Safety Reports Series
No. 37

Methods for Assessing Occupational Radiation Doses Due to Intakes of Radionuclides

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METHODS FOR ASSESSING OCCUPATIONAL RADIATION DOSES DUE TO INTAKES OF RADIONUCLIDES

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FOREWORD

Radioactive material is used in many human activities and, whenever unsealed radioactive sources are present, intakes of radionuclides by workers can occur. These activities include the use of radioactive sources in medicine, scientific research, agriculture and industry, the operation of various facilities that are part of the nuclear fuel cycle, and work involving exposure to enhanced levels of naturally occurring radionuclides. Intakes can occur by a number of routes, and the monitoring of workers and the workplace in such situations is an integral part of any occupational radiation protection programme.

Guidance on monitoring programmes and methods for assessments of intakes of radioactive material arising from occupational exposure is given in a Safety Guide, Assessment of Occupational Exposure Due to Intakes of Radionuclides (Safety Standards Series No. RS-G-1.2), published in 1999. This guidance is in turn supplemented by a Safety Practice on Direct Methods for Measuring Radionuclides in the Human Body (Safety Series No. 114), published in 1996, and a Safety Report on Indirect Methods for Assessing Intakes of Radionuclides Causing Occupational Exposure (Safety Reports Series No. 18), published in 2000, that give practical advice on the methods for individual monitoring of intakes of radionuclides by workers.

This report contains practical advice on the interpretation of monitoring results and the assessment of committed effective doses to workers, using the standard models of the International Commission on Radiological Protection, adopted as a reference in the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (Safety Series No. 115), published in 1996. With its publication the IAEA now provides a complete set of reference publications for use in Member States that have facilities in which workers have the potential to incur intakes of radionuclides. These publications are founded on internationally accepted principles and recommended practices, taking account of the major changes in protection standards and monitoring methods that have occurred over the past decade.

This report was drafted over the course of five Consultants Meetings held between 1997 and 2001 and finalized through a consultancy in 2003. The IAEA is grateful to the experts who took part in the development and review of this publication. The contributions of J. Lipsztein, D. Noßke, A. Phipps, J.W. Stather, R.E. Toohey and D. Whillans are especially acknowledged. The IAEA officer responsible for the preparation of this report was M. Gustafsson of the Division of Radiation, Transport and Waste Safety.

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Occupational exposure from intakes of radionuclides can occur as a result of various activities, including: work associated with the different stages of the nuclear fuel cycle; the use of radioactive sources in medicine, scientific research, agriculture and industry; and occupations that involve exposure to enhanced concentrations of naturally occurring radionuclides. The 1990 Recommendations of the International Commission on Radiological Protection (ICRP) [1], and the statutory requirements of most national authorities, provide that for workers who are expected to be occupationally exposed to radioactive material an assessment be made of doses that may result from intakes of radionuclides. Monitoring procedures are necessary if exposures could arise that are subject to regulatory control.

Guidance on the protection of workers exposed to intakes of radionuclides is provided in the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS) [2]. The BSS give values of dose coefficients (doses per unit intake) for workers that are the same as those issued in ICRP Publication 68 [3] and in the European Union Directive on Basic Safety Standards [4].

For routine operations in which doses are likely to be small, the generalized biokinetic and dosimetric models that have been recommended by the ICRP and incorporated into the dosimetry parameters contained in the BSS [2] are usually sufficient to provide a basis for the estimation of intakes and the determination of doses. In the case of accidents, however, or when operations could result in doses approaching regulatory limits, there may be a need for dose estimates that are more specific to the individuals and the exposure situation, both for dose record keeping and for the effective management of those exposed. Detailed information on the physicochemical form of the radioactive material, the exposure conditions, the retention characteristics of the radionuclides in the body, the anatomical and physiological characteristics of the individual or individuals involved and whether any treatment was given may be needed in order that a more accurate dose assessment can be made.

The Safety Guide on Occupational Radiation Protection [5] gives general advice on the exposure conditions that would necessitate monitoring programmes for assessing radiation doses arising from external radiation and intakes of radionuclides by the workforce. The Safety Guide on Assessment of Occupational Exposure Due to Intakes of Radionuclides [6] provides guidance

on monitoring programmes and methods for assessing intakes of radionuclides taken into the body by a worker. The latter Safety Guide is supported by the Safety Practice on Direct Methods for Measuring Radionuclides in the Human Body [7] and the Safety Report on Indirect Methods for Assessing Intakes of Radionuclides Causing Occupational Exposure [8]. A Safety Report on dosimetry services for individual monitoring, which is under development, will give additional advice.

1.2. OBJECTIVE

The purpose of this report is to provide persons charged with the responsibility for monitoring internal exposures of workers with comprehensive guidance on the methods for assessing committed effective doses from estimated intakes of radioactive material, thereby supporting the information given in Refs [7, 8]. However, in presenting the level of technical detail necessary for this purpose, this report will also be useful to those concerned with the planning and management of occupational monitoring programmes.

1.3. SCOPE

The aim of dose assessment for internal exposures is to obtain from monitoring data estimates of committed effective doses or committed equivalent doses to individual organs or tissues. Monitoring data consist of measurement data on levels of radionuclides in the whole body or in organs and tissues, or on their rates of excretion, or on their levels in the work environment, that can be used as a basis for assessing intakes and for relevant dose calculations.

This report presents the main considerations for dose assessment in both routine situations and accidents. Internal doses are computed by the application of biokinetic and dosimetric models to the results of direct or indirect monitoring measurements. Direct methods cover the measurement of radiations emitted from radionuclides present in the body, whereas indirect methods comprise activity measurements in biological samples, such as excreta, from which intakes of radionuclides can be calculated. Workplace sampling can also provide supporting data, but is not reliable for accurate dose assessments. Effective doses are usually first determined from an estimate of the intakes of radionuclides and application of the effective dose per unit intake coefficients given in the BSS [2]. Where these estimates indicate that doses may be high, the determination may need to calculate doses using a specific dose model, which is

beyond the scope of this report. In some circumstances dose rates may be assessed from measurements of body activity and used to infer doses without relying on biokinetic models. This report offers practical advice on the interpretation of bioassay measurements in terms of intakes of radionuclides and the resulting radiation effective doses for a number of radionuclides, using the standard models recommended by the ICRP and adopted by the BSS [2].

A good programme of workplace radiation protection includes measures other than the monitoring of workers; for example, it will include radiological engineering to provide the optimum engineered radiation protection, given the magnitude of the dose and the resources available, and workplace monitoring adequate to provide early and sensitive indicators of unexpected releases of radioactive material. Guidance on these issues is beyond the scope of this report, but further details can be found in other IAEA reports [5, 9].

This report does not cover dose assessment for the medical exposure of patients or the exposure of members of the public. Neither does this report give specific advice on dose assessment for workers exposed to radon (^{222}Rn) or thoron (^{220}Rn). Guidance on the assessment of occupational exposures to these workers is given in a Safety Guide on Occupational Radiation Protection in the Mining and Processing of Raw Materials [10] and a Safety Report on Radiation Protection against Radon in Workplaces Other Than Mines [11].

1.4. STRUCTURE

The primary biokinetic and dosimetric models for describing the behaviour of radionuclides in the body are summarized in Section 2, as are the origin and use of the dose coefficients relating committed effective dose to intake. Section 3 describes the derivation and use of intake retention (or excretion) functions to assess doses from the results of bioassay measurements, and also includes alternative dose assessment methods. Section 4 describes the uncertainties inherent in internal dose assessments and the possible techniques for minimizing or otherwise controlling them. Recommendations for record keeping and dose reporting are considered in Section 5. Finally, guidance on quality assurance procedures is given in Section 6. References and definitions of terms used in internal dosimetry are also included.

The appendixes and annexes provide additional information. Appendix I provides basic data useful for internal dose assessment, including tables of radiation and tissue weighting factors [1], and Appendix II contains biokinetic models for selected elements. Appendix III, which is complemented by a compact disc attached to the back cover of this publication, provides data sheets that show, for selected radionuclides, values for the retention and

excretion functions after intake. The values have been evaluated for various times after intake. Annexes I–VIII contain detailed examples of dose assessments based on a variety of measurement data and exposure conditions.

2. BIOKINETIC MODELS FOR INTERNAL DOSIMETRY

2.1. INTRODUCTION

Intakes of radionuclides can occur via a number of routes. In the case of occupational exposure the main route of intake is by inhalation; a fraction of material deposited in the respiratory system will, however, be transferred to the throat and swallowed, giving the opportunity for absorption in the gastro-intestinal (GI) tract. Intakes by ingestion may occur, as may absorption through the intact skin for some radionuclides. Damage to the skin by cuts or other wounds can also result in intakes of radionuclides (Fig. 1).

In the case of workers who are occupationally exposed, the ICRP has developed a suite of models for describing the behaviour of radionuclides that have entered the body either by inhalation or ingestion. For other pathways of exposure, intakes are only likely to occur as a result of accidents that cannot be completely prevented by workplace controls or readily predicted. No internationally accepted models have therefore been developed that relate to either skin contamination or entry through wounds, although the National Council on Radiation Protection and Measurements (NCRP) is developing a model that is nearing completion. Some information on this issue has been published [12, 13]. A special case is tritiated water (HTO), which is readily absorbed through the skin; this may be assumed to be the route of intake for an additional amount of tritium equal to 50% of the inhaled material, although this is not a well founded value [3].

For intakes by ingestion, the GI tract model used to calculate the dose coefficients given in the BSS [2] is that described in Ref. [14]. It describes movement through four regions of the GI tract with parameter values for assessing the radiation dose to walls of the stomach and gut and the fractional uptake of elements into the blood, given as f_1 values (f_1, the fractional uptake from the GI tract, is the gut transfer factor). For intakes by inhalation, the ICRP [15] has described a Human Respiratory Tract Model (HRTM), which has replaced the lung model adopted in Ref. [14]. The HRTM takes account of recent information on the physiology of the lungs and is intended to be applicable to the interpretation of bioassay data as well as the calculation of

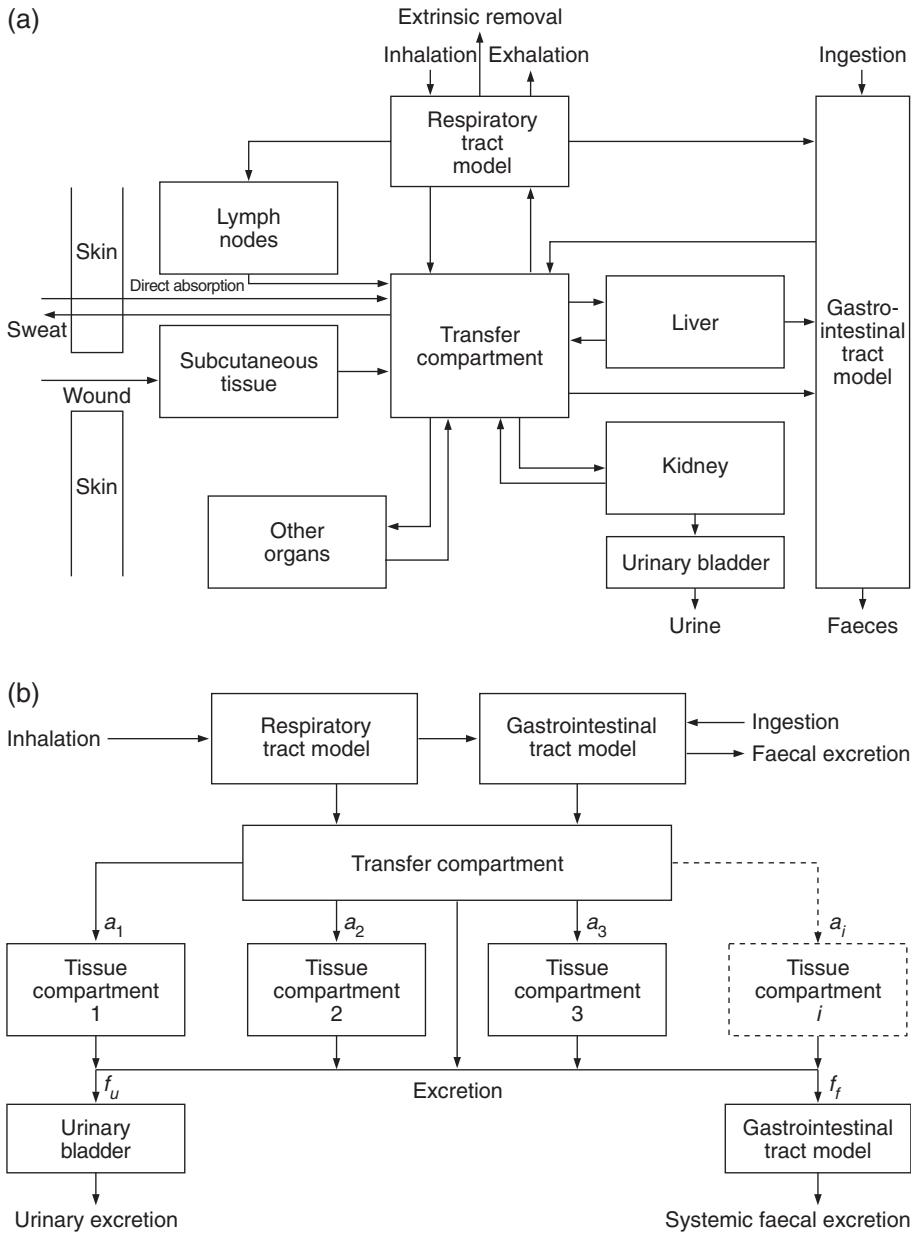

FIG. 1. (a) Routes of intake, transfer and excretion; (b) general model used to represent the kinetics of radionuclides in body compartments (exceptions are noted in the metabolic data for individual elements) [6].

dose coefficients. It has been used for the calculation of inhalation dose coefficients given in the BSS [2].

The current biokinetic models of the ICRP for systemic activity [16–19] were used for calculating dose coefficients given in the BSS [2] for intakes by inhalation and ingestion. These ICRP models comprise: (a) generic compartment models based on the models in Ref. [14] for some radionuclides; and (b) physiologically based recycling models for other radionuclides, all of which are considered in table III in Ref. [6]. This table III indicates, for each radionuclide listed, the ICRP publication that was used as a source for each biokinetic model.

In Ref. [20] the ICRP recommended the use of tissue weighting factors, w_T, to calculate the committed effective dose equivalent from committed dose equivalents to individual tissues. This provided a mechanism for equating doses and risks from external radiations, which are relatively uniform for all body tissues, with those from intakes of radionuclides, which can be very heterogeneous. In Ref. [1] and in the BSS [2] the approach used to calculate the committed effective dose equivalent (now termed 'committed effective dose') has been maintained, although as a result of improved information on the late effects of radiation on the tissues of the body some changes have been made to the values of w_T, and a greater number of tissues now have specified values. A table of these tissue weighting factors is provided in Table 2.

Recommendations on methods for assessing doses from intakes of radionuclides from monitoring data have been made by the ICRP in Ref. [21], which supersedes Ref. [22]. These recommendations are based on the biokinetic models developed by the ICRP and used for the calculation of dose coefficients. These biokinetic models (which are summarized in Appendix II) can also be used for the assessment of doses from indirect and direct measurements, in routine monitoring programmes, task related monitoring or special monitoring, when doses are low [6]. In these cases standard assumptions about the time and pattern of intake, the physicochemical form of the radionuclides and the characteristics of the individual (e.g. body mass) have to be used. However, when doses are greater than a few mSv a year, information from the workplace needs to be gathered, for example the activity median aerodynamic diameter (AMAD), as does more detailed information on the absorption characteristics. The evaluation of doses in accident situations calls for more specific information. Individual specific data on the biokinetics of radionuclides may be obtained through special monitoring (i.e. by repeated direct measurements of the whole body or specific sites and measurements of sequential biological samples).

The models used for calculating the inhalation and ingestion dose coefficients for workers given in the BSS [2] and the dose coefficients for direct

uptake to blood (injection) given in this report are described below. Some discussion of their use in assessing doses based on bioassay data is given, together with some comments on their limitations in different exposure situations.

In the workplace, area air monitoring programmes are conducted to verify the effectiveness of the radioactive material containment, to detect accidental releases and to provide a basis for the implementation of the internal dosimetry programme. The control of airborne activity concentrations in the workplace can be accomplished through the use of appropriate limits, the derived air concentrations (DACs) [6]. Note, however, that area air monitoring results are unlikely to be sufficiently reliable to demonstrate compliance with the DAC on an individual basis. For this application personal air samplers are likely to be necessary.

2.2. ROUTES OF ENTRY

2.2.1. Inhalation

As in the earlier lung model [14], deposition and clearance are treated separately in the HRTM [15]. The scope of the HRTM includes all members of the population, giving reference parameter values for workers as well as members of the public, including infants and children.

Whereas the lung model given in Ref. [14] gives only the average dose to the lungs, and no doses were calculated for extrathoracic (ET) tissues, doses to specific tissues of the respiratory tract are calculated using the HRTM, taking account of perceived differences in their radiosensitivity. In the HRTM, the respiratory tract is represented by five regions (Fig. 2). The ET airways are divided into ET_1, the anterior nasal passage, and ET_2, which consists of the posterior nasal and oral passages, the pharynx and the larynx. The thoracic regions are bronchial (BB), bronchiolar (bb) and alveolar–interstitial (AI), the gas exchange region. Lymphatic tissue is associated with the ET and thoracic airways LN_{ET} and LN_{TH}, respectively.

Deposition of inhaled particles is calculated for each region of the respiratory tract, with account taken of both inhalation and exhalation. This is done as a function of particle size, breathing parameters and/or workload, and is considered to be independent of chemical form. Regional deposition fractions are given for aerosols having log normal particle size distributions. Default deposition parameters are given for a particle size range of 0.6 nm activity median thermodynamic diameter (AMTD) to 100 μm AMAD. For the purpose of calculation, the reference worker is taken to be a normal nose

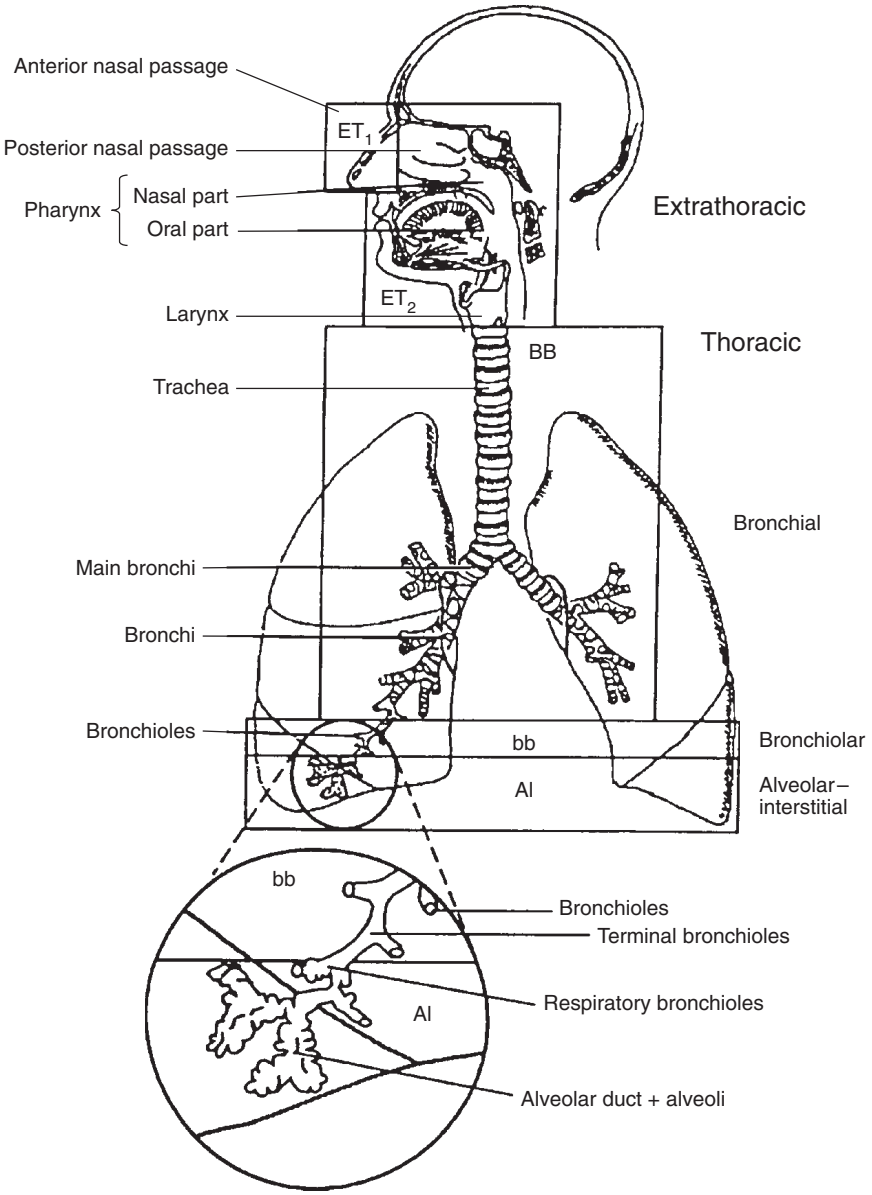

FIG. 2. Respiratory tract regions defined in the new ICRP model (reproduced from Ref. [15]). The ET airways are divided into ET_1, the anterior nasal passage, and ET_2, which consists of the posterior nasal and oral passages, the pharynx and the larynx. The thoracic regions are bronchial (BB: trachea and main bronchi), bronchiolar (bb: bronchioles) and alveolar–interstitial (AI: the gas exchange region). Lymphatic tissue is associated with the ET and thoracic airways (LN_{ET} and LN_{TH}, respectively).

breathing adult male at light work. Regional deposition fractions for inhaled aerosols in the reference worker for a 5 μm AMAD aerosol are given in Ref. [21]. This AMAD is now considered to be the most appropriate default particle size for radionuclides in the workplace [15]. Inhalation dose coefficients in the BSS (Ref. [2], table II-III) are given for an AMAD of 5 μm as well as for an AMAD of 1 μm.

Clearance from the respiratory tract in the HRTM is treated as two competing processes: particle transport (by mucociliary clearance or translocation to lymph nodes) and absorption to blood.

Particle transport is treated as a function of deposition site in the respiratory tract, but is taken to be independent of particle size and material. This time dependent mechanical transport is modelled by considering most regions as a number of compartments with different clearance half-lives; for example, the AI region is divided into three compartments, which clear to bb with biological half-lives of about 35, 700 and 7000 days (Fig. 2). Similarly, bb and BB have fast and slow clearance compartments. Clearance from the AI region also involves transfer to lymphatic tissue. For bb, BB and ET_2 there are compartments to represent material that is sequestered in tissue or transported to lymphatic tissue.

Absorption to blood depends on the physicochemical form of the radionuclide deposited in the respiratory system, but is taken to be independent of deposition site, with the exception of ET_1, for which no absorption is assumed and activity is lost only by extrinsic means, such as nose blowing. The model allows for changes in dissolution and absorption to blood with time. The use of material specific dissolution rates is recommended, but default parameter values for the absorption rate to blood are given for use when no specific information is available. These are absorption Types F (fast), M (moderate) and S (slow), corresponding broadly to the default classes D, W and Y, respectively, in Ref. [14]. For all three absorption types, most of the material deposited in regions other than ET_1 that is not absorbed is cleared to the GI tract by particle transport. Small amounts transferred to lymph nodes continue to be absorbed into body fluids at the same rate as in the respiratory tract.

The transfer to blood for the different absorption types, when expressed as approximate half-lives, and the corresponding amounts of material deposited in each region that reach body fluids, can be summarized as follows:

(a) Type F: There is rapid absorption of almost all material deposited in BB, bb and AI. Half of the material deposited in ET_2 is cleared to the GI tract by particle transport and half is absorbed. All the absorbed material is absorbed with a biological half-life of 10 min. Examples are all the commonly occurring compounds of caesium and iodine.

(b) Type M: There is rapid absorption of about 10% of the deposit in BB and bb, and 5% of material deposited in ET_2. About 70% of the deposit in AI eventually reaches body fluids by absorption. Of the absorbed material, 10% is absorbed with a biological half-life of 10 min and 90% with a biological half-life of 140 days. Examples are compounds of radium and americium.
(c) Type S: There is little absorption from ET, BB or bb, and about 10% of the deposit in AI eventually reaches body fluids by absorption. Of the absorbed material, 0.1% is absorbed with a biological half-life of 10 min and 99.9% with a biological half-life of 7000 days. Examples are insoluble compounds of uranium and plutonium.

For radionuclides inhaled in particulate form, it is assumed for workers that entry into the respiratory system and regional deposition are governed only by the size distribution of the aerosol particles. The situation is different for gases and vapours, for which deposition in the respiratory tract is material specific. Almost all inhaled gas molecules contact airway surfaces, but usually return to the air unless they dissolve in, or react with, the surface lining. The fraction of an inhaled gas or vapour that is deposited in each region thus depends on its solubility and reactivity. Generally, however, the regional deposition of a gas or vapour cannot be predicted on a mechanistic basis, from knowledge of its physical and chemical properties, but has to be obtained from an experimental study in vivo.

In the HRTM [15] gases and vapours are assigned to three default classes, on the basis of the initial pattern of deposition in the respiratory tract:

(a) Class SR-0, insoluble and non-reactive: negligible deposition in the respiratory tract (e.g. ^{41}Ar, ^{85}Kr and ^{133}Xe).
(b) Class SR-1, soluble or reactive: deposition may occur throughout the respiratory tract (e.g. tritium gas, ^{14}CO, ^{131}I vapour and ^{195}Hg vapour).
(c) Class SR-2, highly soluble or reactive: total deposition in the ET airways (ET_2) (e.g. HTO).

Subsequent retention in the respiratory tract and absorption to body fluids is determined by the chemical properties of the specific gas or vapour.

The approach taken by the ICRP and followed in the BSS [2] for giving guidance on the deposition and clearance of gases and vapours is similar to that adopted for the clearance of radionuclides inhaled in particulate form. For those elements for which inhalation of radionuclides in a gaseous or vapour form is potentially important, defaults are recommended for the SR class (which determines deposition), and the corresponding absorption type (which

determines clearance), and may be Type V (very rapid absorption, for which instantaneous absorption is assumed for the purposes of calculation) or Type F (fast absorption). Consideration is given only to the behaviour of gases and vapours at low mass concentrations.

The dose coefficients for inhalation of particulate aerosols given in table II-III and those for inhalation of gases and vapours given in table II-IX of the BSS [2] are reproduced in Table 3.

2.2.2. Ingestion

The GI tract model used to calculate the dose coefficients given in the BSS [2] is that given in Ref. [14], with some modifications introduced to take into account the dose to the colon from systemic activity excreted in faeces and some differences in the values of the fractional uptake from the GI tract. It is a four compartment model, comprising the stomach, small intestine, upper large intestine and lower large intestine (Fig. 3). The mean residence times in the GI tract compartments are 1, 4, 13 and 24 h, respectively. Absorption of radionuclides is usually assumed to occur from the small intestine. The contents of the small intestine are alkaline, so that elements that hydrolyse readily, such as rare earths and the actinides, are poorly absorbed. For the estimation of the equivalent dose to the wall of the GI tract from radionuclides in the lumen, doses are calculated to the mucosal cell layer. Note that the ICRP is currently in the process of developing a new model for the human alimentary tract [23].

The values for f_1 given in the BSS [2] are reproduced in Table 3 and in Appendix II. The dose coefficients for ingestion given in table II-III of the BSS [2] are reproduced in Table 3.

2.2.3. Wounds and intact skin

Wounds and absorption through intact skin are additional routes by which radionuclides can enter the body. While much of the material may be retained at the wound site, soluble material can be transferred to the blood and hence to other parts of the body. Insoluble material will be slowly translocated to regional lymphatic tissue, where it will gradually dissolve and eventually enter the blood. A variable fraction of insoluble material can be retained at the wound site or in lymphatic tissue for the life of the individual.

If the materials deposited in a wound are soluble, then they may translocate to the blood with a time course that depends on their dissolution rate in vivo. The distribution of this soluble component will, in most instances, be similar to that entering the blood from the lungs or GI tract. The biokinetic models developed by the ICRP can be used for the calculation of the effective

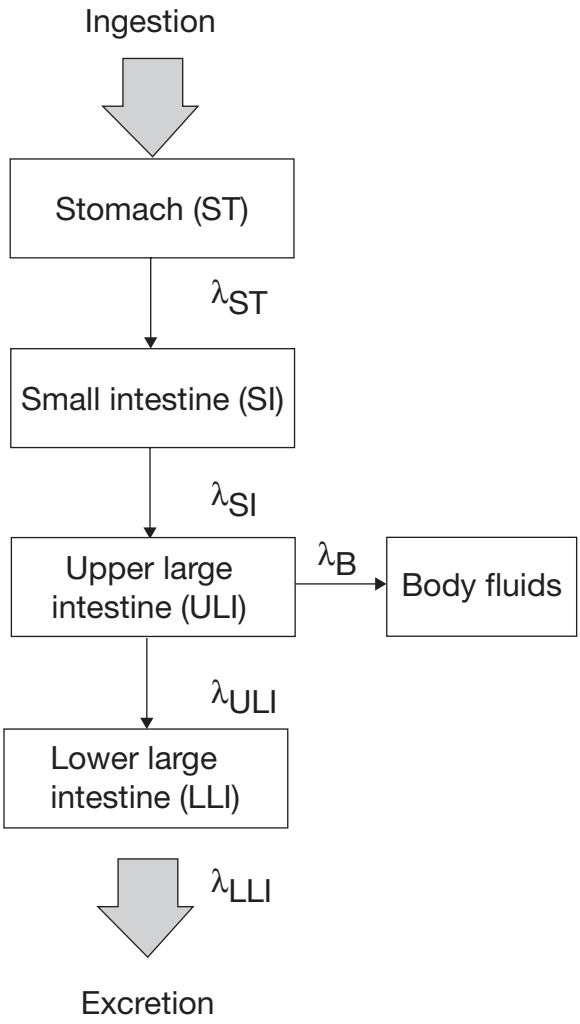

FIG. 3. Mathematical model used to describe the kinetics of radionuclides in the GI tract (reproduced from Ref. [14]).

dose arising from the soluble component once the systemic uptake has been determined. As a first approximation, data for direct uptake to blood (injection) can be used. Note that these evaluations are very crude approximations and are only to be used with caution, as an internationally agreed recommendation on models for wounds is still lacking.

A number of materials, such as specific tritium labelled compounds, organic carbon compounds and compounds of iodine, can penetrate intact skin. In these cases, a fraction of the activity will enter the blood directly. Although in many cases this activity will behave similarly to that which enters blood following inhalation or ingestion, there is some evidence [24, 25] that tritiated organic compounds can behave differently after absorption through skin. Care has therefore to be exercised when assessing intakes through skin using the results for direct uptake given in this report. Dose coefficients for injection are given in Table 3.

2.3. SYSTEMIC ACTIVITY

After translocation from the GI tract or lungs into body fluids (i.e. the transfer compartment), an element is assumed to be cleared to organs, tissues or excreta in accordance with the appropriate ICRP model (Appendix II hereto). In general, a half-life in body fluids of 0.25 day is assumed.

The term 'uptake' refers to the process of translocation of material into the systemic circulation, and may also refer to the quantity of material that has entered the systemic circulation; this quantity, divided by the total amount of material in the intake, is called the 'fractional uptake'.

A number of the revised systemic models for adults retain the generic model structure adopted in Ref. [14], but in some cases with minor changes to the distribution of radionuclides between body compartments and the retention functions. In addition, for a number of elements, the models have been extensively revised, in particular to take account of recycling of radionuclides between compartments. To allow for the known behaviour of radionuclides and to take account of the present knowledge of the physiology of bone, models for plutonium and other actinides (curium, americium, neptunium and thorium) and for the alkaline earths (calcium, strontium, barium and radium) have been developed [16–18]. The alkaline earth model has also been applied, with some modifications, to lead and uranium [17, 18]. The specific ICRP publications from which the biokinetic models were taken are provided in table III in Ref. [6]. For the radionuclides included in this publication, a summary of the systemic biokinetics adopted is given in Appendix II.

A number of radionuclides decay to isotopes of elements that are themselves radioactive. Generally it is assumed that the biokinetic behaviour of the decay products is the same as that of the parent nuclide. However, in the biokinetic models for tellurium, lead, radium, thorium and uranium, separate systemic biokinetics have been applied to the parent and its decay products [19].

2.4. EXCRETION

In the biokinetic models for workers, specific information is given on excretion routes in urine and faeces. These models were adopted in Ref. [21], which gives information on the interpretation of bioassay data for selected radionuclides based on the most recent biokinetic models.

For assessing doses from systemic activity excreted in the faeces, the model for the GI tract is used (Section 2.2.2), assuming secretion of radionuclides into the upper large intestine. Note, however, that this model was not developed with the interpretation of bioassay data in mind: results are therefore to be treated with caution. For urinary excretion a model for the urinary bladder has been adapted for calculating dose to the bladder wall [17]. To represent the kinetics of the bladder in terms of first order processes, the rate of elimination from the bladder is set equal to twice the number of voids per day, taken to be six. That is, the elimination rate from the bladder is taken to be 12 per day (equivalent to a biological half-life of about 1.4 h). This model is used to derive the predicted daily urine excretion data given in this report.

Information is given by the ICRP on levels of excretion in urine and faeces in the specific systemic models for different elements. This information can be given either as a ratio of urinary/faecal excretion (U:F), as for ruthenium or zirconium, or as specific rate constants for loss in urine through the kidneys and in faeces by direct secretion into the lumen of the GI tract (e.g. plutonium and americium). Specific information on the excretion routes is given in Appendix II. Faecal excretion will reflect the unabsorbed fraction of activity entering the body as well as removal via the GI tract of systemic activity. After inhalation of a radionuclide there will also be a component of (non-systemic) activity cleared directly from the respiratory system to the GI tract.

2.5. DOSE COEFFICIENTS

Dose coefficients (committed effective doses per unit intake (Sv/Bq)) are given in the BSS [2] for intakes of radionuclides by ingestion and inhalation; it is always important to remember that dose coefficients refer to unit intake, not, for example, to unit deposition of activity in the respiratory tract following inhalation intake. These values cannot be used directly for assessing doses from direct injection into the blood or from transfer to the blood from wound sites or absorption through the skin. Additional dose coefficients for direct uptake to blood (injection), calculated using the models for systemic activity described in Section 2.3 and Appendix II, are therefore given in Table 3. Note that all values of committed effective dose include doses arising from any decay products formed within the body.

For many radionuclides, dose coefficients are given for various lung absorption types and different values of f_1, the fractional absorption from the GI tract. In the BSS [2] advice is given that the most appropriate value of the dose coefficient must be based on knowledge of the physicochemical characteristics of materials in the workplace. Guidance is then given on the default values of f_1 and lung absorption types for various chemical forms of the elements, which determine the appropriate dose coefficient (see Ref. [2], tables II-IV and II-V).

2.6. WORKPLACE SPECIFIC ASSESSMENTS

This report uses standard biokinetic models with default parameter values and is only intended for assessing doses that may be considered to be small (less than a few per cent of the dose limit [6]). A minimum of information on the intake is necessary in order to use this report, namely: the radionuclides that may have been incorporated (including equilibrium assumptions for the natural series), the chemical form of the compounds, their presumed aerosol size (at least 1 or 5 μm) and the likely time frame, pattern and route of intake.

For exposures that lead to effective dose estimates higher than about 5 mSv (a typical investigation level [6]), it will often be desirable to use parameter values in the calculation of tissue and organ equivalent dose that are more specific to the conditions of exposure and to the individual.

By using such workplace specific parameters, a more realistic dose assessment can be obtained. However, a full discussion of the data and procedures needed for such a task is beyond the scope of this report; further guidance is provided by the ICRP [26]. Readers are cautioned that the dose assessment from exposures to different uranium compounds, plutonium and

other transuranic elements usually calls for specialized help and that it is especially important to keep track of the most recent information on the specific biokinetic parameters for these elements, which are published by the ICRP or can be found in the scientific literature.

3. INTERPRETATION OF DIRECT AND INDIRECT MEASUREMENTS

3.1. INTRODUCTION

Direct and indirect measurements provide information about the amounts of radionuclides present in the body, in parts of the body, including specific body organs or tissues, in a biological sample or in a sample taken from the work environment. The first approach to interpretation of these data is likely to be an estimation of the intake of the radionuclide by the worker. Biokinetic models (see Section 2) that describe body and organ contents and activity in excreta as a function of time following intake, and exposure models that relate intake to workplace conditions, are used for this purpose. Once the intake is estimated, the committed effective dose is then computed from the product of the intake and the appropriate dose coefficient. Alternatively, in some cases measurements of activity in the body can be used to estimate dose rates directly, but the calculation of committed doses still calls for the assumption of a biokinetic model if an insufficient number of measurements is available to determine retention functions.

Figure 4 summarizes the general approach. In order to compute the estimated intake I, the measured body content, body region content or excretion rate, M, is divided by the fraction of a unit intake, $m(t)$, retained in the whole body or in body regions (for direct in vivo measurements) or excreted in a time period, usually per day, from the body (for excreta measurements) at time t (usually in days) after intake. Thus:

$$I = M/m(t)$$

Appendix III provides tables of values of $m(t)$ for selected radionuclides in urine, faeces, the whole body and selected tissues for intakes by inhalation of 1 and 5 μm AMAD particles, inhalation of certain gases and vapours, ingestion and injection directly into the blood (transfer compartment). These values are based on the biokinetic models described in Appendix II.

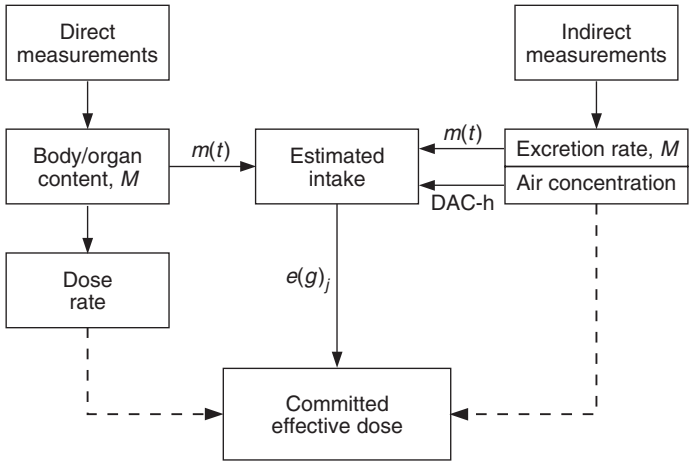

FIG. 4. General scheme for the interpretation of the results of monitoring measurements (possible alternative approaches for calculation are indicated as dashed lines) [6].

When only a single bioassay measurement is available, a point estimate of the intake is made. If multiple measurements are available, a best estimate of intake may be obtained by applying a statistical method. When significant intakes may have occurred, more refined calculations based on individual specific parameter values (special dosimetry) need to be made.

3.2. ASSERTIONS ABOUT $m(t)$

Values of $m(t)$ have been calculated from the models described in Section 2 and are tabulated in Appendix III and on the accompanying CD. For whole body or organ retention they give the fractional retention in the region considered at time t (given in days). Some definitions are needed. Whole body content is the sum of all systemic material, the contents of the urinary bladder, the GI tract and all regions of the respiratory tract. The contents of the lungs is taken to be the sum of the BB, bb and AI regions, together with the thoracic lymph nodes. The contents of the skeleton is taken to be the contents of the bone compartment in the simple models and the sum of all compartments of cortical and trabecular bone and the bone marrow in the more complex models, for example those for plutonium and uranium.

For excretion, in general $m(t)$ is the fraction of the intake excreted during the sampling period of 24 h preceding time t, taking into account radioactive

decay. An exception is HTO, where urinary excretion values $m(t)$ are given in terms of activity concentration in urine at time t per unit intake.

The $m(t)$ values in Appendix III are given for time since intake in days, on an expanding scale (i.e. t = 1, 2, 3,…, 10, 20, 30…, etc.). To obtain a value for a time not listed, a logarithmic interpolation between adjacent values is needed. If the values are not changing rapidly, a linear interpolation may be sufficiently accurate.

3.3. APPLICATION TO INTERPRETATION OF BIOASSAY DATA

For the application of the $m(t)$ tables to the interpretation of bioassay data, knowledge of the time and the route of the intake is necessary.

3.3.1. Assigning the time of intake

A principal source of uncertainty in the interpretation of bioassay data is the determination of the time of intake. It is likely, especially for routine monitoring, that the time will not be known beforehand. Since $m(t)$ may change rapidly with time, a reasonable estimate of the time of intake is vital for the proper interpretation of bioassay data. If an unusual occurrence triggered special bioassay monitoring, then the time of that occurrence is usually taken to be the time of intake.

The most common approach when the time of intake is not known is to assume that it occurred at the midpoint of the monitoring period [20]. However, if a significant intake and effective dose is calculated using this assumption, then a more realistic determination is needed. Sometimes a review of workplace monitoring data, such as airborne or surface contamination levels, can indicate a likely time for the intake to have occurred. Similarly, if other workers in the same workplace have exhibited positive routine bioassay samples, a review of the data and monitoring schedules for the individual workers may help to determine the time of intake for all. Of course, an individual worker may be able to recall the incident that led to the intake.

In addition, if several bioassay results are available, perhaps including different types of measurement, a comparison of these results with the $m(t)$ tables may help in narrowing the period of time in which the intake occurred.

If the time of intake cannot be determined, and if there is evidence that a prolonged intake has occurred, then the bioassay data can be analysed by assuming a chronic intake situation, where, for a monitoring interval of n days, $1/n$ of the total intake is assumed to have occurred each day. This method is discussed in Section 3.3.6.

3.3.2. Defining the route of intake

Although intakes by inhalation alone are the most frequent in the workplace, intakes by ingestion and uptake through wounds and intact skin cannot be excluded. Sometimes a worker touches his or her mouth with contaminated hands and ingestion occurs. If the route of intake is not known and several bioassay results are available, including different types of bioassay measurements, a comparison of these results with the $m(t)$ tables may help in determining the route of intake. Occasionally, simultaneous intakes by inhalation and ingestion can occur. In principle, results from the ingestion and inhalation tables can be combined to give predicted values of $m(t)$, but care will be needed.

If the radionuclide activity can be assessed by direct measurements, lung counting can be used to differentiate between inhaled and ingested material. However, if this is not possible and the radionuclide is in an insoluble form, interpretation of activities excreted in faecal and urine samples in terms of intake is quite problematic. This is because both the inhaled material deposited in the upper respiratory tract and the ingested material will clear through faeces during the first few days after intake. Consequently, it is important to initiate excreta sampling as soon as possible after the intake, and to continue monitoring for an extended period. Material in the faeces after the second week will be exclusively from the respiratory tract, thus later measurements can be used, together with the appropriate values of $m(t)$, to correct the measurements of earlier faecal samples so that they reflect ingestion intakes only. It may be helpful to note that in the monitoring of workers chronically exposed to long lived, insoluble radionuclides, activities in faeces after an absence of 15 days from work will mostly reflect delayed clearance from inhaled material [6].

Note that insoluble particles that have been inhaled and that are larger (e.g. AMAD > 15–20 μm) will preferentially be cleared through the GI tract, and so may present the appearance of an intake by ingestion. In this case, analysis of swabs of the nostrils and mouth may help to characterize the intake route.

3.3.3. Intake estimate from a single bioassay result

Once the time and route of intake have been determined or assumed, the intake, I, is simply given by:

$$I = M/m(t)$$

where

M is the bioassay result;
t is the time since the intake;
$m(t)$ is the value of the bioassay prediction (retention or excretion) taken from the tables given in this report.

Care must be taken to ensure that the bioassay result, M, and $m(t)$ are comparable; for example, in the case of urinalysis the bioassay result must be expressed as the total activity in a 24 h urine sample at the end of collection (not at analysis).

Urine and faecal samples collected over periods of less than 24 h are normalized to an equivalent 24 h value. This is achieved by multiplying the sample bioassay result by the ratio of the reference 24 h excretion volume (or mass) to the volume (or mass) of the sample. The reference volumes, for males and females, respectively, are for urine 1.6 L and 1.2 L, and for faeces 140 g and 120 g [27]. For urine, an alternative method is to normalize to the amount of creatinine excreted per day: 1.7 g for males and 1.0 g for females [8]. If the 24 h sample is less than 500 mL for urine or less than 60 g for faeces, then it is doubtful that it has been collected over a full 24 h period, and normalization needs to be considered.

3.3.4. Intake estimate from multiple bioassay data

Usually, the bioassay data for an intake estimate will consist of results for different samples collected at different times, and even from different monitoring techniques, for example urine data and faecal data, and perhaps also from direct measurements. If the initial result from a routine sample indicates a potentially significant intake, special monitoring is started to characterize the intake more accurately.

Numerous statistical methods are available for taking into account multiple measurements [28]. Most commonly used are a mean of the point estimates and the unweighted least squares fit (ULSF). In some cases weighting factors are applied to give a weighted least squares fit (WLSF), and this can result in a better fit to the data. A more general approach is the minimized chi-square method. Further information is given in the following sections. When choosing a statistical method for multiple measurements, the variability of the data and the reliability of each measurement need to be taken into account; measurements that are suspect or known to be inaccurate need to be excluded from the analysis. In short, the quality of the data set will influence the reliability of the result.

Caution must be used when combining data from different monitoring methods; for example, if the results from direct measurements are several orders of magnitude greater than the results from excreta analyses, the data should not be combined in the methods described below. Ideally all measured bioassay quantities should support consistent estimates of intake and dose. This may require model parameter values to be varied from their default values, but they should not be varied beyond realistic bounds. These bounds will depend on the conditions of exposure; for example, the AMAD may not be known, but available information might indicate that the AMAD must lie between 1 and 5 μm. If the predicted intakes from different bioassay data sets differ significantly, then each of the data sets needs a critical examination; for example, the data could be unreliable or the model could be inappropriate in some respect.

3.3.4.1. Point estimates

In this method, each bioassay measurement is treated separately and is divided by the appropriate predicted value, $m(t)$, to generate a point estimate of the intake. If the resulting point estimates fall within a narrow range, a mean may be taken to be the best estimate of the intake (see Annex I). However, if the point estimates of the intake fluctuate over a rather broad range of values, this is frequently an indicator that the standard biokinetic models used to derive the values of $m(t)$, or the assumed time of intake, or the assumed route of intake, may not be appropriate for this case. When dealing with excreta samples it is important to remember that there is a natural fluctuation in the data, due to physiological factors and the influence of diet.

3.3.4.2. Unweighted least squares fit

The method used with the ULSF method is to minimize the sum of the squares of the deviations of the observed measurements from the model predictions [28]. If M_i represents an observed value at time t_i, I represents the intake at time zero, and $m(t_i)$ is the value taken from the tables for time t_i, the best fit to the data (in the least squares sense) is obtained by minimizing the sum S, where:

$$S = \Sigma_i[M_i - Im(t_i)]^2$$

The minimum can be found by differentiating S with respect to the intake, I, and setting the derivative equal to zero. The resulting expression can be expanded and rearranged to give:

$$I = \Sigma_i[M_i m(t_i)]/\Sigma_i[m(t_i)]^2$$

This represents an unweighted least squares estimate of the intake.

3.3.4.3. Weighted least squares fit

Knowledge of the uncertainty for individual measurements will allow weighting of the importance of each point, or type of bioassay data, and hence weighting will influence the final result [28, 29]. Weighting factors (w_i) could be chosen on the basis of a subjective assessment of confidence in each point or data set, or by using some information on the error associated with each measurement. In practice, the errors are likely to be unknown, and therefore some type of assumption is usually adopted [29, 30]. This method needs to be used with caution.

The weighting factor may be applied at the initial sum of squares and carried through the calculation, that is minimizing the sum S, where:

$$S = \Sigma_i[M_i - Im(t_i)]^2 w_i$$

which yields:

$$I = \Sigma_i[M_i m(t_i) w_i]/\Sigma_i[m(t_i)]^2 w_i$$

3.3.4.4. Maximum likelihood method and chi-square

A more general approach is the maximum likelihood method (of which the ULSF and WLSF are special cases), which yields the most probable fit to the data. The quantity to be minimized with respect to the estimate of intake, I, is known as chi-square, χ^2, where:

$$\chi^2 = \Sigma_i[M_i - Im(t_i)]^2/\sigma_i^2$$

and σ_i is the standard deviation of M_i.

In order to minimize χ^2, this expression is differentiated with respect to I and set equal to zero. Rearranging for I gives:

$$I = \left\{\sum_{i=1}^{n}[M_i m(t_i)/\sigma_i^2]\right\} \Big/ \left\{\sum_{i=1}^{n}[m^2(t_i)/\sigma_i^2]\right\}$$

Clearly this method calls for some knowledge of the standard deviation, σ_i, for each measurement. Ideally this would be known from the measurement

procedure and knowledge of biological variability, but in practice it is usually necessary to make some assumption about σ_i; for example, it could be assumed that σ_i is constant for each measurement, linearly related to the measurement itself (i.e. a constant relative error) or related to the square root of the measurement [30]. Assumptions regarding σ_i can have a significant effect on the estimate of intake, I, and need to be made with care [30, 31].

3.3.5. Bayesian statistical inference

A relatively recent (circa 1990) development in dose assessment is that of Bayesian statistical inference. The essence of the Bayesian approach is that it presumes that the quantities of interest (in this case radionuclide intake and dose) are drawn from a probability distribution, rather than being fixed at some precise, if unknown, value. One first assumes a plausible distribution for the quantities, referred to as a prior distribution, and then uses measured data to produce an improved probability distribution, the posterior distribution. This is done according to Bayes's rule:

$$P(\Theta|y) \sim P(y|\Theta)P(\Theta)$$

where $P(\Theta)$ is the prior probability distribution of the quantity Θ and $P(\Theta|y)$ is the posterior probability distribution of Θ given measured data y. $P(y|\Theta)$ is called the likelihood function; it reflects the relative likelihood of obtaining the measured data, given a particular value of Θ. A detailed explanation of Bayesian methods is beyond the scope of this report; further information is provided in Refs [32–34].

3.3.6. Intake estimates for extended exposures

One of the factors that influence the interpretation of bioassay results is the temporal variation of the intakes of radioactive material. The pattern of intake, although often poorly characterized, is an important factor in the correct interpretation of measurements and thus for dose assessment. In general, the amount of activity present in the body and the amount excreted daily depend on the length of time that the individual has been exposed. Consequently, the correct interpretation of bioassay measurements necessitates information on the complete exposure history of the worker to the particular radionuclide of interest. The bioassay result obtained, for example the amount present in the body, in body organs or in excreta, will reflect the superposition of all the previous intakes, whether isolated or persistent.

3.3.6.1. Exposures over a time period

When exposure is known to extend over several days, perhaps as a result of an undetected incident, bioassay results may be interpreted as containing an independent contribution from each day's intake. Since the translocation of radionuclides among body organs and tissues (compartments) is assumed to be independent of previous intakes, the amounts expected to be present in the body, in body organs or in excreta can be obtained by summing the $m(t)$ values, perhaps weighted to allow for different daily intakes, for single intakes given in this report. The results are added for each time period after single intakes, or for the duration of a persistent intake.

3.3.6.2. Chronic and intermittent exposures

In routine monitoring of workers, especially for long lived radionuclides, it is highly desirable to produce a scheme in which the realistic exposure of the workers (e.g. in a weekly cycle) is considered. The schedule of work may differ for individual workers, and modifications have to be introduced as necessary. The use of an input function that represents a worker's routine intake permits the interpretation of bioassay results according to the day of the week on which samples are taken. In this way the short term components associated with lung clearance will be better accounted for, since the early clearance components of excretion may introduce a significant difference before and after an interruption in exposure, for example over the weekend. The interpretation of this data in most cases calls for appropriate software tools and is beyond the scope of this report.

For long lived radionuclides, chronic exposures that persist for some time, for example in a mining environment, can eventually produce an equilibrium value of activity in the body. Equilibrium values for selected radionuclides have been provided by the ICRP in Ref. [21].

3.3.7. Interferences

It is important to remember some factors that can lead to an inaccuracy in a dose assessment; examples include the presence of ^{137}Cs from global fallout, radionuclides from the uranium and thorium series occurring naturally in the diet or radiopharmaceuticals that may have been administered for diagnostic or therapeutic purposes. Contamination on skin and on watches and jewellery can also interfere with whole body and lung measurements. It is therefore important to consider the body content and interferences from such intakes; more details are given in Ref. [6].

In addition, if medical intervention to prevent uptake or enhance excretion is carried out, note that the biokinetic behaviour will be modified and that the tables of $m(t)$ given in Appendix III may not be appropriate.

3.3.8. Intake estimates from measurements of related nuclides

Some radionuclides cannot be measured directly, but their body content can be assessed by the measurement of a daughter nuclide; examples are the in vivo measurement of: ^{228}Ac for the assessment of ^{232}Th in the body; ^{214}Bi for ^{226}Ra; and ^{234}Th for ^{238}U. These assessments rely on assumptions about the activity ratios or equilibrium of the radionuclides or on a well established degree of non-equilibrium [35, 36]. Values for $m(t)$ for ^{228}Ac in the body following ^{232}Th intakes are given in this report (Appendix III). Other radionuclides may be assessed by a related nuclide that is likely to be present in the intake, as for example the measurement of ^{241}Am for ^{239}Pu.

3.4. OTHER DOSE ASSESSMENT METHODS

3.4.1. Interpretation of air monitoring data

Samples from area air monitoring provide an indication of the radionuclides and their relative concentrations in the work environment. These samples can provide a useful basis for determining the need for individual bioassay monitoring. Air samples may provide information on the particle size distribution and on the chemical form of the aerosol, which is needed for the correct interpretation of bioassay results. For intakes of some radionuclides that do not emit penetrating radiations, and that result in only very low levels in excreta, personal air samples may be used to estimate the intake, when combined with reasonable assumptions about the exposure conditions.

Air monitoring data can be used together with values of DACs taken from Table 4 and with estimated exposure times to give an indication of the likely importance of an exposure. The DAC is that concentration of a radionuclide in the air of the workplace that would result in workers receiving an intake that would produce an effective dose of 20 mSv if they were continuously exposed to the airborne activity for one working year (taken to be 2000 h), breathing at a rate of 1.2 m^3/h [6]. Care must be taken to ensure that the appropriate value of the DAC is used, as it depends on the particle size and HRTM absorption type of the radionuclide. In addition, the air being monitored must be representative of that which the workers are actually

breathing [8]. Area air monitoring results need to be calibrated against personal air samplers before they can be reliably used in this application.

3.4.2. Direct methods of dose calculation without estimating intakes

In standard dose calculations based on intakes, assumptions concerning the uptake, distribution and retention of the activity for a specific form and radionuclide have been established, and on this basis dose coefficients have been calculated [3]. However, there are a few cases for which doses may be calculated directly from the monitoring data, including urinary excretion data for HTO, whole body data for ^{137}Cs and thyroid data for ^{131}I.

In short, this approach employs a simple numerical integration method for calculating the number of nuclear transformations (U) in the body (or some region of the body) from measurement data. The trapezoidal rule (Fig. VI–1) is usually used to integrate a series of activity measurements, M_i, at times t_i as follows:

$$U = C\Sigma_i[(M_{i+1} + M_i)/2](t_{i+1} - t_i)$$

where C is a constant that reconciles any differences between the units of M and t. Other more sophisticated integration methods could be used, but the errors associated with the measurement data could outweigh any increases in accuracy due to the method. A simple estimate of the additional transformations beyond the last measurement (M_n) can be derived by assuming a default half-time (T) to estimate continuing retention:

$$U = CM_n/[\ln (2)/T] \text{ or}$$

$$U = 1.4CM_nT$$

Committed doses can be calculated knowing the energies and yields of the emitted radiation and the masses of the regions where energy is absorbed. This approach is usually only practicable where the distributions of activity and the pattern of energy depositions are simple. An example of this method being applied to HTO is given in detail in Annex VI.

3.5. COMPUTER CODES FOR DOSE ASSESSMENT

As noted in Section 2, the models describing the uptake, distribution and retention of radionuclides taken into the body are complex. The model

describing deposition and clearance, or absorption into the circulation, of inhaled radionuclides may contain over 30 compartments itself, and the biokinetic models for some elements may add another dozen. In addition, the transport codes relating activity in source tissues to energy deposited in target tissues (absorbed dose), and the combination of these tissue doses, appropriately weighted for radiation quality (w_R) and tissue sensitivity (w_T) to determine the effective dose, are computationally complex.

There are codes developed by specialized radiation dosimetry centres, such as the Bundesamt für Strahlenschutz (Germany), National Radiological Protection Board (UK) and Oak Ridge National Laboratory (USA), that are used to calculate the dose coefficients most recently published by the ICRP [3] and contained in the BSS [2]. These codes were used to calculate the values of $m(t)$ given in this report.

For the purposes of the industrial user, however, who has to determine default standards for workplace protection, and to estimate doses for particular incidents, a number of codes for personal computers have been developed that are based on the recommendations of the ICRP. These codes typically contain default models for the most common radionuclides and allow alternative values to be employed for some parameters, such as particle size and breathing rate. The codes then typically calculate retention and excretion for a variety of radionuclides for different absorption types and intake routes, as well as absorbed, equivalent and effective doses. They may also calculate intake and dose from multiple bioassay measurements using the statistical techniques outlined in Section 3.3.

Computer codes must be used with caution, however. It is important that software users maintain the configuration control of their software and operate the software periodically. The software also needs to be benchmarked against a well understood intake with well characterized bioassay data, to determine if it produces reliable results, for example in agreement with the $m(t)$ values given in this report.

3.6. GUIDANCE FOR THE DESIGN OF MONITORING PROGRAMMES

The IAEA has provided guidance on the design of monitoring programmes for intakes of radionuclides by workers [6], including advice on the method and frequency of monitoring. It is important that the method used for monitoring has adequate sensitivity to detect the activity levels of interest.

The frequency and method of monitoring necessary in a routine monitoring programme depend upon the activity being handled, the retention

and excretion of the radionuclide, the sensitivity of the measurement techniques available and the acceptable uncertainty in the estimate of intake and dose [21]. The magnitude and possible fluctuations of exposure levels also need to be taken into account [6].

At some time after an intake, either the retained amount of activity in the body or the amount being excreted from the body might be below the minimum significant activity (MSA: see Glossary) of the direct or indirect bioassay method. The values of $m(t)$ provided in Appendix III can be useful to design bioassay monitoring programmes, since values of intakes that could be missed depending on the method and on the frequency of bioassay sampling can be determined.

4. UNCERTAINTIES

In the process of assessment of radiation doses from intakes of radionuclides there are many sources of uncertainty. These are primarily due to:

(a) The uncertainty in the measurement results themselves;
(b) Lack of knowledge about the intake characteristics (time pattern and physical and chemical form);
(c) The assumed biokinetic and dosimetric models;
(d) The individual variability of biokinetic and dosimetric parameters.

4.1. MEASUREMENT RESULTS

Uncertainties in measurement results are discussed in the IAEA safety publications on direct [7] and indirect [8] methods for measuring radionuclides within the body. There are no standard procedures for indirect or direct bioassay measurements, although some examples of bioassay methods are given in these publications. The choice of the procedure, detector or facility will depend on the specific needs, such as the nuclides of interest, minimum detectable activities, budget, etc. All procedures used to quantify the activities of a radionuclide are sources of random and systematic errors. Uncertainties in measurements are mainly due to counting errors, the validity of the calibration procedures, possible contamination of the source or the measurement system and random fluctuations in the background.

Examples of sources of uncertainty for in vitro measurements include: the quantification of the sample volume or weight; errors in dilution and pipetting; evaporation of the solution in storage; stability and activity of standards used for calibration; similarity of chemical yield between the tracer and radioelement of interest; blank corrections; background contributions and fluctuations; electronic stability; spectroscopy resolution and peak overlap; contamination of the sample and impurities; source positioning for counting; density and shape variation from the calibration model; assumptions about homogeneity in calibration; and statistical counting errors [37].

For in vivo monitoring, common sources of uncertainty include: counting geometry errors; positioning of the individual in relation to the detector; movement of the individual during counting; chest wall thickness determination; differences between the phantom and individual or organ being measured, including geometric characteristics, density, distribution of the radionuclide within the body and organ and linear attenuation coefficient; interference from radioactive material deposits in adjacent body regions; spectroscopy resolution and peak overlap; electronic stability; interfering background activity and interference from other radionuclides; background stability; activity of the standard radionuclide used for calibration; surface external contamination of the person; interference from natural radioactive elements present in the body; counting statistics during calibration and during in vivo counting; and calibration source uncertainties [7, 37].

For partial body measurements, it is difficult to express the result in terms of organ activities. For the determination of lung activity by measurement over the chest, for example, not only individual calibration problems (such as the thickness of the individual's chest wall) must be considered, but also radiation from various other body regions, not only from the lungs, may be detected. So additionally some assumptions must be made about the biokinetic behaviour of the radionuclide. An example for the case of ^{241}Am is given in Ref. [7].

4.2. INTAKE CHARACTERISTICS

For the interpretation of direct and indirect measurements in terms of the intake and resulting effective dose, data on the time pattern and route of intake, on the chemical and physical form of the radionuclides and on previous intakes are needed. In many cases this information is not available.

The time pattern is a main source of uncertainty in the interpretation of bioassay data. Assumptions about the time of intake, and of whether the intake was acute, lasted for a short period of time or extended for a long time, are a major point in the reliability of the interpretation of the bioassay data. For

example, in some cases the retention and excretion functions diminish by orders of magnitude within a few days; the choice of the time pattern of intake can therefore influence the assessed dose within the same range (see tables of $m(t)$ in Appendix III). Inhalation is the main route of intake. Characterization of the intake in terms of aerosol size and absorption type is needed for the application of the $m(t)$ values. The aerosol size will influence deposition in the HRTM and the transfer of unabsorbed particles to the GI tract. In some work environments more than one particle size is detected. As a minimum, $m(t)$ values are given for particle sizes of 1 and 5 μm. The rate of absorption of a radionuclide to blood is very important for interpreting bioassay data, and is a critical parameter in interpreting urine excretion data. The differences between the true absorption rates and the default parameter values that have been assigned to the compound being inhaled are a source of errors that can be very large, especially when deriving intakes from urinary excretion bioassay data.

Further uncertainty is added when the activity of a radionuclide in the body cannot be measured directly but is derived from progeny radionuclides (see Section 3.3.8).

Another source of uncertainty is the assignment of a route of intake. In many circumstances there is a mixture of ingestion and inhalation, and interpretation of results based on wrong assumptions about the pathway of exposure may lead to large errors in interpreting in vitro bioassay results.

Contributions from intakes from natural sources, especially in the diet, may also contribute to the uncertainty of a bioassay result.

4.3. BIOKINETIC AND DOSIMETRIC MODELS

4.3.1. Biokinetic models

The biokinetic models used in this report comprise the most recent models published by the ICRP. Important advances in the models have been made in recent years, and have incorporated increased physiological realism. Developments in this area are ongoing: for example the modifications in the model for the human alimentary tract [23].

The reliability of the biokinetic models is associated with uncertainties in the sources and the quality and completeness of data used in the derivation of the models [38]. These uncertainties include the stochastic variability and the lack of knowledge about a single true value or a true but unknown distribution of values. The reader is referred to Refs [38, 39] for a detailed discussion on the reliability of biokinetic models. Biokinetic parameter values are derived from direct observations of the time distribution and excretion of the element in

humans and from analogies of the behaviour of the element in other species, of the biokinetics of chemically similar elements in humans and animals, and of the in vitro behaviour of the element of interest [39]. This information is sometimes supplemented by considerations of mass balance and physiological data [38].

While there are some elements for which extensive human data are available to develop reliable models, there are also many elements for which the confidence in the model is relatively low; for example, to determine the GI absorption factor (f_1) for antimony, there are only animal data available that lie within a range from less than 0.01 to 0.2, depending on the chemical form of the element, and a value of 0.1 was chosen by the ICRP for ingested antimony [18, 40], but clearly there is a large degree of uncertainty attached to this parameter. In addition, inhalation is the most important route of intake of radionuclides in the human body. In spite of the major advance in the model structure for the respiratory tract, there are areas of uncertainty, which lead to differences in the default parameter values adopted by the ICRP [15] and by the NCRP [41]. The default parameter values for the respiratory tract model often do not represent a particular compound accurately. The ICRP recommends [15] that material specific rates of absorption be used for compounds for which reliable experimental data exist. The use of absorption material specific rates for important compounds is discussed and illustrated by examples in Ref. [25], while only default absorption parameter values were used in the derivation of the $m(t)$ values for this report. Differences in deposition, retention and dosimetry of the ICRP and NCRP respiratory tract models are discussed in Ref. [42].

Even in cases in which extensive human data are available, there still may be much uncertainty in the estimated effective dose if the assumed biokinetic model does not consider all relevant components of the actual biokinetic behaviour of the radionuclide; for example, it is accepted that the whole body retention of caesium can be well described by the sum of two exponential functions with biological half-lives of about two and 110 days, respectively, as has been done by the ICRP [14, 16]. However, the data supporting this model were only collected for a few days to a few months after intake. Longer term data obtained following the Goiânia incident [43], however, indicate that there is an additional, small, long term component (about 0.1% of initial systemic activity) with a biological half-life of about 500 days. This third component has no relevant influence on the effective dose per unit intake, but for the interpretation of bioassay measurements at long times after an intake it may influence the estimated intake activity, and therefore the resulting effective dose, by an order of magnitude.

Although inhalation and ingestion are the most important pathways of internal contamination, absorption through wounds and intact skin may also

occur. While the use of $m(t)$ values, derived for direct uptake into blood (injection), can be used to assess intakes of soluble materials from wounds, note that this could present a significant source of uncertainty.

The models used to derive the $m(t)$ values in this report have been designed to be applied to a typical or reference individual, who might be exposed to low level internal contamination in his or her duties at work. They are meant to ensure the adequacy of radiological controls. In cases in which there is known to be a high degree of uncertainty associated with a model, it is advisable that the user verify that the model is being used to interpret measurements that are roughly in the same range as the data on which the model was based. In such a range, a model put forward in this report may be accepted as reliable.

4.3.2. Dosimetric models

Beyond the uncertainties in the standard biokinetic models discussed above, there are also uncertainties in the models that describe the energy deposition in the target regions. These include uncertainties due to the use of simplifying assumptions about organ masses, sizes and shapes, and due to the geometrical relationships between internal organs that are implicit in the use of computer phantoms. There are also limitations to the computational procedures for the calculation of specific absorbed fractions for penetrating radiations, and in the simplified assumptions about absorbed fractions in the bone and GI tract for non-penetrating radiations.

4.4. INDIVIDUAL VARIATIONS IN BIOKINETIC AND DOSIMETRIC PARAMETERS

The biokinetic and dosimetric models are designed for a reference individual, that is for an individual representing average values for the group considered, such as the Reference Man [27]. There are, however, considerable differences among individuals of such a group. Variations in anatomical and physiological factors influence the distribution and excretion of radionuclides in the body. These are, for example, differences in genetic constitution, age, sex, breathing patterns, lung, renal, liver, GI and cardiovascular functions, pregnancy and lactation. Environmental factors such as exercise, disease, stress, infection, smoking, alcohol intake, dietary factors, barometric pressure and exposure to sunlight may interact with biological factors, producing sizable variations among individuals [39]. Examples of biological and environmental influences are given below.

Different individuals ingesting lead under similar conditions have shown fractional GI absorption values of between 0.01 and 0.16 [44]. It is therefore inevitable that individual parameter values may be significantly different from the average values used in the standard biokinetic models.

Iodine uptake by the thyroid is largely dependent on the stable iodine already in the thyroid, which is influenced by the amount of stable iodine in the individual's diet. Therefore, in countries with low levels of iodine in typical foodstuffs, a higher iodine uptake is observed (45–50% instead of the ICRP value of 30%) [45]. Since this higher uptake is frequently correlated with a higher thyroid mass, this does not influence the thyroid dose and the effective dose per unit intake significantly. However, this higher uptake greatly influences the estimated intake and effective dose based on bioassay data.

The nominal daily urinary excretion from Reference Man is 1.6 L, but since this depends strongly on physiological and environmental conditions there can be very large variations in the excreted activity from one day to another for the same individual, which cannot easily be interpreted by a biokinetic model. For the interpretation of excretion measurements through the $m(t)$ tables of this report, a 24 h sample is preferred (with the exception of HTO); unfortunately, this cannot be assured in all cases, and the normalization of data to 24 h excretion will be another source of uncertainty.

Faecal samples from individual voidings vary widely in mass, composition and transit time through the GI tract. In addition, they are very difficult to interpret, since they contain materials cleared from the lungs, systemic material excreted into the GI tract and material passing unabsorbed through the GI tract following ingestion. Each of these variables are sources of uncertainty when using the values of $m(t)$ for faecal excretion to derive the intake. For many bioassay monitoring programmes, samples need to be collected over a three day period to estimate the daily excretion rate. Often the complete 24 h excretion is not available or the worker cannot provide samples for a period of several days, and normalization to the Reference Man excretion rate is necessary, which introduces another source of error.

An individual specific analysis is only necessary for the few situations in which the worker's dose approaches the dose limit. Even when specific analysis is conducted, the day to day variation, the behaviour of the individual in relation to environmental factors and the limitations of measurements will introduce uncertainties that are not easily quantified.

4.5. SUMMARY

The overall uncertainty in assessed dose is a combination of the uncertainties noted in the previous sections. A reliable estimate of this overall uncertainty is, however, difficult to achieve. The ICRP recommends making a dose assessment on the standard basis and adopting the results as nominal values of intake and dose [21]. If the dose assessed in this way is significant, then the uncertainties need to be considered in more detail.

5. DOSE RECORD KEEPING AND REPORTING

5.1. GENERAL CONSIDERATIONS

Dose record keeping is the creation and maintenance of individual dose records for radiation workers. It is an essential part of the process of monitoring exposures of individuals to radiation and supports the overall objectives of the radiation protection programme. General guidance is given in Ref. [5]. Further information that relates to doses from intakes of radionuclides is given below.

5.2. INDIVIDUAL MONITORING RECORDS

Typical records generated in an internal exposure monitoring programme include both directly relevant and supporting documentation. They must permit traceability of the measurements and the dose assessment. Directly relevant information includes details of the individual, bioassay data, workplace monitoring data, the purpose of the monitoring and dose assessments.

Details of an individual include: a unique identifier, which may include the name of his or her employer; his or her occupation; the radionuclides to which he or she might be exposed; specific workplace locations and tasks; his or her work schedule; and his or her employment history, including, where necessary, different roles within organizations. In some exposure situations, for example in mines, whether or not the individual smokes can influence the assessment and might therefore be usefully recorded.

Information to be included in records for in vivo bioassay data is given in section 5.2 of Ref. [7], for in vitro data in section 8.1 of Ref. [8] and for workplace monitoring in section 8.5 of Ref. [6].

Dose assessment records include: computed results such as the activity concentration in air; body activity contents or daily excretion rates and their statistical analyses; and computed intake values and the biokinetic models from which they were derived. Dose assessment records for each confirmed intake include: the intake pattern assumed; the intake route, with information on whether it is known or assumed; the chemical form of the nuclide, with information on whether it is known or assumed; the particle size, with information on whether it is known or assumed; the classification for gases and vapours; the absorption type assumed; the committed effective doses; the dose coefficients used; and the computer software or reference material used for the complete dose assessment.

If an estimate has been made of the dose to the embryo or foetus of a pregnant worker, this estimate needs to be recorded. The use of the dose coefficients in Ref. [46] is recommended.

In the case of long lived radionuclides, records need to reflect periodic reassessments of effective dose, based on further bioassay results and/or improved methods for dose assessment.

Supporting documentation includes the training and qualification records of dose assessors, quality assurance (QA) procedures and quality control data such as background trends and detector efficiency.

5.3. REPORTING INFORMATION TO MANAGEMENT

The procedures and levels to be used for reporting individual dose assessment results need to be clearly specified by the management or regulatory bodies. Information reported to management needs to be clearly identifiable and understandable. Management may set reporting levels on such parameters as committed effective dose, or estimated intake of activity, that will identify results that are to be reported, usually within specified time periods. Further details can be found in Ref. [6].

6. QUALITY ASSURANCE

6.1. GENERAL CONSIDERATIONS

The maintenance of the effectiveness of any radiation protection programme relies on the ability of those in charge of implementing its various components to adopt a QA programme. General guidance on QA requirements relating to occupational exposure are given in the BSS [2] and in Ref. [47]. Additional guidance is given in Ref. [5] and in Refs [48, 49]. The following deals specifically with issues relating to the assessment of exposure from intakes of radionuclides.

While formal QA procedures can be applied to good effect in laboratories carrying out measurements on individuals or on biological samples, it is difficult to recommend similarly strict rules and procedures for assessments. The scope for subjective decisions based on experience and knowledge is inevitably much wider for the assessment stage than for the measurement stage.

A system needs to be established to provide a quality indicator of the overall internal dosimetry service performance. Assessments of internal dose are complicated and intercomparison exercises have shown that even competent laboratories can arrive at very different estimates of dose given the same original data [50]. This underlines the need for caution in internal dose assessments and the provision of suitable QA procedures where possible.

6.2. DOCUMENTATION

The QA programme related to internal exposure assessment must be thoroughly documented. A QA plan needs to be prepared that contains general instructions on implementing the programme and on the various steps in its operation. Written procedures describe every step to assess internal doses from bioassay data and from workplace monitoring data, including estimates of the minimal detectable activities for the measurement techniques employed, and possible 'missed doses' for the monitoring intervals used. The procedures also have to contain data on quality control requirements, as, for example, national and international intercomparison exercises and training records. Documentation has to include the physical and chemical characteristics of the radionuclides present in the workplace, the methods for calculating internal doses for specific radionuclides, the mixtures of radionuclides and materials of differing chemical characteristics, the type and frequency of monitoring,

monitoring equipment, background trends, the selection of workers for monitoring, and the recording and reporting practices for internal dose assessment. The biokinetic and dosimetric models and the computational codes used for dose assessment need to be well defined. The methods to identify bioassay results above background values and the method to account for the portion of a bioassay result that may be due to prior intakes are to be included in the documentation. Quality control procedures document the use of control charts and other methods for tracking every step for dose assessment, and contain instructions for reporting and correcting deviations, as well as for taking account of changes in operation. It is also necessary to prepare procedures for documenting and reporting results. Likewise, procedures for record preparation, maintenance and archiving will be needed. The documentation provides sufficient information for an auditor to trace the operation from start to finish and to assess its validity.

Appendix I

BASIC DATA FOR INTERNAL DOSE ASSESSMENTS

This appendix provides basic data for the assessment of intakes of radionuclides.

TABLE 1. RADIATION WEIGHTING FACTORS IN THE BSS [2]

Type and energy range of radiation	Radiation weighting factor, w_R
Photons, all energies	1
Electrons and muons, all energies[a]	1
Neutrons, energy:	
<10 keV	5
10 keV–100 keV	10
>100 keV–2 MeV	20
>2 MeV–20 MeV	10
>20 MeV	5
Protons, other than recoil protons, energy >2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20

[a] Excluding Auger electrons emitted from radionuclides bound to DNA, for which special microdosimetric considerations apply.

TABLE 2. TISSUE WEIGHTING FACTORS IN THE BSS [2][a, b]

Tissue or organ	Tissue weighting factor, w_T
Gonads	0.20
Red bone marrow	0.12
Colon[c]	0.12
Lung[d]	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder[e]	0.05

[a] Values of w_T originally from Ref. [1].

[b] The values have been developed for a reference population of equal numbers of both sexes and a wide range of ages. In the definition of effective dose they apply to workers, to the whole population and to either sex [1].

[c] Doses calculated as mass weighted average to upper and lower large intestine:
$H_{\text{colon}} = 0.57H_{\text{ULI}} + 0.43H_{\text{LLI}}$ [17]

[d] Thoracic regions (BB, bb, AI and LN_{TH}) of the respiratory tract.

[e] For the purposes of calculation, the remainder is composed of the adrenal glands, brain, ET regions of the respiratory tract, small intestine, kidneys, muscle, pancreas, spleen, thymus and uterus. In those cases in which the most exposed remainder tissue receives the highest committed equivalent dose of all organs, a weighting factor of 0.025 is to be applied to that tissue or organ and a weighting factor of 0.025 to the mass weighted average dose in the rest of the remainder as defined here [18].

TABLE 3. COMMITTED EFFECTIVE DOSE PER UNIT INTAKE (DOSE COEFFICIENT) BY INHALATION, BY INGESTION AND THROUGH DIRECT INTAKE TO BLOOD FOR SELECTED RADIONUCLIDES

	Inhalation			Ingestion[a]		Injection[b]	
		$e(g)_{inh}$ (Sv/Bq)					
	Type/form[c]	AMAD = 1 μm	AMAD = 5 μm	f_1	$e(g)_{ing}$ (Sv/Bq)	f_1	$e(g)_{inj}$ (Sv/Bq)
^{3}H	HTO[d,e]	1.8×10^{-11}	—	1	1.8×10^{-11}	—	1.8×10^{-11}
	OBT[d,e]	4.1×10^{-11}	—	1	4.2×10^{-11}	—	—
	Gas[d]	1.8×10^{-15}	—	—	—	—	—
^{32}P	F	8.0×10^{-10}	1.1×10^{-9}	0.8	2.3×10^{-10}	—	2.2×10^{-9}
	M	3.2×10^{-9}	2.9×10^{-9}	—	—	—	—
^{55}Fe	F	7.7×10^{-10}	9.2×10^{-10}	0.1	3.3×10^{-10}	0.1	3.0×10^{-9}
	M	3.7×10^{-10}	3.3×10^{-10}	—	—	—	—
^{59}Fe	F	2.2×10^{-9}	3.0×10^{-9}	0.1	1.8×10^{-9}	0.1	8.4×10^{-9}
	M	3.5×10^{-9}	3.2×10^{-9}	—	—	—	—
^{60}Co	M	9.6×10^{-9}	7.1×10^{-9}	0.1	3.4×10^{-9}	—	1.9×10^{-8}
	S	2.9×10^{-8}	1.7×10^{-8}	0.05	2.5×10^{-9}	—	—
^{67}Ga	F	6.8×10^{-11}	1.1×10^{-10}	0.001	1.9×10^{-10}	—	1.2×10^{-10}
	M	2.3×10^{-10}	2.8×10^{-10}	—	—	—	—
^{85}Sr	F	3.9×10^{-10}	5.6×10^{-10}	0.3	5.6×10^{-10}	—	1.1×10^{-9}
	S	7.7×10^{-10}	6.4×10^{-10}	0.01	3.3×10^{-10}	—	—
^{89}Sr	F	1.0×10^{-9}	1.4×10^{-9}	0.3	2.6×10^{-9}	—	3.1×10^{-9}
	S	7.5×10^{-9}	5.6×10^{-9}	0.01	2.3×10^{-9}	—	—
^{90}Sr	F	2.4×10^{-8}	3.0×10^{-8}	0.3	2.8×10^{-8}	—	8.8×10^{-8}
	S	1.5×10^{-7}	7.7×10^{-8}	0.01	2.7×10^{-9}	—	—
^{95}Zr	F	2.5×10^{-9}	3.0×10^{-9}	0.002	8.8×10^{-10}	—	1.0×10^{-8}
	M	4.5×10^{-9}	3.6×10^{-9}	—	—	—	—
	S	5.5×10^{-9}	4.2×10^{-9}	—	—	—	—
^{95}Nb	M	1.4×10^{-9}	1.3×10^{-9}	0.01	5.8×10^{-10}	—	2.1×10^{-9}
	S	1.6×10^{-9}	1.3×10^{-9}	—	—	—	—
^{99}Tc	F	2.9×10^{-10}	4.0×10^{-10}	0.8	7.8×10^{-10}	—	8.7×10^{-10}
	M	3.9×10^{-9}	3.2×10^{-9}	—	—	—	—
^{99m}Tc	F	1.2×10^{-11}	2.0×10^{-11}	0.8	2.2×10^{-11}	—	1.9×10^{-11}
	M	1.9×10^{-11}	2.9×10^{-11}	—	—	—	—
^{106}Ru	F	8.0×10^{-9}	9.8×10^{-9}	0.05	7.0×10^{-9}	—	3.0×10^{-8}
	M	2.6×10^{-8}	1.7×10^{-8}	—	—	—	—
	S	6.2×10^{-8}	3.5×10^{-8}	—	—	—	—

TABLE 3. COMMITTED EFFECTIVE DOSE PER UNIT INTAKE (DOSE COEFFICIENT) BY INHALATION, BY INGESTION AND THROUGH DIRECT INTAKE TO BLOOD FOR SELECTED RADIONUCLIDES (cont.)

		Inhalation		Ingestion[a]		Injection[b]	
	Type/form[c]	$e(g)_{inh}$ (Sv/Bq) AMAD = 1 μm	$e(g)_{inh}$ (Sv/Bq) AMAD = 5 μm	f_1	$e(g)_{ing}$ (Sv/Bq)	f_1	$e(g)_{inj}$ (Sv/Bq)
^{125}Sb	F	1.4×10^{-9}	1.7×10^{-9}	0.1	1.1×10^{-9}	—	5.4×10^{-9}
	M	4.5×10^{-9}	3.3×10^{-9}	—	—	—	—
^{123}I	F	7.6×10^{-11}	1.1×10^{-10}	1.0	2.1×10^{-10}	—	2.2×10^{-10}
	V[c]	2.1×10^{-10}	—	—	—	—	—
^{124}I	F	4.5×10^{-9}	6.3×10^{-9}	1.0	1.3×10^{-8}	—	1.3×10^{-8}
	V[c]	1.2×10^{-8}	—	—	—	—	—
^{125}I	F	5.3×10^{-9}	7.3×10^{-9}	1.0	1.5×10^{-8}	—	1.5×10^{-8}
	V[c]	1.4×10^{-8}	—	—	—	—	—
^{131}I	F	7.6×10^{-9}	1.1×10^{-8}	1.0	2.2×10^{-8}	—	2.2×10^{-8}
	V[c]	2.0×10^{-8}	—	—	—	—	—
^{134}Cs	F	6.8×10^{-9}	9.6×10^{-9}	1.0	1.9×10^{-8}	—	1.9×10^{-8}
^{137}Cs	F	4.8×10^{-9}	6.7×10^{-9}	1.0	1.3×10^{-8}	—	1.4×10^{-8}
^{144}Ce	M	3.4×10^{-8}	2.3×10^{-8}	5×10^{-4}	5.2×10^{-9}	—	1.7×10^{-7}
	S	4.9×10^{-8}	2.9×10^{-8}	—	—	—	—
^{153}Gd	F	2.1×10^{-9}	2.5×10^{-9}	5×10^{-4}	2.7×10^{-10}	—	8.6×10^{-9}
	M	1.9×10^{-9}	1.4×10^{-9}	—	—	—	—
^{201}Tl	F	4.7×10^{-11}	7.6×10^{-11}	1.0	9.5×10^{-11}	—	8.7×10^{-11}
^{210}Pb	F	8.9×10^{-7}	1.1×10^{-6}	0.2	6.8×10^{-7}	0.2	3.5×10^{-6}
^{210}Po	F	6.0×10^{-7}	7.1×10^{-7}	0.1	2.4×10^{-7}	—	2.4×10^{-6}
	M	3.0×10^{-6}	2.2×10^{-6}	—	—	—	—
^{226}Ra	M	3.2×10^{-6}	2.2×10^{-6}	0.2	2.8×10^{-7}	—	1.4×10^{-6}
^{228}Ra	M	2.6×10^{-6}	1.7×10^{-6}	0.2	6.7×10^{-7}	—	3.4×10^{-6}
^{228}Th	M	3.1×10^{-5}	2.3×10^{-5}	5×10^{-4}	7.0×10^{-8}	5×10^{-4}	1.2×10^{-4}
	S	3.9×10^{-5}	3.2×10^{-5}	2×10^{-4}	3.5×10^{-8}	—	—
^{232}Th	M	4.2×10^{-5}	2.9×10^{-5}	5×10^{-4}	2.2×10^{-7}	5×10^{-4}	4.5×10^{-4}
	S	2.3×10^{-5}	1.2×10^{-5}	2×10^{-4}	9.2×10^{-8}	—	—
^{234}U	F	5.5×10^{-7}	6.4×10^{-7}	0.02	4.9×10^{-8}	—	2.3×10^{-6}
	M	3.1×10^{-6}	2.1×10^{-6}	0.002	8.3×10^{-9}	—	—
	S	8.5×10^{-6}	6.8×10^{-6}	—	—	—	—

TABLE 3. COMMITTED EFFECTIVE DOSE PER UNIT INTAKE (DOSE COEFFICIENT) BY INHALATION, BY INGESTION AND THROUGH DIRECT INTAKE TO BLOOD FOR SELECTED RADIONUCLIDES (cont.)

	Inhalation			Ingestion[a]		Injection[b]	
	Type/form[c]	$e(g)_{inh}$ (Sv/Bq) AMAD = 1 μm	$e(g)_{inh}$ (Sv/Bq) AMAD = 5 μm	f_1	$e(g)_{ing}$ (Sv/Bq)	f_1	$e(g)_{inj}$ (Sv/Bq)
^{235}U	F	5.1×10^{-7}	6.0×10^{-7}	0.02	4.6×10^{-8}	—	2.1×10^{-6}
	M	2.8×10^{-6}	1.8×10^{-6}	0.002	8.3×10^{-9}	—	—
	S	7.7×10^{-6}	6.1×10^{-6}	—	—	—	—
^{238}U	F	4.9×10^{-7}	5.8×10^{-7}	0.02	4.4×10^{-8}	—	2.1×10^{-6}
	M	2.6×10^{-6}	1.6×10^{-6}	0.002	7.6×10^{-9}	—	—
	S	7.3×10^{-6}	5.7×10^{-6}	—	—	—	—
^{237}Np	M	2.1×10^{-5}	1.5×10^{-5}	5×10^{-4}	1.1×10^{-7}	5×10^{-4}	2.1×10^{-4}
^{239}Np	M	9.0×10^{-10}	1.1×10^{-9}	5×10^{-4}	8.0×10^{-10}	5×10^{-4}	3.8×10^{-10}
^{238}Pu	M	4.3×10^{-5}	3.0×10^{-5}	5×10^{-4}	2.3×10^{-7}	5×10^{-4}	4.5×10^{-4}
	S	1.5×10^{-5}	1.1×10^{-5}	1×10^{-5}	8.8×10^{-9}	—	—
		—	—	1×10^{-4}	4.9×10^{-8}	—	—
^{239}Pu	M	4.7×10^{-5}	3.2×10^{-5}	5×10^{-4}	2.5×10^{-7}	5×10^{-4}	4.9×10^{-4}
	S	1.5×10^{-5}	8.3×10^{-6}	1×10^{-5}	9.0×10^{-9}	—	—
		—	—	1×10^{-4}	5.3×10^{-8}	—	—
^{240}Pu	M	4.7×10^{-5}	3.2×10^{-5}	5×10^{-4}	2.5×10^{-7}	5×10^{-4}	4.9×10^{-4}
	S	1.5×10^{-5}	8.3×10^{-6}	1×10^{-5}	9.0×10^{-9}	—	—
		—	—	1×10^{-4}	5.3×10^{-8}	—	—
^{241}Pu	M	8.5×10^{-7}	5.8×10^{-7}	5×10^{-4}	4.7×10^{-9}	5×10^{-4}	9.5×10^{-6}
	S	1.6×10^{-7}	8.4×10^{-8}	1×10^{-5}	1.1×10^{-10}	—	—
		—	—	1×10^{-4}	9.6×10^{-10}	—	—
^{241}Am	M	3.9×10^{-5}	2.7×10^{-5}	5×10^{-4}	2.0×10^{-7}	5×10^{-4}	4.0×10^{-4}
^{242}Cm	M	4.8×10^{-6}	3.7×10^{-6}	5×10^{-4}	1.2×10^{-8}	5×10^{-4}	1.4×10^{-5}
^{244}Cm	M	2.5×10^{-5}	1.7×10^{-5}	5×10^{-4}	1.2×10^{-7}	5×10^{-4}	2.4×10^{-4}

[a] f_1 values given here apply only to ingestion, not to the inhalation doses in the adjacent column.

[b] Direct intake into blood. For most of these cases an f_1 value is not relevant. However, in some cases, such as for plutonium, the model involves recycling of material through the small intestine. In such cases the f_1 value is used and is therefore given in the table.

[c] For lung absorption types, see Section 2.2.1.

[d] For inhalation of gases and vapours, the AMAD does not apply for this form.

[e] HTO: tritiated water; OBT: organically bound tritium.

TABLE 4. DERIVED AIR CONCENTRATIONS[a] (DACs) FOR SELECTED RADIONUCLIDES

	Type/form[b]	DAC (Bq/m^3)		
		AMAD = 1 μm	AMAD = 5 μm	Gas/vapour
^{3}H	HTO[c]	—	—	5×10^{5}
	OBT	—	—	2×10^{5}
	Gas	—	—	5×10^{9}
^{32}P	F	1×10^{4}	8×10^{3}	—
	M	3×10^{3}	3×10^{3}	—
^{55}Fe	F	1×10^{4}	9×10^{3}	—
	M	2×10^{4}	3×10^{4}	—
^{59}Fe	F	4×10^{3}	3×10^{3}	—
	M	2×10^{3}	3×10^{3}	—
^{60}Co	M	9×10^{2}	1×10^{3}	—
	S	3×10^{2}	5×10^{2}	—
^{67}Ga	F	1×10^{5}	8×10^{4}	—
	M	4×10^{4}	3×10^{4}	—
^{85}Sr	F	2×10^{4}	1×10^{4}	—
	S	1×10^{4}	1×10^{4}	—
^{89}Sr	F	8×10^{3}	6×10^{3}	—
	S	1×10^{3}	1×10^{3}	—
^{90}Sr	F	3×10^{2}	3×10^{2}	—
	S	6×10^{1}	1×10^{2}	—
^{95}Zr	F	3×10^{3}	3×10^{3}	—
	M	2×10^{3}	2×10^{3}	—
	S	2×10^{3}	2×10^{3}	—
^{95}Nb	M	6×10^{3}	6×10^{3}	—
	S	5×10^{3}	6×10^{3}	—
^{99}Tc	F	3×10^{4}	2×10^{4}	—
	M	2×10^{3}	3×10^{3}	—
^{99m}Tc	F	7×10^{5}	4×10^{5}	—
	M	4×10^{5}	3×10^{5}	—
^{106}Ru	F	1×10^{3}	9×10^{2}	—
	M	3×10^{2}	5×10^{2}	—
	S	1×10^{2}	2×10^{2}	—
^{125}Sb	F	6×10^{3}	5×10^{3}	—
	M	2×10^{3}	3×10^{3}	—

TABLE 4. DERIVED AIR CONCENTRATIONS[a] (DACs) FOR SELECTED RADIONUCLIDES (cont.)

	Type/form[b]	DAC (Bq/m^3)		
		AMAD = 1 μm	AMAD = 5 μm	Gas/vapour
^{123}I	F	1×10^5	8×10^4	—
	V	—	—	4×10^4
^{124}I	F	2×10^3	1×10^3	—
	V	—	—	7×10^2
^{125}I	F	2×10^3	1×10^3	—
	V	—	—	6×10^2
^{131}I	F	1×10^3	8×10^2	—
	V	—	—	4×10^2
^{134}Cs	F	1×10^3	9×10^2	—
^{137}Cs	F	2×10^3	1×10^3	—
^{144}Ce	M	2×10^2	4×10^2	—
	S	2×10^2	3×10^2	—
^{153}Gd	F	4×10^3	3×10^3	—
	M	4×10^3	6×10^3	—
^{201}Tl	F	2×10^5	1×10^5	—
^{210}Pb	F	9×10^0	8×10^0	—
^{210}Po	F	1×10^1	1×10^1	—
	M	3×10^0	4×10^0	—
^{226}Ra	M	3×10^0	4×10^0	—
^{228}Ra	M	3×10^0	5×10^0	—
^{228}Th	M	3×10^{-1}	4×10^{-1}	—
	S	2×10^{-1}	3×10^{-1}	—
^{232}Th	M	2×10^{-1}	3×10^{-1}	—
	S	4×10^{-1}	7×10^{-1}	—
^{234}U	F	2×10^1	1×10^1	—
	M	3×10^0	4×10^0	—
	S	1×10^0	1×10^0	—
^{235}U	F	2×10^1	1×10^1	—
	M	3×10^0	5×10^0	—
	S	1×10^0	1×10^0	—
^{238}U	F	2×10^1	1×10^1	—
	M	3×10^0	5×10^0	—
	S	1×10^0	1×10^0	—

TABLE 4. DERIVED AIR CONCENTRATIONS[a] (DACs) FOR SELECTED RADIONUCLIDES (cont.)

	Type/form[b]	DAC (Bq/m^3)		
		AMAD = 1 μm	AMAD = 5 μm	Gas/vapour
^{237}Np	M	4×10^{-1}	6×10^{-1}	—
^{239}Np	M	9×10^{3}	8×10^{3}	—
^{238}Pu	M	2×10^{-1}	3×10^{-1}	—
	S	6×10^{-1}	8×10^{-1}	—
^{239}Pu	M	2×10^{-1}	3×10^{-1}	—
	S	6×10^{-1}	1×10^{0}	—
^{240}Pu	M	2×10^{-1}	3×10^{-1}	—
	S	6×10^{-1}	1×10^{0}	—
^{241}Pu	M	1×10^{1}	1×10^{1}	—
	S	5×10^{1}	1×10^{2}	—
^{241}Am	M	2×10^{-1}	3×10^{-1}	—
^{242}Cm	M	2×10^{0}	1×10^{0}	—
^{244}Cm	M	3×10^{-1}	5×10^{-1}	—

[a] Calculated assuming an average breathing rate of 1.2 m^3/h, 2000 h worked annually and a dose limit of 20 mSv.
[b] For lung absorption types, see Section 2.2.1.
[c] The DAC does not allow for absorption through intact skin.

Appendix II

BIOKINETIC MODELS FOR SELECTED ELEMENTS AND RADIONUCLIDES

II.1. HYDROGEN

Absorption types, f_1 values and chemical forms for hydrogen are given in Table 5. They are taken from the tables in Schedule II of the BSS [2] and are consistent with those given in Refs [3, 19].

The biokinetic model adopted here in this report, and as adopted in the BSS [2], is taken from Ref. [16]. For HTO it is assumed that 97% of the activity equilibrates with body water and is retained with a biological half-life of ten days. The remaining 3% is assumed to be incorporated into organic molecules and retained with a biological half-life of 40 days. For organically bound tritium (OBT), 50% of the activity is taken to be retained with the ten day biological half-life of water and 50% with the 40 day biological half-life of organic carbon.

For tritium gas (HT) it is assumed that 0.01% of the inhaled HT is absorbed and converted to HTO, while for tritiated methane it is assumed that 1% is metabolized and behaves as HTO [19].

The accompanying CD gives predicted fractions of intake at various times after a single acute intake of tritium. For HTO the concentration in urine is given. For OBT, total body retention and daily urine excretion are given. Daily faecal excretion is also given for ingestion of OBT.

TABLE 5. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR HYDROGEN

	f_1	Intake
Ingestion	1.0	Ingestion of HTO or OBT
Inhalation, Type V, SR-1	[a]	Inhalation of tritium gas and tritiated methane
Inhalation, Type V, SR-2	[a]	Inhalation of HTO and organic compounds

[a] Not applicable, since all activity deposited in the respiratory tract is instantaneously absorbed.

II.2. PHOSPHORUS

Absorption types, f_1 values and chemical forms for phosphorus are given in Table 6. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [14]. Following entry into the transfer compartment, 30% of the activity is taken to be deposited in bone (^{32}P on bone surfaces), where it is retained with a retention half-life of 1500 days. Fifty-five per cent of the activity is deposited in other tissues; of this, 40% is retained with a biological half-life of 19 days and 15% with a biological half-life of two days. The remaining 15% of the activity is taken to be excreted promptly (with a biological half-life of 0.5 day).

For activity lost to excretion from systemic compartments, 50% is assumed to be lost to urine and 50% to faeces [3]. Note that the predicted values of daily excretion in urine and faeces (see Section 2.4) are assumed and therefore will vary in practice.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{32}P: daily urinary and faecal excretion; total body retention; retention in the lungs for intakes of Type M material by inhalation; and retention in the skeleton.

TABLE 6. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR PHOSPHORUS

	f_1	Compound
Ingestion	0.8	All compounds
Inhalation, Type F	0.8	All unspecified compounds
Inhalation, Type M	0.8	Some phosphates: determined by combining cation

II.3. IRON

Absorption types, f_1 values and chemical forms for iron are given in Table 7. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [18]. Following entry into the transfer compartment, most iron is transported to the red bone marrow, incorporated into haemoglobin in newly formed erythrocytes and re-released to the circulation. Smaller amounts of iron are stored in other tissues, principally the liver. Iron from senescent red blood cells is transferred mainly to the red bone marrow, liver and spleen. Losses of iron from the body are largely due to exfoliation of cells from the skin and the GI tract, with smaller amounts in sweat, bile and urine.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{55}Fe or ^{59}Fe: daily urinary and faecal excretion; total body retention; retention in the lungs for intakes of Type M material by inhalation; and retention in the liver.

TABLE 7. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR IRON

	f_1	Compound
Ingestion	0.1	All compounds
Inhalation, Type F	0.1	All unspecified compounds
Inhalation, Type M	0.1	Oxides, hydroxides and halides

II.4. COBALT

Absorption types, f_1 values and chemical forms for cobalt are given in Table 8. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [17]. Following entry into the transfer compartment, 50% of the cobalt is rapidly excreted with a biological half-life of 0.5 day, 5% is taken up by the liver and 45% is uniformly distributed in all other tissues. Fractions of 0.6, 0.2 and 0.2 are assumed to be lost from the liver and other tissues, with biological half-lives of 6, 60 and 800 days, respectively. For activity lost to excretion from systemic compartments, 86% is assumed to be lost to urine and 14% to faeces. Note that the predicted values of daily excretion in urine and faeces (see Section 2.4) are assumed and therefore will vary in practice.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{60}Co: daily urinary and faecal excretion; total body retention; retention in the lungs for intakes by inhalation; and retention in the liver.

TABLE 8. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR COBALT

	f_1	Compound
Ingestion	0.1	All unspecified compounds
Ingestion	0.05	Oxides, hydroxides and inorganic compounds
Inhalation, Type M	0.1	All unspecified compounds
Inhalation, Type S	0.05	Oxides, hydroxides, halides and nitrates

II.5. GALLIUM

Absorption types, f_1 values and chemical forms for gallium are given in Table 9. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [40]. Following entry into the transfer compartment, 30% is deposited on bone surfaces, 9% in the liver, 1% in the spleen and 60% in all other tissues. Gallium is retained in all organs and tissues with biological half-lives of one day (30%) and 50 days (70%). For activity lost to excretion from systemic compartments, 50% is assumed to be lost to urine and 50% to faeces [3]. Note that the predicted values of daily excretion in urine and faeces (see Section 2.4) are assumed and therefore will vary in practice.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{67}Ga: total body retention; retention in the lungs for intakes of Type M materials by inhalation; retention in the liver; and retention in the skeleton.

TABLE 9. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR GALLIUM

	f_1	Compound
Ingestion	0.001	All compounds
Inhalation, Type F	0.001	All unspecified compounds
Inhalation, Type M	0.001	Oxides, hydroxides, carbides, halides and nitrates

II.6. STRONTIUM

Absorption types, f_1 values and chemical forms for strontium are given in Table 10. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [17]. This model describes in detail the kinetics of alkaline earth elements in bone, which is the main site of deposition and retention, and considers also retention in soft tissues and routes of excretion. It takes account of initial uptake on to bone surfaces, transfer from the surface to bone volume and recycling from bone and soft tissues to blood. It also describes the excretion routes for which no constant ratio is used.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{85}Sr, ^{89}Sr and ^{90}Sr: daily urinary and faecal excretion; total body retention; retention in the lungs for intakes of Type S materials by inhalation; and retention in the skeleton.

TABLE 10. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR STRONTIUM

	f_1	Compound
Ingestion	0.3	All unspecified compounds
Ingestion	0.01	Strontium titanate ($SrTiO_3$)
Inhalation, Type F	0.3	All unspecified compounds
Inhalation, Type S	0.01	Strontium titanate ($SrTiO_3$)

II.7. ZIRCONIUM

Absorption types, f_1 values and chemical forms for zirconium are given in Table 11. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [17]. Following entry into the transfer compartment, 50% of systemic zirconium is retained on bone surfaces with a biological half-life of 10 000 days (relating to the rate of bone remodelling), and the other 50% is distributed throughout all other tissues and is retained with a biological half-life of seven days. For activity lost to excretion from systemic compartments, 83% is assumed to be lost to urine and 17% to faeces. Note that the predicted values of daily excretion in urine and faeces (see Section 2.4) are assumed and therefore will vary in practice.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{95}Zr: daily urinary and faecal excretion; total body retention; retention in the lungs for intakes of Type M material by inhalation; and retention in the skeleton.

TABLE 11. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR ZIRCONIUM

	f_1	Compound
Ingestion	0.002	All compounds
Inhalation, Type F	0.002	All unspecified compounds
Inhalation, Type M	0.002	Oxides, hydroxides, halides and nitrates
Inhalation, Type S	0.002	Zirconium carbide

II.8. NIOBIUM

Absorption types, f_1 values and chemical forms for niobium are given in Table 12. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [16]. Following entry into the transfer compartment, 0.4 is deposited in mineral bone, 0.2 in the liver, 0.03 in the kidneys and 0.37 in all other tissues. The retention is described by a two component exponential function for all tissues and organs, with biological half-lives of six days (50%) and 200 days (50%). Niobium-95 in the skeleton is assumed to be distributed over bone surfaces. For activity lost to excretion from systemic compartments, 83% is assumed to be lost to urine and 17% to faeces [17]. Note that the predicted values of daily excretion in urine and faeces (see Section 2.4) are assumed and therefore will vary in practice.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{95}Nb: daily urinary and faecal excretion; total body retention; retention in the lungs for intakes by inhalation; and retention in the skeleton.

TABLE 12. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR NIOBIUM

	f_1	Compound
Ingestion	0.01	All compounds
Inhalation, Type M	0.01	All unspecified compounds
Inhalation, Type S	0.01	Oxides and hydroxides

II.9. TECHNETIUM

Absorption types, f_1 values and chemical forms for technetium are given in Table 13. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [17]. Following entry into the transfer compartment, 0.04 of technetium is taken up by the thyroid gland and retained with a biological half-life of 0.5 day. Further fractions of 0.1 and 0.03 are assumed to be translocated to the stomach wall and liver, respectively, and the remaining fraction is assumed to be uniformly distributed in all other tissues. Biological half-lives for the retention of technetium in all tissues other than the thyroid are taken to be 1.6, 3.7 and 22 days, applying to fractions of 0.75, 0.2 and 0.05, respectively. The biological half-life in blood is assumed to be 0.02 day. For activity lost to excretion from systemic compartments, 50% is assumed to be lost to urine and 50% to faeces. Note that the predicted values of daily excretion in urine and faeces (see Section 2.4) are assumed and therefore will vary in practice.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{99m}Tc and ^{99}Tc: daily urinary and faecal excretion; total body retention; and retention in the lungs for intakes of Type M material by inhalation. Data are not given for specific tissues besides the lungs, since the tissue activity concentrations do not significantly exceed the average activity distribution.

TABLE 13. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR TECHNETIUM

	f_1	Compound
Ingestion	0.8	All compounds
Inhalation, Type F	0.8	All unspecified compounds
Inhalation, Type M	0.8	Oxides, hydroxides, halides and nitrates

II.10. RUTHENIUM

Absorption types, f_1 values and chemical forms for ruthenium are given in Table 14. They are taken from the BSS [2] and are consistent with those given in Refs [3, 19].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [16]. For ruthenium absorbed to body fluids, data have shown that the subsequent tissue distribution is fairly uniform. A model using a three term retention expression is recommended: 35% of activity is retained with a biological half-life of eight days, 30% with 35 days and 20% with 1000 days. The biological half-life in body fluids is taken to be 0.3 day, and 15% of systemic activity is assumed to be excreted directly. For activity lost to excretion from systemic compartments, 80% is assumed to be lost to urine and 20% to faeces. Note that the predicted values of daily excretion in urine and faeces (see Section 2.4) are assumed and therefore will vary in practice.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{106}Ru: daily urinary and faecal excretion; total body retention; and retention in the lungs for intakes by inhalation of Type M and Type S material. Data are not given for specific tissues, besides the lungs, since the tissue activity concentrations do not significantly exceed the average activity distribution.

TABLE 14. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR RUTHENIUM

	f_1	Compound
Ingestion	0.05	All compounds
Inhalation, Type F	0.05	Unspecified compounds
Inhalation, Type M	0.05	Halides
Inhalation, Type S	0.05	Oxides and hydroxides
Inhalation	0.05	Tetroxide

II.11. ANTIMONY

Absorption types, f_1 values and chemical forms for antimony are given in Table 15. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [18]. From that part of antimony entering the circulation, a fraction of 0.2 is rapidly excreted, 0.4 is taken up by bone surfaces, 0.05 by the liver and the remaining fraction of 0.35 is uniformly distributed throughout all other organs. For all tissues, fractions of 0.85, 0.1 and 0.05 are assumed to be retained with biological half-lives of 5, 100 and 5000 days, respectively. For activity lost to excretion from systemic compartments, 80% is assumed to be lost to urine and 20% to faeces. Note that the predicted values of daily excretion in urine and faeces (see Section 2.4) are assumed and therefore will vary in practice.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{125}Sb: daily urinary and faecal excretion; total body retention; retention in the lungs for intakes of Type M material by inhalation; and retention in the skeleton.

TABLE 15. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR ANTIMONY

	f_1	Compound
Ingestion	0.1	All compounds
Inhalation, Type F	0.1	Unspecified compounds
Inhalation, Type M	0.01	Oxides, hydroxides, halides, sulphides, sulphates and nitrates

II.12. IODINE

Absorption types, f_1 values and chemical forms for iodine are given in Table 16. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [16]. It is assumed that, of the iodine reaching the blood, a fraction of 0.3 is accumulated in the thyroid gland and 0.7 is excreted directly in urine. The biological half-life in blood is taken to be 0.25 day. Iodine incorporated into thyroid hormones leaves the thyroid gland with a biological half-life of 80 days and enters other tissues, where it is retained with a biological half-life of 12 days. Most iodine (80%) is subsequently released to the blood and is available in the circulation for uptake by the thyroid gland and urinary excretion; the remainder (20%) is excreted in faeces in organic form.

The biokinetic model for iodine assumes that 0.3 is taken up by the thyroid and the remainder is excreted in urine. In fact, there are relatively large variations, depending on many parameters such as the stable iodine content in common food and thyroid dysfunctions; for example, current uptake values for a European euthyroid adult are in the range 0.20–0.25. However, in countries with iodine deficiency in food, this value is considerably higher. Pathological states of the thyroid may result in uptake values of 0–0.05 (blocked thyroid) to more than 0.5. When such cases are suspected, then individual values need to be introduced in the dose calculation, especially for accidental exposures leading to significant doses, for which a precise assessment is needed.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{123}I, ^{124}I, ^{125}I and ^{131}I: daily urinary and faecal excretion; total body retention; and retention in the thyroid.

TABLE 16. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR IODINE

	f_1	Compound
Ingestion	1.0	All compounds
Inhalation, Type F	1.0	All particulate compounds
Inhalation, Type F, SR-1	1.0	Elemental iodine
Inhalation, Type V, SR-1	[a]	Methyl iodide

[a] Not applicable, since all activity deposited in the respiratory tract is instantaneously absorbed.

II.13. CAESIUM

Absorption types, f_1 values and chemical forms for caesium are given in Table 17. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [16]. Following entry into the transfer compartment, caesium is taken to be distributed uniformly throughout all body tissues; 10% of the activity is assumed to be retained with a biological half-life of two days and 90% with 110 days. For females, however, the biological half-life for the long term component is significantly less than for males [43, 46]. There is also evidence that in some countries the mean biological half-life of caesium in adult males is less than 110 days [51, 52]. Additionally, there is information that a small part of activity is retained with a longer biological half-life, of about 500 days [43]. For activity lost to excretion from systemic compartments, 80% is assumed to be lost to urine and 20% to faeces, as per Ref. [17]. Note that the predicted values of daily excretion in urine and faeces (see Section 2.4) are assumed and therefore will vary in practice.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{134}Cs and ^{137}Cs: daily urinary and faecal excretion; and total body retention. No data are given for specific tissues, because the activity concentration does not significantly exceed the average activity distribution for any organ or tissue.

TABLE 17. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR CAESIUM

	f_1	Compound
Ingestion	1.0	All compounds
Inhalation, Type F	1.0	All compounds

II.14. CERIUM

Absorption types, f_1 values and chemical forms for cerium are given in Table 18. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [16]. Following entry into the transfer compartment, cerium is taken to be distributed in the skeleton (bone surfaces: 30%), the liver (50%) and other tissues (20%). The retention half-life is taken to be 3500 days in all tissues. For activity lost to excretion from systemic compartments, 10% is assumed to be lost to urine and 90% to faeces, as per Ref. [17]. Note that the predicted values of daily excretion in urine and faeces (see Section 2.4) are assumed and therefore will vary in practice.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{144}Ce: daily urinary and faecal excretion; total body retention; lung retention for inhalation; retention in the skeleton; and retention in the liver.

TABLE 18. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR CERIUM

	f_1	Compound
Ingestion	0.0005	All compounds
Inhalation, Type M	0.0005	All unspecified compounds
Inhalation, Type S	0.0005	Oxides, hydroxides and fluorides

II.15. GADOLINIUM

Absorption types, f_1 values and chemical forms for gadolinium are given in Table 19. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [40]. Following entry into the transfer compartment, gadolinium is taken to be distributed to the kidneys (3%), liver (30%) and skeleton (45%), with 22% of material being promptly excreted. Gadolinium in the liver and skeleton is assumed to be retained with a biological half-life of 3500 days, while that in the kidneys is taken to be retained with a biological half-life of ten days. For activity lost to excretion, 50% is assumed to be lost to urine and 50% to faeces, following Ref. [3]. Note that the predicted values of daily excretion in urine and faeces (see Section 2.4) are assumed and therefore will vary in practice.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{153}Gd: total body retention; retention in the lungs for intakes by inhalation; retention in the skeleton; and retention in the liver.

TABLE 19. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR GADOLINIUM

	f_1	Compound
Ingestion	0.0005	All compounds
Inhalation, Type F	0.0005	Unspecified compounds
Inhalation, Type M	0.0005	Oxides, hydroxides and fluorides

II.16. THALLIUM

Absorption types, f_1 values and chemical forms for thallium are given in Table 20. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [40]. Following entry into the transfer compartment, thallium is taken to be distributed instantaneously within the kidneys (3%) and all other organs (97%). Thallium in all tissues is assumed to be retained with a biological half-life of ten days. For activity lost to excretion from systemic compartments, 50% is assumed to be lost to urine and 50% to faeces, as per Ref. [3]. Note that the predicted values of daily excretion in urine and faeces (see Section 2.4) are assumed and therefore will vary in practice.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{201}Tl: total body retention.

TABLE 20. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR THALLIUM

	f_1	Compound
Ingestion	1.0	All compounds
Inhalation, Type F	1.0	All compounds

II.17. LEAD

Absorption types, f_1 values and chemical forms for lead are given in Table 21. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [17]. The model uses the structure of the alkaline earth model [17]; it describes the kinetics of lead in bone, which is the main site of deposition and retention, and also considers retention in the liver, red blood cells and other soft tissues, as well as routes of excretion. It takes account of initial uptake on to bone surfaces, transfer from the surface to bone volume and recycling from bone and other tissues to plasma.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{210}Pb: daily urinary and faecal excretion; total body retention; and skeleton retention.

TABLE 21. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR LEAD

	f_1	Compound
Ingestion	0.2	All compounds
Inhalation, Type F	0.2	All compounds

II.18. POLONIUM

Absorption types, f_1 values and chemical forms for polonium are given in Table 22. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [17]. Following entry into the transfer compartment, polonium is taken to be distributed to the liver (30%), the kidneys (10%), red bone marrow (10%), the spleen (5%) and all other tissues (45%). The retention half-life for polonium is taken to be 50 days for all tissues. For activity lost to excretion from systemic compartments, 33% is assumed to be lost to urine and 67% to faeces. Note that the predicted values of daily excretion in urine and faeces (see Section 2.4) are assumed and therefore will vary in practice.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{210}Po: daily urinary and faecal excretion; total body retention; lung retention for intakes of Type M material by inhalation; and retention in the skeleton.

TABLE 22. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR POLONIUM

	f_1	Compound
Ingestion	0.1	All compounds
Inhalation, Type F	0.1	All unspecified compounds
Inhalation, Type M	0.1	Oxides, hydroxides and nitrates

II.19. RADIUM

Absorption types, f_1 values and chemical forms for radium are given in Table 23. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [17]. The model describes the kinetics of radium in bone, which is the main site of deposition and retention, and also considers retention in the liver and other soft tissues, as well as routes of excretion. It takes account of initial uptake on to bone surfaces, transfer from the surface to bone volume and recycling from bone and other tissues to plasma.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{226}Ra and ^{228}Ra: daily urinary and faecal excretion; total body retention; lung retention for intakes by inhalation; and skeleton retention.

TABLE 23. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR RADIUM

	f_1	Compound
Ingestion	0.2	All compounds
Inhalation, Type M	0.2	All compounds

II.20. THORIUM

Absorption types, f_1 values and chemical forms for thorium are given in Table 24. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [18] and is based on the actinide model of Ref. [17]. It takes account of the initial deposition in bone, the liver, gonads and other tissues, and allows for transfer of activity from bone surfaces to bone volume and marrow, recycling of activity between tissues, as well as loss by excretion.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{228}Th and ^{232}Th: daily urinary and faecal excretion; total body retention; lung retention for intakes by inhalation; retention in the liver; and retention in the skeleton.

TABLE 24. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR THORIUM

	f_1	Compound
Ingestion	0.0005	Unspecified compounds
Ingestion	0.0002	Oxides and hydroxides
Inhalation, Type M	0.0005	Unspecified compounds
Inhalation, Type S	0.0002	Oxides and hydroxides

II.21. URANIUM

Absorption types, f_1 values and chemical forms for uranium are given in Table 25. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [18] and is based on the alkaline earth model of Ref. [17]. The model describes in detail the kinetics of uranium in bone, which is the main site of deposition and retention, and also considers retention in the liver, the kidneys and other soft tissues, as well as routes of excretion. It takes account of initial uptake on to bone surfaces, transfer from the surface to bone volume and recycling from bone and other tissues to plasma.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{234}U, ^{235}U and ^{238}U: daily urinary and faecal excretion; total body retention; lung retention for intakes of Type M and Type S material by inhalation; retention in the kidneys; and retention in the skeleton.

TABLE 25. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR URANIUM

	f_1	Compound
Ingestion	0.02	Unspecified compounds
Ingestion	0.002	Most tetravalent compounds, for example UO_2, U_3O_8 and UF_4
Inhalation, Type F	0.02	Soluble compounds, including hexavalent compounds, for example UF_6, UO_2F_2 and $UO_2(NO_3)_2$
Inhalation, Type M	0.02	Less soluble compounds, for example UO_3, UF_4, UCl_4 and most other hexavalent compounds
Inhalation, Type S	0.002	Highly insoluble compounds, for example UO_2 and U_3O_8

II.22. NEPTUNIUM

Absorption types, f_1 values and chemical forms for neptunium are given in Table 26. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [17] and is based on the actinide model. It takes account of the initial deposition in bone, the liver, gonads and other tissues, and allows for transfer of activity from bone surfaces to bone volume and marrow, recycling of activity between tissues, as well as loss by excretion.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{237}Np and ^{239}Np: daily urinary and faecal excretion; total body retention; lung retention for intakes by inhalation; retention in the liver; and retention in the skeleton.

TABLE 26. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR NEPTUNIUM

	f_1	Compound
Ingestion	0.0005	All compounds
Inhalation, Type M	0.0005	All compounds

II.23. PLUTONIUM

Absorption types, f_1 values and chemical forms for plutonium are given in Table 27. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [17] and is based on the actinide model. It takes account of the initial deposition in bone, the liver, gonads and other tissues, and allows for transfer of activity from bone surfaces to bone volume and marrow, recycling of activity between tissues, as well as loss by excretion.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{238}Pu, ^{239}Pu, ^{240}Pu and ^{241}Pu: daily urinary and faecal excretion; total body retention; lung retention for intakes by inhalation; retention in the liver; and retention in the skeleton.

TABLE 27. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR PLUTONIUM

	f_1	Compound
Ingestion	0.0005	Unspecified compounds
Ingestion	0.0001	Nitrates
Ingestion	0.00001	Insoluble oxides
Inhalation, Type M	0.0005	Unspecified compounds
Inhalation, Type S	0.00001	Insoluble oxides

II.24. AMERICIUM

Absorption types, f_1 values and chemical forms for americium are given in Table 28. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [17] and is based on the actinide model. It takes account of the initial deposition in bone, the liver, gonads and other tissues, and allows for transfer of activity from bone surfaces to bone volume and marrow, recycling of activity between tissues, as well as loss by excretion.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{241}Am: daily urinary and faecal excretion; total body retention; lung retention for intakes by inhalation; retention in the liver; and retention in the skeleton.

TABLE 28. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR AMERICIUM

	f_1	Compound
Ingestion	0.0005	All compounds
Inhalation, Type M	0.0005	All compounds

II.25. CURIUM

Absorption types, f_1 values and chemical forms for curium are given in Table 29. They are taken from the BSS [2] and are consistent with those given in Ref. [3].

The biokinetic model adopted here, and as adopted in the BSS [2], is taken from Ref. [19] and is identical to the americium model of Ref. [17]. It takes account of the initial deposition in bone, the liver, gonads and other tissues, and allows for transfer of activity from bone surfaces to bone volume and marrow, recycling of activity between tissues, as well as loss by excretion.

The accompanying CD gives the following predicted fractions of intake at various times after a single acute intake of ^{242}Cm and ^{244}Cm: daily urinary and faecal excretion; total body retention; lung retention for intakes by inhalation; retention in the liver; and retention in the skeleton.

TABLE 29. COMPOUNDS, ABSORPTION TYPES AND f_1 VALUES FOR CURIUM

	f_1	Compound
Ingestion	0.0005	All compounds
Inhalation, Type M	0.0005	All compounds

Appendix III

RETENTION AND EXCRETION FRACTIONS FOR INTAKES OF SELECTED RADIONUCLIDES

As a primary complement to this appendix, the CD that is attached to this report contains tables showing the $m(t)$ values for the retention and excretion functions for intakes of selected radionuclides. The following exposure pathways are reviewed: inhalation of 1 μm AMAD particles, inhalation of 5 μm AMAD particles, inhalation of gases and vapours (for some elements), and ingestion and injection (i.e. direct intake to blood). If a given radionuclide has more than one absorption type or value for f_1, tables for each are included. These values are based on biokinetic models, and resulting estimates of intakes may be used with the dose coefficients given in Table 3 to compute the effective dose to workers.

The predicted values of retention and excretion of activity given here (i.e. on the CD) are derived from the latest models recommended by the ICRP. Some of these models are more suitable for this application than others. In particular, two aspects of the tables need some explanation.

Firstly, the excretion model for tritium in Ref. [21] can be reliably applied only relatively soon after intake. For this reason, the tables given for tritium are truncated at 100 days after intake.

Secondly, in the models for gallium, gadolinium and thallium, the excretion routes have not been defined as they have for other models. Results for daily urinary and faecal excretion are therefore not given for these elements. Results for retention of these elements in regions of the body are unaffected by the excretion modelling and are therefore given.

The $m(t)$ values are given for time since intake in days, on an expanding scale, that is t = 1, 2, 3,…, 10, 20, 30…, etc. To obtain a value for a time not listed, a logarithmic interpolation between adjacent values is needed. If the values are not changing rapidly, a linear interpolation may be sufficiently precise.

The data files on the accompanying CD were produced and quality assured by A.W. Phipps of the National Radiological Protection Board in the UK and D. Noßke of the Bundesamt für Strahlenschutz in Germany using the PLEIADES and DOSAGE computer codes, respectively. Both codes have been used for a number of years by the ICRP Task Group on Dose Calculations (DOCAL) to derive dose coefficients for such documents as Refs [3, 53] and the excretion coefficients in Ref. [20]. The data files on the accompanying CD are essentially an extension of Ref. [20].

Other sources of $m(t)$ are available [54, 55], which in some areas give additional results to those provided here. The earlier comments in this report regarding the limitations of the models in predicting $m(t)$, for example at early times, or where excretion models are not well established, are reiterated.

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Annex I

DETERMINING INTAKE FROM SINGLE AND FROM MULTIPLE DATA MEASUREMENTS FOR DOSE ASSESSMENT

I–1. A SINGLE MEASUREMENT

For a suspected intake by inhalation of ^{137}Cs by a male worker, the measurement shown in Table I–1 was taken two days after the suspected incident.

I–1.1. Solution

Since the volume of urine collected is equal to the reference daily urinary output for an adult female, the measurement does not need to be adjusted. The estimate of intake, I, is thus simply given by (see Section 3.3.3):

$$I = 50 \text{ kBq}/0.011$$

$$= 4.5 \text{ MBq}$$

From Table 3, the dose conversion factor for inhalation of ^{137}Cs (5 μm AMAD) is 6.7×10^{-9} Sv/Bq, so the estimated effective dose from this intake is:

$$E(50) = (6.7 \times 10^{-9} \text{ Sv/Bq})(4.5 \times 10^{6} \text{ Bq})$$

$$= 0.03 \text{ Sv, or } 30 \text{ mSv}$$

TABLE I–1. MEASUREMENT TAKEN TWO DAYS AFTER THE SUSPECTED INCIDENT

Day	Urine volume	Urine activity	$m(t)$ (from Appendix III, 5 μm AMAD)
2	1400 mL	50 kBq	0.011

I–2. MULTIPLE DATA POINTS: SIMPLE AVERAGE

Further measurements were then made seven and ten days after the incident, as shown in Table I–2.

I–2.1. Solution

In these cases, since urine volumes are substantially lower than the reference daily urinary output for an adult male of 1.4 L[1], the measurements have to be adjusted as follows (see Section 3.3.3):

Day 7: Adjusted activity = (0.9 kBq)(1400/70) = 18 kBq

Day 10: Adjusted activity = (1.2 kBq)(1400/140) = 12 kBq

Point estimates of the intake are obtained from each of these new data in the same manner as above.

Day 7: I = 18 kBq/0.0038 = 4.7 MBq

Day 10: I = 12 kBq/0.0026 = 4.6 MBq

Combining these with the estimate of intake obtained from the measurement after two days gives three estimates, 4.5, 4.7 and 4.6 MBq, of which the mean is 4.6 MBq.

TABLE I–2. MEASUREMENTS MADE SEVEN AND TEN DAYS AFTER THE INCIDENT

Day	Urine volume	Urine activity	$m(t)$ (from Appendix III)
7	70 mL	0.9 kBq	0.0038
10	140 mL	1.2 kBq	0.0026

[1] This example is based on real data gathered some years ago; it therefore uses a value for the daily urine volume taken from Ref. [I–1], which has been superseded by Ref. [I–2].

From Table 3, the dose conversion factor for inhalation of ^{137}Cs is 6.7×10^{-9} Sv/Bq, so the estimated effective dose from this intake is:

$$E(50) = (6.7 \times 10^{-9} \text{ Sv/Bq})(4.6 \times 10^{6} \text{ Bq})$$

$$= 0.03 \text{ Sv, or } 30 \text{ mSv}$$

I–3. MULTIPLE DATA POINTS: UNWEIGHTED LEAST SQUARES FIT (SECTION 3.3.4.2)

I–3.1. Solution

The least squares method may also be used to estimate an intake from the three measurements. The relevant products, $M(t)m(t)$ and $[m(t)]^2$, and their sums are given in Table I–3, along with the data.

The estimated intake using the unweighted least squares fit is:

$$I = 0.65/1.4 \times 10^{-4} \text{ kBq}$$

$$= 4.6 \text{ MBq}$$

From Table 3, the dose conversion factor for inhalation of ^{137}Cs is 6.7×10^{-9} Sv/Bq, so the estimated effective dose from this intake is:

$$E(50) = (6.7 \times 10^{-9} \text{ Sv/Bq})(4.6 \times 10^{6} \text{ Bq})$$

$$= 0.03 \text{ Sv, or } 30 \text{ mSv}$$

TABLE I–3. RELEVANT PRODUCTS AND DATA

Day	$M(t)$ (kBq)	$M(t)$ (from Appendix III)	$M(t)m(t)$	$[m(t)]^2$
2	50	0.011	0.55	1.2×10^{-4}
7	18	0.0038	0.068	1.4×10^{-5}
10	12	0.0026	0.031	6.8×10^{-6}
Sums			0.65	1.4×10^{-4}

In this example the three simple estimates based on single measurements were in good agreement, indicating that the standard biokinetic model used is likely to be appropriate. Since this intake results in a rather significant effective dose, further measurements are advisable.

REFERENCES TO ANNEX I

[I–1] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Reference Man: Anatomical, Physiological and Metabolic Characteristics, Publication 23, Pergamon Press, Oxford and New York (1975).

[I–2] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Basic Anatomical and Physiological Data for Use in Radiological Protection: Reference Values, Publication 89, Pergamon Press, Oxford and New York (2002).

Annex II

DETERMINING THE TIME OF INTAKE FOR DOSE ASSESSMENT

II–1. INCIDENT

A technician was exposed to ^{131}I vapour. A routine monitoring programme with a 15 day interval yielded the following results: Date: 4 December; thyroid (in vivo monitoring): 710 Bq; urine (in vitro monitoring): 126 Bq/24 h.

Confirmatory and investigative monitoring was carried out, with the following results: Date: 6 December; thyroid (in vivo monitoring): 680 Bq; urine (in vitro monitoring): <MDA (minimum detectable activity, 1 Bq/L or 1.4 Bq/24 h). Date: 8 December; thyroid (in vivo monitoring): 490 Bq; urine (in vitro monitoring): <MDA.

II–2. SOLUTION

In order to use the $m(t)$ tables in Appendix III, it is necessary to establish the time at which the intake occurred. In many circumstances this time is not known a priori. Owing to the specific biokinetic behaviour of some radionuclides, comparing the results of different bioassay techniques may shed some light on the time of intake.

One such example is this intake of elemental iodine: On 4 December monitoring showed a ratio of 0.18 between the activities in urine over those in

TABLE II–1. PREDICTED VALUES (Bq PER Bq INTAKE) FOR INHALATION OF ^{131}I VAPOUR

Days after intake	Thyroid	Daily urinary excretion	Expected urine/thyroid ratio
1	2.30×10^{-1}	5.30×10^{-1}	2.30
2	2.20×10^{-1}	4.30×10^{-2}	0.20
3	2.00×10^{-1}	2.50×10^{-3}	0.0125
4	1.90×10^{-1}	2.70×10^{-4}	0.00142
5	1.70×10^{-1}	1.70×10^{-4}	0.00100
6	1.50×10^{-1}	1.80×10^{-4}	0.00120

the thyroid. The $m(t)$ values for inhalation of ^{131}I vapour, taken from Appendix III, and the expected ratios for the activities in urine and in the thyroid, are given in Table II–1.

Thus it is possible to conclude that the intake occurred on 2 December, two days before the monitoring on 4 December, since the results of the confirmatory monitoring are compatible with this date of intake.

Four days after the intake, the amount expected in the thyroid would have been:

$$(0.19/0.22) \times 710 = 613 \text{ Bq}$$

On the same day the amount expected in urine would have been:

$$(2.7 \times 10^{-4}/4.3 \times 10^{-2}) \times 126 = 0.8 \text{ Bq/24 h}$$

Six days after the intake the amount expected in the thyroid would have been:

$$(0.15/0.22) \times 710 = 484 \text{ Bq}$$

On the same day the amount expected in urine would have been:

$$(1.8 \times 10^{-4}/4.3 \times 10^{-2}) \times 126 = 0.5 \text{ Bq/24 h}$$

Thus one may assume an intake two days before the date of the routine monitoring. The intake may be determined using the thyroid results. Using the $m(t)$ values given above, taken from Appendix III, shown in Table II–2, the average of the point estimates of the intake is 3358 Bq.

In this example the results for thyroid monitoring were used instead of those for urine, since they consist of a direct measurement of activity in the body, are less time dependent and thus provide the most accurate assessment of

TABLE II–2. ESTIMATED INTAKE VALUES

Days after intake	Thyroid activity (Bq)	$m(t)$ (from Appendix III)	Point estimates of the intake (Bq)
2	710	0.22	3227
4	680	0.19	3579
6	490	0.15	3267

internal contamination. In this example the urine results would produce an intake similar to the ones obtained with the thyroid data, and could have been taken into consideration when deriving the intake. When urine samples do not produce intake results as close to the thyroid monitoring data, in vivo monitoring results need to be used.

From Table 3, the dose conversion factor for inhalation of vapour ^{131}I is 2×10^{-8} Sv/Bq. The estimated effective dose is:

$$E(50) = 3358 \times 2 \times 10^{-8} = 6716 \times 10^{-8} = 0.07 \text{ mSv}$$

Annex III

DETERMINING THE ROUTE OF INTAKE FOR DOSE ASSESSMENT

III–1. EXAMPLE I

A worker was exposed to UF_6 and UO_2F_2, which are classified as absorption Type F, during his routine work. One day after conducting a special task, he provides 24 h samples of urine and faeces. The activities measured in the samples were, respectively, 360 Bq/24 h of ^{238}U and 140 Bq/24 h of ^{238}U. The volume and mass of the samples of urine and faeces provided were compatible with the expected excretion for 24 h. Further samples of urine and faeces were provided for bioassay purposes two days and four days after the first sampling (days 3 and 5 after the presumed intake): the results are shown in Table III–1.

III–1.1. Route

We know the date of intake. Intake occurs mostly by ingestion, by the worker touching his or her mouth with contaminated hands, but it is necessary to determine the route of intake in this example, in order to interpret the bioassay results in terms of intake and to calculate the dose.

Comparing the $m(t)$ values in Appendix III for absorption Type F, 5 μm AMAD, and ingestion, f_1 = 0.02, with the monitoring data, it could be concluded that inhalation was the route of exposure. At one day after exposure, activities in the urine were higher than in the faeces, a result that would not have been expected if the intake had been by ingestion. At five days after intake, the activities excreted in urine and in faeces were of the same order of magnitude, again a result that was not compatible with the ingestion route of intake.

The worker was thus exposed to inhalation of Type F uranium. Using the $m(t)$ of Appendix III, we have the point estimates of the intake shown in Table III–2, assuming a 5 μm AMAD.

TABLE III–1. SAMPLES OF URINE AND FAECES

Days after intake	Urine (Bq/24 h)	Faeces (Bq/24 h)
3	12	90
5	10	12

TABLE III–2. POINT ESTIMATES OF THE INTAKE

Days after intake	Sample	Activity (Bq/24 h)	$m(t)$ (from Appendix III)	Point estimates of the intake (Bq)
1	Urine	360	1.8×10^{-1}	2000
1	Faeces	140	5.6×10^{-2}	2500
3	Urine	12	5.1×10^{-3}	2353
3	Faeces	90	3.9×10^{-2}	2308
5	Urine	10	4.2×10^{-3}	2380
5	Faeces	12	6.2×10^{-3}	1935
Average				2246

The effective dose due to ^{238}U, using the dose coefficient in Table 3, is:

$$E(50) = 2246 \times 5.8 \times 10^{-7}$$

$$= 1.303 \times 10^{-3} \text{ Sv, or } 1.3 \text{ mSv}$$

The activity of natural uranium is composed of 0.489 ^{234}U, 0.022 ^{235}U and 0.489 ^{238}U. Thus the effective dose due to natural uranium is calculated by adding the contributions from ^{238}U (1.3 mSv), ^{234}U ($2246 \times 6.4 \times 10^{-7} = 1.4$ mSv) and ^{235}U ($((2246/0.489) \times 0.022) \times 6.0 \times 10^{-7} = 0.06$ mSv). Dose coefficients from Table 3 were used. The total effective dose is:

$$E(50) = 2.8 \text{ mSv}$$

III–2. EXAMPLE II

A worker was exposed to airborne oxides of ^{232}Th, which is classified as Type S. Air sampling in the installation, using a cascade impactor, showed that the AMAD was 1 μm. Routine monitoring was accomplished through the collection of samples of faeces, and in general the results were below detection limits. On this occasion, however, just before going on leave and ten days after a negative result, a worker provided a 24 h sample, and results showed an activity of 12 Bq in the faeces. The worker recalled having had an extra load of work the day before he provided the sample of faeces. On the last day of his

20 day vacation, prior to returning to work, he collected, at his home, a 24 h sample of faecal excretion. This sample was analysed and was found to be below the detection limit of the technique (1 mBq/24 h).

III–2.1. Route

Workers often have intakes via ingestion, from their habit of touching the mouth with contaminated hands, in the work environment. The ingested activity causes severe interference with the monitoring results. Thus it is necessary to evaluate the route of intake before the bioassay results are used to calculate the dose to the worker.

III–2.1.1. Inhalation hypothesis

If the main route of intake was inhalation, one would expect, using the $m(t)$ values in Appendix III, for Type S ^{232}Th, 1 μm AMAD, an intake of $I = 12/6.1 \times 10^{-2} = 200$ Bq one day before the routine sample collection.

Using the same table of $m(t)$, an activity of $7.6 \times 10^{-4} \times 200 = 0.15$ Bq/24 h would be expected in faeces after a 20 day vacation. This value is well above the minimum detection limit of the technique.

If the intake had occurred in the middle of the ten day interval between sample collections, the intake would have been $I = 12/8.4 \times 10^{-3} = 1430$ Bq, and the amount excreted in faeces after the 20 day vacation would have been of the order of 1 Bq/24 h, above the detection limit of the measuring technique.

III–2.1.2. Ingestion hypothesis

If the intake had been by ingestion one day before the vacation, the monitoring results would have corresponded to an intake of $I = 12/2.8 \times 10^{-1} = 43$ Bq, using the $m(t)$ values for ingestion ($f_1 = 2 \times 10^{-3}$) in Appendix III.

The expected amount in faeces after the vacation would have been $(12/2.8 \times 10^{-1}) \times 1.5 \times 10^{-8} = 6.4 \times 10^{-7}$ Bq/24 h, a result below the detection limit of the technique. If the intake had occurred in the middle of the 10 day monitoring interval, the intake would have been around 400 Bq ($12/3.1 \times 10^{-2}$), an unrealistic result in terms of just touching the mouth with contaminated hands.

From the above considerations it can be concluded that ingestion was the most probable exposure pathway. It is reasonable to assume that the intake occurred one day before the worker left on vacation, when, due to the extra load of work, the worker may have contaminated his mouth. Using this assumption, the intake was $I = 43$ Bq. Using the effective dose coefficient from Table 3, the effective dose to this worker is calculated as:

$$E(50) = 43 \times 9.2 \times 10^{-8} = 400 \times 10^{-8}$$

$$= 4\ \mu Sv$$

If intake by inhalation were assumed one day before the vacation, the effective dose to the worker would have been calculated as:

$$E(50) = 200 \times 2.3 \times 10^{-5}$$

$$= 4.6\ mSv$$

which is a result three orders of magnitude higher than the dose calculated, assuming ingestion as the pathway of exposure.

Annex IV

ANALYSIS OF AN INTAKE OF MIXED ACTIVATION AND FISSION PRODUCTS FOR DOSE ASSESSMENT

IV–1. EXAMPLE

A worker who was an employee of a small specialized maintenance company performed maintenance work at a nuclear power plant. The work performed was cleaning a tank using a concentrate that must be wet during the process. However, the work was not performed strictly according to written procedures, and the man worked with dry concentrate. When he was leaving the controlled area, surface contamination was found on his face, and subsequently internal contamination was verified.

The first conservative estimation of internal exposure with an influence of surface contamination suggested that the committed effective dose could be above the appropriate derived investigation level; whole body counts were therefore repeatedly performed. The counts identified the corrosion products ^{110m}Ag, ^{58}Co, ^{60}Co, ^{124}Sb and ^{54}Mn. In addition, analysis of excreta was performed.

This case is described in detail in Ref. [IV–1]. Here, in this example, only the interpretation of whole body measurements of ^{60}Co is performed.

IV–2. CHARACTERISTICS OF THE INTAKE

The characteristics of the intake were:

(a) Radiation worker (male, 20 years; weight: 70 kg; height: 162 cm).
(b) Intake via inhalation.
(c) Date of contamination: 3 September 1998.

Table IV–1 shows the whole body count results for ^{60}Co (date of measurement and measured activity). In addition to the dates of the counts, the elapsed time in days after intake is shown. The whole body retention values from Appendix III for inhalation of a 5 μm Type S aerosol are listed in column 4, and the intake is calculated in column 5 by dividing the values of column 3 by the values of column 4, following the formula given in Section 3.1.

TABLE IV–1. WHOLE BODY COUNT RESULTS FOR ^{60}Co

	Days after intake	Measurement result (Bq)	$m(t)$ (from Appendix III)	Calculated intake (Bq)
4 September 1998	1	136 910	0.490	2.8×10^5
7 September 1998	4	3 588	0.098	3.7×10^4
8 September 1998	5	3 793	0.080	4.7×10^4
8 September 1998	5	3 580	0.080	4.5×10^4
9 September 1998	6	3 040	0.073	4.2×10^4
10 September 1998	7	2 978	0.069	4.3×10^4
11 September 1998	8	3 206	0.068	4.7×10^4
14 September 1998	11	2 741	0.064	4.3×10^4
15 September 1998	12	2 808	0.064	4.4×10^4
16 September 1998	13	2 440	0.063	3.9×10^4
18 September 1998	15	2 434	0.061	4.0×10^4
22 September 1998	19	2 745	0.059	4.7×10^4
23 September 1998	20	2 778	0.058	4.8×10^4
30 September 1998	27	2 415	0.055	4.4×10^4
2 October 1998	29	2 753	0.054	5.1×10^4
7 October 1998	34	2 505	0.052	4.8×10^4
9 October 1998	36	2 569	0.052	4.9×10^4
14 October 1998	41	2 564	0.050	5.1×10^4
16 October 1998	43	2 861	0.049	5.8×10^4
30 October 1998	57	2 084	0.046	4.5×10^4
4 November 1998	62	2 346	0.045	5.2×10^4
6 November 1998	64	2 083	0.044	4.7×10^4
11 November 1998	69	2 292	0.043	5.3×10^4
13 November 1998	71	2 021	0.043	4.7×10^4
20 November 1998	78	1 912	0.041	4.7×10^4
27 November 1998	85	1 993	0.040	5.0×10^4
4 December 1998	92	1 888	0.040	4.7×10^4
11 December 1998	99	1 916	0.039	4.9×10^4
18 December 1998	106	1 760	0.039	4.5×10^4
8 January 1999	127	1 767	0.037	4.8×10^4
29 January 1999	148	1 599	0.035	4.6×10^4
26 February 1999	176	1 603	0.033	4.9×10^4

TABLE IV–1. WHOLE BODY COUNT RESULTS FOR ^{60}Co (cont.)

	Days after intake	Measurement result (Bq)	$m(t)$ (from Appendix III)	Calculated intake (Bq)
26 March 1999	204	1 393	0.031	4.5×10^4
27 April 1999	236	1 084	0.030	3.6×10^4
21 May 1999	260	1 141	0.029	3.9×10^4
23 June 1999	293	935	0.027	3.5×10^4

IV–3. DOSE ASSESSMENT

From the best fit of the whole body measurements, the particle size was derived as a 5 μm AMAD, classified as Type S. If the result of the first measurement performed on the day after the intake is excluded, all measurement results show good agreement with the biokinetic standard model: the intakes derived from these measurement results are all within a relatively narrow range. The arithmetic mean of these values is 46 kBq, which gives an effective dose of:

$$E(50) = 46\,000 \times 1.7 \times 10^{-8}$$

$$= 0.78 \text{ mSv}$$

using the dose coefficient from Table 3.

It is possible to disregard the first measurement value; it indicates a higher intake, but it is excreted very fast. This was confirmed by the faecal excretion values obtained in this example, which are not shown here. The model used here is therefore not suitable for the first day after intake, since it does not take into account the substantial fraction of activity that is excreted very fast; however, because of the fast excretion, the contribution to the dose from this fraction of activity can be neglected. The dose estimate given above is therefore in agreement with the whole body measurement results.

This is a simple example, which includes only partial data from the incident. A more complex analysis, including all other measurement results not considered here, may imply some modifications to the model and to the dose assessment.

REFERENCE TO ANNEX IV

[IV–1] FOLTÁNOVÁ, I. et al., "A case of internal contamination of a person with a mixture of radionuclides", Radiation Protection in Central Europe (Proc. Congr. Budapest, 1999), Roland Eötvös Physical Society, Budapest (1999) 496–502.

Annex V

DOSE ASSESSMENT FROM AN EXPOSURE OVER A PERIOD OF TIME

V–1. EVENT

An incident was discovered that had led to airborne activity of ^{131}I in a particular section of a workplace for a period of a few days. A worker had been exposed the day before a weekend break and then for two days after the weekend (i.e. on Friday, Monday and Tuesday). The intakes on these days were assumed to be of equal magnitude and were thought to have occurred over relatively short periods of time in such a way that they could be considered acute in nature. It was assumed that the activity was in the form of a Type F compound with a 5 μm AMAD. Thyroid monitoring was the assay method selected, and measurements were carried out on the Wednesday and Thursday, which showed 480 kBq and 440 kBq, respectively.

V–2. SOLUTION

The relevant data (for ten days only) taken from the tables of $m(t)$ given in Appendix III are shown in Table V–1.

TABLE V–1. RELEVANT DATA

Time (days)	Thyroid $m(t)$
1	1.20×10^{-1}
2	1.20×10^{-1}
3	1.10×10^{-1}
4	9.90×10^{-2}
5	9.00×10^{-2}
6	8.20×10^{-2}
7	7.40×10^{-2}
8	6.80×10^{-2}
9	6.20×10^{-2}
10	5.60×10^{-2}

The data given in Table V–1 can be combined to give predictions for Wednesday and Thursday by introducing time offsets of two and three days for the intakes on Monday and Tuesday, respectively, and summing horizontally (see Table V–2).

The fourth column contains the predicted values, $m(t)$, for this multiple intake. These values can be used to estimate intakes following the methods described in Section 3.

Thyroid monitoring on Wednesday and Thursday provided the following values and estimates of daily intake, I, (which are assumed to be the same for each day):

Wednesday: 480 kBq; thus I = 480 kBq/0.330 = 1455 kBq

Thursday: 440 kBq; thus I = 440 kBq/0.312 = 1410 kBq

The estimates are consistent and a simple average of 1433 kBq can be taken to be the estimated intake for each of Friday, Monday and Tuesday.

The effective dose, using the dose coefficients from Table 3, is:

$$E(50) = 3 \times 1433 \times 10^3 \times 1.1 \times 10^{-8}$$

$$= 47 \text{ mSv}$$

In more complicated cases the intakes on each day may not be equal, and the three columns of Table V–2 for Friday, Monday and Tuesday would have to be multiplied by a suitable factor. In addition, the number of days over which

TABLE V–2. PREDICTED INTAKE VALUES

	Thyroid $m(t)$			
	Intake on Friday	Intake on Monday	Intake on Tuesday	Horizontal sum
Saturday	0.120	—	—	0.120
Sunday	0.120	—	—	0.120
Monday	0.110	—	—	0.110
Tuesday	0.099	0.12	—	0.219
Wednesday	0.090	0.12	0.12	0.330
Thursday	0.082	0.11	0.12	0.312

exposure occurred may not be clear. Nevertheless, the principle illustrated here can be used to calculate the dose for this kind of exposure over a number of days. A further example of this kind is given in Ref. [V–1].

REFERENCE TO ANNEX V

[V–1] BIRCHALL, A., HODGSON, A., MOODY, J.C., Implications of assuming a realistic intake regime for chronic exposure to airborne uranium, Radiat. Prot. Dosim. **79** (1998) 253–257.

Annex VI

DIRECT DOSE ASSESSMENT FOR INTAKES OF TRITIATED WATER

In Canada deuterium–uranium (CANDU) reactors and at other workplaces many workers are exposed chronically to low levels of HTO in the atmosphere, which results in intakes by inhalation and through the skin. Chronic or intermittent intakes of HTO at unknown times with respect to the bioassay sample is one important circumstance in which a direct dose calculation may be preferred over other types of dose assessment (Section 3.4.2).

For both forms of intake, the HTO mixes within minutes throughout body water, and is excreted with the turnover of that body water. Owing to the many roles of body water in human physiology, however, this turnover rate is highly variable. The 90% range of half-times in a large group of workers monitored over several years at the Savannah River plant was 5.5 to 14.3 days [VI–1], but much shorter times (some three days) have been reported in hot countries [VI–2]. In this situation a biokinetic model using default parameters can be grossly unrepresentative and can lead to the underestimation or overestimation of the committed effective dose by a factor of 2 or more. For these reasons, therefore, intakes of HTO in many workplaces are best assessed by a direct dose calculation [VI–3].

Tritium decays with the emission of only a weak beta particle (mean energy 5.7 keV [VI–4]) and intakes are therefore detectable only from excreted activity. Since urine concentrations of tritium rapidly approach those in body water, the dose rate to the soft tissues in which this water is distributed can be estimated from spot urine samples, taken several times per day if necessary. Using the values of E = 0.0057 MeV and m = 68.8 kg [VI–5], the specific effective dose rate per unit activity is calculated to be:

$$\dot{D} = 1.6 \times 10^{-13} \left(\frac{\mathrm{J}}{\mathrm{MeV}} \right) \frac{0.0057\ (\mathrm{MeV})}{68.8\ (\mathrm{kg})}\ 86\,400\ \left(\frac{\mathrm{s}}{\mathrm{d}} \right) \frac{1}{1\ (\mathrm{Bq \cdot s})}$$

$$= 1.15 \times 10^{-12} \left(\frac{\mathrm{Sv}}{\mathrm{d \cdot Bq}} \right) \qquad \text{(VI–1)}$$

That is, the dose rate is 1.15×10^{-12} Sv per day per Bq total tritium burden, or 4.8×10^{-11} Sv per day per Bq/L in the 42 L of body water. Doses over the monitoring period, usually less than two weeks, can then be estimated within 50% at the 95% confidence level by linear interpolation [VI–6].

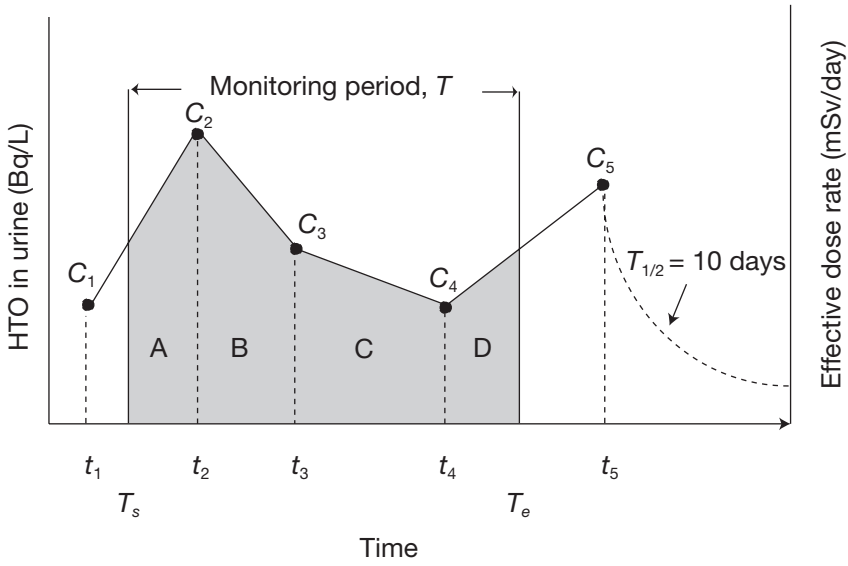

FIG. VI–1. Calculation of effective dose from chronic intakes of HTO by interpolation of dose rates determined from the activity concentration in urine.

From Figure VI–1, the effective dose (Sv) over the period from t_i to t_{i+1} (days) can be estimated from the concentrations of HTO in urine, C_i (Bq/L), using the following equation:

$$\text{Effective dose} = 4.8 \times 10^{-11} [(C_{i+1} + C_i)/2](t_{i+1} - t_i) \quad \text{(VI–2)}$$

A simple estimate of the committed effective dose, E (Sv), resulting from the accumulated burden of tritium for the time period after the last measurement can be derived from the final urine sample, C_n, using a default half-time to estimate continuing retention. In the absence of other evidence, a half-time of ten days has been recommended [VI–7]. The following equation describes this calculation:

$$E = \frac{4.8 \times 10^{-11} C_n}{\ln 2/10} = 6.9 \times 10^{-10} C_n \quad \text{(VI–3)}$$

A small fraction (~1–3%) of an intake of HTO becomes bound to carbon in tissues as a result of metabolism and is assumed to be retained with the mean half-time for carbon turnover, 40 days [VI–8]. Since the committed dose as a result of this bound tritium is only about 10% of that due to the circulating HTO, and independent measurement of the bound tritium is usually not practicable, its

effects on dose are taken into account by increasing the dose coefficients for HTO by 10% [VI–5], to 5.3×10^{-11} Sv per day per Bq/L and 7.6×10^{-10} Sv per Bq/L, respectively. Although this simplified model no longer rigorously predicts the tissue dose rate, it is accurate to within 10% during chronic exposure, and correctly determines the committed effective dose, since the bound tritium is excreted well within the 50 year integration period.

As an example, Table VI–1 shows all the tritium concentrations measured in the urine of a worker over a six week period. Table VI–1 also shows doses received in each of the sampling periods, calculated in accordance with the equations above, with the dose factor adjusted as described above.

The monitoring period, *T*, for which total doses received are to be reported to the regulator is 1 January 2002 to 1 February 2002. The dose to be reported is calculated by apportioning the doses from those sampling periods that include the start and end of *T*. Here the total dose received in *T* is 1.25 mSv. The committed effective dose, calculated from the last sample using an adjusted Eq. (VI–3), is 0.76 mSv.

TABLE VI–1. TRITIUM CONCENTRATIONS MEASURED IN URINE OF WORKER

	Tritium concentration in urine (MBq/L)	Effective dose in sampling period (mSv)
28 December 2001	0.40	—
5 January 2002	1.20	0.34
14 January 2002	0.70	0.45
25 January 2002	0.50	0.35
8 February 2002	1.00	0.56

REFERENCES TO ANNEX VI

[VI–1] BUTLER, H.L., LEROY, J.H., Observation of the biological half-life of tritium, Health Phys. **11** (1965) 283–285.

[VI–2] RUDRAN, K., Significance of in-vivo organic binding of tritium following intake of tritiated water, Radiat. Prot. Dosim. **25** (1988) 5–13.

[VI–3] HEALTH AND WELFARE CANADA, Bioassay Guideline 2, Guidelines for Tritium Bioassay 83-EHD-87, Canadian Department of Health and Welfare, Ottawa (1983).

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Annex VII

ANALYSIS OF A SINGLE INTAKE OF ^{238,239,240}Pu AND ^{241}Am FOR DOSE ASSESSMENT

VII–1. BACKGROUND

This annex is based on Case 8 of the IAEA Co-ordinated Research Project on Intercomparison and Biokinetic Model Validation of Radionuclide Intake Assessment [VII–1]. In this example the use of the tables in this report is demonstrated, as well as the limitations of the results obtained.

On 24 May 1983 at 16:15 there was an explosion in a glovebox of a radiochemical laboratory for the development of advanced nuclear fuels in a nuclear research centre. The pressure of the explosion opened the sluice of the box and destroyed the box gloves; two workers received contamination on their faces, hair and clothes.

The activity composition of the inhaled substance was 9% ^{238}Pu, 55% ^{239}Pu, 26% ^{240}Pu and 10% ^{241}Am. The diameter of the plutonium containing particles is assumed to have been between 3 and 40 μm. The chemical form was a hydroxide gel in washing water containing 10% ammonium nitrate and about 3.5% hexamethylentetramine.

Measurements of plutonium and americium activity in body regions and in excreta for both workers were started immediately and continued over many years. In the example given in this annex, only some measurement results obtained for one of the individuals (a 26 year old male who weighed 80 kg) are used.

Measurements were taken of the ^{241}Am lung burden beginning on the date of the accident. The results are illustrated in Table VII–1 (with an uncertainty of 25% for each value).

Additionally, as shown in Table VII–2, two sets of detailed measurements to determine the activity from ^{241}Am in the lymph nodes, lungs, bone and liver were performed in two different institutions, on 3 August 1993 in laboratory A and on 15 November 1993 in laboratory B.

The uncertainties of the measurement results were between 12% (bone) and 16% (liver) in laboratory A and between 12% (bone) and 33% (liver) in laboratory B.

There were several excretion measurements for ^{239}Pu + ^{240}Pu, as well as for ^{241}Am + ^{238}Pu (Tables VII–3 and VII–4).

Additionally, two measurements to determine the urinary excretion of ^{241}Am were conducted on 25 April 1990 and 25 May 1991; these showed values of 4.3 and 2.3 mBq/day, respectively.

TABLE VII–1. AMERICIUM-241 ACTIVITY IN THE LUNGS

	Activity in the lungs (Bq)
24 May 1983	390
25 May 1983	310
27 May 1983	230
8 June 1983	230
27 June 1983	230
1 July 1983	260
7 July 1983	230
31 October 1983	220
4 November 1983	230
15 May 1984	220
5 May 1986	240
27 May 1991	180

Four further measurements of faecal excretion for ^{241}Am were conducted on 3 May 1988, 27 August 1988, 24 April 1990 and 25 May 1991. These yielded 0.018, 0.025, 0.012 and 0.0056 mBq/day, respectively.

It was necessary to determine the intake of ^{241}Am and of the plutonium isotopes. In addition, the committed effective dose and the committed dose to the most highly exposed organ, the bone surfaces, needed to be calculated.

TABLE VII–2. AMERICIUM-241 ACTIVITY IN OTHER ORGANS

	Organ activity (Bq)	
	Laboratory A	Laboratory B
Lymph nodes	26	72
Lungs	120	120
Bone	69	65
Liver	57	24

TABLE VII–3. URINARY EXCRETION RATES FOR PLUTONIUM AND AMERICIUM

	Urinary excretion rate (mBq/day)	
	$^{239}Pu + ^{240}Pu$	$^{241}Am + ^{238}Pu$
25 May 1983	11	110
26 May 1983	41	100
7 June 1983	4.7	16
14 June 1983	3.7	11
24 June 1983	3.7	5.6
30 June 1983	5.6	5.6
6 July 1983	3.7	5.2
21 November 1983	3.7	4.6
26 May 1984	3.5	4.0
20 January 1985	2.9	3.4
3 May 1986	3.7	2.7
27 August 1988	5.9	4.7
11 February 1989	6.2	3.8
28 January 1994	3.4	2.6

VII–2. DOSE CALCULATION

It is evident from the lung activity data that there was a remarkable decrease of lung activity within the first days, followed by a plateau over a period of three years and only a slight decrease later on. This shows that the behaviour of americium in the lungs is much closer to that of absorption Type S than to that of absorption Type M. The problem in using the tables in this report is that the ICRP in Ref. [VII–2] (and therefore also in Ref. [VII–3]) only considers Type M (moderate absorption), while the actual data show a much slower absorption. Such a slower absorption is, however, also known from assessments of other cases [VII–4].

In this example we have the possibility of using the lung retention data of ^{239}Pu, for which Type S (slow absorption) is given in the tables. Both ^{241}Am and ^{239}Pu have a very long half-life compared with the time period observed here, and therefore the lung retention times are quite similar. In the tables of intake retention fractions given in Appendix III, values of 1 and 5 μm are given for the

TABLE VII–4. FAECAL EXCRETION RATES FOR PLUTONIUM AND AMERICIUM

	Faecal excretion rate (Bq/day)	
	$^{239}Pu + ^{240}Pu$	$^{241}Am + ^{238}Pu$
25 May 1983	5200	1500
26 May 1983	3000	740
27 May 1983	440	74
6 June 1983	0.67	0.16
14 June 1983	0.72	0.15
23 June 1983	0.67	0.12
30 June 1983	0.25	0.078
7 July 1983	0.21	0.059
21 November 1983	0.42	0.094
27 May 1983	0.26	0.059
20 January 1985	0.26	0.075

AMADs. Since the AMAD in this example is given to be between 3 and 40 μm, the higher value seems to be the more appropriate.

In Table VII–5 the measurement values of the lung activity (in Bq) at specified times after intake (in days) are given with the appropriate lung retention values from the data given in this report. From this, for each measurement the intake (in Bq) is calculated. The first measurement value shortly after the intake is not used here because appropriate retention values shortly after intake are not given and because the exact time of measurement is not given.

An intake of about 4–5 kBq of ^{241}Am can be assumed from the first six values. The exact intake value depends on the assumed AMAD, which influences the activity fraction deposited in the lungs, especially in the deep parts of the lungs, which have a long retention period. It can be seen from these calculations that even the assumption of a Type S material underestimates the retention in the lungs at long times after intake, giving very high intake values from these measurement results.

For the evaluation of the excretion measurements for ^{241}Am we have the problem that the ICRP model for americium, and therefore the data given in this report, only considers a Type M behaviour for lung absorption, while we are considering here a Type S behaviour. The biokinetic behaviour of

TABLE VII–5. ESTIMATED INTAKE VALUES BASED ON MEASUREMENTS AT SPECIFIED TIMES AFTER INTAKE

Days after intake	Lung activity (Bq)	$m(t)$ (from Appendix III)	Intake (Bq)
1	310	6.4×10^{-2}	4.8×10^{3}
3	230	6.2×10^{-2}	3.7×10^{3}
15	230	5.5×10^{-2}	4.2×10^{3}
34	230	4.9×10^{-2}	4.7×10^{3}
38	260	4.8×10^{-2}	5.4×10^{3}
44	230	4.5×10^{-2}	5.1×10^{3}
160	220	3.3×10^{-2}	6.7×10^{3}
164	230	3.3×10^{-2}	7.0×10^{3}
357	220	2.7×10^{-2}	8.1×10^{3}
1077	240	1.4×10^{-2}	1.7×10^{4}
2925	180	8.5×10^{-3}	2.1×10^{4}

plutonium is similar, but not identical, to that of americium, and therefore the Type S values for plutonium cannot be used for dose assessment.

Tables VII–6 and VII–7 show the urinary and faecal excretion data for ^{239}Pu + ^{240}Pu, respectively. Both isotopes have a long half-life and can be considered together. As for the americium estimation used in this example, a Type S lung absorption and an AMAD of 5 μm are assumed.

The model urinary excretion function with an assumed intake of 25 kBq for both plutonium isotopes shows good agreement with all urine measurements. The faecal excretion function shows good agreement with the measurement values only for the early measurements and for the measurements made half a year after intake and thereafter if an intake of 10 kBq is assumed for the two plutonium isotopes. However, in this example the urinary measurement results seem to be more reliable for dose assessment, since the faecal excretion is very strongly influenced by the lung retention and the mucociliary transport into the alimentary tract. The intake of 25 kBq for both plutonium isotopes also agrees rather well with the assessed ^{241}Am intake of 4–5 kBq, keeping in mind that the total activity of the plutonium isotopes is about eight times the activity of ^{241}Am.

Evaluation of the organ measurements on ^{241}Am activity is not possible with the material given in this report, since the organ retention functions are only given for Type M material, not for Type S material. For an evaluation it

TABLE VII–6. ESTIMATED INTAKE VALUES BASED ON EVALUATION OF URINARY EXCRETION DATA

	Days after intake	Urinary excretion (Bq/day)	Excretion rate per unit intake ($m(t)$)	Intake (kBq)
25 May 1983	1	1.10×10^{-2}	2.3×10^{-6}	4.7
26 May 1983	2	4.10×10^{-2}	1.4×10^{-6}	30
7 June 1983	14	4.70×10^{-3}	2.1×10^{-7}	25
14 June 1983	21	3.70×10^{-3}	1.8×10^{-7}	21
24 June 1983	31	3.70×10^{-3}	1.7×10^{-7}	22
30 June 1983	37	5.60×10^{-3}	1.7×10^{-7}	33
6 July 1983	43	3.70×10^{-3}	1.7×10^{-7}	22
21 November 1983	181	3.70×10^{-3}	1.6×10^{-7}	23
26 May 1984	368	3.50×10^{-3}	1.7×10^{-7}	21
20 January 1985	607	2.90×10^{-3}	1.8×10^{-7}	17
3 May 1986	1075	3.70×10^{-3}	1.8×10^{-7}	21
27 August 1988	1922	5.90×10^{-3}	1.6×10^{-7}	37
11 February 1989	2090	6.20×10^{-3}	1.6×10^{-7}	40
28 January 1994	3902	3.40×10^{-3}	1.2×10^{-7}	29

would be necessary to calculate these values with the assumed model parameters. However, further modifications would be necessary because, as has been mentioned, the model lung retention function does not agree with the measurement values for extended periods after intake. Therefore, without further modifications to the model, we would obtain incorrect intake estimates.

The doses caused by plutonium isotopes could, if the biokinetic models are not further modified, be calculated by using the effective dose coefficients given in Table 3; for example, with an assumed intake of 25 kBq of ^{239}Pu + ^{240}Pu, we would obtain a committed effective dose of 210 mSv and a committed equivalent dose to bone surfaces of 2.3 Sv (the bone surface dose coefficient for intake of a 5 μm AMAD Type S aerosol for both ^{239}Pu and ^{240}Pu is 9.1×10^{-5} [VII–5]). However, it must be kept in mind that, for example, the lung dose is probably underestimated, since the lung measurement data indicate a much longer retention than due to the standard Type S assumptions used here, which also bear on the effective dose. To assess a dose resulting from an intake of ^{241}Am the dose coefficients given in this report cannot be used, since they are

TABLE VII–7. ESTIMATED INTAKE VALUES BASED ON EVALUATION OF FAECAL EXCRETION DATA

	Days after intake	Faecal excretion (Bq/day)	Excretion rate per unit intake ($m(t)$)	Intake (kBq)
25 May 1983	1	5.20×10^{3}	1.1×10^{-1}	46
26 May 1983	2	3.00×10^{3}	1.6×10^{-1}	18
27 May 1983	3	4.40×10^{2}	8.4×10^{-2}	5.2
6 June 1983	13	6.70×10^{-1}	5.9×10^{-2}	1.3
14 June 1983	21	7.20×10^{-1}	4.3×10^{-4}	1.7
23 June 1983	30	6.70×10^{-1}	3.5×10^{-4}	1.9
30 June 1983	37	2.50×10^{-1}	3.0×10^{-4}	0.830
7 July 1983	44	2.10×10^{-1}	2.6×10^{-4}	0.810
21 November 1983	181	4.20×10^{-1}	4.5×10^{-5}	11
27 May 1984	369	2.60×10^{-1}	2.2×10^{-5}	12
20 January 1985	607	2.60×10^{-1}	1.7×10^{-5}	15

not given for a Type S lung absorption. It would therefore be necessary to calculate them, which would require a major effort.

This annex attempts to give solutions to a real incorporation case using the material given in this report. As for many other cases, it can be seen here that the standard models do not apply. However, with some careful assumptions, some dose assessments can be achieved. Either way, the kinds of error that are introduced by the use of models that are not very appropriate for the case given must be considered.

For a very rigorous dose assessment, powerful tools and expert experience are needed to adapt the models to the particular situation and to calculate intake and dose values using these individually modified models.

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Annex VIII

CHOOSING THE APPROPRIATE MONITORING PERIOD FOR DOSE ASSESSMENT

VIII–1. BACKGROUND

A radiation protection officer of an installation was assigned the duty of establishing the schedule and best bioassay monitoring technique for workers exposed to elemental ^{131}I, classified as vapour. The monitoring frequency had to be chosen in such a way as to detect an intake occurring at the beginning of the monitoring period and corresponding to one tenth of the annual effective dose limit of 20 mSv. There was a further condition that the uncertainty in the calculated intake, because of the unknown time of intake, was to be less than a factor of two. The MDA for the in vivo measurement facility in the installation was 40 Bq for 15 min of thyroid monitoring. The MDA for iodine in urine was found at the in vitro laboratory to be 1 Bq/L.

VIII–2. CALCULATION

VIII–2.1. To comply with the first condition

The effective dose coefficient for ^{131}I was 2×10^{-8} Sv/Bq (Table 3). The intake to be detected by the chosen monitoring technique corresponded to:

$$I = [(1/10 \times 20 \times 10^{-3})/2 \times 10^{-8}] = 1 \times 10^{5} \text{ Bq}$$

For urine monitoring:

MDA = 1Bq/L

$$m(t) = 1/(1 \times 10^{5}) = 1 \times 10^{-5}$$

On the basis of the $m(t)$ table in Appendix III, a maximum monitoring interval of 50 days was advisable.

For in vivo monitoring:

MDA = 40 Bq

$$m(t) = 40/(1 \times 10^{5}) = 4 \times 10^{-4}$$

On the basis of the $m(t)$ table in Appendix III, a maximum monitoring interval of 70 days was advisable.

VIII–2.2. To comply with the second condition

On the basis of the $m(t)$ table in Appendix III for urine, urine monitoring is not appropriate for ^{131}I vapour. The difference in intake assessment from day 1 to day 2 after exposure is more than a factor of 2.

On the basis of the $m(t)$ table in Appendix III for the thyroid, for ^{131}I vapour a maximum monitoring interval of ten days was advisable.

VIII–3. CONCLUSION

In vivo monitoring with a ten day interval was recommended for the installation.

GLOSSARY

acute intake. An intake occurring within a time period short enough that it can be treated as instantaneous for the purposes of assessing the resulting committed dose.

bioassay. Any procedure used to determine the nature, activity, location or retention of radionuclides in the body by direct (in vivo) measurement or by in vitro analysis of material excreted or otherwise removed from the body.

biokinetic model. A mathematical model describing the intake, uptake and retention of a radionuclide in various organs or tissues of the body and the subsequent excretion from the body by various pathways.

biological half-life. The time taken for the quantity of a material in a specified tissue, organ or region of the body (or any other specified biota) to halve as a result of biological processes.

chronic intake. An intake over an extended period of time, such that it cannot be treated as a single instantaneous intake for the purposes of assessing the resulting committed dose.

derived air concentration (DAC). A derived limit on the activity concentration in air of a specified radionuclide, calculated such that Reference Man, breathing air with a constant contamination at the DAC while performing light physical activity for a working year, would receive the annual limit on intake for the radionuclide in question.

fractional absorption in the gastrointestinal tract (f_1). The f_1 value is the fraction of an element directly absorbed from the gut to body fluids.

intake. The act or process of taking radionuclides into the body by inhalation or ingestion or through the skin. Or the activity of a radionuclide taken into the body in a given time period or as a result of a given event.

minimum detectable activity (MDA). The activity which, if present in a sample, produces a counting rate that will be detected (i.e. considered to be above background) with a certain level of confidence.

The "certain level of confidence" is normally set at 95%, i.e. a sample containing exactly the MDA will, as a result of random fluctuations, be taken to be free of activity 5% of the time.

The MDA is sometimes referred to as the detection limit or lower limit of detection. The counting rate from a sample containing the MDA is termed the determination level.

minimum significant activity (MSA). The activity which, if present in a sample, produces a counting rate that can be reliably distinguished from background with a certain level of confidence.

A sample containing exactly the MSA will, as a result of random fluctuations, be taken to be free of activity 50% of the time, whereas a true background sample will be taken to be free of activity 95% of the time.

The MSA is sometimes referred to as the decision limit. The counting rate from a sample containing the MSA is termed the critical level.

radioactive half-life. For a radionuclide, the time required for the activity to decrease by a radioactive decay process, by half.

transfer compartment. The compartment introduced for mathematical convenience into most of the biokinetic models used in ICRP and IAEA publications to account for the translocation of the radioactive material through the body fluids from where they are deposited in tissues.

uptake. The processes by which radionuclides enter the body fluids from the respiratory tract, gastrointestinal tract or through the skin, or the fraction of an intake that enters the body fluids by these processes.

Human Respiratory Tract Model (HRTM):

activity median aerodynamic diameter (AMAD). The value of aerodynamic diameter[1] such that 50% of the airborne activity in a specified aerosol is associated with particles smaller than the AMAD and 50% of the activity is associated with particles larger than the AMAD.

[1] The aerodynamic diameter of an airborne particle is the diameter that a sphere of unit density would need to have in order to have the same terminal velocity when settling in air as the particle of interest.

- Used in internal dosimetry for simplification, as a single 'average' value of aerodynamic diameter representative of the aerosol as a whole.
- The *AMAD* is used for particle sizes for which deposition depends principally on inertial impaction and sedimentation: typically those greater than about 0.5 μm. For smaller particles, deposition typically depends primarily on diffusion, and the ***activity median thermodynamic diameter (AMTD)*** — defined in an analogous way to the *AMAD*, but with reference to the thermodynamic diameter[2] of the particles — is used.

activity median thermodynamic diameter (AMTD). See *activity median aerodynamic diameter (AMAD).*

alveolar–interstitial (AI) region. The respiratory bronchioles, alveolar ducts and sacs with their alveoli, and the interstitial connective tissue.

bronchial (BB) region. The trachea and bronchi.

bronchiolar (bb) region. The bronchioles and terminal bronchioles.

clearance.[3] The removal of material from the respiratory tract by particle transport and by uptake.

deposition. The initial processes determining how much of a material in inhaled air remains in the respiratory tract after exhalation. Deposition of material may occur during both inhalation and exhalation.

extrathoracic (ET) airways. The anterior part of the nose (ET_1) and the posterior part of the nasal passages, mouth, pharynx and larynx (ET_2).

particle transport. Processes that clear material from the respiratory tract to the gastrointestinal tract and to the lymph nodes and move material from one part of the respiratory tract to another.

thoracic (TH) airways. The bronchial (BB), bronchiolar (bb) and alveolar-interstitial (AI) regions.

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[2] The thermodynamic diameter of an airborne particle is the diameter that a sphere of unit density would need to have in order to have the same diffusion coefficient in air as the particle of interest.

[3] In order to avoid ambiguity the definition given in Ref. [15] is used here.

types of materials. Categories of materials in the lung according to their rates of absorption from the respiratory tract to body fluids:

Type F: deposited materials that are readily absorbed into body fluids from the respiratory tract. (Fast rate of absorption.)
Type M: deposited materials that have intermediate rates of absorption into body fluids from the respiratory tract. (Moderate rate of absorption.)
Type S: deposited materials that are relatively insoluble in the respiratory tract. (Slow rate of absorption.)
Type V: deposited materials that are assumed, for dosimetric purposes, to be instantaneously absorbed into body fluids from the respiratory tract — applied only to certain gases and vapours. (Very rapid absorption.)

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