INTERNATIONAL STANDARD

ISO 16638-1

First edition
2015-12-15

Radiological protection — Monitoring and internal dosimetry for specific materials —

Part 1: Inhalation of uranium compounds

Radioprotection — Contrôle et dosimétrie interne des éléments spécifiques —

Partie 1: Inhalation de composés d'uranium

Reference number
ISO 16638-1:2015(E)

ISO copyright office
Ch. de Blandonnet 8 • CP 401
CH-1214 Vernier, Geneva, Switzerland
Tel. +41 22 749 01 11
Fax +41 22 749 09 47
copyright@iso.org
www.iso.org

Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

The committee responsible for this document is ISO/TC 85, *Nuclear energy, nuclear technologies, and radiological protection*, Subcommittee SC 2, *Radiological protection*.

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 requires monitoring potential intakes and/or quantifying actual intakes and exposures. The doses resulting from internal radiation exposure arising from contamination by radioactive substances cannot be measured directly. Decisions have to 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, three International Standards addressing monitoring programmes (ISO 20553:2006), laboratory requirements (ISO 28218:2010) and dose assessments (ISO 27048:2011) have been developed and can be applied in a straightforward manner to many radionuclides. However, for a number of specific materials, the practical application of these International Standards is complex and further guidance may be required, e.g. for accreditation purposes.

This International Standard has been developed to address the specific issue of monitoring and internal dosimetry for inhalation of uranium compounds, which reflects

— the growing interest in nuclear energy production and the associated increase in uranium mining and fuel production,

— the large variation of isotopic compositions of the uranium compounds that may be encountered in the workplace, and

— the importance of taking into account both the chemical and the radiological risks arising from exposures to uranium.

It contributes to harmonizing the practices in the monitoring of occupationally exposed persons while remaining complementary to ISO 20553:2006, ISO 28218:2010 and ISO 27048:2011.

This International Standard describes the need for a monitoring and internal dosimetry programme for the different compounds of uranium and offers guidance on its design. Its development 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 1: Inhalation of uranium compounds

1 Scope

This International Standard specifies the minimum requirements for the design of professional programmes to monitor workers exposed to uranium compounds. It 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 standardised 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 have to be applied.

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

This International Standard addresses, for uranium and its compounds, the following items:

a) purposes of monitoring and monitoring programmes;

b) description of the different categories of monitoring programmes;

c) quantitative criteria for conducting monitoring programmes;

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

e) information that has to be collected for the design of a monitoring programme;

f) general requirements for monitoring programmes (e.g. detection limits, tolerated uncertainties);

g) frequencies of measurements;

h) procedures for dose assessment based on reference levels for routine and special monitoring programmes;

i) assumptions for the selection of dose-critical parameter values;

j) criteria for determining the significance of monitoring results;

k) interpretation of workplace monitoring results;

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

m) reporting/documentation;

n) quality assurance;

o) record keeping requirements.

It is not applicable to the following items:

a) monitoring of exposure due to uranium progeny, including radon;

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

c) dosimetry for litigation cases;

d) modelling for the improvement of internal dosimetry;

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

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

g) dosimetry for ingestion exposures and for contaminated wounds.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/IEC Guide 98-3, *Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

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

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 20553:2006, *Radiation protection — Monitoring of workers occupationally exposed to a risk of internal contamination with radioactive material*

ISO 28218:2010, *Radiation protection — Performance criteria for radiobioassay*

ISO 27048:2011, *Radiation protection — Dose assessment for the monitoring of workers for internal radiation exposure*

ISO 15189:2012, *Medical laboratories — Requirements for quality and competence*

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.

3.1
absorption
movement of material into blood regardless of mechanism, which generally applies to the dissociation of particles and the uptake into blood of soluble substances and material dissociated from particles

3.2
absorption Type F
deposited materials that have high (fast) rates of absorption into body fluids from the respiratory tract

[SOURCE: ICRP 66]

3.3
absorption Type M
deposited materials that have intermediate (moderate) rates of absorption into body fluids from the respiratory tract

[SOURCE: ICRP 66]

3.4
absorption Type S
deposited materials that have low (slow) rates of absorption into body fluids from the respiratory tract

[SOURCE: ICRP 66]

3.5
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.

3.6
activity median aerodynamic diameter
AMAD
value of aerodynamic diameter 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

Note 1 to entry: 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.

3.7
clearance
net effect of the biological processes by which radionuclides are removed from the body or from a tissue, organ or region of the body

Note 1 to entry: The clearance rate is the rate at which this occurs.

3.8
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

3.9
critical value
maximum value for the result of a single measurement in a monitoring programme where it is safe to assume that the corresponding extrapolated annual dose does not exceed a predefined dose level

3.10
decision threshold
fixed or *a posteriori* value of the measurand by which, when exceeded by the result of an actual measurement of a measurand quantifying a physical effect, it is decided that the physical effect is present

3.11
detection limit
smallest true value of the measurand that is detectable by the measuring method

3.12
annual dose
committed effective dose resulting from all intakes occurring during a calendar year

Note 1 to entry: The term “annual dose” is not used to represent the dose received in a year from all preceding intakes.

3.13
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 International Standard, the integration time is 50 years following any intake.

3.14
equivalent dose
product of the absorbed dose and the radiation weighting factor for the specific radiation at this point

3.15
committed equivalent dose
time integral of the equivalent dose rate in a particular tissue or organ following intake of radioactive material into the body of a reference person

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

3.16
excretion function
function describing the fraction of an intake excreted per day after a given time has elapsed since the intake occurred

3.17
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

3.18
intake
<process> act or process of taking radionuclides into the body by inhalation or ingestion or through the skin

3.19
intake
<quantity> activity of a radionuclide taken into the body in a given time period or as a result of a given event

3.20
***in vitro* analyses**
indirect measurements
analyses that include measurements of radioactivity 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.

3.21
***in vivo* measurements**
direct measurements
measurement of radioactivity present in the human body carried out using detectors to measure the radiation emitted

Note 1 to entry: Normally, the measurement devices are whole-body or partial-body (e.g. lung, thyroid) counters.

3.22
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 International Standard distinguishes four different categories of monitoring programmes, namely *confirmatory monitoring programme* (3.23), *routine monitoring programme* (3.24), *special monitoring programme* (3.25) and *task-related monitoring programme* (3.26), as well as two different types of monitoring, namely *individual monitoring* (3.27) and *workplace monitoring* (3.28), which feature in each category.

3.23
confirmatory monitoring programme
monitoring programme carried out to confirm assumptions about working conditions

EXAMPLE Monitoring programme carried out to confirm that significant intakes have not occurred.

3.24
routine monitoring programme
monitoring programme associated with continuing operations and intended to demonstrate that working conditions, including the levels of individual dose, remain satisfactory and meet regulatory requirements

3.25
special monitoring programme
monitoring programme performed to quantify significant exposures following actual or suspected abnormal events

3.26
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

3.27
individual monitoring
monitoring 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

3.28
workplace monitoring
monitoring using measurements made in the working environment

3.29
monitoring interval
period between two consecutive times of measurement

3.30
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

3.31
quality control
part of quality assurance intended to verify that systems and components correspond to predetermined requirements

3.32
quality management
all activities of the overall management function that determine the quality policy, objectives and responsibilities, and that implement them by means such as quality planning, quality control, quality assurance and quality improvement within the quality system

3.33
investigation level
level of dose, exposure or intake at or above which investigation has to be made in order to reduce the uncertainty associated with the dose assessment

3.34
recording level
level of dose, specified by the employer or the regulatory authority, at or above which values of dose received by workers are to be entered in their individual records

3.35
reference level
value of measured quantities above which some specified action or decision should be taken

3.36
retention function
function describing the fraction of an intake present in the body or in a tissue, organ or region of the body after a given time has elapsed since the intake occurred

3.37
scattering factor
geometric standard deviation of the lognormal distribution of bioassay measurements

3.38
time of sampling
<*in vitro* analysis> time at which the biological sample (e.g. urine, faeces) was provided by the individual concerned, i.e. the end time of the collection period

3.39
time of measurement
<*in vivo* analysis> time at which the measurement begins

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 for an integration period of 50 years
$e(50)$	Dose coefficient: committed effective dose per unit intake
f_1	Gastro-intestinal uptake factor
I	Intake
$m(t_i)$	Predicted value of the measured quantity at time, t_i, for unit intake (excretion or retention function at time, t_i, 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)
M_i	Measurement value at time, t_i
M_c	Critical value
ΔT	Duration of the monitoring interval (in days)
$\Delta T/2$	mid-time of the monitoring interval (in days)

$E(t)$	Value of the excretion function at time t (day) after a unit intake
$R(t)$	Value of the retention function at time t (day) after a unit intake
A_{DL}	Detection limit

4.2 Abbreviated terms

AMAD	Activity median aerodynamic diameter
CRM	Certified reference material (ISO 28218)
DAC	Derived air concentration
DIL	Derived investigation level
DL	Annual dose limit = 0,02 Sv
DRL	Derived recording level
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
LEU	Low enriched uranium (uranium with an assay of U-235 from the natural level to 20 %)
LOAEL	Lowest-observed-adverse-effect level
MRL	Minimal risk level
NOAEL	No-observed-adverse-effect level
PAS	Personal air sampler
RPE	Respiratory protective equipment
SAS	Static air sampler
TRS	Transfer reference standard (ISO 28218)
U-nat	Uranium compound with natural isotopic composition
WHO	World Health Organization

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-233 and U-232 are also included. This International Standard describes four different isotopic compositions 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[20]

	U-238		U-235		U-234		Total alpha activity	Alpha activity ratio U-234/ U-238
	Isotopic composition by mass	Total alpha activity	Isotopic composition by mass	Total alpha activity	Isotopic composition by mass	Total alpha activity		
	%	%	%	%	%	%	Bq/g	
U-nat	99,275	48,26	0,72	2,25	0,0055	49,49	2,56E+04	1,03
DU	99,799	83,45	0,2	1,07	0,0010	15,48	1,49E+04	0,186
LEU	96,471	14,78	3,5	3,45	0,02884	81,78	8,12E+04	5,54
HEU	6,41	0,042	92,8	3,92	0,79	96,04	1,89E+06	2282

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 inhalation 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 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. 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 deposition and particle transport data obtained from the ICRP Human Respiratory Tract Model[8] and the ICRP systemic model for uranium[10]; deposition and particle transport parameters are assumed by ICRP to be independent of the chemical form inhaled.

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, and to quantify the likely intake of radioactive material and the resulting committed effective dose received. Decisions about the need for monitoring and the design of the monitoring programme should be made in the light of such a risk assessment, as described in ISO 20553.

Routine monitoring is performed to quantify normal exposures, i.e. where there is no evidence to indicate that acute intakes have occurred but where chronic exposures cannot be ruled out. Routine monitoring programmes assume that working conditions and the risks of intake remain reasonably constant. The design of this type of programme of regular measurements is heavily dependent on the level of the annual dose, which shall be readily and reliably quantified. The level should be well below legally relevant limits, accounting for uncertainties; for example, in activity measurement and dose assessment. If the level is too high, intakes representing considerable fractions of dose limits could be overlooked, while a low value may result in unnecessary efforts at low exposures.

Special monitoring is performed to quantify significant exposures following actual or suspected abnormal events. In comparison to routine monitoring, the time of intake is usually much better known and additional information may be available, which helps to reduce the uncertainty of assessment. The purposes of dose assessment in such cases include

— assistance in decisions about countermeasures (e.g. decorporation therapy),

— compliance with legal regulations, and

— help to improve conditions in the workplace.

In most cases, special monitoring is performed individually. In cases where there is reason to suspect that exposure limits could be exceeded, it may be appropriate to extend the measurements in order to determine individual retention and excretion functions and biokinetic model parameters.

Confirmatory monitoring may be required to check the assumptions underlying the procedures previously selected. It may consist of workplace or individual monitoring, e.g. as occasional measurements to investigate the potential accumulation of activity in the body.

Task-related monitoring applies to a specific operation. The purpose and the dose criteria for carrying out task-related monitoring are identical to those for routine monitoring.

Individual monitoring gives information needed to assess the exposure of a single worker by measuring individual body activities, excretion rates or activity inhaled (using personal air samplers, see 8.2).

Workplace monitoring, which includes *collective monitoring*, provides exposure assessments for a group of workers assuming identical working conditions, i.e. risks of intake as well as all factors influencing the resulting doses. It is mainly used in cases where individual monitoring is not appropriate and it may also be needed in those cases where individual monitoring is not sufficiently sensitive. In some cases results of workplace monitoring are needed to support individual dose assessments (e.g. air monitoring may provide information on the time of an intake).

Factors determining the extent of a monitoring programme are

— the magnitude of likely exposures,

— the requirement to identify accidental exposure events, and

— the need to assess the effectiveness of respiratory protective equipment (RPE).

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 is prevalent when uranium content in the kidney exceeds 3 μg g^{-1} (retrospective) and for radiological hazard 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, particularly lung retention and excretion kinetics. 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 on particle deposition and transport associated with the respiratory tract 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 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 respiratory tract and outdated definitions of the specific activity of uranium, is doubtful. 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 inhaled, inadequate information on the pattern of exposure and an inappropriate choice of the monitoring interval.

The toxicity of uranium varies according to its chemical form, isotopic composition and route of exposure. On the basis of the toxicity of different uranium compounds in animals, it was concluded that the relatively more water-soluble compounds were the most potent renal toxicants. The less water-soluble compounds were of moderate-to-low renal toxicity, and the insoluble compounds had little potential to cause renal toxicity but could cause pulmonary toxicity when exposure was by inhalation.

Uranium is unique among the elements because it presents both a chemical and a radiological hazard. For soluble uranium compounds, with a U-235 enrichment by mass no greater than 3 %, limits on intake

and air concentrations for radiation workers are based on the chemical toxicity of uranium since it is more limiting than the radiological hazard (see Table 2).

Table 2 — The dominant mode of uranium toxicity according to the nature of the exposure

Physicochemical and isotopic characteristics		Toxicity	
Absorption type of uranium compound	U-235 Enrichment by mass	Acute intake or single intake	Chronic intake or multiple intakes
Type F	less than 3 %	Chemical	Chemical
	above 3 %		Radiological
Type M	Less than 30 %	Chemical	Radiological
	above 30 %	Chemical and radiological	
Type S	All enrichment	Radiological	Radiological
All types	With ^{232}U and/or ^{236}U	Radiological	Radiological

6 General aspects

6.1 Radiological aspects

Uranium is an alpha-emitting, radioactive, heavy metal that occurs naturally in the earth's crust at an average concentration of about 2 ppm.[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[1]. Uranium-234 ($T_{1/2}$ = 2,46 × 10^5 years) is a member of the U-238 decay series[42]. The two decay series, which contribute to an important portion of the annual dose from primordial background radiation[2], are shown in Annex A (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 milled 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 can be as follows:

a) *uranium hexafluoride* (UF_6) – uranium hexafluoride is used in the enrichment process and exists in vapour form, but in the presence of water in the atmosphere and in the respiratory tract it is converted to uranyl fluoride (UO_2F_2) aerosol;

b) *uranyl nitrate* ($UO_2(NO_3)_2$) – uranyl nitrate in aqueous solution is widely encountered in nuclear fuel fabrication and reprocessing;

c) *uranyl tributyl phosphate (U-TBP)* – U-TBP is used extensively as an extractant during fabrication of nuclear fuel and for the separation of uranium and plutonium during reprocessing;

d) *ammonium diuranate (ADU)* $(NH_4)_2U_2O_7$ – ADU is an intermediate compound in the uranium fuel cycle;

e) *uranium peroxide hydrate* ($UO_4.nH_2O$) – uranium peroxide hydrate is present at one stage of the enriched uranium fuel cycle;

1) 0,01 vol % (per cent volume fraction) is the equivalent of 100 ppm; ppm is a deprecated unit at ISO.

f) *uranium tetrafluoride* (UF_4) – uranium tetrafluoride is an intermediate product in the uranium fuel cycle;

g) *uranium trioxide* ($UO_3.nH_2O$) – during fuel fabrication uranium trioxide hydrate is formed by heating uranyl nitrate;

h) *uranium octoxide* (U_3O_8) – uranium octoxide can be present in the ore concentrate "yellow cake" and also occurs at later stages in the uranium fuel cycle;

i) *uranium dioxide* (UO_2) – uranium dioxide is the final product in the manufacture of nuclear fuel pellets;

j) *uranium metal* – the metal is used on laser isotopic separation for uranium enrichment and for some reactor fuels;

k) *uranium alloys* – normally with silicon or aluminium, for some reactor fuels.

A wide range of uranium bearing compounds is encountered in the uranium fuel cycle. These range from soluble compounds such as uranyl nitrate ($UO_2(NO_3)_2$) to moderately soluble UO_3 to insoluble compounds such as UO_2 and U_3O_8. 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. Default parameters are presented in Annex B.

This International Standard implements the ICRP 66 lung model[8] and the ICRP 103 dosimetry concepts[19] and is consistent with ICRP 119 compendium of dose coefficients[35].

New default absorption parameters and reviewed dose coefficients for inhalation will be proposed by ICRP in Part 3 of the Occupational Intakes of Radionuclides (OIR series) due to be published in 2016. They will replace the values in Annexes B and D of this International Standard.

6.2 Chemical toxicity

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. 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).

NOTE The NOAEL is defined by WHO[24,25] and IARC[26] 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 may be detected which are judged not to be adverse".

UF_6 is rapidly hydrolyzed to HF gas and UO_2F_2 fumes. Exposure to UF_6 aerosol may result in respiratory tract damage from the HF formed in the air. Thus, the exposure limit to UF_6 may be determined by the LOAELs of hydrofluoric acid rather than the UF_6 itself; see ATSDR 2013[27].

Biomarkers of exposure to uranium include the chemical or radiological detection of uranium in the urine because uranium absorbed through the oral, dermal, and inhalation routes is excreted in urine mostly as uranyl ions. Uranium urinalysis data have been shown to correlate with airborne uranium exposures when averaged over a period of time.

7 Reference levels for uranium

7.1 Radiological aspects

ISO 20553 states that "reference levels are the values of quantities above which a particular action or decision shall be taken". The purpose of setting these levels is so that unnecessary, non-productive assessments or interventions can be avoided and resources can be used where they are most needed. Reference levels include the recording level, above which a dose assessment has to be recorded, lower values being ignored; and the investigation level, above which the exposure estimates have to be confirmed by additional investigations.

ISO 20553 further clarifies (see Table 3) that "the recording level shall be set at a value corresponding (having regard to the length of the monitoring interval) to an annual dose no higher than 5 % of the annual dose limit. The investigation level shall be set at a value corresponding to an annual dose no higher than 30 % of the annual dose limit". Thus, for an annual dose limit of 20 mSv, the recording level should be set at a maximum of 1 mSv and the investigation level at a maximum of 6 mSv.

Table 3 — Reference levels for monitoring internal exposures (ISO 20553)

Level	Meaning
Recording level	The recording level is the level of dose, exposure or intake at or above which dose assessments have to be recorded in the individual exposure records. It shall be set at a value corresponding to an annual dose no higher than 5 % of the annual dose limit. Results falling below this level may be shown as "below recording level".
Investigation level	The investigation level is a level of dose, exposure or intake at or above which investigation has to be made in order to reduce the uncertainty associated with the dose assessment. The level shall be set at a value corresponding to an annual dose no higher than 30 % of the annual dose limit.

The upper level at which the derived recording level (DRL) and derived investigation level (DIL) should be set, based on bioassay measurements, can be calculated according to Formula (1) and Formula (2) respectively:

$$\mathrm{DRL} = \frac{5\% \times \mathrm{DL} \times m\left(\Delta T / 2\right)}{e\left(50\right)} \times \frac{\Delta T}{365} \tag{1}$$

$$\mathrm{DIL} = \frac{30\% \times \mathrm{DL} \times m\left(\Delta T / 2\right)}{e\left(50\right)} \times \frac{\Delta T}{365} \tag{2}$$

where

DRL and DIL are expressed as either retention (Bq) or excretion (Bq d^{-1});

DL is the annual dose limit (Sv);

$e(50)$ is the dose coefficients (Committed effective dose per unit intake) for radiotoxicological hazard (see Table D.1 in Annex D) (Sv Bq^{-1});

$\Delta T/2$ is the mid-point of the monitoring period (d);

$m(\Delta T/2)$ is the value of the excretion or retention function at time $\Delta T/2$ (Bq per Bq intake) or (Bq/d per Bq intake);

$\Delta T/365$ is the fraction of the annual exposure limit attributed to the monitoring interval.

Table 4 — Derived recording and investigation levels for natural uranium compounds

Type of monitoring	Absorption type	Time interval for measurement (days)	Natural uranium[a]		Unit[b]
			Derived recording level	Derived investigation level	
Urine[c]	F – hexafluoride[d]	30	1,4E-01	8,5E-01	Bq d^{-1}
	F - peroxide, nitrate[d]	30	2,4E-01	1,5E+00	Bq d^{-1}
	Ammonium diuranate[d]				
	M	90	2,7E-02	1,6E-01	Bq d^{-1}
	S	90	2,4E-04	1,4E-03	Bq d^{-1}
Faecal[c]	M	180	1,7E-02	9,9E-02	Bq d^{-1}
	S	180	8,7E-03	5,2E-02	Bq d^{-1}
Lung	M	180	5,8E+00	3,5E+01	Bq
	S	180	3,0E+00	1,8E+01	Bq

[a] Isotopic composition in Table 1.

[b] Units expressed in total alpha activities.

[c] Levels where there is no previous intake of uranium and in addition to natural intakes.

[d] Levels for absorption Type F compounds depend on their reactivity.

Table 5 — Derived recording and investigation levels for depleted uranium compounds

Type of monitoring	Absorption type	Time interval for measurement (days)	Depleted uranium[a]		Unit[b]
			Derived recording level	Derived investigation level	
Urine[c]	F – hexafluoride[d]	30	1,5E-01	8,9E-01	Bq d^{-1}
	F - peroxide, nitrate[d]	30	2,5E-01	1,5E+00	Bq d^{-1}
	Ammonium diuranate[d]				
	M	90	2,9E-02	1,7E-01	Bq d^{-1}
	S	90	2,5E-04	1,5E-03	Bq d^{-1}
Faecal[c]	M	180	1,8E-02	1,1E-01	Bq d^{-1}
	S	180	9,2E-03	5,5E-02	Bq d^{-1}
Lung	M	180	6,4E+00	3,8E+01	Bq
	S	180	3,2E+00	1,9E+01	Bq

[a] Isotopic composition in Table 1.

[b] Units expressed in total alpha activities.

[c] Levels where there is no previous intake of uranium and in addition to natural intakes.

[d] Levels for absorption Type F compounds depend on their reactivity.

Table 6 — Derived recording and investigation levels for low enriched uranium compounds

Type of monitoring	Absorption type	Time interval for measurement (days)	LEU[a]		Unit[b]
			Derived recording level	Derived investigation level	
Urine[c]	F – hexafluoride[d]	30	1,4E-01	8,2E-01	Bq d^{-1}
	F - peroxide, nitrate[d]	30	2,3E-01	1,4E+00	Bq d^{-1}
	Ammonium diuranate[d]				
	M	90	2,4E-02	1,5E-01	Bq d^{-1}
	S	90	2,2E-04	1,3E-03	Bq d^{-1}
Faecal[c]	M	180	1,5E-02	9,1E-02	Bq d^{-1}
	S	180	8,2E-03	4,9E-02	Bq d^{-1}
Lung	M	180	5,3E+00	3,2E+01	Bq
	S	180	2,8E+00	1,7E+01	Bq

[a] Isotopic composition in Table 1.

[b] Units expressed in total alpha activities.

[c] Levels where there is no previous intake of uranium and in addition to natural intakes.

[d] Levels for absorption Type F compounds depend on their reactivity.

Table 7 — Derived recording and investigation levels for high enriched uranium compounds

Type of monitoring	Absorption type	Time interval for measurement (days)	LEU[a]		Unit[b]
			Derived recording level	Derived investigation level	
Urine[c]	F – hexafluoride[d]	30	1,4E-01	8,1E-01	Bq d^{-1}
	F - peroxide, nitrate[d]	30	2,3E-01	1,4E+00	Bq d^{-1}
	Ammonium diuranate[d]				
	M	90	2,4E-02	1,4E-01	Bq d^{-1}
	S	90	2,2E-04	1,3E-03	Bq d^{-1}
Faecal[c]	M	180	1,5E-02	8,9E-02	Bq d^{-1}
	S	180	8,0E-03	4,8E-02	Bq d^{-1}
Lung	M	180	5,2E+00	3,1E+01	Bq
	S	180	2,8E+00	1,7E+01	Bq

[a] Isotopic composition in Table 1.

[b] Units expressed in total alpha activities.

[c] Levels where there is no previous intake of uranium and in addition to natural intakes.

[d] Levels for absorption Type F compounds depend on their reactivity.

Tables 4 to 7 present derived recording and investigation levels for natural, depleted, low enriched and high enriched uranium compounds, with isotopic compositions given in Table 1, for intakes via inhalation of 5 µm AMAD particles. For other compounds, or where the specific material is known along with the absorption parameter values, specific values should be calculated.

Some of the derived recording levels listed in Tables 4 to 7 are under the detection limits of the usual bioassay technique, especially for lung monitoring, which proves that, for routine monitoring, the corresponding measurement method alone is not sufficient and underlines the importance of complementary *in vivo, in vitro* and workplace monitoring programmes. Data for these compounds are provided to give a numerical basis for decisions on whether the monitoring method is appropriate.

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. Thus 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[32,52] (see 13.3).

7.2 Chemical toxicity

7.2.1 General

In some cases, particularly for Type F uranium compounds, limits arising from chemical toxicity may be more restrictive than the DRL and DIL values.

Estimates of exposure levels posing a minimal risk level (MRL) to humans have been made and published for uranium by ATSDR[27]: "An MRL is defined as an estimate of daily human exposure to a substance that is likely to be without an appropriate risk of adverse effects over a specified duration of exposure". MRLs can be derived for acute and chronic duration exposures for inhalation and oral routes. The concept of NOAEL is informative and used to identify the point of departure for the MRLs.

While the MRL gives guidance on a lower level below which the chemical toxicity of uranium does not need to be considered, the exposure limits provide an upper level at which action is required. Between these levels account still needs to be taken of potential chemical toxic effects.

The MRLs for toxicological profiles[53] fixed by the Agency for Toxic Substances and Disease Registry (ATSDR)[27] are presented in Table 8.

— MRL of 8E-03 mg U m^{-3} for intermediate-duration inhalation exposure to insoluble compounds of uranium based on a NOAEL of 1,1 mg U m^{-3} for renal effects in dogs.

— MRL of 4E-04 mg U m^{-3} for intermediate-duration inhalation exposure to soluble compounds of uranium based on a LOAEL of 0,15 mg U m^{-3} for renal effects in dogs.

— MRL of 3E-04 mg U m^{-3} for chronic-duration inhalation exposure (365 days or more) to soluble compounds of uranium based on a NOAEL of 0,05 mg U m^{-3} for renal effects in dogs.

Table 8 — Minimal risk levels (MRLs) for toxicological profiles for uranium compounds

Compound	Route	Duration	MRL	End point
Uranium highly soluble salts	Inhalation	Acute	4E-04 mg U m^{-3} (1,0 E-02 Bq m^{-3})[a]	Renal
		Chronic	3 E-04 mg U m^{-3} (7,7E-03 Bq m^{-3})[a]	Renal
Uranium insoluble compounds	Inhalation	Acute	8E-03 mg U m^{-3} (2,1E-01 Bq m^{-3})[a]	Renal

[a] In brackets, correspondence in term of activity for natural uranium (by the use of specific activity in Table 1).

7.2.2 Exposure limits

In the United States, the current Occupational Safety and Health Administration (OSHA) permissible exposure limits (PELs) for uranium and the insoluble uranium compounds (measured as uranium) are 0,2 milligrams per cubic metre (mg m^{-3}) of air as an 8 h time-weighted average (TWA) concentration and 0,6 mg m^{-3} as a 15 min TWA short-term exposure limit (STEL). A STEL is the maximum 15-min concentration to which workers may be exposed during any 15 min period of the working day [29 CFR 1910.1000]. The National Institute for Occupational Safety and Health (NIOSH) has not issued a

recommended exposure limit (REL) for uranium or its insoluble uranium compounds; however, NIOSH concurs with the PEL established for this substance by OSHA [NIOSH 1988]. The American Conference of Governmental Industrial Hygienists (ACGIH) has assigned uranium and the insoluble uranium compounds a threshold limit value (TLV) of 0,2 mg m^{-3} as a TWA for a normal 8 h workday and a 40 h workweek and a STEL of 0,6 mg m^{-3} for periods not to exceed 15 min [ACGIH 1988, p. 37[55]]. The OSHA and ACGIH limits are based on the risk of kidney and blood disorders and on the radiological damage associated with exposure to uranium or an insoluble uranium compound.

7.3 Application of reference levels

Urine assay is the method of choice for assessing the chemical risk for uranium compounds. Where Table 2 indicates that chemical toxicity could be significant, it shall be confirmed that chemical limits are not exceeded. Uranium urine analysis data have been shown to correlate with airborne uranium exposures when averaged over a period of time. Thus, urine samples can be used to verify the adequacy of air sampling. Table 9 indicates the derived investigation levels in urine for this risk, based on a maximum kidney concentration of 3 µg g^{-1}[48].

Table 9 — Derived investigation levels for the chemical risk of uranium compounds[48]

Type of monitoring	Absorption type	Time interval for measurement (days)	Chemical toxicity	Unit
			Derived investigation level	
Urine	F	30	20	µg d^{-1}
	M	90	16	µg d^{-1}
	S	90	0,17	µg d^{-1}

That can be also achieved by measuring air concentrations directly.

8 Routine monitoring programmes

8.1 General

Routine monitoring programmes are established to quantify exposures where there is the possibility either of undetected accidental intakes or of chronic intakes. Measurements in a routine monitoring programme are made at pre-determined times and are not related to any known intake events. Decisions, therefore, have to be made in advance concerning methods, frequencies and the underlying biokinetic models. For the evaluation of measured values in terms of intakes it is also necessary to make assumptions concerning the time interval between intake and measurement. Routine monitoring programmes shall be established including suitable workplace monitoring and individual monitoring according to the criteria in ISO 20553.

The objectives of a monitoring programme and the way it is to be organized shall be documented according to Clause 14 including the basis for interpreting the results. The monitoring programme shall be reviewed by means of a confirmatory monitoring programme after any major modifications have been made to the installation, to operations or to the regulatory requirements.

8.2 Workplace monitoring

Workplace monitoring includes collective monitoring (i.e. individual monitoring of selected workers representing groups of workers), and measurements of airborne activity and surface contamination in the workplace. Surface contamination is not directly related to individual exposure but can indicate increased risk of intake.

Continuous monitoring of airborne radioactive material is important, because inhalation is generally the main exposure pathway for workers. The main objectives of monitoring airborne activity are

— to help to assess the internal exposure of workers through inhalation,

— to rapidly detect abnormal or deteriorating conditions, thereby making it possible to take the appropriate protective action, for example, the use of respiratory protective equipment, and

— to provide information for setting up individual monitoring programmes for workers.

The establishment of an air-monitoring system in order to detect and assess collective or individual exposure requires knowledge of the conditions at the workplace and the materials handled there. The design of the system is expected to be tailored to the risk of intake.

The results of air-monitoring can be used to estimate the intake of a radioactive substance by workers but reliance on measurement of airborne activities alone can lead to errors in exposure estimates. This is true when sources of air contamination are localized or change position over time, often because of worker action or movement.

Workplace air-monitoring results can be considered as representative provided they meet two criteria. Firstly, they reliably shall not underestimate the intakes as measured *in vivo* or by *in vitro* individual measurements (see Annex C). Secondly, they shall be confirmed by a confirmatory monitoring programme, involving the use of individual air-sampling devices or the use of individual excretion measurements.

Underestimation may be avoided by applying correction factors that take into account spatial and temporal variability of radionuclide concentrations in the worker's breathing zone.

8.3 Individual monitoring

8.3.1 General

Routine monitoring programmes are established to quantify exposures where there is the possibility either of undetected accidental intakes or of chronic intakes. Measurements in a routine monitoring programme are made at pre-determined times and are not related to any known intake events. Decisions, therefore, have to be made in advance concerning methods, frequencies and the underlying biokinetic models. For the evaluation of measured values in terms of intakes it also is necessary to make assumptions concerning the time interval between intake and measurement. Routine monitoring programmes shall be established including suitable workplace monitoring and individual monitoring.

The general requirements described in 8.3.2 and 8.3.3 shall be observed when specifying a routine monitoring programme.

The acceptable methods for the quantification of uranium in urine should have a detection limit of 5 µg l^{-1} (0,13 Bq l^{-1} for U-nat or 0,2 Bq d^{-1} based on a 1,6 l d^{-1} daily excretion[15]) and a precision of 30 %.

8.3.2 Dosimetric and radiation

For a dosimetric and radiation purpose

— the consequences resulting from an unknown time interval between intake and measurement shall be limited so that on average over many monitoring intervals, doses are not underestimated,

— the maximum underestimate of the dose resulting from a single intake, due to the assumption regarding the time of intake, does not exceed a factor of three,

— the detection of all annual exposures that can exceed 1 mSv shall be ensured – for some uranium compounds, this requirement can only be achieved by workplace monitoring, and

— at least two measurements shall be performed annually, as required in ISO 20553.

8.3.3 Chemical hazard

For a chemical hazard

— the consequences resulting from an unknown time interval between intake and measurement shall be limited so that on average over many monitoring intervals, exposures are not underestimated, and

— the detection of daily exposures that can exceed the toxicological limits shall be ensured.

8.4 Methods and monitoring intervals

8.4.1 General

The methods for determining monitoring intervals are based on the occupational risk and hazard evaluation of the working environment. Information from past collective and individual monitoring is also taken into account in determining the frequency of sampling. It would be prudent to sample at a higher than required rate in a new facility compared to an old one. The time intervals provided in 8.4.2 and 8.4.3 are based upon a well-known working area, regular exposures and a routine monitoring programme.

8.4.2 Time intervals for toxicological risk

Urine samples are collected on a "spot sample" basis for the survey of toxicological risk assessment. For workers, there are several routine monitoring options for systematic exposure to uranium compounds, depending on the interpretation (exposure, uptake and accumulation), spot sample at the beginning, or at the end of the working period. Table 10 summarizes the maximum time intervals for natural or depleted uranium.

Table 10 — Maximum time intervals for routine monitoring programmes after inhalation of Type F compounds for natural or depleted uranium in case of toxicological risk

In vitro analyses urine sampling by "spot sample"		
Radionuclide / material	**Absorption type**	**Days**
Uranium hexafluoride	F	30
Uranium peroxide	F	30
Uranium nitrate	F	30
Ammonium diuranate	F	30

8.4.3 Time intervals for radiotoxicological risk

The measurement frequency required for a routine monitoring programme depends on the retention and excretion of the radionuclide, the sensitivity of the available measurement techniques and the uncertainty that is acceptable when estimating annual intake and committed effective dose:

for *in vivo* measurements for *in vitro* analyses

$$e(50)\cdot\frac{A_{DL}}{R(\Delta T)}\cdot\frac{365}{\Delta T}\leq 1\,\text{mSv} \qquad e(50)\cdot\frac{A_{DL}}{E(\Delta T)}\cdot\frac{365}{\Delta T}\leq 1\,\text{mSv} \tag{3}$$

If exposure to more than one radionuclide cannot be ruled out, this requirement shall be adjusted accordingly so that a total annual dose of 1 mSv can reliably be detected and assessed.

The maximum potential underestimation shall not exceed a factor of three, as required in ICRP 75[12] and in ISO 20553; assuming that a single intake occurred in the middle of the monitoring interval this requirement means:

for *in vivo* measurements for *in vitro* analyses

$$\frac{R\left(\frac{\Delta T}{2}\right)}{R\left(\Delta T\right)} \leq 3 \qquad \frac{E\left(\frac{\Delta T}{2}\right)}{E\left(\Delta T\right)} \leq 3 \tag{4}$$

8.4.4 Principles and assumptions

The methods and time intervals summarized in 8.4 were derived from the principles laid down above and the following assumptions:

— ICRP 66 models for inhalation (default values for workers; AMAD = 5 µm);

  — $e(50)$ = dose coefficient: committed effective dose accumulated within 50 years following a unit intake;

— element-specific retention and clearance functions defined by ICRP 78;

  — $E(t)$ = value of the excretion function at time t (day) after a unit intake;

  — $R(t)$ = value of the retention function at time t (day) after a unit intake;

— acute intake by inhalation at the mid-point of the monitoring interval. This is a reasonable assumption for chronic intakes and on average it prevents the underestimation of intakes; and

  — ΔT = duration of time interval (day) between two measurements in a routine monitoring programme;

— with A_{DL} values of the detection limit for routine measurements as from ICRP 78.

Table 11 summarizes the maximum time intervals for routine monitoring programmes for specified uranium compounds for default values of parameters recommended by ICRP publications. In case of validated specific values of solubility or other biokinetic models, these time intervals can be recalculated.

Table 11 — Maximum time intervals for routine monitoring programmes for uranium compounds in case of radiological risk

		In vitro analyses		*In vivo* measurements
Material	**Absorption type**	**Urine (days)**	**Faeces (days)**	**Lungs (days)**
Uranium hexafluoride	F	30	-	-
Uranium peroxide	F	30	-	-
Uranium nitrate	F	30	-	-
Ammonium diuranate	F	30	-	-
Uranium tetrafluoride	M	90	180	180
Uranium trioxide	M	90	180	180
Uranium octoxide	S	90	180	180
Uranium dioxide	S	90	180	180

9 Special monitoring programmes

9.1 Workplace monitoring

Special monitoring refers to measurements when intake is suspected following an event. Special workplace monitoring is based on the same principles as for routine workplace monitoring and the same requirements shall be fulfilled. Devices fitted with alarms and which operate continuously should be used.

9.2 Individual monitoring

The goal of special individual monitoring is to ensure that significant intake is 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 vivo* measurements and *in vitro* analyses in association with the appropriate biokinetic model.

9.2.1 Recommended monitoring for toxicological risk

For a single event involving soluble compounds of uranium, "spot sample" collections should be made to quantify the excretion of uranium and to follow the biomarkers involved for kidney diseases. Follow-up of excretion over the ensuing days can be also important because of the information it provides concerning the amount of intake. 24 h samples make it possible to identify the transferability class of the compound. Table 12 summarizes the recommended methods for natural or depleted uranium.

Table 12 — Recommended methods for special monitoring programmes after inhalation of Type F compounds for natural or depleted uranium in case of toxicological risk

Compound	*In vitro* analyses urine	
	Spot sample	24 h
Uranium hexafluoride	R	S
Uranium peroxide	R	S
Uranium nitrate	R	S
Ammonium diuranate	R	S
R = recommended S = supplementary (helpful but not mandatory)		

9.2.2 Recommended monitoring and period for radiotoxicological risk

The analyses made following a contamination event enable quantification of the significance of the incident and estimation of the value of the intake according to ICRP models. The intake route assumed in systematic monitoring is inhalation. Given that, for uranium, the lung counting results are often below the detection limits, 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 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 and to carry out specific checks. Large fluctuations in the fecal excretion of radionuclides from one day to the next give rise to uncertainty when interpreting the results. Consequently, fecal samples should preferably be collected over a period of about three consecutive days to reduce this uncertainty. Table 13 shows the recommended methods for special monitoring after inhalation of uranium compounds.

Table 13 — Recommended methods for special monitoring programmes after inhalation of Types F, M or S uranium compounds for all enrichment in case of radiological risk

Compound	Nasal sample	*In vitro* analyses		*In vivo* measurements
		Urine	Faeces	Organ
		24 h	72 h	Lung
Uranium hexafluoride	R	R		
Uranium peroxide	R	R		
Uranium nitrate	R	R		
Ammonium diuranate	R	R		
Uranium tetrafluoride	R	R	S	S
Uranium trioxide	R	R	S	S
Uranium octoxide	R	R	R	R
Uranium dioxide	R	R	R	R
R = recommended S = supplementary (helpful but not mandatory)				

For special monitoring, the duration of the sampling or measurement is function of time after the event. It could be noted that, dependent upon the biokinetic of the compound, there may be a restricted period in which useful results can be obtained. Table 14 gives the range of time corresponding to the allowance to achieve an investigation level for uranium compounds.

Table 14 — Minimum sampling frequency after an acute inhalation of specified compounds

Compound	Lung	Urine	Faeces
Uranium hexafluoride	Not applicable	1 to 90 d	Not applicable
Uranium peroxide			
Uranium nitrate			
Ammonium diuranate	1 to 7 d	1 to 90 d	1 to 180 d
Uranium tetrafluoride	1 to 7 d	1 to 90 d	1 to 180 d
Uranium trioxide	1 to 180 d	1 to 365 d	1 to 365 d
Uranium octoxide			
Uranium dioxide			

10 Task-related monitoring programmes

10.1 Workplace monitoring

Workplace monitoring is based on the same principles as for routine workplace monitoring and the same requirements shall be fulfilled. The establishment of an air-monitoring system in order to detect and assess collective or individual exposure requires knowledge of the conditions at the workplace and the materials handled there.

10.2 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.

11 Performance criteria for laboratories

11.1 General

ISO 27048 defines the critical value, M_c, as "the maximum value for the result of a single measurement where the corresponding extrapolated annual dose does not exceed a predefined dose level". It specifies that critical values "shall be derived for each routine monitoring programme. This dose level shall be set such that lower doses may be considered negligible".

11.2 Critical values

M_c, defined in ISO 27048:2011, can be used to fix the criteria of service laboratories for each routine monitoring programme. Assuming a single acute intake at the midpoint of the monitoring interval, M_c for a routine monitoring programme can be calculated using Formula (5):

$$M_c = \frac{D_v \times m(\Delta T / 2)}{e(50)} \times \frac{\Delta T}{365} \quad (5)$$

where

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

$m(\Delta T/2)$ is, for *in vitro* measurements, the value of the excretion function at time $\Delta T/2$ (days) after a unit intake, and, for *in vivo* measurements, the value of the retention function at time $\Delta T/2$ (days) after a unit intake;

$e(50)$ is the dose coefficient: the committed effective dose per unit intake for inhalation (appropriate absorption type).

For measurement results below M_c, there is no need to evaluate the intake or dose explicitly: the dose may be regarded as insignificant. The measured value (if above the decision threshold) shall be recorded in order to document the fact that the measurement was carried out and to provide information to support any possible future reassessment of dose. Table 15 lists values of M_c for the monitoring periods specified in ISO 20553 and for a value of D_v of 10^{-4} Sv.

Table 15 — Critical values (M_c) for various uranium compounds for routine monitoring

Type of monitoring	Absorption type	Max. time interval for measurements (days)	Critical value for D_v = 0.1 mSv[a]	Unit[b]
Urine	F - hexafluoride	90	0,01	Bq d^{-1}
	F - peroxide, nitrate, ammonium diuranate	30	0,02	Bq d^{-1}
	M	90	0,003	Bq d^{-1}
	S	90	2 E-05	Bq d^{-1}
Faecal	M	180	2 E-03	Bq d^{-1}
	S	180	9 E-04	Bq d^{-1}
Lung	M	180	0,6	Bq
	S	180	0,3	Bq

[a] Data are presented for natural uranium.

[b] Units expressed in total alpha activities.

11.3 Reference values

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 (6):

$$\text{reference} \cdot \text{value} = \frac{D_v \times m\left(t1 \div t3\right)}{e\left(50\right)} \tag{6}$$

where

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

$m\left(t1 \div t3\right)$ is, for *in vitro* and *in vivo* measurements, the sum of the excretion or retention function during the first 3 days after the event;

$e(50)$ is the dose coefficient: the committed effective dose per unit intake for inhalation (appropriate absorption type).

Table 16 lists reference values related to the total excretion or retention in the 3 first days, after inhalation.

Table 16 — Reference values for various uranium compounds for special monitoring

Type of monitoring	Absorption type	Derived value for D_v = 0,1 mSv[a]	Unit[b]
Urine	F - hexafluoride	1,5 E+01	Bq d^{-1}
	F - peroxide, nitrate, ammonium diuranate	1,5 E+01	Bq d^{-1}
	M	5,8 E-02	Bq d^{-1}
	S	8 E-03	Bq d^{-1}
Faecal	M	1,8 E+01	Bq d^{-1}
	S	2 E+01	Bq d^{-1}
Lung	M	1,0 E+01	Bq
	S	1,1 E+01	Bq

[a] Data are presented for natural uranium.

[b] Units expressed in total alpha activities.

For some monitoring types, actual detection limits do not fulfil these requirements. Data are provided to give a numerical basis for decisions on whether the monitoring method is appropriate. The detection limits are adequate for special monitoring. For routine monitoring, bioassay techniques can be used, but for lung monitoring the usual detection limits would not be adequate to detect intakes at these levels.

11.4 Performance criteria for workplace monitoring

The measurement or assessment of concentrations of radioactivity in air may be used to quantify the exposure of the workers. The assessment procedures have been described in ISO 27048:2011, Clause 6 and assume that the measured activity concentration is representative of the air in the breathing zone. For operational purposes, exposure expressed as product of derived air concentrations (DAC as described in ICRP 30, Part 1[7]) times the exposure time (and expressed e.g. in units of DAC-h) can be used to estimate exposures and keep them within limits.

12 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) intra-laboratory analyses (e.g. known quantities, replicates and blanks);

e) participation in available inter-laboratory 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 International Standard;

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. In the case of *in vivo* radiobioassay, measurement system response stability shall be established by means of a check source and a "tolerance chart". The response should not vary by more than 5 % from the established mean. The response should be checked at the beginning of the operating period and at the conclusion of the operating period. Replicate *in vivo* measurements should also be made periodically. Techniques such as quality control or tolerance charts shall be used for the evaluation of instrument performance. A quality control measurement shall be performed prior to use of the instrument, and the number of quality control measurements should comprise at least 5 % of the measurement with no fewer than five quality control measurements.

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 vivo* or *in vitro* analyses and/or assessments for internal dosimetry should participate in national or international intercomparison exercises.

13 Procedure for the assessment of exposures

13.1 General

The general procedure for the assessment of exposures is described in ISO 27048:2011. 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.

13.2 Assessment of workplace monitoring data

Workplace monitoring gives an idea of the order of magnitude of exposures. It is a collective and continuous survey of potential atmospheric releases and provides information on long-term air concentrations and also rapid warning of high level releases. Workplace monitoring is complementary to individual monitoring.

13.3 Assessment of individual monitoring data

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. 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. Alternatively, published data may be used, particularly those reported in IDEAS Guidelines, section 4.1.3[52]. 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 mentioned actions above are taken, the individual's drinking water and food supply shall be investigated.

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.

13.4 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 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.

13.5 Uncertainties

In routine monitoring, the time of any acute intake is generally unknown. Typically, it is assumed that the intake takes place at the midpoint of the interval, or a possible uniform chronic intake. If the actual intake is a single intake occurring at the beginning of the monitoring interval, then the assessed dose underestimates the true dose[28,29,39,46]. Conversely, if it occurs at the end of the monitoring interval, the dose is overestimated. The magnitude of both the underestimate and overestimate should be evaluated.

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.

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 17. See also Annex E. 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

   1) the particle size distribution of the aerosol, as described by the AMAD and the geometric standard deviation[35],

   2) the absorption characteristics of the material, as described by the absorption type (F, M or S) or absorption parameter values, f_r, s_r, s_s, f_b and s_b,

   3) the gastro-intestinal uptake factor, f_1, and

   4) 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. The information recorded should be determined for each monitoring procedure in use; for individual cases, the information should be collected only for doses above the investigation level (see ISO 20553:2006).

Table 17 — 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 time or period of intake			
Uncertainty in measured quantity (Type A and Type B combined)			
Uncertainty in particle size distribution			
Uncertainty in absorption classification and gastro-intestinal absorption factor			

13.6 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, ISO 20553 and ISO 27048. 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 intercomparison exercises[32,43].

14 Reporting and documentation

14.1 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) identification of the individual responsible for the report.

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

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

14.2 Reporting results for *in vivo* measurements

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

a) subject identification;

b) date and (as appropriate) time of measurement;

c) identification of uranium isotopes detected;

d) identification of specific measurement procedures and equipment;

e) quantification of the amount of each uranium isotope or progenies measured in each part of the body counted at the time of measurement;

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

g) values of the decision threshold and detection limit;

h) the value of the customer-specified or service laboratory action level for prompt notification;

i) identification of the individual responsible for the report.

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

14.3 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 (compound, AMAD, etc.),

c) a precise isotopic composition of uranium compound,

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 AMAD and f_1, chemical and physical nature of the radioactive aerosol, together with assumptions on the absorption type,

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

h) the results expressed in terms of 50 year 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.

Account shall be taken of the national requirements specified by national legal regulations.

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 days	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 days	Alpha
Po-218	3,10 min	Alpha
Pb-214	26,8 min	Beta
Bi-214	19,9 min	Beta
Po-214	0,00016 s	Alpha
Pb-210	22,2 years	Beta
Bi-210	5,013 days	Beta
Po-210	138,4 days	Alpha
[a] According to ICRP 107 Nuclear Decay Data for dosimetric calculations[20]		

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 days	Alpha
Ra-223	11,43 days	Alpha
Rn-219	3,96 s	Alpha
Po-215	0,00178 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[20]		

Annex B
(informative)

Default classification of uranium compounds

Typical compounds encountered, from milling to fuel fabrication, along with their associated lung clearance types and f_1 factors assigned by the ICRP, are listed in Table B.1. Various authors have reported results of solubility studies, presenting the absorption parameter values of the ICRP Human Respiratory Tract Model (HRTM)[48] specific to the materials investigated. These absorption parameters describe the fraction of material that rapidly dissolves in the respiratory tract as well as the rates of dissolution of the rapid and slow phases of the material from the respiratory tract to blood. They consist of

— rapidly dissolving fraction, f_r,

— rapid dissolution rate, s_r, and

— slow dissolution rate, s_s.

The absorption parameter values for the ICRP 66[8] default Types F, M, and S are also listed in Table B.1. Generally, solubility studies of uranium bearing compounds have found the rapid dissolution rate, s_r, for these compounds to be less than the default value of 100 d^{-1}, and varied by about two orders of magnitude from 0,1 d^{-1} to about 10 d^{-1}.

Table B.1 — Summary of absorption parameter values of default ICRP 66 lung clearance types

ICRP lung absorption parameter	Typical compounds	f_1	HRTM absorption parameter values		
			f_r	s_r (d^{-1})	s_s(d^{-1})
F	Most hexavalent compounds, e.g. UF_6, UO_2F_2, $UO_2(NO_3)_2$	0,02	1	100	-
M	Less soluble compounds, e.g. UO_3, UF_4, UCl_4 and most other hexavalent compounds	0,02	0,1	100	5 E-03
S	Highly insoluble compounds, e.g. UO_2, U_3O_8	0,002	0,001	100	1 E-04

In ICRP 68:(1995)[9]

— uranyl nitrate, uranium hexafluoride, ammonium diuranate were considered to be as a Type F behaviour,

— trioxide and tetrafluoride were considered to be typically represented as a Type M compound, and

— uranium octoxide and uranium dioxide were considered to be Type S compounds.

Uranium metal, uranium peroxide and tributyl phosphate have not yet been assigned to absorption types by ICRP.

New default absorption parameters for inhalation will be proposed by ICRP in Part 3 of the Occupational Intakes of Radionuclides (OIR series) and will replace the values in Table B.1.

Annex C
(informative)

Measurement techniques for uranium

C.1 General

Uranium can enter the human body through inhalation, ingestion or through skin wounds. Measurement of the quantities of uranium in the body can be performed by two primary methods: *in vivo* measurements and *in vitro* measurements. These types of measurements are called bioassays. *In vivo* techniques measure the quantities of internally deposited uranium directly using a whole body counter, while *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 body activities, excretion rates or activity inhaled (using personal air samplers).

For routine monitoring, special monitoring, or task-related monitoring, *in vitro* and/or *in vivo* measurement techniques, workplace monitoring techniques, or a combination of these 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. As detailed description of the measurement methods and techniques is beyond the scope of this International Standard, C.2 to C.4 give a brief introduction to the measurement techniques available for *in vitro* measurement, *in vivo* measurement, and workplace monitoring.

The ethics and human dignity of sampling regimes shall be ensured according to the Convention on Human Rights and Biomedicine[54] and ISO 15189 for the accreditation of laboratories.

C.2 *In vitro*

C.2.1 General

In vitro measurement is used widely for the monitoring of internal contamination of uranium[3-5]. Urine and faecal excreta are the typical bioassay samples collected for measurement. Nasal, blood or other biological samples may be used in some special cases, although the accuracy of these methodologies is not fully determined. Urine analysis is the most widely used method, but faecal measurement is often used, especially when the exposure involves relatively insoluble uranium compounds due to the large (up to four orders of magnitude) difference in excretion function values.

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[4]) or specific gravity of the sample (Dai et al. 2011[33]). 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.1 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 28218:2010.

Table C.1 — 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 µg l^{-1} (2,5 mBq l^{-1})	Dupzyk and Dupzyk 1979[36]
KPA	Urine wet ashed and solubilised	0,05 µg l^{-1} (1,3 mBq l^{-1})	Birkenfeld et al. 1995[30]
Alpha spectrometry	Urine wet ashed followed by coprecipitation, solvent extraction and electrodeposition	0,1 mBq l^{-1} for U-238	Singh and Wrenn 1988[47]
ICP-MS	Acidification, dilution	3 ng l^{-1} (0,077 mBq l^{-1})	Karpas et al. 1996[40]

[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. ^{236}U and ^{232}U are sometimes spiked in the samples to track the chemical recovery of the concerned uranium isotopes.

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.

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[21-23].

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 kg^{-1} in bone and 0,003 Bq 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 µg 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 µg d^{-1}. Others report similar results, with mean concentrations of 0,0094 µg l^{-1}[34], 0,098 µg l^{-1}[50], 0,01 µg l^{-1}[38], 0,485 µg l^{-1}[45]

and 0,0045 µg l^{-1}[40]. A range of 0,01 to 0,4 µg d^{-1} has also been reported[48]. More recently, ranges of 0,003 to 3,62 µg d^{-1} and from 0,001 to 8,45 µg d^{-1}[49] have been observed. ICRP reports faecal excretion rates to vary from 1,4 to 1,8 µg d^{-1}[6]. A more recent study found faecal excretion rates to range from 0,2 to 500 µg d^{-1}[51]. Faecal excretion data may need correction for dietary intakes of uranium. IDEAS guidelines[52] give background values and rules to distinguish between natural or non-occupational intake and occupational intake.

C.3 *In vivo*

In vivo measurement of uranium is limited to insoluble forms of U-235 in lungs. Other forms and solubilities of uranium either do not have a photon emission of a detectable energy and yield, or the detection limits are too high for the data to be useful.

As presented in Annex A, U-238 transforms through Th-234 and Pa-234m to U-234. The immediate daughter of U-238, Th-234, has a half-life of 24,1 days (transitions 63 keV and 93 keV). Th-234 and Pa-234m can be detected by *in vivo* monitoring, especially following depleted and natural uranium exposures. They can be used as indicators of the equilibrium of the uranium isotopes.

The remainder of C.3 describes lung counting for U-235. Lung counting techniques are described in numerous papers and detailed information is not provided here. The photon energy available for detection is 186 keV with a decay yield of 57 %. Due to the relatively high absorption of photons of this low energy in a typical chest cavity, consideration of the thickness of the individual's chest wall shall be taken into account. This is commonly done through the use of a height/weight algorithm, but ultrasound techniques also are available. Detectors should be placed as close to the chest as possible to minimize geometry effects and further absorption in air. Calibration is typically performed with the Livermore Realistic Torso Phantom developed at Lawrence Livermore National Laboratory or similar. This phantom has removable organs that can be produced with a known concentration of the radionuclide in question and also has chest plates of varying thicknesses. The selection of a specific *in vivo* measurement technique needs to satisfy ISO 28218:2010. Table C.2 shows expected detection limit values for lung counting.

Table C.2 — Reported *in vivo* measurement techniques for uranium

Isotope or compound	Organ	Description	Counting time (s)	Detection limit (Bq)	Reference
U-235	Lung	4 Ge(HP) detectors on the thorax and LIVERMORE phantom calibration	3 000	3 to 8 depending on the chest wall thickness	Lynch (2011) [44]
U-nat via U-235 determination	Lung	4 Ge(HP) detectors on the thorax and LIVERMORE phantom calibration	3 600	180 to 760 depending on the chest wall thickness and for natural uranium	Kramer (2001) [41]

C.4 Workplace monitoring

Monitoring the level of uranium in the air of the workplace provides important information for potential internal contamination. This is usually done through the measurement of uranium on air filters collected in the workplace. Surface swipes may also be used. If the proper sampling and analysis methodologies are used, workplace monitoring can also provide other essential information about the contamination, such as the chemical composition and the particle size distribution of uranium in the air of the workplace, which are important in radiation dose assessment.

Both personal air samplers (PAS) and static air samplers (SAS) are used for workplace monitoring. While an SAS can be placed in a representative area of the workplace, a PAS is typically placed in the breathing zone of the worker. SAS devices may provide analysis within the device, while PAS devices typically require subsequent analysis of the sample by proportional counting (if the airborne radionuclides