compliance once the source has been introduced.

(30) Prospective assessments are also undertaken to indicate whether a continuing situation will comply with the appropriate dose constraint for an upcoming year. They may incorporate more detailed information about present site-specific conditions available and may also have less uncertainty because conditions may be better known than a prospective assessment for the distant future. When a prospective assessment is to be used specifically for developing authorisation for sources and for demonstrating compliance, the form and scope of the assessment should be specified to correspond with the basis for the requirement.

(31) Prospective assessments are also conducted in emergency situations if an event takes place that releases radiation or radioactive material. The assessment takes what may be limited field data and measurements, and translates them into estimates of dose for decision makers who must make recommendations for short-term protective actions.

(32) Prospective assessments also are used in the late phase of an emergency response, after the event has been controlled and early protective actions have been implemented. The situation posed by any remaining residual radioactivity is essentially one of continuing exposure and is conceptually the same as an existing exposure.

(33) Finally, prospective assessments may be undertaken to assess an existing situation that was previously unrecognised, and they may be part of the information used to determine if protective actions should be introduced to reduce unacceptable exposures

(34) Existing situations may require prospective assessments or retrospective assessments to determine the implications of proposed actions. When such cases have been identified, the assessment provides the basis for understanding the future consequences if no actions are taken, or for understanding the dose averted if certain actions are implemented. They also provide the basis for communication with those exposed in the situation, and the options that may be available.

(35) Retrospective assessments may be undertaken to retrospectively demonstrate compliance with the Commission's dose constraint or could be used as the basis of epidemiological studies (e.g., as in historical dose reconstruction) and generally incorporate more information in calculations than prospective analyses. Additionally, retrospective assessments may be undertaken following the initial phases of an emergency situation to accurately characterise and report the actual impacts and the effects of protective actions that may have been undertaken, and to provide information to individuals.

(36) In emergency situations, there is the potential for relatively high doses to be delivered over relatively short periods of time. During emergency planning activities, prospective assessments may be made modelling potential source terms and the populations around a particular source, so that pre-planned protective measures can be established. These assessments are used to identify individuals and groups that would be subject to dose constraints for actions, if the emergency scenario actually were to occur. Emergency countermeasures are intended to restrict or control the dose to individuals in these short time periods.

(37) Protective actions in emergency situations are often based on protecting specific groups, such as children. In these situations, age-specific habits and age-specific dose coefficients are used to assess the relevant doses and to make decisions on countermeasures. In emergency response, therefore, information on age groups or populations that were exposed should be included explicitly in the assessment. .

2.3. Overview of the dose assessment process

(38) Dose assessment can be thought of as a multi-stage process, as demonstrated in Figure 1. The first stage is to obtain information about the source, including data on the types and quantities of radionuclides and radiations emitted. The second stage is to obtain information about the environment, specifically the concentrations of radionuclides in environmental media arising from the source in question. For external doses, either the concentrations in air, soil, or water, or the external dose rates are needed. For internal doses, it is necessary to know concentrations in food, water, or air that may be taken into the body. The third stage of the process is to combine concentrations with habit data that are selected based on exposure scenarios of the relevant person or group. For external doses, the amount of time spent in different radiation fields is needed, while for internal exposures, information on the amount of food and water consumed or air breathed is required to estimate activity intakes. The next stage is to use dose coefficients that either relate concentrations in air or soil to external dose rates (external doses), or that convert a unit of intake into dose (internal doses). Dose coefficients for internal exposure are estimated using models of radionuclide behaviour and radiation absorption in the body. They have been derived and published by ICRP. The final stage is to sum the contributions from external and internal exposure as appropriate. As an aid to clarification, and for intakes of radionuclides in particular, it is useful to consider the stages separately.

(39) In stage one, the source of the exposure should be characterised. In the case of discharges to the environment, this characterisation may include discharge rates for radionuclides of interest, stack heights, proximities of relevant neighbouring buildings, physical and chemical forms of the material, and meteorological conditions. Direct radiation from sources through shielding, or via scattering or refraction by material in the atmosphere, should also be examined.

(40) In stage two, environmental concentrations at various locations are obtained by measurements, or by modelling the dispersion, deposition, and transport of radionuclides through environmental media, or by a combination of both. Both measurements and modelling will have associated uncertainties. The result for each location is a distribution of concentrations of activity for each radionuclide and environmental pathway, as a result of the source. In this stage, the development of the distribution should be independent of the presence or absence of individuals and should be based on whether there is the potential that an individual could be present at the location.

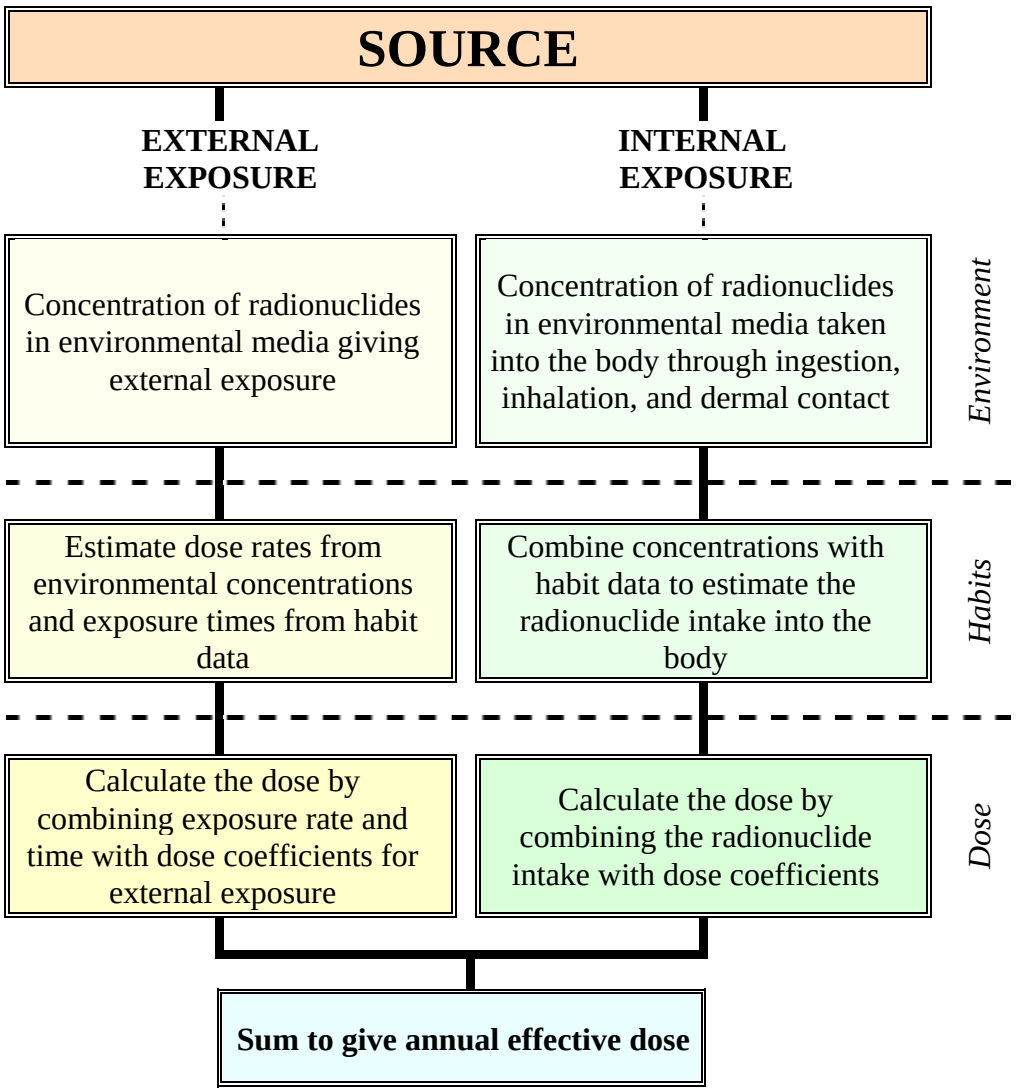

Figure 1. Assessment of annual dose.

(41) The third stage of the process is the combination of concentrations of radionuclides in environmental media with habit data and other information on the representative individual that are defined by exposure scenarios and allow estimation of exposure and dose. Information that needs to be considered include location, diet, lifestyle activities leading to radiation exposure, and age-dependent physiological factors such as age and breathing rates. The selection of this information is discussed in detail in Section 3. In many cases, these data can be obtained from available information about local populations. However, some situations may require regional or national information to be used in the absence of site-specific data.

(42) The fourth stage of the dose assessment process is the application of dose coefficients and related quantities. For intakes of radionuclides, these dose coefficients are expressed in terms of committed effective dose per unit activity intake or equivalent dose to an organ. Summation of the contributions from internal and external irradiation results in a total annual dose.

(43) This report provides guidance primarily on the third and fourth stages of the process.

2.4. Treatment of uncertainties in dose assessment

(44) It is recognised that uncertainties are inherent in any process of defining individual characteristics and in estimating doses. Whether doses are estimated by using measurement data, by applying models, or through a combination of measurements and calculations, the uncertainty for a given annual dose estimate is represented by a distribution of possible values. Uncertainty in dose assessment is a result of the inherent variability of some of the processes involved or a lack of knowledge about specific data that are needed for evaluating the dose.

(45) The Commission draws a distinction between quantities having values that are measured or estimated and quantities that have values that are selected, either by the Commission or by other organizations. For example, dose constraints, weighting factors, and dose coefficients, when used in the process of assessing compliance and in decision making, are assumed not to be uncertain. They are assumed to be point values. The Commission recognises uncertainties in the models linking detriment to dose. These uncertainties are considered in establishing selected values of quantities such as limits and constraints.

(46) Uncertainties associated with estimation of dose may be taken into account either deterministically by using single values for parameters chosen to take account of uncertainty, or probabilistically by incorporating distributions for parameter values. With either methodology, the goal should be to perform a realistic evaluation of dose.

(47) The Commission considers that the final decision on how to include uncertainties in the estimation of dose for compliance purposes should be made by the regulatory authority.

2.5. Deterministic and probabilistic methods for dose assessment

(48) As stated above, dose to the representative individual may be calculated either deterministically or probabilistically, or a mixture of these methods may be applied. The method used will depend on the particular situation and the capabilities and data available. Understanding the differences between these methods is important in applying guidance on how compliance with the Commission's recommendations is determined. Therefore, a brief description of these methods follows.

(49) The simplest deterministic method for assessing compliance is by a screening evaluation. This method typically makes use of simplifying assumptions that lead to a very conservative estimate of doses based on, for example, concentrations of radionuclides at the point of discharge from the source. If the results of relatively conservative screening assessments demonstrate that doses are well below the applicable dose constraint, there may be no need for further detailed assessment of dose. A number of screening methods have been developed and are available for application (NCRP, 1996; IAEA, 2001).

(50) In another form of the deterministic method, a general assessment of the involved populations, pathways, and radionuclides has to be made with the goal of identifying the group or groups receiving the highest dose using expert opinion, measurement data, or simple calculations. In some situations, people receiving the highest dose are easily identified because site-specific exposure data are readily available and habit information is known. In other situations, identifying these individuals is an iterative process that considers key pathways of exposure and populations receiving doses from the source. The iterative process will usually indicate the areas that are likely to receive the greatest exposure from each pathway. These areas should be investigated in more detail. Ultimately, a group is identified that is expected to receive the highest exposure. Dose to this group is compared to the dose constraint to determine compliance. This method is consistent with the earlier recommendations of the Commission based on the critical group approach.

(51) With advances in technology, decision makers have available powerful tools that allow the variability of data needed to estimate dose to be taken into account. The probabilistic method combines the distribution of values for each of the parameters into a composite distribution that present a range of possible doses based on their probability of occurrence. The distribution of dose incorporates (1) the uncertainty and natural variability in the estimated environmental media concentration (i.e., radionuclide concentration in air, water, soil, and food) and (2) uncertainty in the habit data (i.e., breathing rate, food and water ingestion rates, time spent at various activities). However, decision makers need guidance on how to determine compliance with the Commission's recommendations.

(52) A mixture of the deterministic and probabilistic methods is often used. One example of this is the use of measurement data in an existing exposure situation to determine dose to individuals (IAEA 1991, Lochard 2004). In this case, a distribution of doses is produced among the exposed population because of the variability of habit and measurement data, and it is this distribution that becomes the basis for determining compliance.

3. THE REPRESENTATIVE INDIVIDUAL

3.1. Definition of the representative individual

(53) Since dose to the public cannot be measured directly, it must be estimated using environmental concentrations and appropriate habit data. Therefore, for the purpose of protection of the public, it is necessary to define a hypothetical exposed person to be used for determining compliance with the dose constraint and for introduction of a practice. This is the representative individual. The representative individual is the hypothetical individual receiving a dose that is representative of the most highly exposed individuals in the population.

(54) In considering dose to the representative individual, a number of factors must be taken into account: (1) the dose must account for all pathways of exposure; (2) the dose must consider spatial distribution of radionuclides to be assured that the group receiving the highest dose is included in the assessment; (3) habit data should be based on the group or population exposed and must be reasonable, sustainable, and homogeneous; (4) dose coefficients must be applied appropriate to specific age categories. Once these factors are taken into account and depending on the assessment approach employed (deterministic or probabilistic or a mixture of these), the representative individual can be identified and used to determine compliance. Additional elaboration follows on each of these factors.

3.2. Pathways of exposure, time frames, and spatial distribution of radionuclides

(55) It is important that dose to the representative individual includes appropriate contributions from all modes of exposure (e.g., atmospheric discharges, liquid discharges, and direct external exposure). It is possible that in some assessments one pathway or a few pathways dominate the exposure and simplifying assumptions can be made to demonstrate that only the pathways that contribute significantly to the exposure need to be taken into account. The key to which pathways must be included depend on the type of assessment, but the overall goal should be to be certain that no important pathway has been omitted.

(56) The prospective assessment of individual exposure in general terms covers the present generation for a period of 50 years. This corresponds approximately to the lifetime operation for most nuclear or other facilities using radioactive materials. For this time period, it is reasonable to assume that characteristics of individuals can be based on current habit data. Nevertheless, it is important to occasionally re-evaluate the selected characteristics during the lifetime of a facility to account for significant changes that might occur in demographic data and lifestyles.

(57) In assessing doses in prospective situations, it may be appropriate to recognise that institutional controls on land use (e.g., designation as a national park or wilderness area) will be in effect. These might preclude types of activity (e.g., residential use or arable cropping) in the designated area so that obtaining staple food supplies from the area would not be possible. Climatic conditions might also preclude or dictate potential for future habitation and locally produced foodstuffs (e.g., in an arid zone, availability of water might preclude both extended residence and sustainable food production). Therefore, the selection of appropriate characteristics should take these conditions into account.

(58) The spatial distribution of radionuclides discharged and the build-up of long-lived radionuclides over the lifetime of a facility have to be taken into account. One example of this build-up is the accumulation in river or lake sediments of radionuclides from liquid releases. Such build-up could result in the most exposed individuals being distant from the facility or being exposed later in time.

(59) The possibility of future changes in land use may need to be considered in a prospective assessment. For example, currently there may be no agricultural production in the vicinity of a proposed facility, but such production could start during the facility's proposed lifetime. Whether this agricultural production is assumed in a prospective assessment should be determined by the regulatory authority.

3.3. Characteristics of the representative individual

(60) As indicated in paragraph 4, characteristics of an individual are described by age-dependent physiological parameters and habit data that include dietary information, residence data, use of local resources, and any other information that is necessary to estimate dose.

(61) It is important that the individual habits (e.g. consumption of foodstuffs, location, use of local resources) used in the deterministic approach are average habits of a small number of individuals representative of those most exposed and not the habits of a single extreme member of the population. Consideration may be given to some extreme or unusual habits, but they should not dictate the characteristics of the individuals considered. An exception may be the habits of a single individual that might reasonably be expected to continue for an extended period of time by that individual or others.

(62) When distributions of habit data are employed in a probabilistic approach, the habit data considered should include the range of all possible values found within a population, including extreme values on either end that may apply to only a small number of people. The distributions of habits should be appropriate for the location or situation under consideration. For example, if discharges to a coastal environment are the subject of an assessment, the distributions of habits should reflect the behaviours of residents of coastal communities.

(63) If specific habit data for a local population are not available (e.g., fish consumption from a coastal area with a local discharge of radionuclides into the marine environment), values may be derived from national or regional population data. A distribution of these data may be used in probabilistic assessments, or a value on the distribution may be selected for deterministic calculations. Established databases suggest that the 95^{th} percentile of consumption rates for many staple foods tend to exceed the mean value of the distribution by approximately a factor of 3 (Byrom et al., 1995). Therefore, with deterministic methods, using the 95^{th} percentile of behaviour is considered to represent a cautious, but acceptable, assumption for defining a reasonable and sustainable intake rate.

(64) Generally, one exposure pathway for a particular source will dominate the dose to the representative individual from that source. If more than one intake route for radionuclides provides a significant contribution to dose, it may not be reasonable to assume that 95^{th} percentile habit data are applicable to all routes; the more dominant route should be assigned a 95^{th} percentile intake, and a lower value assigned to other pathways, consistent with the requirement that assessments represent a set of habits that are reasonable and sustainable. Even if more than one exposure pathway has a significant contribution to the summed

effective dose, the individuals receiving the highest exposures tend to be fairly homogeneous in regard to habits (Hunt 1982 and Hunt 2004).

(65) The critical group concept as described in previous ICRP publications has some potential weaknesses because it implies a detailed knowledge of local habits, because those habits may not be fixed over the time period of dose assessment, and because local habit data may vary from one similar site to another at any particular time, leading to potentially varying operating regimes. These weaknesses may be avoided if habit data are derived from national or regional information using the 95^{th} percentile as described above.

(66) In selecting characteristics of the representative individual, reasonableness, sustainability, and homogeneity must be considered.

(67) Reasonableness implies that characteristics realistically apply to an individual and are not outside the range of what an individual encounters in day-to-day life. Reasonableness of characteristics must be considered whether probabilistic or deterministic methods are employed.

(68) Sustainability and homogeneity are aspects of reasonableness. In the deterministic approach, the question of reasonableness in selection of characteristics is related to that of homogeneity because the dose constraint is intended to apply to doses derived from the mean characteristics in a reasonably homogeneous group. Homogeneity addresses the degree to which extremes in particular characteristics are, or are not, included in the assessment.

(69) The Commission has previously stated (ICRP, 1985) that the necessary degree of homogeneity in the highest exposed group depends on the magnitude of the mean dose in the group as a fraction of the relevant dose limit or constraint. If that fraction is less than about one-tenth, the group should be regarded as homogenous if the distribution of individual doses lies substantially within a total range of a factor of 10 (i.e., a factor of about 3 on either side of the mean). At fractions above one-tenth, the total range should be less, preferably no more than a factor of 3.

(70) Sustainability addresses the degree to which the selected characteristics can be continued over the time frame of the assessment. The characteristics selected need to be sustainable. For example, the total dietary intake should be consistent with credible calorific requirements. Habits should correspond to an individual's personal requirements. It is inappropriate to assume, for example, that the same individual receives daily nutrient requirements independently from each of several different pathways (e.g., agriculture, and fishing). Also, it is inappropriate to assume that all foods consumed in an area are grown within that area if it is apparent that the location and land area available could not support the assumed dietary intake. Similarly, the intakes of wild game from an area should not exceed feasible game-capture rates. In the case of significant contributions to the dose from external exposure, reasonable estimates of times spent in areas of elevated exposure rates are required. In general, maintenance of exposure situations for a period of at least 5 years would be considered sustainable.

3.4. Age-specific dose coefficients

(71) It is generally recognised that for external exposure, there is little variability in dose with age (Golikov et al., 1999; Golikov et al., 2000). However, the Commission has issued age-specific dose coefficients for intakes of radionuclides in seven age ranges covering the time period from the foetus to age 70 years (ICRP, 1996; ICRP, 2002). These coefficients allow the calculation of dose for specific age groups. This section provides further guidance on the incorporation of age-specific dose coefficients for internal exposure for the representative individual and distinguishes among their use in different situations. As a basis for understanding the use of age-specific dose coefficients in determining compliance, several goals and fundamental concepts underlying the Commission's recommendations need to be discussed.

(72) As stated in the draft 2005 Recommendations (ICRP, 2005a), one goal of the Commission is simplification of its recommendations. The number of age-specific internal dose coefficients has continued to evolve and increase over time, making it possible to calculate dose to more age groups. This refinement in dose coefficients, however, must be weighed in relation to the ability to predict concentrations in the environment from a source and the ability to account for variations in habit data for individuals exposed. Uncertainties in estimates of dose, particularly for prospective calculations, are generally not significantly reduced by increasing the number of age categories for which dose coefficients have been provided. Therefore, the Commission believes that some consolidation of the age-specific dose coefficients is warranted in these situations.

(73) Paragraph 19 points out that the dose constraint is set, at least in part, on the basis of exposures to individuals that are assumed to continue to occur for a number of years into the future. Therefore, it is the same individual being exposed for a number of years for whom compliance is being determined. This fundamental concept of continuing exposure to the same individual justifies the use of age categories that cover several years of a person's life.

(74) These dose coefficients provided by the Commission take into account the committed dose resulting from the accumulation of radionuclides in the body over a period of 70 years. This conservative accounting assures individuals are protected over a lifetime of exposure, regardless of the number of years they are exposed.

(75) The Commission allows averaging over a five-year period in evaluating compliance with the dose the dose constraint (ICRP 1991; ICRP 2005a) and, therefore, recommends that a similar approach is appropriate for establishing the number of age groups to be considered in prospective assessment of continuing exposure. Experience to date indicates that age categories can be combined without impacting protection of members of the public in these situations.

(76) With these goals and fundamental concepts in mind, the Commission has considered the change in internal dose as a function of age when unique age-specific habit data and dose coefficients are applied. These data are discussed and presented in Appendix A. It is evident from these calculations that with the exception of the actinides, the differences among dose to different age groups are generally small (generally less than a factor of 3) in comparison to uncertainties typically found in assessment of dose to the public. For the actinides, dose

coefficients take into account the integrated commitment for a lifetime of exposure, which tends to overestimate dose to an individual in any given year.

(77) In view of the goals and fundamental concepts underlying the Commission's recommendations, some consolidation of the age-specific dose coefficients for internal exposure is justified.

(78) Therefore, for the purpose of compliance with the dose constraint for continuing exposure, the Commission recommends annual dose for representative individuals be defined by three age categories. These categories are 0 to <6 years (infant), 6 to <16 years (child), and 16 to 70 years (adult). The shorter time period (5 years) is selected for the 0-to-5-year age category, when dosimetric characteristics are changing most rapidly, to avoid any unwarranted reduction in the importance attached to doses to younger age groups. Use of these three age categories is sufficient to characterise the radiological impact of a source and assure consideration of younger, more sensitive populations. For practical implementation of this recommendation, dose coefficients and habit data for the 1-year-old infant, 10-year-old child, and adult should be used as representing the three age categories. These recommendations are summarized in Table 2.

(79) The 0-to-<6-year age category does not include the foetus or breast-fed infant. In most cases, the dose to the foetus or breast-fed infant will not be substantially different from the assessed dose for the 0-to-<6-year age category. However, some radionuclides, principally isotopes of phosphorus and the alkaline earths, can deliver significantly higher doses to the foetus and breast-fed infant than to the mother (ICRP, 2002). Typically, these radionuclides will also deliver relatively higher doses to the infant, so basing compliance on the doses to this age group would normally ensure that the dose to the mother and to the foetus is also in compliance. Nevertheless, the Commission recognises the foetus as an individual deserving a comparable level of protection. Therefore, if assessed doses to the other age groups include significant contributions from radionuclides known to give rise to relatively high doses to the foetus, and they are approaching the value of the dose criterion, the dose to the foetus or breast-fed infant should be separately assessed to assure that the quantitative recommendations are respected. In light of the fact that this dose will only be received over a very limited proportion of the individual's lifetime, the Commission considers that an appropriate level of protection can be achieved by comparing the assessed dose to the foetus or breast-fed infant with the dose limit for members of the public.

(80) This consolidation of age-specific dose coefficients helps provide a system of protection for the public that is robust, that can accommodate changes of dose coefficients within an age category, and yet that allows the continued development of age-specific dosimetry information as the science evolves. The Commission also believes the use of three age categories is consistent with ICRP's dose constraint, which are based on continuing exposure of an individual from a source for a number of years.

(81) The use of all of ICRP's age-specific dose coefficients for some situations continues to be applicable. For example, in the reconstruction of doses where measurements of concentrations in the environment or in persons exposed are available, all of the available age-specific dose coefficients that apply should be considered. In these cases, the quality and extent of site-specific data needed to estimate dose generally determine whether age-specific

coefficients published by the Commission improve the quality of doses and reduce their uncertainty.

(82) The Commission continues to encourage the use of all available age-specific dose coefficients in the planning for and response to accidents. However, the consolidated age categories proposed by the Commission in this report may be acceptable in some accident situations, especially when prospective assessments are being made of future consequences of the accident or remediation alternatives. This decision should be made by appropriate regulatory authorities.

Table 2. Dose coefficients recommended for determining compliance with the dose constraint

Age category (y)	Name of age category	Dose coefficient to be used
0–<6	infant	1 year old
6–<16	child	10 year old
16–70	adult	adult

3.5. Determining compliance

(83) Compliance with the Commission's quantitative recommendations exists when the dose to the representative individual is less than the corresponding dose constraint. Overall compliance with the Commission's recommendations also requires optimisation to achieve further levels of protection.

(84) With deterministic methods, compliance exists when dose to the representative individual is less that the dose constraint. Since this dose is based on the average characteristics of the highest exposed group, the Commission's goal is achieved.

(85) For probabilistic assessments, defining the representative individual is more complex than for deterministic methods. Appendix B describes various distributions of dose and how these distributions may be used to identify the representative individual for the purpose of determining compliance. The Commission does not prescribe a specific method to be used for probabilistic assessments. As noted above, there are many different approaches and numerous distributions of dose may result.

(86) In probabilistic assessments, it is important to first identify the region over which the assessment is conducted. This region defines the population under consideration. Care must be used to include all hypothetical individuals whose dose could possibly be representative of persons receiving the highest dose, including extremes. No specific guidance can be provided to define the region and population being considered in probabilistic assessments because almost every situation will be unique.

(87) For some prospective probabilistic assessments of dose, it is possible that essentially all doses on the distribution will be predicted to be less than the dose constraint set by ICRP. In this case, compliance is readily met.

(88) In a prospective probabilistic assessment of dose to hypothetical individuals, whether from a planned facility or an existing situation, the Commission recommends that the representative individual be identified such that the probability is less than about 5% that a person drawn at random from the hypothetical population will receive an annual effective dose exceeding the dose constraint. This hypothetical individual should be representative of, at most, a few tens of people who are the most highly exposed. If this dose to the representative individual is below the dose constraint set by the Commission, then the design and planned operations are determined to be in compliance.

(89) In a probabilistic assessment of prospective dose to hypothetical individuals, if a homogeneous group of a few tens of persons or more is found to exist whose dose is above that for the representative individual, then the presence of a new homogeneous group (and thus different representative individual) needs to be explored. Determining the existence of a homogeneous group in a probabilistic assessment can be problematic. For example, if a large population is being considered within the region of study, the existence of a homogeneous group of individuals above the dose constraint may be difficult to distinguish from a histogram or distribution curve. Therefore, care must always be taken to fully investigate the distribution of doses above the dose constraint to consider carefully all plausible scenarios of exposure, and to avoid the premature conclusion that these scenarios would correspond to few if any "random" individuals. Close attention must be paid to suggestions from members of the public of existing or likely exposure situations that might reflect extremes in the population. Such contributions may not have been considered in the operator's analysis, and although they most often correspond to low exposures, experience has shown that they sometimes point out potentially significant exposure pathways that have not been considered and that warrant further investigation. If it can be shown that such a pathway, in combination with other exposure, is likely to affect a few tens of persons and elevate their doses above the dose constraint, then a revision of the analysis must be undertaken. If such a homogeneous group is found to exist above the dose constraint, then the mean dose to this group becomes the basis for compliance.

(90) For retrospective assessments of dose to specific individuals, either for the purpose of determining compliance for a past period of operation of a practice or an existing situation, the Commission recognises that estimated doses above the dose constraint must be evaluated on a case by case basis. In most cases it may be expected that the extremes represented by these individuals will continue for only a short time or may actually never be realised. However, if doses to specific individuals exceeded the dose constraint and these doses are expected to continue for a protracted period of time, a decision must be made by the operator and the regulator whether a reduction in the source is required or whether changes in habits of the individuals exposed might be proposed and supported. Such a situation might warrant additional monitoring to reduce uncertainty in the dose estimate or verify the magnitude of dose. The above considerations should be separate from any decision regarding whether the previous design or operations were in compliance with their basis of authorisation.

(91) Regardless of the approach taken to determine compliance, the Commission stresses that application of the total system of protection, utilising both compliance with the quantitative constraint and optimisation of protection, is necessary for radiological protection.

Table 3. Summary of methods used for determining dose to the representative individual

	CALCULATION METHOD	
	Probabilistic	**Deterministic**
Environmental concentration data	Distribution of estimated or measured concentration	Single "best estimate"
Physiological or habit data	Range or fixed values of physiological parameters or habit data	Average value for the highest exposed group or 95th percentile of national or regional data
Dose coefficient	Fixed value based on age	Fixed value based on age
Dose to the representative individual	Method selected by operator or regulator. Representative individual is identified such that the probability is less than about 5% that a person drawn at random from the hypothetical population will receive an annual effective dose exceeding the dose constraint.	Product of above values

4. OTHER CONSIDERATIONS RELEVANT TO THE REPRESENTATIVE INDIVIDUAL

4.1. Relationship between environmental monitoring, modelling, and the representative individual

(92) Prospective assessments are usually undertaken to establish the acceptability of proposed controlled releases to the environment. They almost always involve the use of models, which usually provide the only means of estimating the concentrations of radionuclides in the environmental materials. The representative individual should be assumed to exist at the location where the estimated environmental concentrations lead to the highest doses subject to the requirements for reasonableness, sustainability, and homogeneity noted earlier. The temporal and spatial scales represented by the models must also be appropriate for the intended use.

(93) When a source already exists (continuing practices, existing situations, and emergency situations), monitoring radionuclide levels in the environment will normally be the most robust method for determining environmental concentrations of radionuclides. This was the primary focus of ICRP Publication 43 (ICRP, 1985). Monitoring programmes should be guided by the identification of dominant pathways and radionuclides, taking the detection limits and source of radionuclides into account. Environmental modelling is also an important and complementary component of monitoring. ICRP Publication 43 (ICRP, 1985) gives guidance on the use and limitations of both monitoring and modelling to estimate doses.

4.2. Situations of potential exposure

(94) In normal exposure situations annual doses are either being delivered or will certainly occur in the future. But there may also be situations in which the exposure is not certain to occur and the attributed dose may have only a small probability of occurring. These are termed situations of potential exposure. Potential exposure situations can cover a wide range of circumstances, including equipment failures and accidents involving radiation sources as well as highly non-uniform distribution of radioactive residues.

(95) According to the Commission's recommendations, a potential exposure situation should be evaluated on the basis of the combination of the probabilities that a radiation dose will be incurred and the probability of harm given that the dose has occurred. (ICRP, 1993). The product of these probabilities is the unconditional probability of incurring the health effect. It should be noted, however, that it is more informative for decision-making purposes to present the probability of incurring a dose separately from that dose (ICRP, 2000a).

(96) The identification of the representative individual in potential exposure situations must take into account the probability of exposure in addition to the other factors in the assessment. The annual dose that such an individual would incur, should the exposure actually take place, is not a sufficient indicator although the magnitude of the dose could be important in deciding what risk factor to use. Thus, in addition to characterising the habits, locations, and environmental concentrations of radionuclides, it is necessary to characterise the probability that the individual is exposed. This probability may in fact be the combination of several probabilities, including that of being in the particular location and being engaged in the specific activity causing an exposure to occur. In deterministic assessments, this

requires selection of the value for probability of exposure to be included in the calculations. For probabilistic assessments, a distribution may be used if such information is available.

(97) An example of an environmental potential exposure situation is presented by areas contaminated with sparsely distributed hot particles and has been illustrated in the assessment of the radiological situation created by plutonium hot particles present on the motus (islets) of Colette, Ariel, and Vesta, in the Atoll of Mururoa, French Polynesia (IAEA 1998). In contrast to the usual assumptions of relative uniform contamination, there may be only a relatively small probability that the individual would be exposed to one of the hot particles, and an even lower probability that this material would result in an internal exposure through ingestion or absorption through a wound in the body. Even though such a scenario is not likely to occur, should people be exposed to the contaminated area and a hot particle be actually incorporated through a wound, the resulting local dose might be relatively large and could even be a cause of localized deterministic effects such as micro-necroses around the incorporated hot particles. The potential for this exposure would remain for as long as the hot particles were present in the environment.

(98) The quantitative approaches to potential exposure are also of use in other situations where exposure may be intermittent or infrequent.

4.3. Value of stakeholder input to characterising the representative individual

(99) As noted in ICRP Publication 82 (ICRP, 2000b), in the wider decision-making process, the role of stakeholders should be recognised. This role for stakeholders was described in Publication 82 in the context of protection of the public in situations of prolonged exposure. Since Publication 82 was published, the Commission has continued to consider and support the role of stakeholders in the ICRP system of protection. However, the Commission believes this role needs to be defined, clarified, and expanded to include other situations. Further information on this subject will be provided in ICRP Publication XX (ICRP, 2005b); however, it is important to provide several key principles related to stakeholder involvement in the characterisation of the individual being described in this report.

(100) By definition, the decision maker and the operator have clearly defined roles and responsibilities in the characterisation of the individual and in determining compliance. Beyond this, there are other types of involved individuals or groups. These are considered stakeholders, and include, for example, individuals who have a personal, financial, health, or legal interest in policy or recommendations that affect their well being or that of their environment. In most cases, the role of stakeholders is to aid in the decision-making process. There may be situations where stakeholders have the authority and responsibility for making or recommending decisions (such as a nationally appointed board or committee). Generally, however, the operator and regulator are the decision makers, and the stakeholders help in the process by providing information and guidance related to decisions being made.

(101) In the case of defining characteristics of the representative individual, stakeholder involvement can play an important role. Stakeholders can provide valuable input regarding habit data that are specific to their location. In particular, stakeholders can be helpful in determining reasonableness, sustainability, and homogeneity of data. Collaboration with stakeholders can significantly improve the quality, understanding, and acceptability of

characteristics of the representative individual, and also strengthen support from stakeholders in the compliance and decision-making process.

(102) If stakeholder involvement is used as part of the overall decision-making process, guidelines should be established to ensure the process is effective and meaningful for all parties. Some of these guidelines include, but are not limited to: (1) clearly defining the role of stakeholders at the beginning of the process, (2) agreeing on a plan for involvement, (3) providing a mechanism for documenting and responding to stakeholder involvement, and (4) recognising, by operators and regulators, that stakeholder involvement can be complex and require additional resources to implement.

(103) The Commission understands the concept of stakeholder involvement may vary significantly from one country to another for cultural, societal and political reasons. Therefore, the value and extent of stakeholder involvement must be considered by individual authorities in those countries. Nevertheless, the Commission believes that stakeholder involvement can play an important role in the implementation, understanding, and acceptance of the ICRP system of protection.

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APPENDIX A. ANALYSIS OF AGE CATEGORIES FOR USE IN ASSESSMENT OF DOSE TO THE PUBLIC

A.1. Introduction

(A1) The Commission has specified dose coefficients for the embryo/foetus and for six age groups in the population. This appendix investigates whether the number of age groups could be reduced to three for the purposes of assessing doses for comparison with the Commission's dose constraint, particularly in prospective assessments (see section 3.4). These groups would be 0 to <6 years (infant), 6 to <16 years (child) and 16 to 70 years (adult). For practical implementation of this recommendation, dose coefficients and habit data for the 1-year-old infant, 10-year-old child, and the adult should be used as representing the three age categories.

A.2. Background

(A2) Following the Chernobyl accident in 1986, it became apparent that there was a requirement for dose coefficients (doses per unit intake, Sv Bq^{-1}) that could be used for assessing doses from intakes of radionuclides by inhalation and ingestion for all age groups in the population. Task Groups of Committee 2 of ICRP developed age-specific biokinetic models that were used for calculating dose coefficients for various age groups in the population. In a series of publications (ICRP, 1989; ICRP, 1993; ICRP, 1995a; ICRP 1995b; ICRP, 1996), age-specific dose coefficients were given for selected radionuclides of 31 elements. To allow for the effect of body mass and for changes in the biokinetics of radionuclides and dosimetry with increasing age, Committee 2 provided dose coefficients for six representative age groups in the population. These are the 3-month-old infant; the 1-, 5-, 10-, and 15-year-old child, and the adult. In circumstances for which dose coefficients are required for other age groups in the population, it is recommended that the dose coefficients can be used for the age ranges given below:

3-month infant	from 0 to 1 year of age
1- year-old child	from 1 year to 2 years
5- ear-old child	more than 2 years to 7 years
10-year-old child	more than 7 years to 12 years
15-year-old child	more than 12 years to 17 years
adult	more than 17 years

(A3) Recently, dose coefficients for the embryo and foetus also were published by ICRP in Publication 88 (ICRP 2001). Dose coefficients for intakes of radionuclides by infants in mothers' milk will be published in 2005 (ICRP 2005).

(A4) The dose coefficients published by ICRP for the six age ranges were adopted in the European Basic Safety Standards (EU, 1996) and in the International Basic Safety Standards (IAEA 1996) as well as being used in many national regulations and guidance notes. They are established as a widely accepted international standard.

(A5) In circumstances where comprehensive, detailed information is needed on doses to individuals, such as in some dose reconstruction studies and in dose assessments for the planning for and response to accidents, it is appropriate to use these dose coefficients. In

many situations, however, this level of detail is not required, and it would be convenient to use a more limited range of dose coefficients. In deciding whether such a limited range of age-specific dose coefficients is appropriate for use in assessments of dose, it is important to consider the doses that arise from intakes of radionuclides by the different age groups in the population. Straightforward comparison of dose coefficients is not sufficient because the radiological criteria against which the results of the assessment would be compared are specified primarily in terms of dose per unit intake. Additionally, the intakes of radionuclides by different age groups will not be identical for the same foodstuffs because consumption rates differ between age groups. Therefore, for consumption of the same foodstuff by different age groups, the relative doses will depend not only on the values of the age-specific dose coefficient, but also on the age-specific consumption rates.

(A6) This appendix examines the option of using a limited range of age-specific dose coefficients by calculating doses to three selected age groups in the population resulting from ingestion of radionuclides in foods using representative consumption rates. These results are compared with doses obtained using all six dose coefficients.

A.3. Method

(A7) Annual doses to the six age groups were separately calculated using unit concentrations of radionuclides in milk, green vegetables, beef, and air. The intake rates used are shown in Table A1. They are taken from Smith et al. (2003) and are derived from United Kingdom data. Consumption rate data for specific foodstuffs may vary from country to country, but such data usually follow the same general trends. For example, milk is consumed in higher rates by the young, and the rates for solid foods are highest for the adult. Thus, the overall conclusions from this analysis are expected to be generally applicable. Dose calculations were carried out for every radionuclide for which the Commission has published dose coefficients.

A.4. Results

(A8) The results for important radionuclides for each exposure pathway are given in Tables A2 to A5 as ratios. To establish whether the dose to a 1-year-old child can adequately represent the doses for the range of ages from 3 months to 5 years, the ratios of the 1-year dose to the 3-month dose, and the ratio of the 1-year dose to the 5-year dose are provided in the tables. Similarly, to establish whether the dose to a 10-year-old child can adequately represent the range from 6 years to 15 years, the ratio of the 10-year dose to the 15-year dose is also presented.

(A9) The results show that the largest differences are observed for doses calculated using the 3-month dose coefficient, particularly for the milk pathway. This is largely because the 3-month dose coefficients are generally higher than for the other age groups, both because of the smaller body mass and, in many cases, because of the adoption of an increased f_1 value. The 3-month dose coefficients are, however, applicable to infants on all milk diets, which would be breast milk or formula milk. When infants are introduced to solid foods, the dose coefficients decrease progressively to the value for a 1-year-old. Therefore, the doses calculated for solid foods using the 3-month dose coefficients are considered to be unrealistic and may be ignored for the purposes of this assessment. Similarly, the doses for the milk

pathway calculated using the 3-month dose coefficients are not likely to be relevant for the following reasons:

- The radionuclides giving the highest doses via the milk pathway, which are the actinides (see Table A2), do not transfer readily to breast milk; thus, intakes of these radionuclides via other pathways by other age groups would be limiting.
- Formula milk would not be made from cow's milk taken solely from the geographical area affected by controlled releases of radionuclides, an area which tends to be limited in size. Rather, it would be derived from a much wider area so local pathways exposing other age groups would be limiting. Furthermore, the actinides do not transfer readily to cow's milk.
- It can be argued that formula milk could be reconstituted using local water that may be contaminated. Many radionuclides, however, do not transfer readily to drinking water due to the various natural and artificial filtration processes that apply to drinking water.

(A10) It should be noted, however, that in calculating doses for the infant resulting from intakes of radionuclides in mothers' milk, the 3-month dose coefficients are used for the six months prior to weaning, during which time the infant is assumed to be consuming mothers' milk.

A.5. Conclusions

(A11) The results for all radionuclides for which the Commission has published dose coefficients are summarised in Table A6. It can be seen that, with the exception of the milk pathway discussed above, the ratios are within factors of a few. Therefore, it can be concluded that, in many situations, the dose calculated for a 1-year-old can adequately represent doses in the age range 3 months to 5 years. Similarly, the dose to the 10-year-old can adequately represent the range from 6 years to 15 years.

(A12) The use of a limited set of age-specific dose coefficients representing the infant (1-year-old dose coefficient), the child (10-year-old dose coefficient), and the adult is consistent with the likely availability of data on consumption rates. Specific consumption rate data for the six age groups for which the Commission has specified dose coefficients are unlikely to be generally available in most cases. Data on consumption rates for the three broad categories—infant, child, and adult—are more likely to be available. Doses for the six age groups, however, may be needed in dose reconstruction studies and in the planning for and response to accidents.

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Table A1. Habit data used in calculating the doses				
	Milk consumption rate ($kg\ y^{-1}$)	Green vegetable consumption rate ($kg\ y^{-1}$)	Beef consumption rate ($kg\ y^{-1}$)	Inhalation ($m^3\ h^{-1}$)
3 month	350	15	10	0.12
1 year	320	30	20	0.22
5 year	280	32.5	25	0.37
10 year	240	35	30	0.64
15 year	260	45	35	0.84
Adult	240	80	45	0.92

Table A2. Ratio of the doses from the ingestion of milk			
Radionuclide	1 year : 3 month	1 year : 5 year	10 year : 15 year
H-3	0.69	1.77	1.18
H-3 (organically bound tritium)	0.91	1.88	1.25
C-14	1.04	1.85	1.30
Na-22	0.65	2.04	1.37
Mg-28	1.07	2.16	1.54
P-32	0.56	2.31	1.58
S-35 (organic)	0.64	2.29	1.55
K-42	0.54	2.29	1.47
Ca-45	0.41	2.15	1.28
Fe-59	0.30	1.98	1.40
Co-60	0.46	1.82	1.29
Ni-63	0.48	2.09	1.44
Zn-65	0.41	1.89	1.31
Se-75	0.59	1.79	1.79
Sr-90	0.29	1.78	0.69
Zr-95	0.60	2.13	1.46
Nb-95	0.64	2.03	1.37
Mo-99	0.58	2.22	1.34
Tc-99m	0.59	2.06	1.42
Ru-106	0.53	2.24	1.61
Ag-110m	0.53	2.05	1.41
Sb-125	0.51	2.05	1.38
Te-127m	0.40	2.17	1.60
I-131	0.91	2.06	1.41
Cs-137	0.52	1.43	0.71
Ba-133	0.26	1.82	0.58
Ce-144	0.54	2.35	1.56
Po-210	0.31	2.29	1.50
Np-237	0.10	1.71	0.92
Pu-239	0.09	1.45	1.04
Am-241	0.09	1.57	1.02
Cm-242	0.12	2.23	1.48

Table A3. Ratio of the doses from the ingestion of green vegetables			
Radionuclide	1 year : 3 month	1 year : 5 year	10 year : 15 year
H-3	1.50	1.43	0.99
H-3 (organically bound tritium)	2.00	1.52	1.06
C-14	2.29	1.49	1.09
Na-22	1.43	1.65	1.16
Mg-28	2.33	1.75	1.30
P-32	1.23	1.87	1.33
S-35 (organic)	1.40	1.85	1.31
K-42	1.18	1.85	1.24
Ca-45	0.89	1.74	1.08
Fe-59	0.67	1.60	1.18
Co-60	1.00	1.47	1.08
Ni-63	1.05	1.69	1.21
Zn-65	0.89	1.52	1.11
Se-75	1.30	1.45	1.51
Sr-90	0.63	1.43	0.58
Zr-95	1.32	1.72	1.23
Nb-95	1.39	1.64	1.16
Mo-99	1.27	1.79	1.13
Tc-99m	1.30	1.67	1.19
Ru-106	1.17	1.81	1.36
Ag-110m	1.17	1.66	1.19
Sb-125	1.11	1.66	1.17
Te-127m	0.88	1.75	1.35
I-131	2.00	1.66	1.19
Cs-137	1.14	1.15	0.60
Ba-133	0.56	1.47	0.49
Ce-144	1.18	1.89	1.32
Po-210	0.68	1.85	1.26
Np-237	0.21	1.38	0.78
Pu-239	0.20	1.17	0.88
Am-241	0.20	1.26	0.86
Cm-242	0.26	1.80	1.24

Table A4. Ratio of the doses from the ingestion of beef			
Radionuclide	1 year : 3 month	1 year : 5 year	10 year : 15 year
H-3	1.50	1.24	1.10
H-3 (organically bound tritium)	2.00	1.32	1.16
C-14	2.29	1.29	1.20
Na-22	1.43	1.43	1.27
Mg-28	2.33	1.51	1.43
P-32	1.23	1.62	1.47
S-35 (organic)	1.40	1.60	1.44
K-42	1.18	1.60	1.37
Ca-45	0.89	1.51	1.19
Fe-59	0.67	1.39	1.30
Co-60	1.00	1.27	1.19
Ni-63	1.05	1.46	1.33
Zn-65	0.89	1.32	1.22
Se-75	1.30	1.25	1.66
Sr-90	0.63	1.24	0.64
Zr-95	1.32	1.49	1.36
Nb-95	1.39	1.42	1.27
Mo-99	1.27	1.56	1.24
Tc-99m	1.30	1.44	1.32
Ru-106	1.17	1.57	1.50
Ag-110m	1.17	1.44	1.31
Sb-125	1.11	1.44	1.29
Te-127m	0.88	1.52	1.49
I-131	2.00	1.44	1.31
Cs-137	1.14	1.00	0.66
Ba-133	0.56	1.27	0.54
Ce-144	1.18	1.64	1.45
Po-210	0.68	1.60	1.39
Np-237	0.21	1.20	0.86
Pu-239	0.20	1.02	0.96
Am-241	0.20	1.10	0.94
Cm-242	0.26	1.56	1.37

Table A5. Ratio of the doses from inhalation				
Radionuclide	Lung absorption rate	1 year : 3 month	1 year : 5 year	10 year : 15 year
H-3 (tritium compounds)	F	1.41	1.08	1.06
H-3 (tritium compounds)	M	1.46	1.15	1.18
H-3 (tritium compounds)	S	1.53	0.94	1.03
H-3 (Inhalation of organically bound tritium)		1.83	0.93	1.02
C-14	F	2.01	1.11	1.16
C-14	M	1.46	0.98	0.85
C-14	S	1.64	0.92	0.88
Na-22	F	1.38	1.14	1.22
Mg-28	F	1.63	1.27	1.36
Mg-28	M	1.81	1.22	1.17
P-32	F	1.15	1.39	1.40
P-32	M	1.25	1.11	1.01
S-35 (Inhalation of sulphur dioxide)		1.29	1.15	1.23
S-35 (Inhalation of carbon disulphide)		1.28	1.19	1.24
K-42	F	1.15	1.35	1.32
Ca-45	F	0.96	1.27	1.00
Ca-45	M	1.34	0.99	0.85
Ca-45	S	1.47	0.99	0.84
Fe-59	F	1.13	1.09	1.23
Fe-59	M	1.32	0.98	0.91
Fe-59	S	1.40	0.95	0.87
Co-60	F	1.41	0.98	1.11
Co-60	M	1.48	0.96	0.95
Co-60	S	1.71	0.87	0.90
Ni-63 (Inhalation of nickel carbonyl)		1.54	0.99	1.04
Ni-63	F	1.59	1.08	1.11
Ni-63	M	1.39	1.03	1.01
Ni-63	S	1.64	0.95	1.00
Zn-65	F	1.22	1.04	1.16
Zn-65	M	1.40	1.04	0.96
Zn-65	S	1.62	0.91	0.92
Se-75	F	1.41	1.05	1.59
Se-75	M	1.53	1.07	1.00
Se-75	S	1.54	0.96	0.95
Sr-90	F	0.73	1.00	0.59

Sr-90	M	1.34	1.01	0.78
Sr-90	S	1.75	0.88	0.86
Zr-95	F	1.68	1.02	1.14
Zr-95	M	1.47	0.98	0.88
Zr-95	S	1.45	0.94	0.87
Nb-95	F	1.39	1.15	1.22
Nb-95	M	1.40	1.00	0.88
Nb-95	S	1.40	0.97	0.87
Mo-99	F	1.36	1.31	1.38
Mo-99	M	1.34	1.19	1.04
Mo-99	S	1.28	1.19	1.08
Tc-99m	F	1.33	1.26	1.22
Tc-99m	M	1.40	1.15	1.08
Tc-99m	S	1.41	1.14	1.07
Ru-106 (Inhalation of ruthenium tetroxide)		1.26	1.07	1.28
Ru-106	F	1.38	1.23	1.33
Ru-106	M	1.44	1.02	1.01
Ru-106	S	1.62	0.98	0.98
Ag-110m	F	1.47	1.11	1.17
Ag-110m	M	1.47	0.98	0.99
Ag-110m	S	1.63	0.94	0.91
Sb-125	F	1.43	1.09	1.17
Sb-125	M	1.47	0.95	0.89
Sb-125	S	1.66	0.94	0.87
Te-127m (Inhalation of tellurium vapour)		1.28	1.16	1.25
Te-127m	F	1.22	1.28	1.33
Te-127m	M	1.36	1.03	0.91
Te-127m	S	1.48	0.98	0.89
I-131 (Inhalation of methyl iodide)		1.83	1.04	1.17
I-131 (Inhalation of elemental iodine vapour)		1.73	1.01	1.18
I-131	F	1.83	1.16	1.32
I-131	M	1.25	1.09	1.05
I-131	S	1.29	1.05	0.91
Cs-137	F	1.13	0.89	0.64
Cs-137	M	1.48	0.96	0.90
Cs-137	S	1.67	0.85	0.87
Ba-133	F	0.75	1.03	0.47
Ba-133	M	1.22	0.93	0.71
Ba-133	S	1.66	0.86	0.90
Ce-144	F	1.38	1.15	1.24
Ce-144	M	1.54	1.08	1.02

Ce-144	S	1.57	0.97	0.96
Po-210	F	1.19	1.30	1.29
Po-210	M	1.34	0.98	0.88
Po-210	S	1.43	0.97	0.88
Np-237	F	1.74	0.92	0.81
Np-237	M	1.67	0.85	0.76
Np-237	S	1.59	0.91	0.82
Pu-239	F	1.75	0.79	0.83
Pu-239	M	1.76	0.76	0.78
Pu-239	S	1.66	0.86	0.85
Am-241	F	1.83	0.89	0.83
Am-241	M	1.73	0.80	0.76
Am-241	S	1.59	0.88	0.85
Cm-242	F	1.43	1.25	1.16
Cm-242	M	1.50	0.97	0.87
Cm-242	S	1.45	0.94	0.86

Table A6. Minimum and maximum ratios for the pathways for all radionuclides

Pathway	Ratio	Minimum ratio	Maximum ratio
Ingesting milk	1 year : 3 month	0.08	1.62
	1 year : 5 year	1.14	2.51
	10 year : 15 year	0.49	3.15
Ingesting green vegetables	1 year : 3 month	0.18	3.54
	1 year : 5 year	0.92	2.03
	10 year : 15 year	0.41	2.66
Ingesting beef	1 year : 3 month	0.18	3.54
	1 year : 5 year	0.80	1.76
	10 year : 15 year	0.46	2.93
Inhalation	1 year : 3 month	0.55	2.51
	1 year : 5 year	0.54	1.65
	10 year : 15 year	0.41	2.84

APPENDIX B. DETERMINING COMPLIANCE WHEN DOSE TO THE PUBLIC IS ESTIMATED PROBABILISTICALLY

B.1. Introduction

(B1) When dose to the public is estimated probabilistically and uncertainties are taken into account, a distribution of possible doses is the result. It is likely that the use of probabilistic methods will become more frequent in the future as improvements in technology improve the ability to account for uncertainties inherent in any estimation of dose. It is also expected that probabilistic methods will become more widespread as the techniques in their application become more familiar to regulators, operators, and stakeholders. Therefore, the Commission needs to provide guidance on the use of a distribution of dose rather than a deterministic (point) estimate of dose for the purpose of determining compliance. This appendix provides a discussion of distributions of dose resulting from probabilistic assessments.

(B2) It is not within the Commission's scope to prescribe how doses may be estimated probabilistically. Many different methods exist. With some distributions of dose, it is possible that doses on the extreme high end of the distribution are well below the dose constraint set by the Commission. In this case, it can be readily determined that compliance exists. However, it is also possible that a probabilistic assessment results in doses on the high end of the distribution that exceed the dose constraint set by ICRP. Further guidance is needed to address this situation to be sure that members of the public are protected in accordance with the Commission's dose constraint.

(B3) In considering probabilistic assessments of dose, it is important to distinguish whether the distribution of dose is retrospective or prospective, whether dose is for hypothetical individuals or specific individuals, and whether the doses are from planned or existing situations. Prospective exposures to hypothetical individuals may be for planned or existing situations. Retrospective exposures apply to specific individuals for existing (or formerly existing) exposure situations. The next section addresses these situations.

B.2. Retrospective and prospective dose for specific and hypothetical individuals

(B4) Methods of carrying out a risk assessment for a radiological source and interpretation of the results vary according to whether the effects were realised in the past (retrospective assessment) or are contemplated for the future (prospective assessment). A prospective assessment might be applied to a newly designed system, apparatus, or facility, or to future operation of an existing source. Similar mathematical and probabilistic techniques may be used in either temporal frame, but the questions that the analyses seek to answer are usually different.

(B5) Retrospective assessments may apply to past acute exposures or to chronic exposures over an extended period in the past. They may seek to provide dose and risk estimates to support epidemiological investigations in the exposed population. They may also provide information to decision makers concerning remediation of contaminated spaces or compensation of individuals with claims of health or property damage. In such cases, the exposures have already been incurred (and in some cases may be continuing). In principle, the exposed individuals are identifiable and their doses may be reconstructed, though

possibly from fragmentary and uncertain information. The exposed individuals are specific individuals, and the resulting estimates may be provided in the context of probabilistic uncertainty analysis. Components of such analysis might include uncertainties concerning sources, transport of effluents through the environment, and concentrations of released radioactive material over time in the environmental media to which people were exposed. Other components of uncertainty might relate to data on individual habits that would affect the estimates (e.g., times spent in contaminated locations, quantities of contaminated food that might have been consumed, and ages at the times of particular exposures). Such information might need to be gathered from surveys designed and analysed by specialists, and uncertainties in the survey results would be based on their analysis. Uncertainties in the doses and risks would be affected by both of these components (source-environment and individual habits.

(B6) Distributions of dose to specific individuals in retrospective assessments serve a number of purposes. Primarily, they are used in epidemiological studies or to inform decision makers whether action is warranted to further reduce exposures if the source continues to exist. Since retrospective doses have already occurred, they are generally not within the scope of the Commission, although the Commission's recommendations may provide a useful guideline for their evaluation.

(B7) Prospective assessments often aim to assist in answering questions related to siting and design of planned facilities and to compliance with regulations. In such cases the exposed population may be unknown, and the analysis must be based on numerous assumptions. In this connection, the concept of a hypothetical representative individual can provide guidance in preliminary assessments based on tentative design, location, and operational assumptions. Such a hypothetical representative individual would be defined by an exposure scenario based on locations, physical characteristics, and habits that individually would be reasonably expected possibilities for some individuals in the exposed population. However, the locations, physical characteristics, and habits of the hypothetical representative individual should not collectively correspond to extreme combinations that are almost certain not to be found in the exposed population. When the analysis is applied to present and future operation of an existing facility, the present exposed population should be known, and it should be possible to investigate the existence of potentially high doses. In this case, too, analysis of the habits of a hypothetical individual can be adapted to provide first-order operational guidance, subject to adjustment if critical groups are identified or if conditions exist that produce some doses above the Commission's dose constraint for the public. As defined earlier by the Commission, a critical group is at least a few tens of exposed individuals with common attributes (some combination of habits, physical characteristics, and location, but possibly not all of these) that contribute to an estimate of average dose to the group that is used as the basis for compliance with the dose constraint. Such a homogeneous group might be identified if a sufficient number of people (a few tens, as indicated) were found to be consuming substantial quantities of fish that they regularly caught from a radioactivity-contaminated stream. Continuing attention by the operator to public concerns is an essential part of the information flow that can identify potential critical groups and conditions that might require operational response.

(B8) Uncertainty analysis of prospective assessments should be distinguished from its counterpart in retrospective assessments. The hypothetical representative individual is not a real member of the exposed population and may not resemble any specific individual, but

rather is a mathematical construct for defining a criterion for operational guidance. It is based on assumptions that would correspond to a possible dose that is expected to be high relative to doses estimated for most of the population. It is possible that this potential dose is not realised at all in the real exposed population. Therefore, it is important to distinguish uncertainties associated with the source and the environment (which are real) from ranges of values assigned by analysts to parameters that define the hypothetical individual (e.g., breathing rate, age, dietary habits, and fractions of time spent in specified exposure situations).

(B9) Ranges of variation in these variables for the hypothetical individual do not constitute uncertainty distributions; rather, the variables are parameters to be set by the analyst. When ranges of these variables are combined probabilistically with uncertainty distributions that represent releases from the source and the transport and concentrations in environmental media of the released radioactivity, interpretation of the composite distribution of artificial ranges and real uncertainties is not straightforward. The hypothetical individual cannot reasonably be interpreted as a random individual chosen from the affected population. It seems preferable to specify fixed central or slightly conservative values for the parameters that define the hypothetical individual, leaving the final uncertainty distribution of dose to reflect only the real source and environmental uncertainties. If it is necessary to study the sensitivity of potential dose to the hypothetical parameters, multiple dose distributions might be generated, with each one corresponding to a parameter point of interest for the hypothetical individual. Such an exercise might indicate the behaviour of a high percentile (possibly the 95^{th}) of the potential dose distribution and indicate combinations of the hypothetical individual's parameters to which the potential dose shows the greatest sensitivity. This kind of approach helps avoid confusion of the interpretations of sensitivity to hypothetical parameters and uncertainty associated with real quantities.

B.3. Distributions related to dose

(B10) In the analysis of dose to individuals and populations, the concept of a distribution arises in two primary contexts, with extension to a third:

(1) When uncertainty is considered in estimates of dose to individuals that are derived from model calculations or contamination measurements, the weighting of a dose distribution is usually interpreted as probability, so that one may make statements such as, "The probability that the annual dose to the specified individual does not exceed 1 mSv is 0.95 (or 95%)." Such distributions assign probability weight to intervals of dose, and the distribution quantifies the analyst's perception of the uncertainty that affects the estimate. This type of distribution might be useful in connection with the hypothetical individual as defined in paragraph (B7) above.

(2) When (deterministic) point estimates of dose are made for all individuals of an exposed population (or for categories of exposure with numbers of individuals known or estimated for each category), the weighting of each dose interval may be the fraction of the total exposed population receiving a dose within that interval. Such a distribution could be used to estimate the fraction of the exposed population whose annual dose does not exceed some specified level, such as 1 mSv; or it could be used to estimate the annual dose that is not exceeded in 95% of the population (i.e., the 95^{th} percentile of the distribution). Dose distributions of this type could be useful in quantifying dose limitation guidance that is to be applied to "the vast majority of the population."

(3) When the distribution types (1) and (2) above are combined, a weighting scheme replaces the point estimate of dose to each individual in item (2) with a marginal probability distribution that expresses the uncertainty of dose to the individual, given the individual's exposure conditions. The distribution representing the aggregate population would need to be interpreted as probability of dose to a randomly chosen member of the exposed population. The uncertainty distributions associated with individuals would be marginal relative to a rather complex joint distribution of exposure and dose, taking into account relevant correlations for factors such as location and common influence of sources of released radioactivity. Distributions of this kind, combined with risk estimates, could be useful in estimating the number of health effects arising from the collective dose.

(B11) Distributions are estimated from theory or data, assumed on the basis of experience, or assumed generically (i.e., somewhat arbitrarily, but of a form considered reasonable). In retrospective studies, where dose has been received by specific people and some records exist for reconstruction, one would expect to have available or to develop a database supporting a distribution of type (2) above for information on the population and exposure factors. The difficulty is that information may be fragmentary and uncertain for exposed individuals, and the environmental processes that contributed to the exposures must be reconstructed with some combination of historical data assessment and mathematical modelling. Thus, elements of the type (3) distribution become important. Where modelling of the source-term and environmental transport is used, it may be necessary to introduce uncertainties into the structure and parameters of the models in order to estimate uncertainty propagation into exposure and dose. The mechanism for representing the uncertainties in the source-term and environmental transport usually takes the form of probability distributions that substitute for parameters in the models.

(B12) Proposed distributions may be based on measurements—authentic data are used when such measurements exist for relevant times, locations, and processes, but often surrogate data based on other times or locations must be used. In either case, one has the choice of using an empirical distribution, based directly on a histogram of the data, or a theoretical distribution, which is an idealization of the histogram, probably represented as a continuous curve. The mathematical form of a theoretical distribution is an assumption based on theory or experience (and usually convenience), possibly supported by a demonstration of its consistency with the relevant data. If the data are too fragmentary to be suggestive of a theoretical distribution type, the assumption is generic; common choices for distributions that represent environmental data are normal and lognormal distributions, but others are possible and may be practical. Sometimes theory is suggestive of the standard distributions in a given case; or a trend of the data may indicate a form of theoretical distribution, even in the absence of a theoretical justification for it, in which case the choice is considered empirical.

(B13) In a prospective assessment of dose to members of an exposed population, the population is usually hypothetical, although it may be based on a real population that exists at the time of the study (one must remember, however, that this population will change in unknown ways during the future of the exposure). The purpose could be to assess the effect of the location or design of a proposed power plant or other nuclear facility, or it could be to study the effects of future management of an existing source (e.g., contaminated land). In such a prospective study, the uncertainties related to the source term and environmental

transport of released radioactivity (as previously discussed) are applicable, whereas individual detail about members of the population are not available (except as assumptions or extrapolations based on a population existing at the time of the study). The purpose is to assure that the dose constraint is unlikely to be exceeded.

(B14) To this end, it is important to evaluate and understand exposure scenarios for hypothetical individuals that would lead to high doses relative to the majority of the population. Limitation of the dose to such a hypothetical representative individual assures the protection of most of the population. One could consider a type (1) probability distribution of annual dose to the hypothetical individual, given the exposure scenario, with uncertainty components due only to the source term and environmental transport. For example, one might determine by reference to the distribution that the annual dose to the hypothetical individual would exceed 0.3 mSv with only 2% probability, given the exposure scenario. If the exposure scenario is accepted as being at the upper margin of normal habits and characteristics but not extreme, such a conclusion would imply protection of most of the population. In such an exercise, it would be useful to consider only fixed exposure scenarios (i.e., any parameters such as breathing rates or frequencies associated with habits of the individual should be given fixed but possibly conservative values); attempts to introduce probability distributions into the exposure scenarios and combine them with uncertainty components associated with the source term and environmental transport may produce results that are more difficult to interpret and possibly misleading.

(B15) A type (2) distribution of dose (population weighted) may be derived for the hypothetical population of a prospective study, but the information in the distribution is limited by the detail contained in the definition of the population and the methods of estimating dose to different categories of individuals (i.e., exposure scenarios). For example, if one were considering only exposure to airborne radioactivity from a point source, and the spatial distribution of the population were marked out in 1-km radial increments of 16 wind sectors, with the number of individuals residing in each 1-km by 22.5-degree sub-region beyond 1 km, out to 15 km from the source, then with source-term data (or a model of the release) and an atmospheric transport model, it is possible to estimate a ground-level air concentration of each released radionuclide in each sub-region (assuming, for simplicity, that there is only one radionuclide in the release). The crudest level of exposure scenarios assumes that there is a uniform average breathing rate, that there is no mobility of population among sub-regions, and that any difference between indoor and outdoor air concentrations is to be neglected. The sub-region point estimates (assumed to be local averages) are the product of the annual release (Bq), the diffusion factor for the centre of the sub-region (sometimes called χ/Q or "chi-over-Q", s m^{-3}), the breathing rate (m^3 s^{-1}), and the dose coefficient for inhalation dose (Sv Bq^{-1}). It is then possible to construct the population-weighted distribution by tabulating the estimated sub-region averages of dose from smallest to largest, along with the population numbers for the respective sub-regions. For many purposes, it is useful to normalise the distribution by dividing the tabulated population number for each sub-region by the total number of individuals in the exposed population.

(B16) A similar exercise to the one described in the preceding paragraph leads to a distribution of type (3) when uncertainties for the source term and χ/Q are considered. The interpretation of such a type (3) distribution would involve statements such as, "The probability is less than 2% that a person drawn at random from the hypothetical population will receive an annual dose exceeding 0.3 mSv." The reader should recall the earlier remark

that the calculations underlying a type (3) distribution may be of greater utility than the distribution itself. The reason for the suggested omission is that for the simulation considered in Example (2), there is no point in considering the joint distribution; it would only be used if a collective risk analysis were undertaken for the population (i.e., number of health effects occurring), and risk models with age dependence and latency periods were applied.

B.4. Specific forms of dose distributions

(B17) Appropriate assumption of a mathematical form for a distribution arising in the context of environmental dose assessment depends on the role that the distribution is intended to play in the analysis. It is emphasized that there is nearly always an element of the analyst's experience and judgment that influences the choice; indeed, the success of the undertaking depends on the availability of experienced and skilled personnel to plan and carry out the quantitative analysis. The subject is embedded in decades of statistical and computational theory and practice, of which no summary can be attempted here.

(B18) At the most specialized level, there are distributions that represent parameters in models of the source term and the environmental transport of the released radionuclides. The complexity of the models usually dictates Monte Carlo methods for simulating the propagation of uncertainties into estimates of concentrations in exposure media (e.g., air, soil, food, water). There can be dozens, if not hundreds, of such parameters, some of which depend on primary or surrogate data from source-term related processes, on estimates of uncertainty in diffusion model predictions of air concentrations of released materials, or on samples from exploratory wells that monitor groundwater. For some parameters, the literature provides guidance; for others, the analyst must make the case in the context of the study.

(B19) Transport models are often empirically tuned to environmental measurements, and in such cases the parameters may be less literally representative of directly observed quantities. Instead, distributions of the parameters may be inferred by regression methods from residuals that are computed as the difference of model predictions and corresponding measurements of the modelled quantity (e.g., concentration of a radionuclide in air or soil). In such a setting, the residuals (or some transformed version of them) are often (but not always) treated as a sample from a normal distribution with zero mean and variance to be determined by the regression; this choice is sometimes suggested by the theoretical background of the regression method. The process is somewhat complex, but the results can be quite powerful and persuasive. The models are often nonlinear in the parameters under study, and the subject appears in the literature under the name "nonlinear parameter estimation."

(B20) Sets of environmental data are often presented in a discussion of an existing facility. It is usual to summarize such a data set with reference to a distribution, from which the data are construed as a random sample, though the actual acquisition procedure may not be consistent with this characterisation. Perhaps the most common assumption for legacy data is that of the normal distribution, and the assumption may be used to present confidence intervals for the mean (which if done by traditional textbook methods would also involve the "student" t distribution). The normal distribution necessarily assigns probability symmetrically to semi-infinite negative and positive intervals, and this property can present awkward problems of physical interpretation where physically positive quantities are concerned. It is also the case that histograms of primary data often lack the symmetry that characterises the normal distribution. One approach attempts to get around these problems by using truncated forms of the normal distribution (i.e., one or both tails of the distribution are

taken off at specified points). The truncated distribution may give a better fit to the data, but it unfortunately loses much of the mathematical tractability of the un-truncated distribution.

(B21) A common theoretical paradigm for skewed distributions is the lognormal distribution: a random variable *y* is said to be lognormally distributed if its natural logarithm *ln y* is normally distributed, and the distribution can be thought of as arising from a transformation of the primary data (all of which must be positive) by taking the natural logarithm and applying the normal distribution. Many skewed distributions, however, are not well fitted by the lognormal distribution, and when the sample size is sufficient, it is sometimes argued that an empirical distribution based directly on the data is the most satisfactory representation. If a distribution represented by a smooth frequency curve is required for mathematical or other convenience, and if direct application of the standard distributions must be ruled out, it is usually possible for an experienced practitioner to fit an empirical frequency curve with the desired properties to the frequency histogram (It is possible that the cumulative representation may be used for fitting).

B.5. Normal distribution and central limit theorem

(B22) The Central Limit Theorem is usually cited as a principal justification for the ubiquity of the normal distribution in observational science. In a very rough form, the Central Limit Theorem states that under appropriate hypotheses, the sequence of probability distributions of the standardized sums of an infinite sequence of independent random variables $\{x_i\}_{i=1}^{\infty}$ tends to the standard normal distribution:

$$P\left[\frac{\sum_{i=1}^{n}(x_i-\mu_i)}{\sqrt{\sum_{i=1}^{n}\sigma_i^2}}<y\right]\rightarrow\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{y}e^{-t^2/2}dt \text{ as } n\rightarrow\infty$$

where x_i has mean μ_i and standard deviation σ_i. The integral expression after the arrow represents the cumulative probability distribution function of the standard normal distribution, evaluated at *y*. There are numerous references to studies of hypotheses under which this convergence is shown to be valid. Apart from those restrictions, the random variables $\{x_i\}_{i=1}^{\infty}$ are not required to have any specified form of distribution, nor must all have the same form (Wilkes 1962).

(B23) The Central Limit Theorem is usually invoked to support the claim that sums of environmental random variables, even for relatively small *n*, are approximately normally distributed. (However, the approximation may in some circumstances be poor, even for moderately large *n*.) The application of the Central Limit Theorem to the lognormal distribution uses the sequence of logarithmically transformed random variables $\{\ln x_i\}_{i=1}^{\infty}$. Since the lognormal distribution has become commonplace in environmental dose studies, the next section examines some theoretical support for processes that might lead to it in this and related fields.

B.6. Occurrence of lognormal distribution

(B24) Considerable discussion of the origin and applications of the lognormal distribution exists in scientific literature. See Aitchison and Brown (1969, Chapter 3) for examples and further references.

(B25) A basic mathematical model that yields a lognormal distribution is a stochastic process satisfying the equation

$$X_k - X_{k-1} = \varepsilon_k X_{k-1}, \quad k = 1,2,\ldots \tag{1}$$

where the ε_k are mutually independent and also independent of the X_k preceding them in the sequence. If the process goes on for n steps, we may solve the recursion in Equation (1) to get

$$X_n = (1+\varepsilon_n)X_{n-1} = (1+\varepsilon_n)(1+\varepsilon_{n-1})X_{n-2} = \cdots = (1+\varepsilon_n)(1+\varepsilon_{n-1})\cdots(1+\varepsilon_1)X_0 . \tag{2}$$

If the ε_k are sufficiently small in magnitude, we may use the approximation $1+\varepsilon_k \approx e^{\varepsilon_k}$ in Equation (2):

$$X_n = X_0 e^{\varepsilon_1} e^{\varepsilon_2} \cdots e^{\varepsilon_n} = X_0 \exp\left(\sum_{k=1}^{n} \varepsilon_k\right). \tag{3}$$

Taking logarithms in Equation (3) gives

$$\ln X_n = \ln X_0 + \sum_{k=1}^{n} \varepsilon_k , \tag{4}$$

a sum of independently distributed random variables, which by the Central Limit Theorem is asymptotically normally distributed (i.e., tends to a normal distribution as n tends to infinity, as indicated in the previous section), so that the distribution of X_n approaches lognormality. If the index k marks a series of time steps, the model of Equation (1) could represent a process of growth of an organism resulting from a variety of independent multiplicative effects represented by the ε_k. In such an interpretation, X_n could represent, for example, the mass, height, or some other physical property of the organism after n steps in its growth. In the abstract, the time step is arbitrary; it could represent seconds or years, depending on the context. The model of Equation (1) could also represent a sum of money invested at compound interest at a rate per time step that varies with random changes in the economy (for example, if the index k counts years, the ε_k would represent annual interest rates). Forecasts of the value of the investment after, say, n = 30 years, would reasonably be modelled as being lognormally distributed. In other applications, the index k could count effects unrelated to time.

(B26) The lognormal distribution has been found useful in the field of aerosol physics in applications to particle size. Indeed, in discussions of properties relative to particle size, the lognormal distribution seems to be the generic assumption. Aitchison and Brown (1969) present a breakage model that seems relevant to certain populations of particles. They consider abstract elements (e.g., particles), each having a positive dimension (e.g., mass or effective diameter). The population is subjected to a series of independent operations having as their effect the random breakage of the elements.

(B27) A more specific particle model is considered here: a binary process in which at each breakage stage, each particle is severed into exactly two pieces, one of which is a “small” part of the original. Assume that the original population of particles is of homogeneous density and that the quantity of interest is the mass of the particle. The “small” fraction is

restricted to no more than a fixed fraction φ, which is less than 0.5 (in this illustration, φ is equal to 0.125). The random value of the small fraction is selected from a uniform distribution of numbers between 0 and φ (excluding zero). The complementary fraction represents the larger part.

(B28) If a particle is chosen at random from breakage stage *n*, it has a unique ancestry of particles leading back to some particle P_0 in the original population. Thus, its mass can be derived from that of P_0 as a sequence of multiplications by independent random factors:

$$\text{mass}(P_n) = \text{mass}(P_0)\,\eta_1\eta_2\cdots\eta_n, \tag{5}$$

where the η_k are identically and independently distributed,

$$\eta_k = \begin{cases} \zeta \text{ with probability } 0.5 \\ 1-\zeta \text{ with probability } 0.5 \end{cases}$$

and the random variable ζ is uniformly distributed on the interval (0, 0.125] (zero is excluded, 0.125 is not). The probabilities of 0.5 reflect the fact that a particle in stage k may equally likely be the smaller or the larger part resulting from breakage of the parent (stage k−1) particle. Thus, from Equation (5)

$$\ln\big(\text{mass}(P_n)\big) = \ln\big(\text{mass}(P_0)\big) + \ln\eta_0 + \ln\eta_1 + \cdots + \ln\eta_n, \tag{6}$$

The Central Limit Theorem is used to conclude that the logarithm of the mass of P_n is asymptotically normally distributed, so that the mass of P_n is asymptotically lognormally distributed. Figure B-1 shows log-probability distributions for the first five and the 10^{th} stages of breakage, beginning with an initial population of particles with masses selected at random from the uniform distribution over the interval (0,1). The near-linear graph for the 10^{th} stage suggests the approach of the stages of breakage to lognormality. These distributions were obtained by Monte Carlo simulations with the model just described, using 200 trials for each stage.

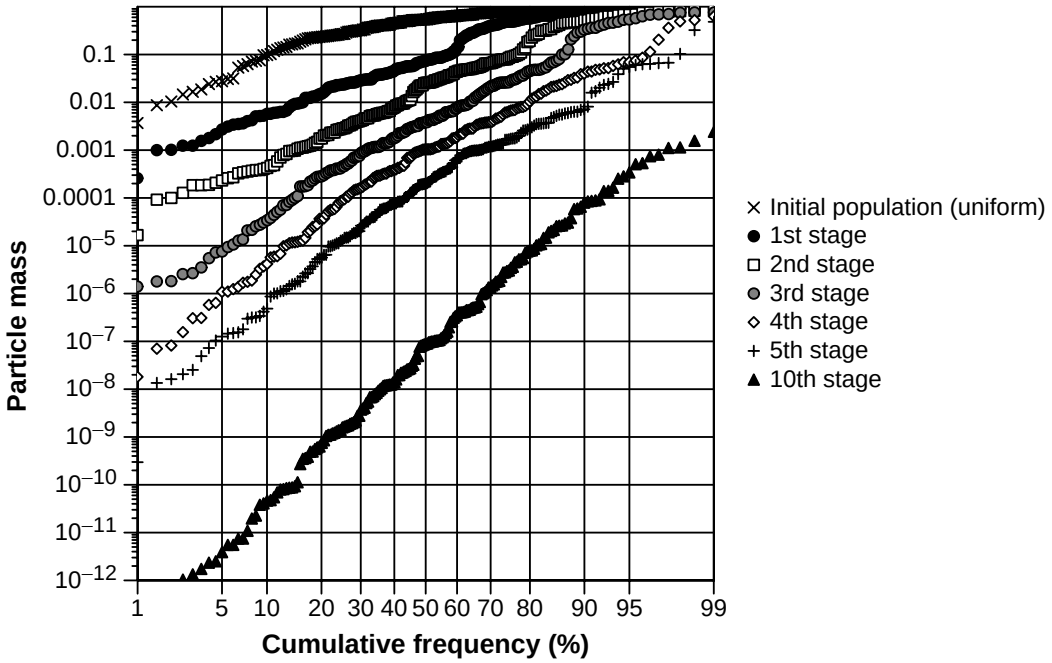

Figure B-1. Sequence of asymmetric binary breakages of particles, beginning with a uniformly distributed population, with mass distribution between 0 and 1. Distributions represent particle masses. The mass of the smaller member of a severed pair has the uniform distribution (0, 0.125). The tendency toward linearity at the 10^{th} stage is suggestive of the effect of the Central Limit Theorem.

Such a model as the one just illustrated might be applicable to weathering of some types of soils.

(B29) Another type of particle model is that of a particle population formed by agglomeration of small particles onto larger condensation nuclei. Such a process could be interpreted in the light of the model of Equation (1), provided the incremental particles are sufficiently small relative to the acquiring particles. In such cases, that model would lead to the conclusion of asymptotic lognormality of the population after a sufficient number of acquisitions.

(B30) In reality, there are many effects that depart from the simple models suggested here and that thwart convergence to lognormality. It is sometimes found that a population of particles under investigation is more reasonably viewed as a mixture of two or more distinct subpopulations, which themselves are approximately lognormally distributed, but such as to render the super-population non-lognormal. For example, windborne particles may at times consist of sand (diameters of 10 to several hundred micrometers), clay and silt (diameters of less than one to some tens of micrometers), and fine particles such as combustion products (diameters of a few hundredths to a few tenths of a micrometer). These distinct subpopulations (which individually are sometimes reasonably approximated as lognormally distributed) usually do not combine into an aggregate with a distribution that resembles a lognormal. Aerosol scientists often analyse particle size distributions with the lognormal distribution, but there are special cases that are not well fitted by the lognormal distribution and to which they apply special distributions. Some examples are certain coarse dusts (e.g.,

crushed coal), sprays with large ranges of diameters, and certain powders (Hinds 1982, appendix to Chapter 4).

(B31) Other quantities of interest are often sums of more fundamental variables, which themselves may or may not appear to be lognormally distributed. It is sometimes the case that a sum of lognormally distributed random variables has a distribution that can reasonably be approximated by a lognormal distribution, even though sums of lognormally distributed random variables are known (mathematically) not to be lognormally distributed. This is a special case of a more general phenomenon, where plotting a dataset of interest suggests that the data resulted from sampling a lognormal distribution, even though no known theory points to such a conclusion. Nevertheless, it is common practice to model skewed empirical distributions generically with the lognormal, even when nothing but experience indicates such a choice.

(B32) Radiation dose or risk to a specific human population may sometimes fit into the empirically lognormal category just described (e.g., distributions of type (1), (2), or (3) discussed previously). There are many ways such a distribution may be arrived at, but few of them obviously imply lognormality, notwithstanding log-probability plots suggesting a linear trend. It is fairly easy to construct simple examples of dose distribution to a population downwind from a release point of airborne radioactivity that are not lognormally distributed with respect to population count (see Example 2 in the next section).

B.7. Examples

(B33) This section develops two relatively simple examples of the distribution types discussed in this appendix. Realistic examples would be a great deal more complicated than what is presented here, but the added detail might obscure the main points.

(B34) **Example 1: Type (1) distribution.** A fictitious existing nuclear facility releases radionuclides to the atmosphere. Studies of data measured at air monitoring stations and comparisons with release estimates suggest a distribution for the boundary location where annual average air concentrations would be near-maximum. There is theory and evidence to indicate that the concentrations would tend to decrease as the distance from the facility increases. It would be reasonable to position a hypothetical individual at the maximum boundary location, assuming that he/she lives near that location, spends most days outdoors, and remains near home most of the time. A single released radionuclide is assumed for simplicity. To estimate the dose from inhalation, one would parameterize an equation similar to the following:

$$H_{\text{inhal}} = [\chi / Q]_{\text{annual}} Q_{\text{annual}} (B_{\text{out}} U_{\text{out}} + B_{\text{in}} U_{\text{in}} R) D_{\text{inhal}}$$

where:
H is the annual dose by inhalation (mSv)
$[\chi/Q]$ is the ground-level concentration per unit release rate (s m^{-3})
D is the dose coefficient for effective dose by inhalation (mSv Bq^{-1})
B are breathing rates typical of indoors and outdoors, such as exercising and resting (m^3 s^{-1})
U are fractions of time spent indoors and outdoors
R is a fractional factor to estimate a reduced radionuclide concentration in indoor air

A similar equation would represent external dose from photons emitted by the airborne radionuclide:

$$H_{\text{extern}} = [\chi / Q]_{\text{annual}} Q_{\text{annual}} (U_{\text{out}} + U_{\text{in}} S) D_{\text{extern}} \times 3.156 \times 10^7$$

where:
H is the annual external dose from the airborne radionuclide (mSv)
$[\chi/Q]$ is the ground-level concentration per unit release rate (s m^{-3})
D is the dose rate coefficient for effective dose by external exposure to the radionuclide in air (mSv s^{-1} per Bq m^{-3})
S is a fractional factor for lower indoor exposure rate due to reduced indoor concentration and shielding from the outdoor concentration
3.156×10^7 is seconds per year.

It is assumed that all food comes from uncontaminated sources, since there are no known gardens or agricultural operations near the facility.

Adding the previous equations and rearranging gives:

$$H_{\text{total}} = H_{\text{inhal}} + H_{\text{extern}} = [\chi / Q]_{\text{annual}} Q_{\text{annual}} K$$

where K is a constant expression that depends on the exposure scenario parameters. The factors for the release Q and atmospheric diffusion $[\chi/Q]$ are subject to uncertainty.
It is assumed that the atmospheric data suggest a lognormal distribution and provide an estimate of geometric standard deviation GSD = 1.8 for $[\chi/Q]$, and the operator analyses variability in past release data to conclude that Q is lognormally distributed with GSD = 1.3. The product of these independently distributed random variables is lognormally distributed with:

$$\text{GSD} = \exp\sqrt{\ln^2 1.8 + \ln^2 1.3} = 1.9$$

(B35) Lognormality implies that the geometric mean (GM) of H_{total} is the product of the geometric means for $[\chi/Q]$ and Q and the constant K. It is assumed that the data and parameters are such that this product is GM = 0.4 mSv. Figure B-2 is a cumulative log-probability plot of this annual dose distribution. The figure shows the 95$^{\text{th}}$ percentile of the annual dose as 1.15 mSv; thus for this exposure scenario, the probability is 5% that the annual dose could exceed 1.15 mSv. If investigation indicates that few if any members of the exposed population are likely to experience this degree of exposure (an assumption that guided the definition of the hypothetical individual), then it is unlikely that members of that

population will equal or exceed an annual dose of about 1 mSv from the facility's future releases.

(B36) Given the temporal nature of the data for the source term and fence-line air concentrations, it is possible that some would extend the interpretation of the 5% probability to that of exceeding 1.15 mSv one year out of 20. However, one must be cautious of such interpretations for data limited to too few years.

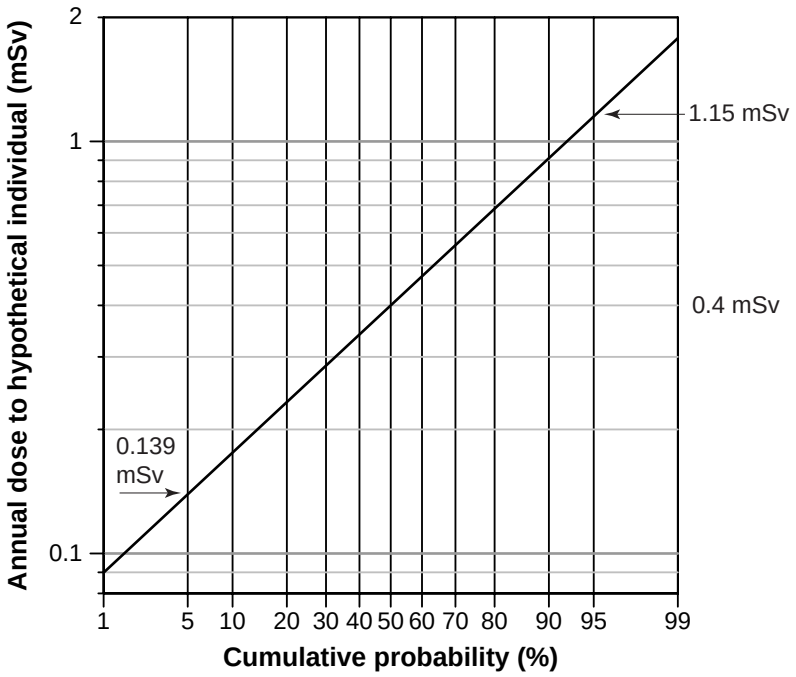

Figure B-2. Type (1) lognormal probability distribution for the hypothetical individual of Example 1. Given the fixed parameters that define the hypothetical individual, this distribution assigns probabilities to intervals of dose, based on quantified uncertainties in the release of radionuclides to the atmosphere and variability in observed concentrations at the facility fence near the hypothetical individual's location. The atmospheric concentrations at this location are assumed to exceed any that the vast majority of the exposed population would encounter. The 95th percentile (1.15 mSv) indicates a probability of 5% that the hypothetical individual would exceed this annual dose.

(B37) **Example 2. Type (2) and type (3) distributions.** A second fictitious nuclear facility releases radionuclides to the atmosphere (again, for simplicity, one radionuclide is assumed). The exposed population is contained in a single 22.5-degree wind sector from the facility's release stack, between radial distances of 1 km and 15 km from the stack. The spatial distribution of the population is uniform with respect to land area. For the normalised distributions derived here, it is not necessary to know the total number of individuals in the population, nor is it necessary to know release rates. The wind sector is divided into 15 sub-regions, each with a radial distance of 1 km, with population in the 14 of them that begin at 1 km from the source. The air concentrations of the released radionuclide are estimated with the sector-averaged Gaussian plume model:

$$\frac{\chi}{Q} = \sqrt{\frac{2}{\pi}} \frac{fn}{2\pi\sigma_z ur} \exp\left(-h^2/(2\sigma_z^2)\right)$$

where:
f is the fraction of time the population is downwind from the source
n = 16 is the total number of wind sectors (of which only one is used for the example)
u is the average wind speed
r is the radial distance from the source to the point where $[\chi/Q]$ is evaluated.
The symbol σ_z (m) denotes a vertical dispersion coefficient for rural Class D conditions (taken as average) given by:

$$\sigma_z = \frac{0.06r}{\sqrt{1 + 0.0015r}}$$

(Hanna et al. 1982). Uncertainty in the predictions of annual average concentrations by this model for regular terrain and meteorological conditions have been estimated by Miller and Hively (1987) and are reasonably interpreted as lognormally distributed with geometric standard deviation GSD = 1.53 for distances within 10 km and GSD = 2.32 for distances from 10 km to 150 km. Killough and Schmidt (2000) suggest a lognormal distribution with GSD = 1.53 for the uncertainty introduced by the use of composite meteorological data for several recent years. These two uncertainty distributions are used to compute the type (3) distribution but do not affect the type (2) distribution.

(B38) For the type (2) distribution, one computes — deterministically — annual dose as an average for each 1-km sub-region. The distribution is plotted in Figure B-3 with dark circles connected by line segments. This type of distribution assigns to each annual dose interval the fraction of the population that receives that annual dose. The 50th percentile is 0.1 mSv, and the 95th percentile is about 0.5 mSv. Thus there is a 5% of chance that any individual would receive an annual dose that exceeds 0.5 mSv. There is no implication of *quantified* uncertainty here, and the interpretation is not probabilistic.

(B39) Computation of the type (3) distribution requires the uncertainty distributions for the plume model and the meteorological data mentioned previously (a distribution for uncertainty in the annual release would also be required, but that was omitted from the example). The Monte Carlo procedure follows two steps at each realisation: (1) select a 1-km sub-region with probability proportional to the number of people in it and record the model-estimated dose as the GM of the lognormal uncertainty distribution; (2) sample from the lognormal distribution with this GM and a GSD representing the composite distribution for the product of the distributions for the plume model and the meteorological data. This sampling is as if one chose at random a single individual from the population (with all individuals having an equal chance) and from the uncertainty distribution associated with the chosen individual's exposure scenario (in this case, location) sampled from the lognormal distribution an annual dose for that individual. Thus, the type (3) distribution assigns to intervals of annual dose probabilities based on the uncertainty of the dose estimation. The uncertainty may be associated with the source term and atmospheric transport only, when the population is hypothetical. In retrospective cases, one might also consider uncertainties associated with the population, but a distribution of this type is less likely to be useful for retrospective assessments than one obtained from sampling that considers various correlations and possibly sophisticated models of risk applied to the exposures for a collective assessment. Figure B-3 shows the example of a type (3) distribution as the rough line (based on 1,000 realisations);

the approximate linearity derives from the lognormal distribution that was applied to each individual's dose uncertainty.

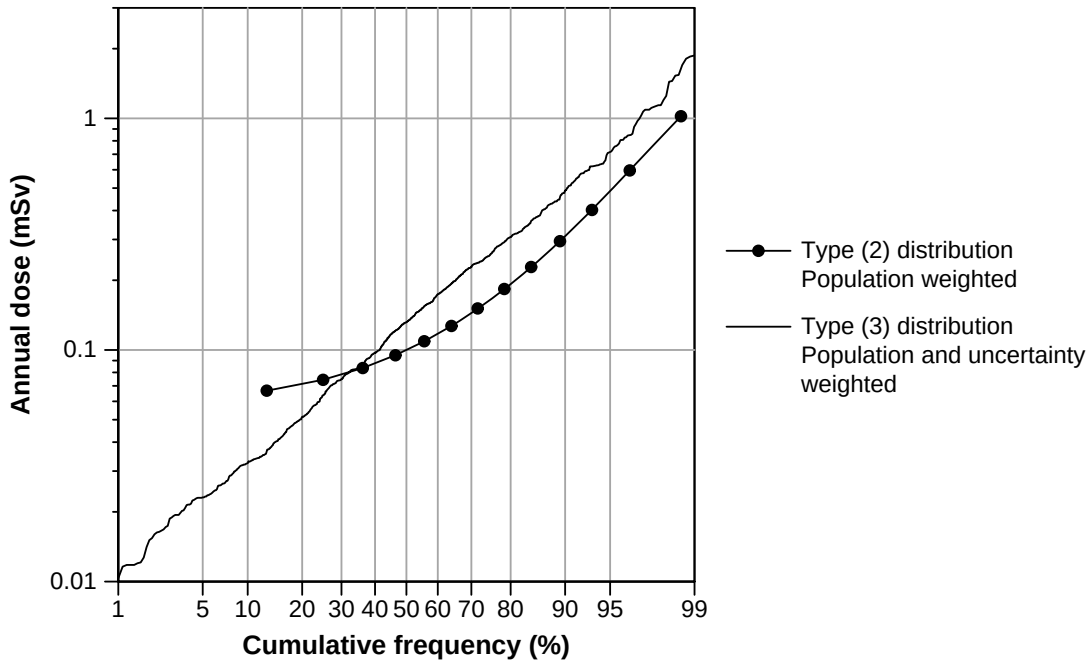

Figure B-3. Distributions of type (2) and type (3) for Example 2. The type (2) distribution weights intervals of deterministically estimated annual dose with fractions of the population receiving those annual doses (note that this distribution lacks the linear trend of lognormality). The type (3) distribution incorporates uncertainty in the dose estimates, in addition to population proportions, so that the interpretation for a dose interval is the probability that an individual chosen at random from the exposed population will have an annual dose in the interval.

(B40) The 95th percentile of the type (3) distribution is 0.72 mSv, indicating an interpretation that a randomly chosen individual from the exposed population would have a 5% probability of exceeding this annual dose value. However, from the graph, one could estimate a 3% probability of the random individual's exceeding an annual dose of 1 mSv. An annual dose in excess of ten times 1 mSv (10 mSv) is off the graph (well beyond the 99th percentile) and would seem to meet any reasonable definition of "extremely unlikely." One must also remember, for example, that a probability of 3% of exceeding 1 mSv given by a type (3) distribution is not the equivalent of asserting that only 3% of the population would exceed this annual dose. From an inspection of the type (2) curve (and the output file from the calculations), one can estimate that fewer than 2% of the population would exceed this dose when it is deterministically estimated. In lower-dose regions, the difference between the distributions is greater. For example, the 90th percentile of the type (3) curve (0.5 mSv) is approximately the same as the (interpolated) 95th percentile of the type (2) curve.

B.8. Conclusions

(B41) The Commission does not prescribe a specific method to be used for probabilistic assessments. This is because no single mathematical approach or percentage criterion can be

applied to the diversity of distributions that may be encountered in probabilistic assessments of dose. Nevertheless, some guidance is necessary to aid operators and regulators in determining when compliance is met when probabilistic assessments are used.

(B42) For some prospective probabilistic assessments of dose, it is possible that essentially all doses on the distribution will be predicted to be less than the dose constraint set by ICRP (e.g., Example 1). In this case, compliance is readily met.

(B43) In a prospective probabilistic assessment of dose to hypothetical individuals, whether from a planned facility or an existing situation, the Commission recommends that the representative individual be identified such that the probability is less than about 5% that a person drawn at random from the hypothetical population will receive an annual dose exceeding the dose constraint. This hypothetical individual should be representative of, at most, a few tens of people who are the most highly exposed. If this dose to the representative individual is below the dose constraint set by the Commission, then the design and planned operations are determined to be in compliance.

(B44) Particular attention must be given to the region and accompanying population where the assessment is being conducted to define the representative individual. Care must be used to include all hypothetical individuals whose dose could possibly be representative of persons receiving the highest dose, including extremes. However, it is evident that including too large a region (and population) could dilute the impact of the number of doses in a distribution, and permit an unacceptable number of hypothetical individuals to receive doses in excess of the dose constraint. Therefore an iterative approach using sequentially smaller regions and populations is recommended. However, it is important to be certain scenarios that represent the highest doses are included in the region being evaluated. This approach should be repeated until the number of hypothetical individuals with doses that exceed the constraint is an acceptable number. It is understood that once the representative individual is identified, the hypothetical individuals that exceed the dose constraint are assumed to represent a heterogeneous population whose dose is the combination of random extremes of habits and environmental concentrations that are not likely to exist but are the result of a possibilities inherent in the probabilistic approach to estimating dose.

(B45) In a probabilistic assessment of prospective dose to hypothetical individuals, if a homogeneous group of a few tens of persons or more is found to exist whose dose is above that for the representative individual, then the presence of a new critical group (and thus different representative individual) needs to be explored. Determining the existence of a homogeneous group in a probabilistic assessment can be problematic. For example, if a large population is being considered within the region of study, the existence of a homogeneous group of individuals above the dose constraint may be difficult to distinguish from a histogram or distribution curve. Therefore, care must always be taken to fully investigate the distribution of doses above the dose constraint to consider carefully all plausible scenarios of exposure, and to avoid the premature conclusion that these scenarios would correspond to few if any “random” individuals. Close attention must be paid to suggestions from members of the public of existing or likely exposure situations that might reflect extremes in the population. Such contributions may not have been considered in the operator’s analysis, and although they most often correspond to low exposures, experience has shown that they sometimes point out potentially significant exposure pathways that have not been considered and that warrant further investigation. If it can be shown that such a pathway, in combination

with other exposure, is likely to affect a few tens of persons and elevate their doses above the dose constraint, then a revision of the analysis must be undertaken. If such a critical group is found to exist above the dose constraint, then the mean dose to this group becomes the basis for compliance.

B.9. References

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