1. Executive Summary

The objective of this Report is to review the current state-of-knowledge of uncertainties in internal dose assessments, including uncertainties in the measurements that are used to perform these assessments. In a previously published report (NCRP, 2007), the current state-of-knowledge of uncertainties in external radiation measurements and dosimetry was reviewed. The scope of this Report is limited to internal radiation exposure. It is intended to be used primarily by radiation dosimetrists, including health physicists, radiation protection professionals, and medical physicists who need to evaluate of the uncertainties in estimates of absorbed doses. The scope of application ranges from the improvement of routine dosimetry procedures to the reconstruction of individual doses in epidemiological studies to treatment planning for therapeutic nuclear medicine. Sections 1 to 4 are descriptive in nature and do not present a high level of technical difficulty and so may provide useful knowledge to health physicists, radiation protection professionals, and medical physicists who are involved in the assessment of doses from internal sources of radiation. Sections 5 to 10 are more technical and address issues of interest to health physicists involved in the assessment of uncertainties. The appendices, in which details of various methods and models are presented, are meant to be read by those scientists interested in a particular issue.

Because one cannot directly measure the absorbed dose to a human organ, all internal doses have to be estimated based on indirect measurements (*e.g.*, bioassay data, environmental data) and based on mathematical models that simulate the transfer and bioaccumulation of the radionuclide in the human body. Given that models are only approximations of reality and they are built on the basis of sparse, and sometimes only partially-relevant data, internal doses are uncertain. Thus, a dosimetrist is faced not only with the challenge of evaluating an internal dose, but also with the challenge of evaluating the uncertainty in that dose. For research or scientific purposes, an assessment of the uncertainty in the estimate of dose is often recommended or required. For example, for epidemiological studies any credible estimate of risk will depend on the uncertainty in the dose estimates. It will depend on survey or monitoring planning for characterizing contaminated sites and the

uncertainty in the estimated dose which may have significant impact on remediation and thus cost. For retrospective dose reconstructions (*e.g.*, weapons fallout, accidents, occupational exposures) there are legislatively mandated compensation programs in place (*e.g.*, atomic veterans and nuclear-weapons workers) that require not only an estimate of dose but also an evaluation of its uncertainty which is further used to evaluate the uncertainty in the probability of causation of a disease. Radiation medical treatment or diagnostic procedures also often require an evaluation of the uncertainty in the administered activity to avoid unnecessary exposure but ensure sufficient administered activity to achieve the required objective.

For radiation protection purposes, the need for an evaluation of the uncertainty in dose estimates is more limited. International standards have been developed that set dose limits in various types of radiation situations in order to ensure that the doses to individuals will not exceed these limits. The dose limits that are recommended by the International Commission on Radiological Protection (ICRP) for regulatory purposes are based on the use of values of dose per unit intake that are to be applied without any consideration of uncertainty. Nevertheless, it is scientifically and ethically necessary to assess the possibility that persons with assigned estimates of internal dose did not in fact receive much larger doses. This is the reason to evaluate the uncertainties in assigned dose. In at least one country (Russia), regulations mandate that the uncertainties in the internal dose estimates be considered in the decision-making process of the design of an acceptable internal-dosimetry monitoring program.

The various types of internal dose assessments discussed in this Report are very different in nature. They occur in the occupational, environmental, and medical fields, and may result from intravenous administration or from intakes by inhalation, ingestion or absorption through intact or damaged skin. The internal dose assessments discussed may also address past exposures [retrospective dosimetry (typically based on measurements)] or future exposures [prospective dosimetry (mostly based on models)]. They may be related to specific individuals, for whom some anatomic or physiological parameter values may be known, or to unspecified individuals, for whom group values must be assumed.

The uncertainty in an individual's dose may be understood in frequentist terms as the distribution of possible true dose given whatever measurements have been made. However, in many cases, the evaluation of uncertainties requires analysis and interpretation of incomplete data and other complementary information, and

it relies on professional judgment, a process that is subjective in nature. Thus, different analysts may produce different statements of dose and of uncertainty in dose for the same dose assessment endpoint. Since two analysts may produce different results, it is useful, at least for important studies, to obtain assessments from several independent experts in the field, a process known as expert elicitation. One should note that expert judgment is needed at all stages of a dose assessment process, but expert judgment is a complement to, rather than a substitute for, other sources of scientific and technical information and data.

To the extent possible, the mathematical language of probability is used in this Report to describe the uncertainty in a given quantity (*e.g.*, dose, any biokinetic or dosimetric parameters). However, in many cases, uncertainties are provided as simple ranges of possible values obtained by professional judgment based on available data.

The process of evaluation of uncertainty depends on the assessment endpoint (*e.g.*, specific versus unspecified individual, environmental versus occupational versus medical exposures). The magnitude of uncertainty depends strongly on the amount of data available. For example, the uncertainty in the lung dose from inhalation of plutonium can be very different depending whether the bioassay data are available or not. Even if bioassay data are available, the magnitude of the uncertainty in dose will depend on the type of bioassay, on the number of bioassay data points and on the measurement and normalization uncertainties associated with such data. For this reason, it is not feasible to provide a comprehensive set of uncertain doses per unit intake that would cover all possible situations. Thus, the main purpose of this Report is to describe a set of methods and techniques that can be used by an analyst to perform credible analyses of uncertainty in internal doses for a range of assessment questions that can be asked. A number of realistic examples of dose assessments are included in this Report in support of the presented methods and techniques. In addition, this Report provides uncertainties in doses per unit intake for selected radionuclides and several postulated exposure situations for unspecified individuals.

1.1 Methods Used to Determine Doses from Internal Irradiation

The determination of doses from internal irradiation is, as much as possible, based on measurements but, it involves in all cases models. These models address the four components of the dose calculation:

1. determination of the intake, which is defined as the total amount of radioactive material that enters the three-dimensional confines of the human body;
2. assessment of the uptake, which is the fraction of the intake that is absorbed into body fluids (primarily blood and lymph, known collectively as the transfer compartment);
3. assessment of the fraction of the uptake transferred to particular organs or tissues of the body and the subsequent behavior of the radioactive material in those organs and tissues and in the transfer compartment; and
4. assessment of the absorbed doses in organs and tissues of the body per decay of the radionuclides in each source organ (site of deposition) or transfer compartment.

The third component involves the use of biokinetic models, which calculate the time-dependence of the activity of the radionuclides in each source organ or transfer compartment per unit activity absorbed into body fluids (or, alternatively, the number of decays in each source organ or transfer compartment over some period of time per unit activity absorbed). The fourth component involves the use of dosimetric models, which are based on radionuclide decay data and calculations of radiation transport in model representations of human anatomy and elemental compositions of organs and tissues. In medical absorbed-dose calculations, techniques have been developed that use individual patient imaging in place of biokinetic models and model representations of human anatomy.

When measurements are available, some of the models listed above may not be needed to calculate absorbed doses. For example, in nuclear medicine, the radionuclide activities in the patients' organs of interest may be monitored by external measurements in such a way that only dosimetric models are needed to estimate the dose. Similarly, the measurements of ^{131}I thyroid activities that were conducted after the Chernobyl nuclear reactor accident precluded the need to estimate the thyroid uptake. Also, exposures to tritiated water and alkali metals such as ^{40}K and ^{137}Cs result in irradiation that is uniformly distributed in the body, so that the biokinetic models are only needed to estimate the rate at which the radionuclide will be eliminated from the body. In all cases, however, dosimetric models are needed to calculate the doses.

The methods used to determine doses from internal irradiation are described in some detail in Section 3. Under conditions of retrospective dosimetry, human and/or environmental measurements of activity related to intake and/or uptake may be available and they

can be used as a basis to estimate doses. Retrospective doses are often calculated for specific individuals (*e.g.*, in the case of medical exposures, epidemiological studies, or worker compensation programs), using the available human and environmental measurements as well as the less frequently available information on morphometric and physiological characteristics of the studied individual. However, in cases of low-level occupational or environmental exposures retrospective doses are typically calculated for unspecified individuals, and in the absence of any personal information or measurements.

Under conditions of prospective dosimetry, no measurements of intake or uptake are available. Typically, prospective doses are calculated to unspecified individuals, but in the case of medical treatment planning, prospective doses need to be calculated for specific individuals, based on available morphometric and physiological characteristics. Characteristics of retrospective or prospective assessments performed for specific or unspecified individuals are presented in Table 3.1.

Following the procedure adopted by ICRP (2007), the absorbed doses that are considered in this Report are not calculated for a specific point in matter; they are averages over the volume of a specified organ (*e.g.*, thyroid) or tissue (*e.g.*, bone marrow) or a region of a tissue (*e.g.*, endosteal surfaces of the skeleton). The extent to which these average absorbed doses are representative of the local absorbed doses throughout organs, tissues, or tissue regions depend on a number of factors including the penetration and ranges of the radiations emitted and the structure of the organ or tissue (*e.g.*, walled organs such as the urinary bladder, airways of the respiratory tract, and the highly heterogeneous mixture of bone mineral, inactive and active bone marrow).

The intake, biokinetic and dosimetric models recommended by ICRP are described and discussed in Section 3. The schema established by the Medical Internal Radiation Dose (MIRD) Committee is also presented, as it is used for the assessment of doses from medical exposures. The ICRP and the MIRD approaches are very similar, and the methodologies described in this Report reflect an effort to harmonize the equations and symbols used in internal dosimetry. The wound model that was developed by the National Council on Radiation Protection and Measurements (NCRP, 2006) is described in Section 8.

1.2 Types and Categories of Uncertainties

Each component that makes up the process of dose determination is also a source of uncertainty in the estimated dose. The sources of

uncertainty can be divided into two major groups. One group includes the uncertainties introduced by bioassay or environmental measurements used to determine the activity of a radionuclide in the human body or in environmental media. The other group includes uncertainties in the parameter values and mathematical structure of the biokinetic and dosimetric models used in internal dosimetry. Detailed information on the types and categories of uncertainties is provided in Section 4.

Application of existing biokinetic and dosimetric models to estimate internal doses and quantify their uncertainties requires understanding of the sources of uncertainty, and of the types and categories of uncertainty. Different types/categories of uncertainty can be encountered in internal dosimetry:

- random versus systematic errors;
- aleatory (by chance) versus epistemic (known) uncertainties; and
- Classical versus Berkson errors.

The errors related to an unbiased estimator are called random errors and they can arise, for instance, from natural limitations of making physical measurements. Repeated measurements of the same property often differ even if they are performed on a single instrument that is calibrated and operated properly. Such variations establish the precision of the measurement. The precision is also referred to as the reproducibility.

In many assessments, however, the estimated quantity can be biased with respect to the true value, and the bias can be positive (*i.e.*, a tendency towards overestimation) or negative (*i.e.*, a tendency towards underestimation). Biases can occur, for example, when a measurement technique yields systematically high or low results, or is improperly calibrated, or is applied correctly but with a deficient device. A single sample or measurement is considered, in general, an unbiased estimate of the mean of the distribution describing the measurement error. In particular, a bias can occur if the measurement errors have a lognormal distribution and the measured value is assumed to be the median instead of the mean of the lognormal distribution. Biases can arise from sources other than the measurement process itself. A significant and common source of bias is an incorrect assumption used in the calculation of dose. For example, a bias can occur when an inhalation dose is calculated assuming that the radionuclide inhaled was in a soluble form, when, in reality, the radionuclide was in an insoluble form.

One of the purposes of dosimetry in general and internal dosimetry in particular is to provide biologically-relevant dose estimates

which can be used to examine dose-response relationships in an epidemiological study. The resulting dose response can be distorted significantly by ignoring or improperly treating the uncertainty in dose. Thus, it is important for an internal dosimetrist to distinguish between the two models of uncertainties in radiation doses, defined with respect to their influence on an epidemiological study. One type of uncertainty is called *Classical* while the other type is called *Berkson*. Section 4 describes these two uncertainty models with a focus on the typical dose-response relationships in radiation epidemiology described by the relative risk as a linear function of the organ-specific dose of radiation. The discussion starts by defining Classical and Berkson models for the idealized case of a single source of dose uncertainty, and later the discussion is expanded to incorporate uncertainties in multiple parameters used in estimation of an internal dose.

The concepts of aleatory and epistemic uncertainties are related to stochastic (or inter-individual) variability and to lack of knowledge uncertainties, respectively. From the point of view of the assessment endpoint, a dosimetrist may be asked to provide an estimate of the true but unknown dose received by a given (specific or unspecified) individual. The uncertainty in such a dose is epistemic (or Type B). However, a dosimetrist may be asked to provide an estimate about the stochastic variability of true but unknown doses in a population. This type of variability is called aleatory (or Type A). A Type-A assessment endpoint [*e.g.*, a variability of doses in a population described as a probability distribution with unknown mean and standard deviation (SD)] is typically affected by Type-B uncertainties as well, because any estimates of the unknown mean and SD are accompanied by epistemic uncertainties. Section 4 elaborates on the concepts of aleatory and epistemic uncertainties as they relate to the assessment endpoint, but also from the point of view of evaluating uncertainties in the input parameters of various internal-dosimetry models.

A number of idealized internal-dosimetry examples selected to emphasize the differences between aleatory and epistemic, or Classical versus Berkson uncertainties, and to discuss systematic errors and biases, are presented in this Report. All examples refer to estimation of thyroid doses from exposure to ^{131}I. Some examples refer to a highly idealized situation when the only source of uncertainty is the mass of the thyroid gland, while the energy deposited in the gland is perfectly known. A more realistic example addresses a situation involving uncertainties in the parameters of both the biokinetic and dosimetric models for ^{131}I in the thyroid gland.

1.3 Uncertainties in the Measurements

Uncertainty in measurement results and detection and quantification limits for the measurement process are intimately linked through the error structure of the latter. Knowledge of the detailed organization of the measurement process and its error components is as essential for the assessment of its detection and quantification performance characteristics as it is to derive meaningful uncertainty evaluations for results of the measurement process.

In estimating the overall uncertainty, it may be necessary to take each source of uncertainty and treat it separately to obtain the contribution from that source. Each of the separate contributions to uncertainty is referred to as an uncertainty component. For a measurement result, the total uncertainty provides an interval within which the value of the measurement is believed to lie with a higher level of confidence. Uncertainties in measurements used for internal dose assessment are not very different from uncertainties in external dose assessment, arising principally from calibration methods in which the response of the detector is determined in a well-characterized radiation field, and then a measurement is made with that detector in an unknown radiation field. Uncertainties in the measurements are covered in Section 6 and Appendices B and D.

1.4 Uncertainties in the Intakes

Intakes are the activities that enter the human body by one way or another. Intakes can be acute or protracted, occur *via* inhalation, ingestion, absorption through intact or damaged skin, or intravenous administration, and present a variety of physical and chemical characteristics in the environmental, occupational and medical settings.

Even though one of the main purposes of this Report is to assess the uncertainties in the doses per unit intake, it is important to realize that there are inherent uncertainties in the intakes related to dose assessments and that the characteristics of the intakes can play a major role in the estimation of the internal doses.

The assessment of the intakes and of their uncertainties under conditions of retrospective dosimetry is presented in Section 7 for each of the principal modes of entry of the activity into the body.

1.5 Uncertainties in the Biokinetic and Dosimetric Model Structure and Parameters

Doses from internal emitters depend on the intake route of the radionuclide, on the amount that is transferred to blood, on the bioaccumulation of the radionuclide in the various organs of the

human body, and on the energy deposited in any one organ by the decay of the radionuclide at sites of deposition or transit. All these aspects represent complex processes that have been studied under certain conditions (*e.g.*, human or animal studies, chronic or acute exposures, trace studies of the element of interest or of chemically-similar elements). Based on usually limited experimental data, mathematical models have been designed to predict the transfer and bioaccumulation of a radionuclide in various organs (*i.e.*, biokinetic models), and to estimate the energy delivered to any one organ (*i.e.*, dosimetric models).

The sources of data used in building biokinetic models are classified into four categories:

1. direct measurement in humans (*i.e.*, quantitative measurements of the element in humans);
2. observations of the behavior of chemically-similar elements in humans;
3. observations of the behavior of the element in nonhuman species; and
4. observations of the behavior of chemically-similar elements in nonhuman species.

The preferred source of data is Category 1 (direct measurements in humans), while data in the other categories serve as surrogates for that source of data. The four sources of data are supplemented with other types of information or constraint such as physiological information (*e.g.*, rates of bone restructuring), considerations of mass balance, predictions of theoretical models based on fundamental physical, chemical and mathematical principles (*e.g.*, a theoretical model of deposition of inhaled particles in different segments of the lung), experimental data derived with anatomically-realistic physical models, and *in vitro* data (*e.g.*, dissolution of compounds in simulated lung fluids).

There are uncertainties associated with the structure of a model because the structure provides an oversimplified representation of known processes, because unknown processes have been omitted from the model, or because part or all of the model formulation is based on mathematical convenience rather than consideration of processes.

In the absence of bioassay data for the individual for whom internal doses are reconstructed, predicted bioaccumulation and estimated doses from internal emitters are affected by uncertainties in model parameter values due to lack of precise knowledge about parameter values (*e.g.*, insufficient relevant data), or due to

the natural, stochastic variability of parameter values. The natural variability of parameter values refers to either inter-individual variability, or variability with time for metabolic and physiological reasons.

Section 8 provides discussions of uncertainties in the Human Respiratory Tract Model (HRTM) and the Human Alimentary Tract Model (HATM), in the structure and parameters for the systemic models for strontium, iodine, carbon, cesium, ruthenium, plutonium, uranium, californium, and radon progeny, and in the anatomic and dosimetric models and parameters. Uncertainties reflect exposures by adults, with several discussions about childhood exposures [*e.g.*, systemic model for iodine, absorption from the gastrointestinal (GI) tract of many elements, or masses for selected organs]. Detailed information on HRTM and HATM is provided in Appendices E and F, respectively, while the systemic models are covered in depth in Appendix G.

1.6 Statistical Methods Used to Evaluate Uncertainties in Internal Dose Assessments

A common language for expressing uncertainties in model parameters, model structure, or quantities of interest (*e.g.*, such as those relating to dose or activity) is mathematical probability. The Bayesian approach is emphasized in Section 5 for internal-dosimetry problems with relevant measurement data (*e.g.*, urinalysis data from which inferences might be made about parameters in a biokinetic model and/or intake values). In the Bayesian approach, initial (prior) distributions are first assigned to model parameters, competing model structures, and/or intake values. Then the prior distributions are updated to incorporate information from measurement data. The updated probability distributions are called *posterior distributions*, and the updating is accomplished by applying Bayes' Theorem, an elementary result of probability theory. Bayes' Theorem states that posterior distributions (*e.g.*, for biokinetic parameter values) are proportional to prior distributions assigned to the parameter values multiplied by the probability distributions for the measurements given the parameter values, which is termed the *likelihood function*. Although the theoretical expression for the posterior probability is given immediately by Bayes' Theorem, complex mathematical techniques must often be applied to evaluate the integrated (marginal) distributions for quantities of interest such as dose or intake.

The choice of prior distributions is often the most controversial component of a Bayesian analysis. Although the process of assigning

prior probability distribution functions (PDFs) to model parameters can be based on analysis of data (*i.e.*, fitting probability distribution curves through existing data), it often must rely on subjective judgment on the state-of-knowledge that may relate to specific model parameters. Practitioners often use simple common sense rules to assign probability distributions based on judgment. A uniform probability distribution might be applied when the parameter is known to vary between a minimum and maximum value, but values within this range are considered equally likely. A triangular distribution might be used when parameter values near the middle of the range of possible values are considered to be more likely than values near either extreme (Morgan and Henrion, 1990). When minimum or maximum values cannot be defined, unbounded distributions (*e.g.*, normal, lognormal) are appropriate. On the other hand, bounded or truncated distributions must be used when the parameter has physical limits (*e.g.*, a parameter representing a fraction is always greater than zero and less than one). If the parameter value is expected to vary over more than one order of magnitude, it is often best to use a distribution which is most naturally defined on the logarithmic scale (*e.g.*, log-uniform, log-triangular, lognormal).

The subjectively-derived prior distributions may reflect the opinions of a single expert or, alternatively, a panel of experts. A formal elicitation process is often used, in which there is a predetermined structure for selecting and training experts and for eliciting, processing, and documenting expert judgments and their rationales (NCRP, 1996a). When judgment is elicited about ranges of values for a given parameter, piecewise uniform or log-uniform distributions can be used to assign weights to the different possible ranges suggested by the experts. Similarly, discrete probability distributions can be used to assign weights to different possible discrete values obtained from data analysis or provided by different experts. Additional discussions about deriving uncertainty distributions from subjective information are included in the Report.

It is emphasized that the selection of a probability function based on judgment often describes the degree of belief that the possible values of the parameter are within a certain range (with some subjectively-assigned probability), rather than describing the statistical frequency of measured values.

Another important component of quantitative uncertainty analyses is the propagation of uncertainties in model parameters, which can be accomplished using analytical methods or numerical uncertainty propagation methods (such as Monte-Carlo simulation). Morgan and Henrion (1990) define the propagation of uncertainties as the uncertainty in output values induced by uncertainty

in input values. For internal-dosimetry problems, output values are typically doses or activity levels with values that depend, in part, on the solution to a series of differential equations which defines a biokinetic model. The propagation of uncertainties allows one to make statements of uncertainty for doses and activity quantities. These often consist of a range of values and a probability that the range contains the dose or activity quantity of interest (*e.g.*, the dose is between 10 and 100 mGy, with 90 % probability). Uncertainties can be presented as a "factor of x," where x represents the square root of the ratio of the upper and lower bounds of dose or of the upper bound and the central value of dose (*e.g.*, the true dose is expected to be within a factor of three above or below 30 mGy, with 90 % probability). Similarly, uncertainties can be expressed as a "$\pm x$," where x is equal to 1 SD (*e.g.*, the true dose is expected to be within 30 ± 10 mGy).

Statistical methods that can be used to evaluate (and propagate) uncertainties are described in some detail in this Report. A commonly used method for calculating output uncertainties is Monte-Carlo simulation. In Monte-Carlo simulation, probability distributions are used to define the uncertainty in inputs, and random values for the input values are then generated based on these distributions. Outputs are then calculated for each set of the randomly generated inputs. The resulting simulated distribution of outputs is used to evaluate the uncertainty in outputs induced by input uncertainty. The Monte-Carlo simulations might also be used to identify important inputs to dosimetric and biokinetic models, and for simplifying the biokinetic and dosimetric models which need to be considered. A detailed example of Monte-Carlo simulation, using a Windows® (Microsoft Corporation, Redmond, Washington) version of the Bayesian Inference Using Gibbs Sampling (WinBUGS) software package, which is a free software package downloadable from the internet, is provided in this Report.

Bayesian methods provide direct answers to questions of greatest interest such as "What is the probability distribution for a certain dose quantity given bioassay or other relevant data?" However, non-Bayesian methods may also be used to evaluate uncertainties about such quantities. This Report provides a brief description of Classical statistical methods such as the method of maximum likelihood, and shows how these methods will often yield results similar or even identical to results obtained from the Bayesian approach. The Classical maximum-likelihood method corresponds to choosing parameter values that maximize the likelihood function, which is the same as maximizing the Bayesian posterior probability for a uniform prior probability distribution.

The application of the methods based on Bayes' Theorem requires a somewhat higher level of expertise and computer software than ordinarily used in internal dosimetry. However, it is noteworthy that one example (Section 10.7) makes use only of spreadsheet calculations. Because of the rapid development of the Bayesian methods in recent years in the field of radiation dosimetry, it was judged important to review them critically and to discuss their advantages and disadvantages. This Report discusses practical difficulties in applying the Bayesian approach to internal-dosimetry problems, which typically involve a large number of parameters nested within several alternate complex models, and it also shows in many examples how the Bayesian approach is useful in practice. The example in Section 10.12 was solved using the software package WinBUGS, which is widely used for Bayesian calculations in other fields. The advantages and disadvantages of using WinBUGS and four other approaches for solving Bayes' Theorem Internal Dosimetry Code, Weighted Likelihood Monte-Carlo Sampling (WeLMoS), importance sampling, and unfolding algorithm are presented in Section 5.6. All five approaches are demonstrated in several case examples in Section 10.

1.7 Application, Results and Examples

There is no uncertainty in the dose coefficients (dose per unit intake) published by ICRP, because they describe the dose received from a known distribution of activity by a known object (*i.e.*, a specific region of a well-defined phantom). The uncertainty arises from the use of ICRP dose coefficients to assign doses to humans from intakes determined by one or another method. When uncertainties in dose coefficients are discussed, it is in the context of their applicability and adequacy to the situation at hand. Evaluating the uncertainties in the doses per unit intake for any individual is a very difficult problem. The solution depends on the setting in which the dose is estimated (occupational, environmental or medical), on whether it is estimated for a specific or to an unspecified individual, and on the type and precision of information available regarding the intake and on the behavior of the radionuclide in the person under consideration.

In the case of prospective dose assessments to unspecified individuals, substantial efforts are made in this Report to evaluate the overall uncertainties in the absorbed doses per unit intake for a variety of conditions involving specific radionuclides. The complete set of results prepared within the framework of this Report is presented in Tables 9.1 and 9.2 of Section 9. The values that are presented refer to typical healthy males; there are no uncertainties

on the intakes, except, in some of the examples, for the physical and chemical form of the radionuclide. There are also no uncertainties on the anatomic characteristics of the unspecified individual. The uncertainty ranges are subjective judgments based on a review of published analyses of uncertainties in the biokinetics, dosimetry, and dose per unit intake of these radionuclides that is included in this Report. The lower and upper bounds are not intended as lowest and highest possible values but are meant to represent a likely range based on current information. As indicated by multiple cases considered for some radionuclides, the uncertainty in dose per unit intake may differ considerably from one intake scenario to another for the same radionuclide. For example, uncertainties in dose per unit intake are relatively low for the case of ingestion of ^{137}Cs that is biologically incorporated in food or in soluble inorganic form but are much greater for the case of ingestion of ^{137}Cs in unknown form. In practice, some information of the physical and chemical form of the radionuclide is usually known.

With regard to retrospective dose assessments to specific individuals, a number of examples are presented in the Report to illustrate the manner in which the uncertainties in the dose estimates can be evaluated in the occupational, environmental and medical settings. The examples illustrate the use of the statistical techniques described in the Report. They are ranked in order of increasing difficulty. The simplest example (Section 10.1), taken from the program of dose reconstruction of atomic veterans, illustrates a situation when the uncertainty is determined arbitrarily as a policy decision, and thus does not involve any calculation. The most complex example (Section 10.17), which requires the use of an extensive Bayesian analysis, illustrates the use of the prior probability distribution of biokinetic parameters representing inter-individual variability and uncertainty of biokinetic parameters for Mayak workers.

Serious consideration of uncertainties of internal doses is relatively new. A realistic assessment of uncertainties in the dose estimates is often required for research purposes and usually leads to improved dose estimates. However, for the time being, it is usually not required for regulatory practices or in the medical setting. In the future, however, consideration of internal dose uncertainty can only become more commonplace.

It must be emphasized that the uncertainties presented in Table 9.1 only reflect the judgment of NCRP and are presented for illustration purposes. Generally speaking, the uncertainties in the doses per unit intake are evaluated for research or scientific purposes and not for regulatory purposes. The values of the doses per

unit intake (dose coefficients) used for regulatory purposes in the United States are those recommended by ICRP, which, by definition, have no uncertainty because the physical and chemical characteristics of the intake, the biokinetic and dosimetric models, and the parameter values used in these models, are fixed. When calculating doses using the ICRP dose coefficients, the only uncertainties that may be considered are those related to the intakes.