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Radiological protection — Monitoring and internal dosimetry for specific materials —

Part 2: Ingestion of uranium compounds

Radioprotection — Contrôle et dosimétrie interne des éléments spécifiques —

Partie 2: Ingestion de composés d'uranium

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 85, *Nuclear energy, nuclear technologies, and radiological protection*, Subcommittee SC 2, *Radiological protection*.

A list of all the parts in the ISO 16638 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

In the course of employment, individuals may work with radioactive materials that, under certain circumstances, could be taken into the body. Protecting workers against the risks of incorporated radionuclides needs monitoring for potential intakes and/or quantifying actual intakes and exposures. Internal radiation exposure caused by the contamination of radioactive substances results in doses, which cannot be measured directly. Decisions should be made regarding which methods, techniques, frequencies, etc., to select in order to measure and assess these doses. The criteria for determining the design of a monitoring programme, i.e. its requirements, methods and schedule, usually depends on legislation, the purpose of the overall radiation protection programme, the probabilities of potential radionuclide intakes and the characteristics of the materials handled.

For these reasons, four International Standards addressing monitoring programmes (ISO 20553), laboratory requirements (ISO 28218), dose assessments (ISO 27048) and special cases of inhalation of uranium compounds (ISO 16638-1) have been developed and can be applied in a straightforward manner to many radionuclides for accreditation purposes.

This document has been developed to address the specific issue of monitoring and internal dosimetry for ingestion of uranium compounds. It contributes to harmonizing the practices in the monitoring of occupationally exposed persons while remaining complementary to ISO 16638-1. Occupational intakes solely by ingestion are rare however they may need to be considered in some circumstances, for example; external contamination of the mouth or lips; in cases of poor working practices such as food being eaten in contamination areas. Intakes by ingestion can also occur alongside inhalation depending on the circumstances of the event. Monitoring and dose assessment for intakes by inhalation (ISO 16638-1) are covered in a separate document and would take precedence over the requirements for assessing intakes by ingestion. However, the monitoring requirements are very similar. Uranium is both radiologically and chemically toxic. Hence, the scientific bases of current occupational exposure standards are reviewed in addition to radiation exposure limits.

This document describes the need for a monitoring and internal dosimetry programme for the different compounds of uranium in case of a risk of ingestion and offers guidance on its design. The design of the workplace, the work practices and hygiene practices followed and the protective equipment worn, may all be essential in controlling exposure to this risk. The development of this document has taken into account recommendations from international expert bodies and persons with international experience of the practical application of its recommendations in radiological protection programmes. Its application facilitates the exchanges of information between authorities, supervisory institutions and employers.

Radiological protection — Monitoring and internal dosimetry for specific materials —

Part 2: Ingestion of uranium compounds

1 Scope

This document specifies the minimum requirements for the design of professional programmes to monitor workers exposed to a risk of ingestion to uranium compounds. This document establishes principles for the development of compatible goals and requirements for monitoring programmes and dose assessment for workers occupationally exposed to internal contamination. It establishes procedures and assumptions for risk analysis, monitoring programmes and the standardized interpretation of monitoring data in order to achieve acceptable levels of reliability for uranium and its compounds. It sets limits for the applicability of the procedures in respect to dose levels above which more sophisticated methods need to be applied.

This document addresses those circumstances when exposure could be constrained by either radiological or chemical toxicity concerns.

This document addresses, for ingestion of uranium and its compounds, the following items:

a) purposes of monitoring and monitoring programmes;

b) description of the different categories of monitoring programmes;

c) suitable methods for monitoring and criteria for their selection;

d) information that is collected for the design of a monitoring programme;

e) procedures for dose assessment based on reference levels for special monitoring programmes;

f) criteria for determining the significance of monitoring results;

g) uncertainties arising from dose assessment and interpretation of bioassays data;

h) reporting/documentation;

i) quality assurance;

j) record keeping requirements.

It is not applicable to the following items:

a) detailed descriptions of measuring methods and techniques for uranium;

b) modelling for the improvement of internal dosimetry;

c) potential influence of counter-measures (e.g. administration of chelating agents);

d) investigation of the causes or implications of an exposure;

e) dosimetry for inhalation exposures and for contaminated wounds.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 5725-1, *Accuracy (trueness and precision) of measurement methods and results — Part 1: General principles and definitions*

ISO 5725-2, *Accuracy (trueness and precision) of measurement methods and results — Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method*

ISO 5725-3, *Accuracy (trueness and precision) of measurement methods and results — Part 3: Intermediate measures of the precision of a standard measurement method*

ISO 15189, *Medical laboratories — Requirements for quality and competence*

ISO/IEC Guide 99, *International vocabulary of metrology — Basic and general concepts and associated terms (VIM)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO/IEC Guide 99, ISO 5725-1, ISO 5725-2, ISO 5725-3 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
absorption
movement of material to blood regardless of mechanism

Note 1 to entry: Absorption generally applies to the uptake into blood of soluble substances and material dissociated from particles.

3.2
activity
number of spontaneous nuclear disintegrations per unit time

Note 1 to entry: The activity is stated in becquerels (Bq), i.e. the number of disintegrations per second.

3.3
clearance
the action that results in the movement of radioactive material from the site of deposition in tissues and organs

Note 1 to entry: This action can be natural or induced by therapeutic means.

Note 2 to entry: The clearance rate is the rate at which this occurs.

3.4
contamination
radioactive substances on surfaces or within solids, liquids or gases (including the human body), where its presence is unintended or undesirable, or the process giving rise to its presence in such places

3.5
decision threshold
value of the estimator of the measurand which, when exceeded by the result of an actual measurement using a given measurement procedure of a measurand quantifying a physical effect or quantity, it is decided that the physical effect or quantity is present

Note 1 to entry: Otherwise, this effect is assumed to be absent.

3.6
detection limit
smallest true value of the measurand which ensures a specified probability of being detectable by the measurement procedure

3.7
committed effective dose
sum of the products of the committed organ or tissue equivalent doses and the appropriate tissue weighting factors

Note 1 to entry: In the context of this document, the integration time is 50 years following any intake.

Note 2 to entry: The committed effective dose is expressed in Sievert (Sv).

3.8
excretion function
function describing the fraction of an intake excreted per day after a given time has elapsed since the intake occurred

Note 1 to entry: The excretion function is expressed in becquerels per day (Bq/d).

3.9
event
any unintended occurrence, including operating error, equipment failure or other mishap, the consequences or potential consequences of which are not negligible from the point of view of protection or safety

3.10
intake
activity (3.2) of a radionuclide taken into the body in a given time period or as a result of a given *event* (3.9)

Note 1 to entry: The intake is expressed in becquerels (Bq).

3.11
in vitro analyses
analyses that include measurements of radionuclides present in biological samples taken from an individual

Note 1 to entry: These include urine, faeces and nasal samples; in special monitoring programmes, samples of other materials such as blood and hair may be taken.

3.12
monitoring
measurements made for the purpose of assessment or control of exposure to radioactive material and the interpretation of the results

Note 1 to entry: This document distinguishes three different categories of monitoring programmes, namely *confirmatory monitoring programme* (3.13), *special monitoring programme* (3.14) and *task-related monitoring programme* (3.15), as well as one type of monitoring, namely *individual monitoring* (3.16), which features in each category.

3.13
confirmatory monitoring programme
monitoring programme carried out to confirm assumptions about working conditions and that a routine monitoring programme for dose assessment purposes is not required

3.14
special monitoring programme
monitoring programme performed to quantify suspect significant exposures following an *event* (3.9)

3.15
task-related monitoring programme
monitoring programme related to a specific operation, or providing information on a specific operation of limited duration, or following major modifications applied to the installations or operating procedures, or confirming that the routine monitoring programme is suitable

3.16
individual monitoring
monitoring (3.12) by means of equipment worn by individual workers, by measurement of the quantities of radioactive materials in or on the bodies of individual workers, or by measurement of radioactive material excreted by individual workers

3.17
quality assurance
planned and systematic actions necessary to provide adequate confidence that a process, measurement or service satisfy given requirements for quality such as those specified in a licence

3.18
quality control
part of *quality assurance* (3.17) intended to verify that systems and components correspond to predetermined requirements

3.19
reference level
value of measured quantities above which some specified action or decision should be taken

3.20
scattering factor
geometric standard deviation of the lognormal distribution of bioassay measurements

4 Symbols and abbreviated terms

4.1 Symbols

D_v committed effective dose due to annual intake (Sv) such that lower doses may be discounted for the purpose of the monitoring programme

$E(50)$ committed effective dose (Sv) for an integration period of 50 years

$e(50)$ dose coefficient: committed effective dose per unit intake ($Sv \cdot Bq^{-1}$), for an integration period of 50 years

f_A alimentary tract transfer factor, fraction of activity entering the alimentary tract that is absorbed from the gut in the absence of both radioactive decay losses and endogenous input to the tract

I intake in Bq (3.13)

$m(t_i)$ predicted value of the measured quantity (Bq/d/Bq = d^{-1}) at time, t_i, for unit intake (excretion or retention function, for unit intake)

$m_c(t_i)$ predicted value of the quantity measured after a period of t_i, days of a chronic unit intake per day (excretion or retention function at time, t_i, for chronic unit intake per day)

4.2 Abbreviated terms

CRM certified reference material (see ISO 28218[2])

DU depleted uranium (uranium with an assay of U-235 that is lower than its content in natural uranium)

HEU high enriched uranium (uranium with an assay of U-235 equal to or more than 20 %)

IARC International Agency for Research on Cancer

ICRP International Commission on Radiological Protection

LDH lactate dehydrogenase

LEU low enriched uranium (uranium with an assay of U-235 from the natural level to 20 %)

LOAEL lowest-observed-adverse-effect level

NOAEL no-observed-adverse-effect level

TRS transfer reference standard (see ISO 28218[2])

U-nat uranium compound with natural isotopic composition

5 Purpose and need for monitoring programmes

Uranium compounds are considered a mixture of three major isotopes: U-234, U-235 and U-238; but in certain cases U-236, U-233 and U-232 are also included. This document describes four different isotopic compositions, as examples, representing natural (U-nat), depleted (DU), low (LEU) and high (HEU) enriched uranium forms (see Table 1) based on their typical uranium isotopic compositions encountered in the nuclear industry. Specific isotopic compositions should be used if available.

Table 1 — Isotopic composition of natural uranium (U-nat), depleted uranium (DU), low enriched uranium (LEU) and high enriched uranium (HEU), by mass and total uranium alpha activities, based on specific activity values in ICRP 107[12]

	U-238		U-235		U-234			
	Isotopic composition by mass	Total alpha activity	Isotopic composition by mass	Total alpha activity	Isotopic composition by mass	Total alpha activity	Total alpha activity	Alpha activity ratio U-234/U-238
	%	%	%	%	%	%	Bq/g	
U-nat	99,275	48,26	0,72	2,25	0,005 5	49,49	2,56E+04	1,03
DU	99,799	83,45	0,2	1,07	0,001 0	15,48	1,49E+04	0,186
LEU	96,471	14,78	3,5	3,45	0,028 84	81,78	8,12E+04	5,54
HEU	6,41	0,042	92,8	3,92	0,79	96,04	1,89E+06	2287

The general population is exposed to ubiquitous uranium in the environment with ingestion of food and drinking water being the primary contributors to body burden. In industry, uranium can be present in a variety of chemical forms, often in association with other radionuclides. In general, there is insufficient high-quality data regarding ingestion by workers to be able to determine the absorption parameters for uranium and, therefore, describe the biokinetics of the material which would form the base for assessing radiological or chemical constraints or optimising monitoring procedures. However, the absorption data can be obtained from animal studies designed specifically to calculate the material specific absorption parameters in a range of industrial materials. The relative importance of chemical and radiological toxicities of ingested uranium depends on the degree of enrichment of U-235 (and U-234), the compound solubility, and the chemical speciation. In order to recommend material-specific dose coefficients and predict the biokinetics of uranium in humans, the absorption parameter values obtained from the animal studies are combined with human physiology data obtained from the ICRP human alimentary tract model (HATM)[10] and the ICRP systemic model for uranium[8].

The purpose of monitoring in general is to verify and document that the worker is protected adequately against risks from radionuclide intakes and the protection complies with legal requirements. Therefore, monitoring forms part of the overall radiation protection programme. The programme starts with an assessment to identify work situations in which there is a risk of internal contamination of workers by ingestion, and to quantify the likely intake of radioactive material and the resulting committed effective dose received.

Work-related ingestion of uranium compounds can occur after ingestion of contaminated food or beverages; by transfer of contamination by hand-to-mouth or object-to-mouth contact; and by the more passive but more direct mechanism of deposition of contaminants around the mouth and into the oral cavity. Intakes by ingestion can be controlled through effective hand washing and cleaning or minimized with occupational hygiene recommendations of no food and no drink consumption in the workplace and by wearing individual protective equipment. Exposures by ingestion would not be expected under normal circumstances and hence there is no requirement for a routine monitoring programme. Work-related accidental ingestion can occur as a result of poor work practices and lack of personal hygiene. Decisions about the need and the design of the monitoring programme should be made in the light of such a risk assessment with mainly special or confirmatory or task-related individual monitoring. Factors determining the extent of a monitoring programme are the magnitude of likely exposures and the requirement to identify accidental exposure events.

In order to improve both risk assessment and management of uranium, there is a need for adapted exposure limit values. The process of setting exposure limits begins with a careful analysis of toxicological studies with relevant conditions of exposure, which is compared with actual exposure. The final value takes into account the risk, as well as practical and economic constraints. Protective values are regularly revised and modified depending on: new research, new risk assessment or improvement of detection limits following new instrumental analysis methods. The toxicity of uranium varies according to its chemical form and isotopic composition. Absorption rates differ with the solubility of the compound. Those limits need to take into account both chemical and radiological risks. Most regulatory bodies agree that uranium chemical toxicity requires consideration when the uranium content in the kidney exceeds 3 $\mu g \cdot g^{-1}$ (retrospective) and regarding radiological hazards when the annual effective dose is above 6 mSv (prospective).

Judgements on the efficacy and accuracy of monitoring programmes depend on detailed information about the biokinetics of uranium. Generally, this information is not available from human exposures. It is often based on biokinetic data predicted by combining material-specific absorption parameter values, obtained from animal or in vitro studies, with human data and on the systemic behaviour of uranium. The ICRP have long considered it appropriate to use such material-specific parameters rather than default parameters. For all uranium compounds, large errors in the assessment of intake can occur in the absence of material specific biokinetic data for the chemical form ingested.

For uranium and its compounds, the risk analysis shall be based both on consideration of its chemical toxicity and its radiation toxicity. The validity of currently recommended limits for uranium, which were derived from judgemental decisions on nephrotoxicity, simplistic biokinetic models of the human alimentary tract and outdated definitions of the specific activity of uranium, is doubtful.

6 General aspects

Uranium is an alpha-emitting, radioactive, heavy metal that occurs naturally in the earth's crust at an average concentration of about 2 $mg \cdot kg^{-1}$. Uranium occurs naturally in the environment and, therefore, in people. There are three naturally occurring isotopes of uranium, U-238, U-235, and U-234, all emitting mainly alpha particles of energies ranging from about 4,0 MeV to 4,5 MeV. Two of these isotopes, U-238 ($T_{1/2}$ = 4,47 × 10^9 years) and U-235 ($T_{1/2}$ = 7,04 × 10^8 years), are the parents of naturally occurring radioactive decay series[4]. Uranium-234 ($T_{1/2}$ = 2,46 × 10^5 years) is a member of the U-238 decay series[28]. The two decay series, which contribute to an important portion of the annual dose from primordial background radiation[4], are shown in Annex A (see Tables A.1 and A.2). Because of the long half-lives of U-238 and U-235 relative to their progeny, unless they are subjected to physical or chemical separation, the progeny are at secular equilibrium with their respective parent. Following mineral extraction, uranium ore is processed to remove all progeny that are not uranium. A few months after milling, the Th-234 and Pa-234m activities return to an equilibrium state with their U-238 parent.

Naturally occurring uranium is an isotopic mixture containing a large percentage of U-238 and very small percentages of U-234 and U-235, by mass. The industrial process called enrichment is used to increase the percentage of U-235 and decrease the percentage of U-238 in natural uranium.

The main compounds found in the working area in the uranium fuel cycle can be uranium hexafluoride (UF_6), uranyl nitrate [$UO_2(NO_3)_2$], uranyl tributyl phosphate (U-TBP), ammonium diuranate (ADU) $(NH_4)_2U_2O_7$, uranium peroxide hydrate ($UO_4 \cdot nH_2O$), uranium tetrafluoride (UF_4), uranium trioxide ($UO_3 \cdot nH_2O$), uranium octoxide (U_3O_8), uranium dioxide (UO_2), and uranium metal and alloys. The physical and chemical form of the uranium compound, as well as its physical history, influence its solubility characteristics, e.g. sintering temperature (calcination) can affect lung retention[40]. Default values for fractional absorption from the alimentary tract are given in Annex B.

This document is consistent with ICRP 119 compendium of dose coefficients[37].

Uranium is a heavy metal with chemical hazards. The kidney is the major target organ of acute uranium toxicity whatever the route and duration of exposure. Histopathological changes including degenerative changes or necrosis of the proximal tubular epithelium and glomeruli have been observed after acute exposure. Some histological alterations have been noted in renal tubules following a chronic exposure. It appears that acute exposure may lead to glomerular and tubular alteration, but chronic exposure to uranium seems to affect only tubular functions. After acute exposure, renal alterations have been associated with modified blood or urine biomarkers of kidney function. To help the occupational physician address the needs of workers exposed to a uranium compound, the level of toxicity is based on the different routes of exposure: inhalation, oral and dermal; and by the health effects: systemic, immunological, neurological, reproductive, developmental, genotoxic and cancer effects (ATSDR[19]). Levels of significant exposure for each route and duration shall be controlled by reference to no-observed-adverse-effect levels (NOAELs) and lowest-observed-adverse-effect levels (LOAELs). In humans, there have not been any long term chemical injuries or permanent renal system damage from exposure to uranium compounds (Kathren[39]).

NOTE The NOAEL is defined by WHO[13][14][15][16] and IARC[18] as "the greatest concentration or amount of a substance, which causes no detectable adverse alteration of morphology, functional capacity, growth, development or life span of the target organism under defined conditions of exposure. Alterations of morphology, functional capacity, growth, development or life span of the target can be detected which are judged not to be adverse".

For adults, overall country-specific lower- and upper-bound intakes of environmental uranium varied between (0,05 and 0,28) $\mu g \cdot kg^{-1}$ body weight per day considering different exposure scenarios. When high local concentrations occur together with a high consumption, the lower- and upper-bound uranium intake estimates varied between (0,39 to 0,45) $\mu g \cdot kg^{-1}$ body weight per day[17].

Biomarkers of exposure to uranium include the chemical or radiological detection of uranium in the urine because uranium absorbed through the oral routes is excreted in urine mostly as uranyl ions. Although there are no unique biomarkers for uranium toxicity, common biomarkers for chemical toxicity from heavy metals in general include urinary levels of glucose, lactate dehydrogenase (LDH)

and protein albumen (often by ratio to creatinine)[40]. This sort of monitoring may be considered for very large intakes.

7 Special monitoring programmes

The goal of special individual monitoring is to ensure that significant intakes are detected at an early stage and that the associated committed doses are evaluated. Special monitoring programmes are investigative; they are usually based on a suitable combination of in vitro analyses (see Annex C) in association with the appropriate biokinetic model.

The analyses made following an ingestion event enable quantification of the significance of the incident and estimation of the value of the intake according to ICRP models (see Annex D). Faecal and urine samples provide information on the extent of exposure to non-transferable compounds. For internal dosimetry purposes, only bioassay results from 24 h urine and faecal samples should be used for validating the intake. In addition to providing a daily excreted activity, the physician or dosimetrist can test these samples to ascertain the origin of the exposure. Large fluctuations in the faecal excretion of radionuclides from one day to the next give rise to uncertainty when interpreting the results. Consequently, faecal samples should preferably be collected over a period of about three consecutive days to reduce this uncertainty.

For a single event involving soluble compounds of uranium, "spot sample" collections (from a single voiding) may be made to verify an intake has occurred and to assist in the design of the special monitoring programme.

8 Task-related monitoring programmes for individual monitoring

Individual monitoring as part of task-related monitoring programmes normally takes the form of confirmatory monitoring. Individual monitoring may require the setting in place of a series of suitable measurements combining one measurement at the beginning and at the end of the task period with, depending with the duration of the task, one or more samples during the task period.

9 Reference values as performance criteria for laboratories

Reference values can be used to provide service laboratories with the required levels at which to perform specific actions, such as immediate notification of the client or for a first order of magnitude of the dosimetric impact of the event. Assuming a single acute intake for a special monitoring programme, the reference value can be calculated using Formula (1):

$$\text{derived reference value} = \frac{D_{\text{v}}\, m(t_1, t_3)}{e(50)}\ \text{Bq}\cdot\text{d}^{-1} \tag{1}$$

where

D_{v} is the level of annual dose (Sv) such that lower doses may be discounted for the purpose of the monitoring programme;

$m(t_1, t_3)$ is, for in vitro measurements, the sum of the excretion function (d^{-1}) during the first 3 days after the event;

$e(50)$ is the dose coefficient: the committed effective dose per unit intake (Sv·Bq−1) for ingestion (appropriate absorption type), see Annex E.

Table 2 lists derived reference values related to the total excretion (Bq) in the three first days after ingestion. These values can be used to determine the requirement for dose assessment. A DRL based on a radiological dose of 0,1 mSv also satisfies the requirement for a DRL based on chemical toxic effects.

Table 2 — Derived reference values for various uranium isotopic composition and transfer factors for special monitoring based on ICRP 30 HATM and ICRP 69 uranium biokinetic model

Type of monitoring	f_A	$m(t_1,t_3)$	Derived reference value for D_v = 0,1 mSv				
			U-nat	DU	LEU	HEU	Unit[a]
Faecal	0,02	0,852	1 800	1 900	1 800	1 700	Bq excreted in 3 days
Faecal	0,002	0,867	11 000	11 000	11 000	10 000	Bq excreted in 3 days
Urine	0,02	0,014	29	30	28	28	Bq excreted in 3 days
Urine	0,002	0,001 4	17	18	17	16	Bq excreted in 3 days
[a] Units expressed in total alpha activity of U-234, U-235 and U-238.							

The normal uses of in vitro techniques (relative detection limit, etc.) are adequate for special monitoring.

10 Quality assurance and quality control for bioassay laboratories

Performance checks shall be conducted to ensure the conformance of analytical processes, measurement equipment and the facilities to predetermine operational requirements. The laboratory shall have written quality control procedures to verify that the quality of measurements or radioactivity determinations complies with the accuracy requirements. The quality control procedures shall include the following:

a) use of traceable radionuclide reference standards;

b) performance checks of measurement systems;

c) instrument calibration;

d) intralaboratory analyses (e.g. known quantities, replicates and blanks);

e) participation in available interlaboratory inter-comparison programmes;

f) computational checks;

g) review of procedures, specifications and operating logs;

h) observation of operations and evaluation of quality control data;

i) evaluating conformance to the performance criteria of this document;

j) evaluating quality control data to ensure the long-term consistency of analytical results; and

k) verification of determinations of the detection limits.

Performance of the measurement equipment shall be checked and evaluated at regular intervals while the equipment is in use. These checks shall be sufficient to demonstrate that the measurement equipment is properly calibrated and that all components are functioning properly. Measurements should include instrument background and response checks.

Radionuclide standards used for equipment calibrations and to test the accuracy of analytical procedures and/or measurement equipment shall either be those designated as certified reference material (CRM), transfer reference standard (TRS), or standards directly compared with appropriate CRMs and, where available, with the same measuring apparatus.

In addition, laboratories performing in vitro analyses and/or assessments for internal dosimetry should participate in national or international inter-comparison exercises.

11 Procedure for the assessment of exposures

11.1 Assessment of individual monitoring data

The general procedure for the assessment of exposures is described in ISO 27048[1]. The choice and efficacy of each procedure is dictated by the pattern of exposure, the physicochemical form of the uranium, the time between intake and measurement, and the detection limit of the analytical procedure used.

Radionuclides from the three natural radioactive decay series of uranium are present in all environmental media and, therefore, are also contained in foodstuffs, drinking water and in the air. This results in intakes among the general population and a range of values for the normal body content and excretion of uranium. Knowledge of the natural background activity found in the bioassay (faeces and urine) is essential if an occupational intake is to be assessed. Interpretation of measurements of uranium isotopes in bioassay samples shall take into account the natural background levels of these isotopes where the contribution from natural background could have a significant effect on the assessed dose. If natural background levels are not taken into account, it shall be demonstrated that their contribution to assessed dose is not significant. The natural background levels in bioassay samples arise from dietary intakes of natural uranium. Where the occupational exposure is to either depleted or enriched uranium, measurement of the isotopic content of a bioassay sample allows the contribution from the natural uranium background to be determined and subtracted. If the isotopic composition cannot be determined, or where the occupational exposure is to natural uranium, a range of reference values shall be set to distinguish between occupational exposures and natural background. A "blank" bioassay sample should be obtained prior to commencing work in potentially contaminated areas, in order to be able to distinguish between natural or non-occupational intakes and occupational intakes[35]. Tests to determine whether an occupational exposure has occurred should include a test to determine whether such a reference value is exceeded.

For an individual worker, the reference value shall, where feasible, be determined by one or more measurements of blank bioassay samples taken before work with uranium commences. Where this is not feasible or is shown to be not reliable, data from measurements performed on bioassay samples provided by a representative population of unexposed workers may be used to establish background ranges and reference values. If this is not feasible, measurements of the uranium content in representative samples of drinking water may be used to set reference values[20]. Alternatively, published data may be used, particularly those reported in IDEAS Guidelines, section 4.1.3[37]. Whichever method is used, it shall be demonstrated that the reference value is representative of the natural background level for the worker to whom it is applied. After the actions mentioned above are taken, the individual's drinking water and food supply may be investigated[20], only under conditions in which it is believed that background levels are of sufficient magnitude relative to investigation and/or detection level requirements to influence ability to identify occupational intakes.

When an occupational exposure has been detected, the mean natural background level should be subtracted from the measured bioassay result (especially for faecal bioassay measurements) prior to any dose assessment.

11.2 Properties of a software tool

The criteria for selecting one software or computer code for bioassay data interpretation are based in the requirement of the following capabilities of the software:

a) type of intake (inhalation, ingestion, injection), pattern of intake (acute, chronic or mixed) and date;

b) type of information on the element or compound, such as number of radionuclides available, physicochemical characteristics of the compound (AMAD or absorption parameters) and choice between default and/or specific values;

c) type of measurement (urine, faeces, lung), the possibility of simultaneously treating several data, the flexibility of entering, handling and treating data (type of uncertainties, implemented algorithms for automatic and/or interactive data processing, ability to deal with values below the detection limit);

d) models available for calculation: biokinetic models of ICRP 78[9] or other models;

e) methods of data fitting (least-squares fit, maximum-likelihood fit, Bayesian) and interpretation (algorithms, data weighting and data uncertainty processing) and the possibility of analysing simultaneous intakes.

11.3 Uncertainties

In monitoring of an ingestion case, the time of any acute intake is generally well known.

The distributions of a measured bioassay quantity arising from the various components of uncertainty can be described using lognormal distributions, with the uncertainty quantified using the geometric standard deviation. The geometric standard deviation is often known as the scattering factor (K_{SF}) and values are provided in ISO 27048:2011, Annex B[1].

It is reasonable to expect dosimetry services to provide information on uncertainties in assessed doses, although there is no requirement for dosimetry services to use the procedure presented here. The contributions to overall uncertainty in assessed doses may be recorded in the format shown in Table 3. See also Annex F. The main factors that may need to be considered when evaluating the overall uncertainty are:

a) the uncertainty in the time or period of intake;

b) the uncertainty in the measured bioassay quantities (sometimes known as Type A uncertainties);

c) inter-subject and intra-subject variability in the measured bioassay quantities (sometimes known as Type B uncertainties); and

d) uncertainty or variability in the characteristics of the material to which a worker may have been exposed, in particular, the gastro-intestinal uptake factor, f_A, and the composition of the radionuclide mixture.

Methods for determining how these factors contribute to overall uncertainty are described in ISO 27048:2011, Clause 8 (where further information is given together with an example). Where this information applies to a particular monitoring procedure, the doses per unit measurement should be assessed, with the measurement value chosen to be a factor of 10 greater than the detection limit for that measurement. Where the information applies to an individual case, the actual measurement value or values should be used.

Table 3 — Format for recording the contributions to overall uncertainty in assessed doses

Factor contributing to overall uncertainty	Lower value of assessed dose	Assessed dose using best estimate parameter values and/or default assumptions	Upper value of assessed dose
Uncertainty in measured quantity (Type A and Type B combined)			
Uncertainty in the alimentary tract transfer factor (f_A)			

11.4 Quality assurance of the assessment process

The continued effectiveness of any radiation programme relies on those in charge implementing its various components, including the adoption of an effective quality assurance (QA) programme based on ISO 28218[2], ISO 20553 and ISO 27048[1]. QA includes quality control, which involves all those actions by which the adequacy of tools and procedures is assessed against established requirements. QA requirements may be determined by national regulations. In addition, laboratories performing assessments for internal dosimetry should participate in national or international inter-comparison exercises[35].

12 Reporting and documentation

12.1 Reporting results for in vitro measurements

The results obtained by the service laboratory shall be reported to the customer and shall include the following items as a minimum:

a) sample identification:

   1) assigned number;

   2) total volume or mass of sample submitted;

   3) reference date(s) and start and stop times of sample collection and analysis;

   4) elemental or alpha activities measurement;

   5) sample type;

   6) sample preservation;

   7) date of sample receipt by service laboratory;

   8) condition of package.

b) quantification of sample activity at the time of measurement, taking account of appropriate blanks and correction factors (e.g. analysis of creatinine);

c) estimates of counting uncertainty and the total propagated uncertainty (depending on the client's prescription);

d) identification of equipment and specific measurement procedures;

e) values of the decision threshold and detection limit;

f) in case of a risk of chemotoxicity, quantification of biomarkers [glucose, lactate dehydrogenase (LDH) and protein albumen (often by ratio to creatinine)] according to specific requirements of medical laboratories as specified by ISO 15189; and

g) identification of the individual responsible for the report.

The service laboratory shall retain, in a retrievable form, records required by this document.

These records include the indicated items for a period of time as specified by national legal requirements or as long as they remain current.

12.2 Documentation of the dose assessment

Arrangements shall be made to ensure that the results of all assessments are reported to the client's dose record-keeping service accurately and in reasonable time.

Sufficient records shall be kept of the details of all assessments so that the exact conditions of assessment may be reproduced in the future. All reports and records shall be authenticated by the competent person responsible. Account shall be taken of the national requirements in respect of record-keeping.

Each assessment shall have

a) a unique identification of dose assessment for one person and for one event;

b) the physical and chemical properties of compounds manipulated, if possible;

c) a precise isotopic composition of uranium compound, if possible;

d) the date and time of the measurements and quantities measured;

e) the route and mode of intake(s);

f) the procedure for calculating doses: assumptions made in respect of route of intake, temporal pattern of intake, default or specific value of f_A, chemical and physical nature;

g) the method of dose calculation; manually or with a computer software;

h) the results expressed in terms of 50 years committed effective dose from intakes of each uranium isotope occurring during the monitoring interval. All doses shall be given in units of millisieverts correct to one decimal place; and

i) uncertainties only if explicitly requested by the customer shall be reported.

The user shall be aware of applicable national requirements.

Annex A
(informative)

Nuclear data of U-238 and U-235 decay

Table A.1 — U-238 decay

Radionuclide	Half-life[a]	Mode of decay
U-238	$4{,}47 \times 10^9$ years	Alpha
Th-234	24,1 d	Beta
Pa-234m	1,17 min	Beta
U-234	$2{,}46 \times 10^5$ years	Alpha
Th-230	$7{,}54 \times 10^4$ years	Alpha
Ra-226	1 600 years	Alpha
Rn-222	3,82 d	Alpha
Po-218	3,10 min	Alpha
Pb-214	26,8 min	Beta
Bi-214	19,9 min	Beta
Po-214	0,000 16 s	Alpha
Pb-210	22,2 years	Beta
Bi-210	5,013 d	Beta
Po-210	138,4 d	Alpha

[a] According to ICRP 107 Nuclear Decay Data for dosimetric calculations[12].

Table A.2 — U-235 decay

Radionuclide	Half-life[a]	Mode of decay
U-235	$7{,}04 \times 10^8$ years	Alpha
Th-231	25,52 h	Beta
Pa-231	$3{,}276 \times 10^4$ years	Alpha
Ac-227	21,77 years	Beta
Th-227	18,68 d	Alpha
Ra-223	11,43 d	Alpha
Rn-219	3,96 s	Alpha
Po-215	0,001 78 s	Alpha
Pb-211	36,1 min	Beta
Bi-211	2,14 min	Beta
Tl-207	4,77 min	Alpha

[a] According to ICRP 107 Nuclear Decay Data for dosimetric calculations[12].

Annex B
(informative)

Default classification of uranium compounds

Experimental data on ingestion by laboratory animals, reviewed by Leggett and Harrison (1995), suggest that alimentary tract transfer factors are:

— for uranyl nitrate, f_A = 0,02;

— for UO_4, and UO_3, f_A = 0,01;

— for UF_4, UO_2 and U_3O_8, f_A = 0,000 2.

In ICRP 30 (1979), an f_A of 0,05 was recommended for water soluble inorganic forms of U(VI) and a value of 0,002 for U(IV) in relatively insoluble compounds such as UF_4, UO_2 and U_3O_8. In ICRP 69 (1995), an f_A of 0,02 was adopted for dietary intakes of U on the basis of human data as reviewed by Harrison (1991)[26] and Leggett and Harrison (1995)[29]. The available human and animal data indicate that a value of 0,02 is also appropriate for occupational exposures to more soluble inorganic forms, including $UO_2(NO_3)_2{\cdot}6H_2O$, UO_2F_2 and $Na_2U_2O_7$.

Table B.1 — Absorption parameter values for ingested uranium

Specific parameter values	Alimentary tract transfer factor f_A
Uranyl Tri-Butyl-Phosphate (U-TBP)	0,02
Uranyl nitrate, $UO_2(NO_3)_2$	0,02
Uranium peroxide hydrate UO_4	0,01
Ammonium diuranate, ADU	0,02
Uranium trioxide UO_3	0,01
Uranium tetrafluoride UF_4	2×10^{-4}
Triuranium octoxide U_3O_8	0,005
Uranium dioxide UO_2	2×10^{-4}
Uranium aluminide UalX	0,002

In this document, a f_A value of 0,002 is adopted for the fractional absorption of relatively insoluble compounds (e.g. UO_2, U_3O_8) and a f_A value of 0,02 is adopted for all other more soluble chemical forms (see Table B.2).

Table B.2 — Summary of default absorption parameter

Typical compounds	Alimentary tract transfer factor f_A
UF_6, UO_2F_2, $UO_2(NO_3)_2$	0,02
UO_3, UF_4, UCl_4, UO_4	0,02
UO_2, U_3O_8	0,002

New default absorption parameters for inhalation are available at the ICRP 137[43] and may replace the values of Table B.2.

Annex C
(informative)

Measurement techniques for uranium in case of ingestion

C.1 General

Measurement of the quantities of uranium in the body can be performed by in vitro measurements. These types of measurements are called bioassays. In vitro techniques permit estimation of internally deposited uranium by analysis of excreta. Individual monitoring provides the information needed to assess the exposure of a single worker by measuring individual excretion rates. For special monitoring, or task-related monitoring, in vitro measurement techniques may be used, depending on factors such as the chemical composition of uranium involved, the likely level of contamination and the availability of these measurement techniques. A detailed description of the measurement methods and techniques is beyond the scope of this document.

NOTE The ethics and human dignity of sampling regimes is described in the Convention on Human Rights and Biomedicine[38] and ISO 15189 for competence of laboratories.

C.2 In vitro measurement

C.2.1 General

In vitro measurement is used widely for the monitoring of internal contamination of uranium[6][7][8]. Urine and faecal excreta are the typical bioassay samples collected for measurement. Blood or other biological samples may be used in some special cases, although the accuracy of these methodologies is not fully determined. Faecal analysis is sometimes used for uranium monitoring, but urine analysis is preferred, despite the much lower excretion function, because it is less affected by dietary contributions.

For the measurement of uranium in a faecal sample, a single voiding can be used. However, measurement of samples collected over several days is preferred as the excretion might show a large fluctuation. This is especially significant at early times following an intake due to early clearance through the gastrointestinal tract, either from direct ingestion or early clearance from the respiratory tract, but is less of an issue at longer times when the faecal excretion is from systemic metabolism only. At those early times post intake, faecal monitoring is an excellent indicator of intake, if not as useful for quantification. The sample is "ashed" (i.e. reduced in a muffle furnace), and the resulting ash dissolved in an acid solution. Depending on the analysis methodology, either the entire solution or an aliquot of the solution is then analysed for the measurement of total uranium concentration or uranium isotopes using the separation and measurement methods for urine.

Table C.1 — Analytical method for measuring natural uranium in faeces

Analytical method	Sample preparation	Detection limit	Reference
Alpha spectrometry	Calcination and mineralisation of faecal ashes followed by coprecipitation, solvent extraction and electrodeposition	0,1 mBq·kg^{-1} for U-238	Juliao 1988[30]

For the measurement of uranium in urine, 24 h samples are typically recommended to minimize diurnal variances. Increased sample volume is also needed when performing alpha spectrometry to reduce uncertainty in measurement, but this is not necessary for mass spectrometry. When a spot sample is used, it is preferred that the daily excretion is normalized by measuring either the concentration of

creatinine in the sample (IAEA 2000[5]) or specific gravity of the sample (Dai et al., 2011[22]). For most cases, an aliquot of the sample, spot or 24 h, is sufficient to be used for the assessment.

There are quite a few methods suitable for the measurement of total uranium in urine. Table C.2 provides detection limits and brief descriptions of sample preparation for each method. The selection of a specific method depends on the level of radioactivity in the samples and the availability of instrumentation and technical expertise in the laboratory. The selected method also needs to satisfy the performance criteria for radiobioassay set by ISO 28218[2].

Table C.2 — Some analytical methods for measuring natural uranium in urine

Analytical method	Sample preparation	Detection limit[a]	Reference
Fluorimetry	Urine wet ashed, ion exchange and solvent extraction for enrichment and purification	0,1 $\mu g \cdot l^{-1}$ (2,5 $mBq \cdot l^{-1}$)	Dupzyk and Dupzyk, 1979[24]
KPA	Urine wet ashed and solubilised	0,05 $\mu g \cdot l^{-1}$ (1,3 $mBq \cdot l^{-1}$)	Birkenfeld et al., 1995[21]
Alpha spectrometry	Urine wet ashed followed by coprecipitation, solvent extraction and electrodeposition	0,1 mBq l^{-1} for U-238 or 0,2 $mBq \cdot l^{-1}$ for natural uranium	Singh and Wrenn, 1988[32]
ICP-MS	Acidification, dilution	3 $ng \cdot l^{-1}$ (0,077 $mBq \cdot l^{-1}$)	Karpas et al., 1996[27]
[a] In brackets, correspondence in term of total uranium alpha activity for natural uranium.			

In some cases where uranium with an altered isotopic composition (e.g. enriched uranium or depleted uranium) is involved, the measurement of uranium isotopes in the urine samples may be required. Although alpha spectrometry is an established method for the measurement of uranium isotopes, mass spectrometry such as inductively coupled plasma mass spectrometry (ICP-MS) offers much shorter sample turnaround time, although is incapable of quantifying shorter-lived isotopes (e.g. U-234).

For the measurement of either the total uranium concentration or the isotopes in a urine sample, more often than not, chemical separation of uranium from the sample following sample digestion is needed. The selection of a specific method is determined by the size of the sample, the level of uranium in the sample, the purpose of the measurement, and the availability of instrumentation and expertise. U-236 and U-232 are sometimes spiked in the samples to track the chemical recovery of the concerned uranium isotopes.

C.2.2 Natural background

The natural background is the amount of radiation to which a member of the general population is exposed from natural sources, such as terrestrial radiation from naturally occurring radionuclides in the soil and naturally occurring radionuclides deposited in the human body.

Measurements of concentrations of uranium have been made in human tissues and body fluids resulting from consumption of food and water and from natural background sources[24][25][26].

Concentrations of uranium are variable depending on the environmental media and location. In humans, the concentration of U-238 is typically about 0,1 $Bq \cdot kg^{-1}$ in bone and 0,003 $Bq \cdot kg^{-1}$ in soft tissue. This corresponds to 0,71 Bq in the whole body[7]. Diet results in variable daily intakes of uranium, with a mean value of 1,9 $\mu g \cdot d^{-1}$, as has been reported[6].

Urinary excretion rates in persons not occupationally exposed to uranium have been shown to depend on diet and location, that is the concentration in the indigenous soil and consumption of local food products. ICRP reports the typical range of urinary excretion of background uranium to be from (0,05 to 0,5) $\mu g \cdot d^{-1}$. Others report similar results, with mean concentrations of 0,009 4 $\mu g \cdot l^{-1}$[23], 0,098 $\mu g \cdot l^{-1}$[35], 0,01 $\mu g \cdot l^{-1}$[25], 0,485 $\mu g \cdot l^{-1}$[31] and 0,004 5 $\mu g \cdot l^{-1}$[27]. A range of (0,01 to 0,4) $\mu g \cdot d^{-1}$ has

also been reported[33]. More recently, ranges of (0,003 to 3,62) $\mu g \cdot d^{-1}$ and from (0,001 to 8,45) $\mu g \cdot d^{-1}$[34] have been observed.

ICRP reports faecal excretion rates to vary from (1,4 to 1,8) $\mu g \cdot d^{-1}$[6]. A more recent study found faecal excretion rates to range from (0,2 to 500) $\mu g \cdot d^{-1}$[36]. Faecal excretion data may need correction for dietary intakes of uranium. IDEAS guidelines[37] give background values and rules to distinguish between natural or non-occupational intake and occupational intake.

Annex D
(informative)

Excretion rates for ingestion of uranium compounds

Tables D.1 and D.2 give the excretion rates for uranium after ingestion.

Table D.1 — Faecal excretion rate after single $m(t_i)$ and chronic $m_c(t_i)$ intake of uranium compounds by ingestion using ICRP 30 HATM and ICRP 69 uranium models

Time (d)	Value of $m(t_i)$ after single intake in Bq/d per 1 Bq incorporated activity (Bq·d^{-1}/Bq)		Value of $m_c(t_i)$ after chronic intake in Bq/d per 1 Bq daily incorporated activity (Bq·d^{-1}/Bq·d^{-1})	
	f_A = 0,02	f_A = 0,002	f_A = 0,02	f_A = 0,002
1	2,8E-01	2,8E-01	2,80E-01	2,80E-01
2	3,8E-01	3,8E-01	6,60E-01	6,70E-01
3	1,9E-01	1,9E-01	8,50E-01	8,70E-01
4	8,0E-02	8,0E-02	9,29E-01	9,51E-01
5	3,1E-02	3,1E-02	9,60E-01	9,82E-01
6	1,2E-02	1,2E-02	9,72E-01	9,94E-01
7	4,3E-03	4,3E-03	9,76E-01	9,98E-01
8	1,6E-03	1,6E-03	9,78E-01	1,00E+00
9	5,8E-04	5,8E-04	9,90E-01	
10	2,1E-04	2,1E-04	9,95E-01	
14	4,4E-06	4,4E-06	1,00E+00	
15	1,9E-06	1,9E-06		
20	3,6E-07	3,6E-07		
30	2,1E-07	2,1E-07		
40	1,5E-07	1,5E-07		
45	1,3E-07	1,3E-07		
50	1,1E-07	1,1E-07		
60	8,8E-08	8,8E-08		
70	6,9E-08	6,9E-08		
80	5,5E-08	5,5E-08		
90	4,3E-08	4,3E-08		
100	3,5E-08	3,5E-08		
120	2,2E-08	2,2E-08		

Table D.2 — Urinary excretion rate after single $m(t_i)$ and chronic $m_c(t_i)$ intake of uranium compounds by ingestion using ICRP 30 HATM and ICRP 69 uranium models

Time (d)	Value of $m(t_i)$ after single intake in Bq/d per 1 Bq incorporated activity (Bq·d^{-1}/Bq)		Value of $m_c(t_i)$ after chronic intake in Bq/d per 1 Bq daily incorporated activity (Bq·d^{-1}/Bq·d^{-1})	
	f_A = 0,02	f_A = 0,002	f_A = 0,02	f_A = 0,002
1	1,3E-02	1,3E-03	7,9E-03	7,9E-04

Table D.2 *(continued)*

Time (d)	Value of $m(t_i)$ after single intake in Bq/d per 1 Bq incorporated activity (Bq·d^{-1}/Bq)		Value of $m_c(t_i)$ after chronic intake in Bq/d per 1 Bq daily incorporated activity (Bq·d^{-1}/Bq·d^{-1})	
2	6,9E-04	7,1E-05	1,3E-02	1,3E-03
3	3,7E-04	3,7E-05	1,3E-02	1,3E-03
4	3,3E-04	3,3E-05	1,4E-02	1,4E-03
5	3,0E-04	3,0E-05	1,4E-02	1,4E-03
6	2,7E-04	2,7E-05	1,4E-02	1,4E-03
7	2,5E-04	2,5E-05	1,5E-02	1,5E-03
8	2,3E-04	2,3E-05	1,5E-02	1,5E-03
9	2,1E-04	2,1E-05	1,5E-02	1,5E-03
10	1,9E-04	1,9E-05	1,5E-02	1,5E-03
14	1,4E-04	1,4E-05	1,6E-02	1,6E-03
15	1,3E-04	1,3E-05	1,6E-02	1,6E-03
20	8,9E-05	8,9E-06	1,7E-02	1,7E-03
30	4,8E-05	4,8E-06	1,7E-02	1,7E-03
40	3,0E-05	3,0E-06	1,8E-02	1,8E-03
45	2,5E-05	2,5E-06	1,8E-02	1,8E-03
50	2,1E-05	2,1E-06	1,8E-02	1,8E-03
60	1,6E-05	1,6E-06	1,8E-02	1,8E-03
70	1,3E-05	1,3E-06	1,8E-02	1,8E-03
80	1,0E-05	1,0E-06	1,8E-02	1,8E-03
90	8,4E-06	8,4E-07	1,8E-02	1,8E-03
100	7,1E-06	7,1E-07	1,9E-02	1,9E-03
120	5,1E-06	5,1E-07	1,9E-02	1,9E-03
180	2,2E-06	2,2E-07	1,9E-02	1,9E-03
200	1,7E-06	1,7E-07	1,9E-02	1,9E-03
300	6,2E-07	6,2E-08	1,9E-02	1,9E-03
360	4,0E-07	4,0E-08	1,9E-02	1,9E-03
400	3,2E-07	3,2E-08	1,9E-02	1,9E-03
500	2,3E-07	2,3E-08	1,9E-02	1,9E-03
600	2,0E-07	2,0E-08	1,9E-02	1,9E-03
700	1,8E-07	1,8E-08	1,9E-02	1,9E-03
800	1,8E-07	1,8E-08	1,9E-02	1,9E-03
900	1,7E-07	1,7E-08	1,9E-02	1,9E-03
1 000	1,6E-07	1,6E-08	1,9E-02	1,9E-03
2 000	1,1E-07	1,1E-08	1,9E-02	1,9E-03
3 000	7,6E-08		1,9E-02	1,9E-03
4 000	5,5E-08		1,9E-02	1,9E-03
5 000	4,1E-08		2,0E-02	2,0E-03
6 000	3,2E-08		2,0E-02	2,0E-03

Annex E
(informative)

Committed effective dose per unit intake after ingestion of uranium compounds

This document describes four different isotopic compositions representing natural (U-nat), depleted (DU) and low (LEU) and high (HEU) enriched uranium forms (see Table 1), representing the typical uranium isotopic compositions encountered in the nuclear industry. Specific isotopic composition should be used as far as they are available.

Tables E.1 and E.2 provide dose coefficients for individual uranium isotopes and uranium mixtures of varying uranium isotopic compositions.

Table E.1 — Dose coefficients ($Sv \cdot Bq^{-1}$) for ingestion of uranium isotopes using ICRP 30 HATM and ICRP 69 uranium models

Alimentary tract transfer factor	Dose coefficients ($\times 10^{-9}$ Sv Bq^{-1})		
	U-238	U-235	U-234
$f_A = 0{,}02$	44	46	49
$f_A = 0{,}002$	7,6	8,3	8,3

Table E.2 — Dose coefficients ($Sv \cdot Bq^{-1}$) for the ingestion of natural uranium (U-nat), depleted uranium (DU), low enriched uranium (LEU) and high enriched uranium (HEU) using ICRP 30 HATM and ICRP 69 uranium models

Alimentary tract transfer factor	Dose coefficient ($\times 10^{-9}$ $Sv \cdot Bq^{-1}$)			
	U-nat	DU	LEU	HEU
$f_A = 0{,}02$	46,52	44,80	48,16	48,88
$f_A = 0{,}002$	7,96	7,72	8,20	8,30

New dose coefficients for ingestion are available at ICRP 137 [43] and may replace the values in Tables E.1 and E.2.