



# STANDARD OF CHINA ATOMIC ENERGY

System number: CAEA-AB0013  
Originated from: EJ/T 308—2016

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## **Monitoring, dose estimation and assessment of plutonium internal exposure of radiation workers**

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CHINA ATOMIC ENERGY AUTHORITY

# EJ

## **Nuclear Industry Standard of the People's Republic of China**

Translation of EJ/T 308—2016

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### **Monitoring, dose estimation and assessment of plutonium internal exposure of radiation workers**

Issue date: 2016—01—19

Implementation date: 2016—03—01    Translation issue date: XX—XX—XX

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ENGLISH VERSION OF THIS STANDARD IS ISSUED BY  
CHINA ATOMIC ENERGY AUTHORITY

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## Foreword

This standard replaces the EJ/T 308-1987(*Dose estimation and assessment of plutonium internal exposure*) in whole.

In addition to a number of editorial changes, the following technical deviations have been made with respect to the EJ/T 308-1987(*Dose estimation and assessment of plutonium internal exposure*)

- In the aspect of internal exposure model, the original standard adopts the model in ICRP2 and ICRP10, while this standard adopts the model in ICRP30 for gastrointestinal tract model, the model in ICRP66 for respiratory tract model and the model in ICRP78 for whole-body biokinetic model.
- It adopts the recommended intake estimation methods and data complying with GBZ 129 (*specifications for individual monitoring of occupational internal exposure*), EJ 375-2005 (*regulations for individual monitoring of occupational internal exposure*) and GB/T16148-2009 (*specification for estimation of intakes and internal exposure doses of radioactive nuclides*) to replace the original methods and data.
- The chapter “Normative reference documents” is added.
- Terms are updated and added.
- The chapter “Measurement contents and relevant requirements” is divided into two chapters “Monitoring requirements” and “Measurement methods and precautions”. The general requirements for internal exposure monitoring are deleted and the requirements and precautions for plutonium monitoring are added.
- The chapter “Dose estimation and assessment” is divided into three chapters “Estimation methods”, “Uncertainty” and “Internal exposure assessment”, and the estimation and assessment methods are modified.

In this standard, Annex A, Annex B, Annex C, Annex D, Annex E, Annex F, Annex G, Annex H and Annex I are informative Annexes.

This standard was proposed by China National Nuclear Corporation.

This standard was prepared by Institute for Standardization of Nuclear Industry.

# Monitoring, dose estimation and assessment of plutonium internal exposure of radiation workers

## 1 Scope

This standard specifies the monitoring requirements and methods, intake, dose estimation and assessment of plutonium internal exposure of radiation workers.

This standard is applicable to the dose estimation and assessment of  $^{238}\text{Pu}$ ,  $^{239}\text{Pu}$  and  $^{240}\text{Pu}$  internal exposure of radiation workers.

This standard is not applicable to the public.

## 2 Normative references

The following normative documents contain provisions which through reference in this text, constitute provisions of this standard. For dated references, subsequent amendments (excluding corrections), or revisions, of any of these publications do not apply to this standard. However parties to agreement based on this standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies.

EJ 375-2005 Regulations of individual monitoring for occupational internal exposure

## 3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

### 3.1 in vivo measurement

Also known as direct measurement, it is a process that the content of radioactive material in body is measured with an instrument that directly detects the ray emitted from radioactive nuclide in the body

Note: In general, the measuring device is a whole-body or partial-body (such as lung or thyroid) counter.

### 3.2 in vitro analyses

Also known indirect or in vitro measurement, it is a process that the radioactive material in human excreta or other biological samples is measured and analyzed

### 3.3 personal air sample analysis

It is a process that, with the personal samplers carried by the workers, the radioactive aerosol in air at personal breathing zone is sampled and analyzed

### 3.4 human respiratory tract model (HRTM)

It is the respiratory tract model described in ICRP publication 66, which is divided into 5 parts: anterior nasal passages ET1, all the other extra thoracic airways ET2, the trachea bronchi BB, bronchioles bb, and the alveolus AI

### 3.5 human gastrointestinal tract model (HGITM)

It is the gastrointestinal tract model described in ICRP30, which is divided into four parts: stomach, small intestine, upper large intestine and lower large intestine. When estimating the effective dose, these four parts are treated as separate organs

### 3.6 type F material

The materials absorbed into body fluids from the respiratory tract at a rapid rate. All materials are absorbed with a half-time of 10 min

### 3.7 type M material

The materials absorbed into body fluids from the respiratory tract at a medium rate. 10% materials absorbed with a half-time of 10 min and 90% a half-time of 140d

### 3.8 type S material

The relatively insoluble materials absorbed into body fluids from the respiratory tract at a slow rate. 0.1% materials absorbed with a half-time of 10 min and 99.9% a half-time of 7000d

### 3.9 committed dose

The committed effective dose and (or) committed equivalent dose

**3. 10 committed effective dose**

The committed effective dose  $E(\tau)$  is defined as:

$$E(\tau) = \sum_T W_T \bullet H_T(\tau) \dots\dots\dots (1)$$

Where in:

$H_T(\tau)$  - The time integral of the equivalent dose of organ or tissue;

$W_T$  - tissue weighting factor of tissue T.

If the standard does not make special regulations on  $\tau$ ,  $\tau=50$  years.

**3. 11 committed equivalent dose**

$$H_T(\tau) = \int_{t_0}^{t_0+\tau} H_T(t) dt \dots\dots\dots (2)$$

The committed equivalent dose  $H_T(\tau)$  is defined as:

Wherein:

$t_0$  -- time of intaking radioactive material;

$H_T(t)$  -- equivalent dose rate received by organ or tissue T at the time of t;

$\tau$  -- time after radioactive material is intaken.

If the standard does not make special regulations on  $\tau$ ,  $\tau=50$  years.

**3. 12 committed absorbed dose**

The committed absorbed dose  $D(\tau)$  is defined as:

$$D(\tau) = \int_{t_0}^{t_0+\tau} D(t) dt \dots\dots\dots (3)$$

Wherein:

$t_0$  -- time of intaking radioactive materials;

$D(t)$  -- absorbed dose rate at the time of t;

$\tau$  -- time after radioactive materials is intaken.

If the standard does not make special regulations on  $\tau$ ,  $\tau=50$  years.

**3. 13 annual limit on intake (ALI)**

The limit on intake of a certain radioactive nuclide into the human body within one year. If the intake amount of radioactive nuclide of workers in one year is this value, the committed effective dose is equivalent to the annual limit of dose 20 mSv

**3. 14 derived air concentration (DAC)**

It is a derived limit for the concentration of radioactive nuclide in air and is a secondary limit in radiation protection regulations. If the workers undertake light work for one year (2000h) in an environment with an average concentration of 1DAC of radioactive nuclide in the air, the committed effective dose is equivalent to the annual limit of dose 20mSv. The unit of DAC is Bq/m<sup>3</sup>

**3. 15 breathing zone**

The zone near operators' mouth and nostrils. When operators are working, the air in this zone is inhaled through their mouth or nose

**3. 16 routine monitoring**

The monitoring carried out according to a regular monitoring plan and on a prescribed schedule

**3. 17 special monitoring**

The monitoring carried out to solve a particular problem or when there are abnormalities or suspected to have abnormalities

**3. 18 task related monitoring**

Nonroutine monitoring carried out to provide relevant information for a particular operation or to provide basis for an operation sometimes

## 4 Monitoring general requirements

- 4.1 For workers to conduct plutonium related operation, routine individual internal exposure monitoring shall be carried out for them. For workers engaged in plutonium related operation, an individual internal exposure monitoring shall be carried out before they start to undertake the work that may lead to internal exposure and after they leave the position.
- 4.2 Routine individual internal exposure monitoring plan shall be formulated and constantly improved. The contents of the monitoring plan shall include objectives, requirements, objects, frequency, measurement methods, estimation methods, assessment methods and quality assurance.
- 4.3 The frequency of the routine individual internal exposure monitoring shall be reasonably determined based on the internal exposure level and possible fluctuation, the potential possibility of internal exposure, the physical and chemical characteristics of nuclide intaken and the metabolism behavior in human body, the accessible sensitivity of measurement techniques, the estimated intake and the acceptable uncertainty of the committed effective dose. However, the monitoring shall be carried out at least once a year.
- 4.4 For routine monitoring, it is usually hard to determine the intake time. Under this case, it can be assumed that the intake occurs at the middle time in the monitoring interval ( $T/2$ ). Annex A shows the intervals of routine individual internal exposure monitoring and the intake retention or excretion fractions at the middle time of monitoring interval under inhaled case for selection. When determining the monitoring frequency, it shall be noted such assumption adopted will not result in an underestimate of intake by more than three times (see Annex F).
- 4.5 In order to provide the information about internal exposure of workers for some specific operation, individual task related internal exposure monitoring shall be carried out for the workers and information about intake amount and committed effective dose shall also be provided if necessary. In the case of abnormal or possibly abnormal working conditions, equipment overhaul, incidents and incident handling, accidents and accident handling, special individual internal exposure monitoring shall be carried out.
- 4.6 If the workers may have wound contamination, they shall be monitored for wound contamination.
- 4.7 Workers shall have individual internal exposure monitoring after receiving medical interventions such as absorption inhibition and discharge promotion.
- 4.8 Except for routine monitoring, the time and frequency of individual internal exposure monitoring can be determined according to the exposure situation and the purpose and requirements of the monitoring.
- 4.9 The intake and the committed effective dose shall be estimated according to the measurement results. The committed absorbed dose shall also be given in case of an accident.
- 4.10 The quality assurance of individual internal exposure monitoring shall meet relevant requirements specified in regulations of individual monitoring for occupational internal exposure, see EJ 375-2005.
- 4.11 The samples related to the plutonium internal exposure monitoring shall be analyzed in a low-background laboratory. The collection, storage, processing and analysis of samples shall avoid external and/or cross-contamination and loss of nuclides to be tested and shall be carried out in accordance with relevant standards. Equipment and instruments that meet requirements and work normally shall be selected for use, and they shall be regularly verified/calibrated and maintained. Selected measurement methods shall be compared regularly and the monitoring shall be carried out by qualified personnel.

## 5 Monitoring methods and precautions

### 5.1 Monitoring method

- 5.1.1 For routine monitoring, in vivo monitoring does not have sufficient sensitivity but it can be used for special monitoring.
- 5.1.2 After radiochemical separation, the method using  $\alpha$  spectrum to measure urine plutonium has higher sensitivity than in vivo monitoring. For type M plutonium, it can be used for routine monitoring. For type S plutonium, it is only applicable to special monitoring generally. However, if the sensitivity is significantly

improved by neutron exposure fission track analysis or mass spectrometer analysis or other technologies, they can both be used for routine monitoring. After radiochemical separation, the method using  $\alpha$  spectrum to measure faecal plutonium has sufficient sensitivity in the routine monitoring of type S compound but lacks sensitivity in the routine monitoring of type M compound. However, this method can be used for special monitoring of both of them though it has high uncertainty.

5. 1. 3 When in vivo monitoring and excreta measurement methods are adopted, attention should be paid to the complexity of interpretation of data results especially in the case of workers with a long history of exposure. The results measured during one monitoring interval may be affected by previous intake of nuclides, which shall be deducted if necessary.

5. 1. 4 Air sampling at workplace is useful for determining the average exposure level of workers and can provide early indications of abnormalities. It is often used as an important auxiliary means for internal exposure monitoring. Routine monitoring methods usually include the combination of workplace air sampling analysis, personal air sampling analysis and excreta measurement. Generally, workplace air sampling is used to measure contamination distribution, and a few personal air sampling analyses are used for verification or modification. It should be noted that the direct use of workplace air sampling data to estimate individual dose is highly uncertain.

5. 1. 5 When using the results of workplace air sampling and monitoring and the record of staff residence time to estimate the individual internal exposure dose, a special monitoring plan should be developed and implemented after approval by the audit department. Particle size has significant influence on the estimation of particle deposition and dose in respiratory tract. The size distribution of inhaled particles should be measured and determined or it should be assumed to be in line with the reality. In the absence of specific data on particle sizes, it can be assumed that the activity median aerodynamic diameter (AMAD) is  $5\mu\text{m}$  in the workplace. In vivo monitoring can be used in conjunction with specific investigations. Common measurement methods are shown in Annex B.

## 5. 2 In vivo monitoring

5. 2. 1 Specially designed germanium detectors with high energy resolution at low energy can be used for plutonium monitoring of the lungs, and detector arrays can be placed near the body surface of the chest. Plutonium with known activity placed in a human body model representing the attenuation characteristics of human tissue should be used for calibration. Response to understand attenuation characteristics of human tissue, the chest wall thickness shall be measured or estimated. At this time, the chest wall thickness of the measured objects can be estimated based on the ratio of weight to height, or measured based on ultrasonic measurement or magnetic resonance imaging, so as to select the appropriate scaling factors or modify them.

5. 2. 2 Normally, plutonium materials contain  $^{241}\text{Am}$  generated from  $^{241}\text{Pu}$ . Therefore,  $^{241}\text{Am}$ , with higher radiation energy, can be used as a tracer of plutonium in some cases. In the early stages after inhalation, the content of americium in the lungs can be measured to estimate the intake of the plutonium mixture. At this point, the activity ratio of plutonium/americium should be obtained through analysis of substances collected in the workplace or by analysis of fecal excretion to interpret the measurement results,  $^{241}\text{Am}$  of liver and bone can also be measured and intakes and dose can be estimated.

## 5. 3 In vitro monitoring

5. 3. 1 Biological samples such as urine, faeces and nasal excretion can be analyzed by  $\alpha$  counting or  $\alpha$  spectrometry after radiochemical separation.  $\alpha$  spectrometry can distinguish nuclides with a low background. Adding  $^{242}\text{Pu}$  tracer to the sample can improve the accuracy of measurement of  $^{239}\text{Pu}$  and  $^{238}\text{Pu}$ . The sensitivity can be improved by analyzing 24h urine sample and increasing the time of spectrometry.

5. 3. 2 Biological samples can obtain high sensitivity by fission track analysis or mass spectrometer analysis, and the detection limit is sufficient to meet the requirements of routine individual internal exposure monitoring.

## 5. 4 PAS/SAS monitoring

5. 4. 1 For  $^{238}\text{Pu}$ ,  $^{239}\text{Pu}$  and  $^{240}\text{Pu}$ , no matter they are M type or S type, special or routine monitoring, they can be monitored by air sampling method. The PAS/SAS monitoring method has high sensitivity.

5. 4. 2 Air sampling may include sampling at a fixed location in the workplace, sampling at a staff member's respiratory zone, or sampling with a portable personal air sampler (PAS) carried by the staff member. The workplace stationary air sampler(SAS) is poorly representative and may lead to an underestimation of plutonium intake activity by an order of magnitude or more. Personal air samples have a good representativeness. The ratio of personal air sampler and stationary air sampler can be determined by comparing the measurement results. This ratio can be used to interpret the measurement results of stationary air sampler to reduce the uncertainty of intake and dose estimation.

5. 4. 3 The physical and chemical properties (particle size and absorption parameters, etc.) of aerosols of inhaled plutonium can be measured by using air samplers. This information can be used to interpret measurements made by other methods and to use specific dose coefficients for actual inhalation of plutonium rather than default values. When the committed effective dose of annual plutonium inhalation is likely to be more than 6 mSv, it is advisable to measure the properties of the inhaled materials and estimate dose according to measured parameters.

## 6 Estimation of intake and dose

### 6. 1 Biokinetic models and parameters

6. 1. 1 When the committed effective dose of annual intake is significantly lower than 20mSv, the reference model and its parameters can be used to estimate the intake and the committed effective dose, referring to Annex C for the reference models and its parameters. In the absence of specific data on particle size of radioactive aerosols in workplace, it can be assumed that the activity median aerodynamic diameter (AMAD) is 5 $\mu\text{m}$ .

6. 1. 2 When the committed effective dose by annual intake is close to or more than 20mSv, or medical intervention such as blocked absorption and discharge promotion are taken, then the general reference model and parameters are inappropriate, all possible data should be collected to select the appropriate dynamic patterns and parameters for the individual, based on which to estimate the intake and the committed effective dose. For the inhalation route, the AMAD value of aerosol should be determined by measurements, and then the initial deposition fractions should be determined.

6. 1. 3 In order to make individual evaluation of large amount of intake, the distribution, retention, transfer and excretion of plutonium in specific individuals and their parameters can be determined by analyzing and measuring the physical and chemical morphology of the intake substances and fitting a series of tracking and monitoring results. It is difficult to determine individual patterns and their parameters by analyzing measurements data, but it can make useful modifications to reference patterns and their parameters, such as rate of absorption into blood, rates of transfer of parts of organs or tissues, variation patterns of retention in the body, and excretion rates.

6. 1. 4 To the extent possible, the form of the intake is known or analyzed to select the type of intake (for inhalation) or the  $f_1$  value of the gastrointestinal absorption score (for ingestion). When the substance form is unknown, it can be treated according to the strictest category, i.e. the category with the strictest limit of annual intake or  $f_1$  value.

6. 1. 5 For routine individual internal exposure monitoring, a single intake may be assumed at the mid-point of the monitoring interval. For special and task-related monitoring, the intake time is known. Special monitoring plans should be developed for post-intervention monitoring to track the distribution, retention and excretion of pollutants in the intake body and to make specific estimates of the committed dose based on these data.

### 6. 2 Retention fractions, excretion fractions and committed dose coefficients

6. 2. 1 The content in the whole body, some organ or tissue at a certain time (t) after unit intake is referred to as the intake retention fraction. The excretion rate of urine or faeces at a certain time (t) after unit intake is

referred to as the intake and excretion fraction. Intake retention fraction and excretion fraction are expressed as  $m(t)$  ( $m(t)$  derived from the reference model and parameters is called the expected value in ICRP publications). The committed effective dose of the unit intake is called the committed effective dose coefficient, denoted by  $e$ . The committed equivalent dose of each organ of the unit intake is called the committed equivalent dose coefficient, expressed by  $h$  organ or tissue.

6.2.2 The intake retention and excretion fraction  $m(t)$  and the committed effective dose coefficient  $e$  which are calculated according to the reference model and its parameters are shown in Annex D and E respectively. If the data is given as a curve, the  $m(t)$  value of  $t$  days can be obtained directly from the curve. If the data is given in tabulated form, the  $m(t)$  value of  $t$  days can be obtained directly from the table, or the  $m(t)$  value of  $t$  days can be calculated by linear interpolation of the table data. The organ or tissue with the committed equivalent dose coefficient  $h$  can use the data provided by ICRP through its website.

### 6.3 Estimation of intake

#### 6.3.1 Estimation based on retention or excretion

6.3.1.1 If to conduct only one measurement after a single intake, the intake  $I(\text{Bq})$  can be estimated by Formula (4):

$$I = M(t) / m(t) \dots\dots\dots(4)$$

Wherein:

$I$  -- intake, unit (Bq);

$M(t)$  -- content of the whole body, an organ or tissue measured by individual internal exposure monitoring or daily excretion of urine or faeces within  $t$  days after intake, unit (Bq or  $\text{Bq}\cdot\text{d}^{-1}$ );

$m(t)$  -- the expected value of intake retention or intake and excretion fraction at  $t$  days after intake per unit activity (dimensionless or  $\text{d}^{-1}$ ).

For routine monitoring, if the time of intake is not clear, it is assumed that a single intake occurs at the midpoint of the monitoring interval  $T(\text{d})$ . See Annex H for the example of intake estimation.

6.3.1.2 In case of only one measurement after multiple or continuous intakes, the intake estimation can be superimposed as per single intake. See Annex H for the example of intake estimation.

6.3.1.3 If multiple measurement results are obtained, the least square method can be used to estimate the optimal intake  $I(\text{Bq})$ , as shown in Formula (5):

$$I = \sum [m(t_i)M(t_i)] / \sum m^2(t_i) \dots\dots\dots(5)$$

Wherein:

$I$  -- intake, unit (Bq);

$i$  -- number of measurements, for example, the  $i$ th measurement;

$M(t_i)$  -- content of the whole body, an organ or tissue measured by individual internal exposure monitoring or daily excretion of urine or faeces within  $t_i$  days after intake, unit (Bq or  $\text{Bq}\cdot\text{d}^{-1}$ );

$m(t_i)$  -- the expected value of intake retention or intake and excretion fraction at  $t_i$  days after intake (dimensionless or  $\text{d}^{-1}$ ). For the individual assessment of large intake, the general expected value should be replaced by the score value fitted or modified based on the results of multiple tracking monitoring.

The intake can be estimated only after the measurements for each monitoring interval deduct the contribution of all previous intakes according to the methods in 6.3.1.1, 6.3.1.2 or 6.3.1.3.

#### 6.3.2 Estimation based on aerosol activity concentration

In the absence of respiratory protector, the intake volume  $I(\text{Bq})$  can be obtained by multiplying aerosol activity concentration  $C(\text{Bq}/\text{m}^3)$  calculated based on air sampling and analyzing in the workplace by the working time  $t(\text{h})$  and respiratory rate  $R$  (reference value is  $1.2\text{m}^3\cdot\text{h}^{-1}$ ), as shown in Formula (6):

$$I = C \times t \times R \dots\dots\dots(6)$$

The intake volume  $I(\text{Bq})$  can be calculated by multiplying the time integral concentration of  $C_{\text{individual}}$  ( $\text{h} \cdot \text{Bq}/\text{m}^3$ ) obtained from data of personal air samples analyses by breathing rate  $R$  (reference value of  $1.2\text{m}^3/\text{h}$ ), as shown in Formula (7):

$$I = C_{\text{individual}} \times R \dots\dots\dots(7)$$

#### 6.4 Committed effective dose estimation

In routine monitoring, the committed effective dose can be calculated by multiplying the intake by the effective dose coefficient. The committed effective dose of intake radioactive materials in a year can be calculated by adding all the committed effective doses of intake radioactive materials in a year. See Annex H for the example of committed effective dose estimation.

#### 6.5 Estimation of committed equivalent dose and committed absorbed dose

The committed equivalent dose of corresponding organ can be obtained by multiplying the intake by the committed equivalent dose coefficient. In general cases where a person has not been medically treated, the committed equivalent dose coefficients issued by ICRP can be applied.

For  $^{238}\text{Pu}$ ,  $^{239}\text{Pu}$  and  $^{240}\text{Pu}$ , the committed equivalent dose of each organ can be divided by 20 (radiation weighting factor of  $\alpha$  particle) and approximately taken as the committed absorbed dose of the corresponding organ. For the above three nuclides, the committed absorbed dose calculated by the method is sufficient to meet the accuracy requirements of any radiation protection.

### 7 Uncertainty of internal dose estimation

#### 7.1 Overview

The internal radiation dose estimation of plutonium usually has great uncertainty. If the technical conditions permit, the key factors affecting the uncertainty of internal radiation dose estimation can be analyzed to reduce the uncertainty by appropriate technical means.

#### 7.2 Main sources of uncertainty in internal dose estimation

In the internal dose estimation, the main sources of the uncertainty are as follows:

- a) Uncertainty at the time of acute intake or duration of continuous intake;
- b) Uncertainty of measured results;
- c) Uncertainty of the estimated dose due to the characteristics of the intake materials by the personnel.

Although the uncertainties of the following parameters with an impact on actual uncertainties, they need not and should not be taken into account for general radiation protection purposes:

- Physiological parameters (for example: body figure, organ quality and breathing rate of workers);
- Parameters of the ICRP human respiratory tract model, except when the physicochemical properties of the intake materials are available;
- Parameters of the ICRP biological model that describes the system behaviors;
- Dosimetric model parameters (such as absorbed fractions), the decay data of radionuclides, radiation weighting factors and tissue weighting factors.

Note: The impact of body figure on the uncertainty of the dose results is not taken into account in the calculation of dose from intake, but the impact on the uncertainty of measurement results shall be considered. In fact, the body figure contributes to uncertainty of type B in the measurement.

The uncertainty data of the estimated dose due to uncertainty at the time of acute intake are shown in Annex F. The typical value of logarithmic normal distribution dispersion coefficient  $K_{\text{SF}}$  is given in Annex G, and the value is used in the uncertainty analysis of measurement results, and the specific method of use is given by example in Annex I. Estimation examples of intake, dose and dose uncertainty are given in Annex I.

### 8 Internal dose assessment

8.1 If there is only internal exposure on the site, and only one nuclide is taken in by one route within a year and only one reference model and its parameters are used for all intake dose estimations, then the air concentration obtained by the individual respiratory sampler can be directly compared with the derived air concentration DAC in the assessment. The intake can be compared directly with the annual intake limit (ALI), or the committed effective dose shall be compared with the individual dose limit due to annual intake.

8.2 If there is only internal exposure on the site but with more than one intaking route with multiple nuclides in one year, or individual modes and parameters are adopted for dose estimation, or different reference modes and parameters are adopted for each dose estimation in one year, the total effective doses of all intake radioactive materials in one year shall be estimated according to different specific conditions and compared with the individual dose limit.

8.3 If both internal and external exposures exist, the effective dose corresponding to the intake of all intake radioactive materials in one year shall be added to the effective dose of external exposures in the same year to calculate the effective dose of external exposures in the year, and the annual dose shall be compared with the individual dose limit.

8.4 In order to strengthen the management of individual monitoring, the annual intake or air concentration shall also be compared with the corresponding survey level. The committed effective dose caused by annual intake shall be compared with the dose constraint value. In case of any abnormality, corresponding measures shall be taken according to relevant regulations.

8.5 Under abnormal exposure, the committed absorbed dose shall be calculated as far as possible. In case of accidental exposure, the committed absorbed dose shall be calculated. In the case of concurrent external exposure, the committed absorbed dose of all radioactive materials ingested shall be added to the absorbed dose of external exposure in case of abnormal or accidental exposure. After calculating the absorbed dose, the absorbed dose shall be compared with the dose threshold of various deterministic effects.

**Annex A**  
**(informative)**

**Routine monitoring intervals and retention and excretion fractions  $m(T/2)$  under inhaled case for selection**

Table A.1 shows the routine monitoring interval T and intake retention and excretion fraction  $m(T/2)$  for selection after  $^{238}\text{Pu}$ ,  $^{239}\text{Pu}$  or  $^{240}\text{Pu}$  with AMAD as  $5\mu\text{m}$  aerosol particles are inhaled.

Note: The data in Table A.1 are from Table A.12.9 “Routine monitoring: expected values of inhaled  $^{238}\text{Pu}$  (intake per Bq)” and Table A.12.16 “Routine monitoring: expected values of inhaled  $^{239}\text{Pu}$  or  $^{240}\text{Pu}$  (intake per Bq)” in ICRP78. This standard combines these two tables.

Table A.1 Routine monitoring interval T for selection and corresponding intake retention and excretion fractions  $m(T/2)$  (Bq or Bq/d) for inhalation of  $^{238}\text{Pu}$ ,  $^{239}\text{Pu}$  or  $^{240}\text{Pu}$

Monitoring interval(d)	Type M			Type S		
	Lungs retention $m(T/2)$	Daily urinary excretion $m(T/2)$	Daily fecal excretion $m(T/2)$	Lungs retention $m(T/2)$	Daily urinary excretion $m(T/2)$	Daily fecal excretion $m(T/2)$
360	1.2E-02	5.4E-06	1.7E-05	3.2E-02	1.6E-07	3.7E-05
180	2.2E-02	7.1E-06	(6. 6E-05)a	3.8E-02	1.6E-07	1.1E-04
120	2.8E-02	8.1E-06	(1.3E-04)	4.2E-02	1.6E-07	1.9E-04
90	3.3E-02	8.7E-06	1.9E-04	4.5E-02	1.7E-07	2.5E-04
60	3.8E-02	9.5E-06	2.8E-04	4.9E-02	1.7E-07	3.5E-04
30	4.6E-02	1.1E-05	4.3E-04	5.5E-02	1.9E-07	4.9E-04
14	5.2E-02	2.4E-05	(2.3E-03)	6.0E-02	3.1E-07	(2. 5E-03)
7	5.4E-02	5.3E-05	(3.4E-02)	6.1E-02	5.9E-07	(3.5E-02)

<sup>a</sup>The values in brackets are not applicable as these monitoring intervals fail to meet the requirement that “When determining the monitoring frequency, the time of intake is unknown and it assumes the intake occurs on one day in the middle of the monitoring interval, it shall be ensured such assumption adopted will not result in an underestimate of intake by more than three times”.

**Annex B**  
**(informative)**

**Individual plutonium internal exposure measurement techniques**

Table B.1 and Table B.2 list some common individual  $^{238}\text{Pu}$ ,  $^{239}\text{Pu}$  and  $^{240}\text{Pu}$  internal exposure measurement methods for selection.

Note: The data in Table B.1 and Table B.2 are respectively from Table A.12.5 “Measurement techniques” and Table A.12.12 “Measurement techniques” in ICRP 78.

Table B.1 Measurement Methods of  $^{238}\text{Pu}$

Method of measurement	Measured organs or samples	Typical detection limit
Lung measurement, measure characteristic x ray	Lungs	1.0kBq
Radiochemical separation and a-ray spectrometry	Urine	1.0mBqL <sup>-1</sup>
	Feces	1.0mBq

<sup>a</sup>Depends on chest wall thickness.

Table B.2  $^{239}\text{Pu}$  or  $^{240}\text{Pu}$  Measurement Methods

Method of measurement	Measured organs or samples	Typical detection limit
Lung measurement, measure characteristic x ray	Lungs	2.0KBq
Radiochemical separation and a-ray spectrometry	Urine	1.0mBqL <sup>-1</sup>
	Feces	1.0mBq

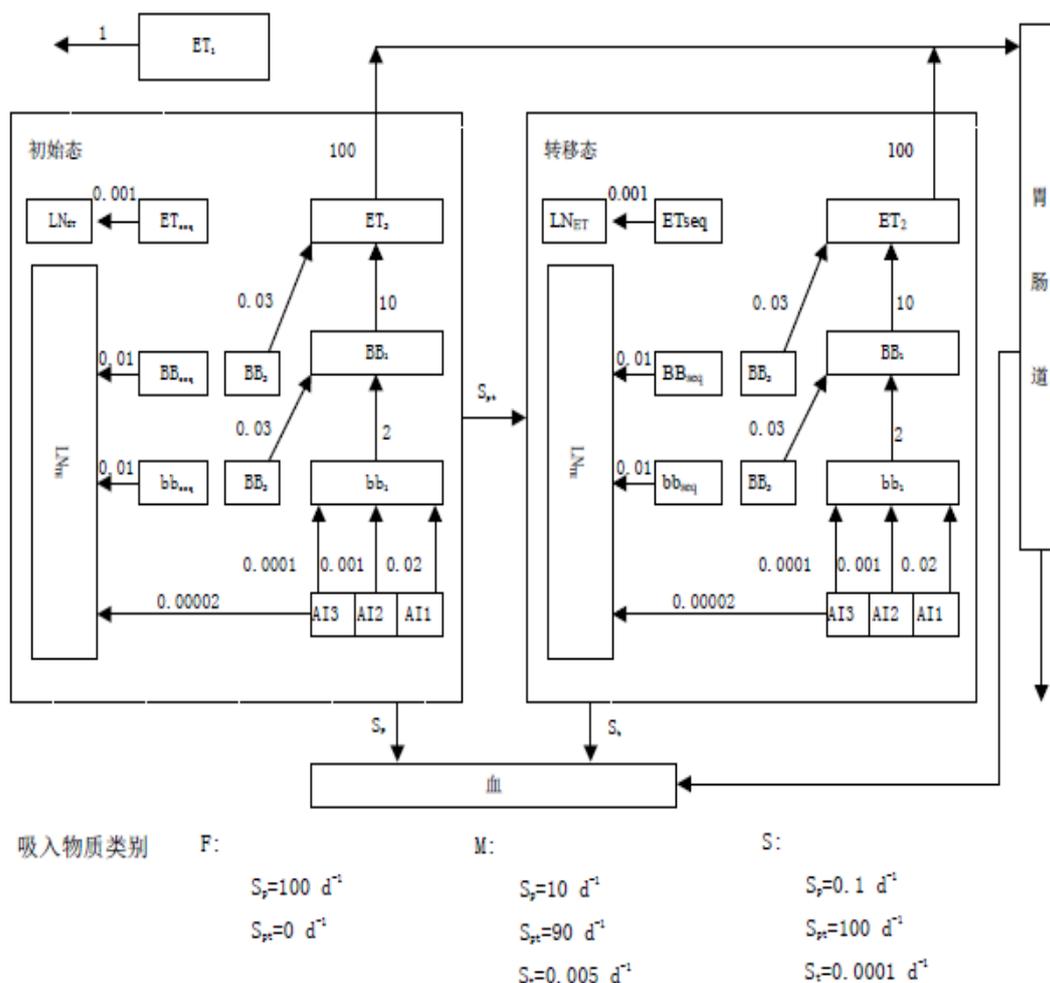
<sup>a</sup>Depends on chest wall thickness.

## Annex C (informative)

### Biokinetic model describing metabolism

**C.1** Refer to Chart C.1 for respiratory tract model and its parameters and refer to Fig. C.1 for initial deposition fractions.

Notes: Chart C.1 is drawn according to the respiratory tract model and parameters described in ICRP 78. The data in Table C.1 are calculated using the model and parameters described in ICRP 66. The data in Table C.2 and Table C.3 are from Table A.12.2 “Compounds, absorption types and f1 values” in ICRP 78. Chart C.2 is drawn according to the gastrointestinal tract model and parameters described in ICRP 78. Chart C.3 is drawn according to the plutonium whole body biokinetic model and parameters described in ICRP 78.



Sp—inflow rate to blood under initial state  
 Spt—transfer rate from initial state to transformed state  
 St—inflow rate to blood under transformed state  
 ET—Extrathoracic Region  
 BB—Bronchial Region  
 bb—Bronchiolar Region  
 AI—Alveolar-Interstitial Region  
 LN—lymphatics and lymph nodes Region

Chart C.1 Respiratory Tract Model and Its Transfer Rates ( $\text{d}^{-1}$ )

Table C.1 Initial Deposition Fractions in Each Respiratory Tracta

AMAD( $\mu\text{m}$ )	ET1	ET2	BBfast+seq	BBsiow	bbfast+seq	bbsiow	AI
0.2	5.5 E-02	6.1 E-02	3.3 E-03	3.3 E-03	1.5 E-02	1.5 E-02	1.5 E-01
0.5	8.9 E-02	1.1 E-01	4.0 E-03	3.9 E-03	1.1 E-02	1.1 E-02	1.2 E-01
0.7	1.2 E-01	1.5 E-01	5.1 E-03	4.8 E-03	9.4 E-03	9.2 E-03	1.1 E-01
1.0	1.7 E-01	2.1 E-01	6.6 E-03	5.8 E-03	8.4 E-03	8.1 E-03	1.1 E-01
2.0	2.5 E-01	3.2 E-01	9.9 E-03	7.4 E-03	8.0 E-03	6.8 E-03	9.2 E-02
3.0	3.0 E-01	3.7 E-01	1.1 E-02	7.3 E-03	7.7 E-03	6.0 E-03	7.7 E-02
5.0	3.4 E-01	4.0 E-01	1.2 E-02	5.9 E-03	6.6 E-03	4.4 E-03	5.3 E-02
7.0	3.5 E-01	4.0 E-01	1.1 E-02	4.6 E-03	5.5 E-03	3.2 E-03	3.8 E-02
10.0	3.5 E-01	3.8 E-01	9.5 E-03	3.1 E-03	4.2 E-03	2.1 E-03	2.4 E-02

Notes: BB<sub>fast+seq</sub> — Fast and latent transfer in the bronchial region.  
 BB<sub>slow</sub> — Slow transfer in the bronchial region.  
 bb<sub>fast+seq</sub> — Fast and latent transfer in the bronchiole region.  
 bb<sub>slow</sub> — Slow transfer in the bronchiole region.  
<sup>a</sup>It means that under normal nasal inhalation case, the respiratory rate is 1.2 m<sup>3</sup>h<sup>-1</sup>.

C.2 See Table C.2 for inhaled compounds, lung absorption type and gastrointestinal tract absorption fractions  $f_1$ .

Table C.2 Inhaled compounds, lung absorption types and  $f_1$  values

Elements	Absorption types	$f_1$	Compounds
Plutonium	M	5.0E-04	All unspecified compounds
	s	1.0E-05	Insoluble oxides

C.3 See Chart C.2 for gastrointestinal tract model and its parameters.

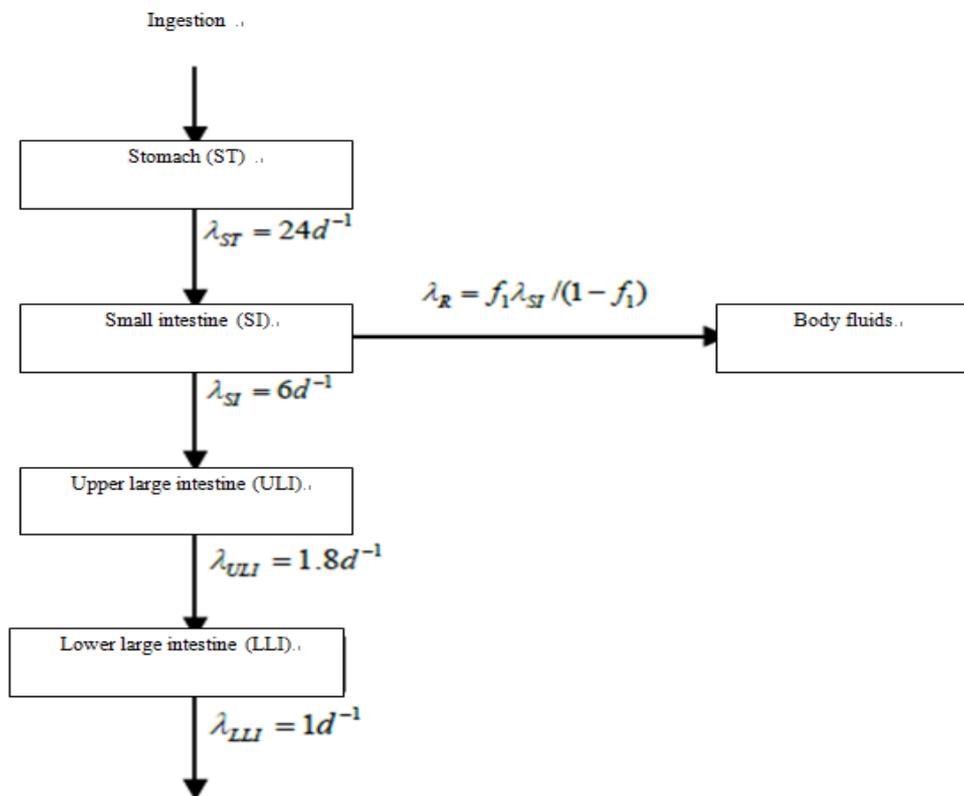


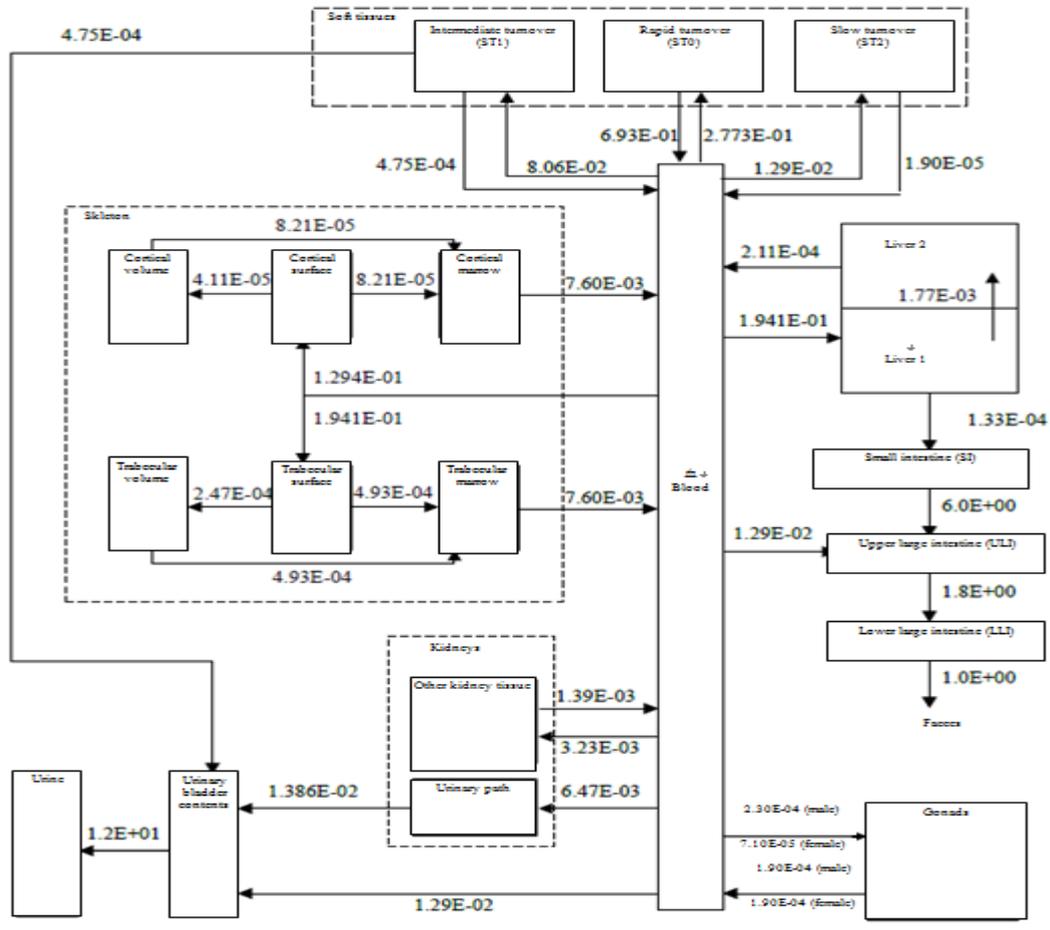
Chart C.2 Gastrointestinal Tract Model and Transfer Rates ( $d^{-1}$ )

C.4 See Table C.3 for ingested compounds and gastrointestinal tract absorption fraction  $f_1$ .

Table C.3 Compounds and  $f_1$  Value

Elements	$f_1$	Compounds
Plutonium	1.0E-05	Insoluble oxides
	1.0E-04	Nitrates
	5.0E-04	All unspecified compounds

C.5 See Chart C.3 for whole body biokinetic model and its parameters.



Note: Values are given to sufficient precision for calculational purposes and may be more precise than the biological data would support.

Chart C.3 Whole Body Biokinetic Model and Transfer Rates ( $d^{-1}$ )

**Annex D**  
**(informative)**

**Expected values of intake retention and excretion**

**D.1** See Table D.1 and Table D.2 for the intake retention and excretion fractions  $m(t)$ s of  $^{238}\text{Pu}$  inhalation route (AMAD is  $5\mu\text{m}$ ) and ingestion route respectively.

Note: The data in Table D.1 and Table D.2 are from Table A.12.6 “Special monitoring: predicted values (Bq per Bq intake) for inhalation of  $^{238}\text{Pu}$ ” and Table A.12.7 “Special monitoring: predicted values (Bq per Bq intake) for Ingestion of  $^{238}\text{Pu}$ ” in ICRP78.

Table D.1  $m(t)$ s (Bq or Bq/d) for Inhalation of  $^{238}\text{Pu}$  (AMAD is  $5\mu\text{m}$ )

Time after Intake(d)	Type M			Type S		
	Lungs	Daily urinary excretion	Daily faecal excretion	Lungs	Daily urinary excretion	Daily faecal excretion
1	5.8E-02	2.3E-04	1.1E-01	6.4E-02	2.3E-06	1.1E-01
2	5.6E-02	1.3E-04	1.5E-01	6.3E-02	1.4E-06	1.6E-01
3	5.5E-02	7.8E-05	8.0E-02	6.2E-02	8.3E-07	8.4E-02
4	5.4E-02	5.3E-05	3.4E-02	6.1E-02	5.9E-07	3.5E-02
5	5.3E-02	3.9E-05	1.3E-02	6.1E-02	4.5E-07	1.4E-02
6	5.3E-02	3.0E-05	5.4E-03	6.0E-02	3.7E-07	5.7E-03
7	5.2E-02	2.4E-05	2.3E-03	6.0E-02	3.1E-07	2.5E-03
8	5.1E-02	2.0E-05	1.2E-03	5.9E-02	2.7E-07	1.3E-03
9	5.0E-02	1.7E-05	7.6E-04	5.8E-02	2.4E-07	8.2E-04
10	5.0E-02	1.5E-05	5.8E-04	5.8E-02	2.2E-07	6.5E-04

Table D.2  $m(t)$ s (Bq/d) for Ingestion of  $^{238}\text{Pu}$

Time after Intake(d)	$f_1 = 5.0\text{E-}04$		$f_1 = 1.0\text{E-}04$		$f_1 = 1.0\text{E-}05$	
	Daily urinary excretion	Daily faecal excretion	Daily urinary excretion	Daily faecal excretion	Daily urinary excretion	Daily faecal excretion
1	3.4E-06	2.8E-01	6.7E-07	2.8E-01	6.7E-08	2.8E-01
2	2.6E-06	3.9E-01	5.2E-07	3.9E-01	5.2E-08	3.9E-01
3	1.4E-06	2.0E-01	2.9E-07	2.0E-01	2.9E-08	2.0E-01
4	9.3E-07	8.1E-02	1.9E-07	8.1E-02	1.9E-08	8.1E-02
5	6.5E-07	3.1E-02	1.3E-07	3.1E-02	1.3E-08	3.1E-02
6	4.7E-07	1.2E-02	9.4E-08	1.2E-02	9.4E-09	1.2E-02
7	3.6E-07	4.4E-03	7.1E-08	4.4E-03	7.1E-09	4.4E-03
8	2.8E-07	1.6E-03	5.5E-08	1.6E-03	5.5E-09	1.6E-03
9	2.2E-07	6.0E-04	4.4E-08	6.0E-04	4.4E-09	6.0E-04
10	1.8E-07	2.2E-04	3.6E-08	2.2E-04	3.6E-09	2.2E-04

**D.2** See Table D.3 and Table D.4 for the intake retention and excretion fractions  $m(t)$ s of  $^{238}\text{Pu}$  or  $^{240}\text{Pu}$  inhalation route (AMAD is  $5\mu\text{m}$ ) and ingestion route respectively.

Note: The data in Table D.3 and Table D.4 are from Table A.12.13 “Special Monitoring: Predicted Values (Bq per Bq intake) for Inhalation of  $^{239}\text{Pu}$  or  $^{240}\text{Pu}$ ” and Table A.12.14 “Special Monitoring: Predicted values (Bq per Bq intake) for Ingestion of  $^{239}\text{Pu}$  or  $^{240}\text{Pu}$ ” in ICRP78.

Table D.3 m(t)s (Bq or Bq/ d) for Inhalation of  $^{239}\text{Pu}$  or  $^{240}\text{Pu}$ (AMAD is  $5\mu\text{m}$ )

Time after Intake(d)	Type M			Type S		
	Lungs	Daily urinary excretion	Daily faecal excretion	Lungs	Daily urinary excretion	Daily faecal excretion
1	5.8E-02	2.3E-04	1.1E-01	6.4E-02	2.3E-06	1.1E-01
2	5.6E-02	1.3E-04	1.5E-01	6.3E-02	1.4E-06	1.6E-01
3	5.5E-02	7.8E-05	8.0E-02	6.2E-02	8.3E-07	8.4E-02
4	5.4E-02	5.3E-05	3.4E-02	6.1E-02	5.9E-07	3.5E-02
5	5.3E-02	3.9E-05	1.3E-02	6.1E-02	4.5E-07	1.4E-02
6	5.3E-02	3.0E-05	5.4E-03	6.0E-02	3.7E-07	5.7E-03
7	5.2E-02	2.4E-05	2.3E-03	6.0E-02	3.1E-07	2.5E-03
8	5.1E-02	2.0E-05	1.2E-03	5.9E-02	2.7E-07	1.3E-03
9	5.0E-02	1.7E-05	7.6E-04	5.8E-02	2.4E-07	8.2E-04
10	5.0E-02	1.5E-05	5.8E-04	5.8E-02	2.3E-07	6.5E-04

Table D.4 m(t)s (Bq/d) for Ingestion of  $^{239}\text{Pu}$  or  $^{240}\text{Pu}$ 

Time after Intake(d)	f1 = 5.0E-04		f1 = 1.0E-04		f1 = 1.0E-05	
	Daily urinary excretion	Daily faecal excretion	Daily urinary excretion	Daily faecal excretion	Daily urinary excretion	Daily faecal excretion
1	3.4E-06	2.8E-01	6.7E-07	2.8E-01	6.7E-08	2.8E-01
2	2.6E-06	3.9E-01	5.2E-07	3.9E-01	5.2E-08	3.9E-01
3	1.4E-06	2.0E-01	2.9E-07	2.0E-01	2.9E-08	2.0E-01
4	9.3E-07	8.1E-02	1.9E-07	8.1E-02	1.9E-08	8.1E-02
5	6.5E-07	3.1E-02	1.3E-07	3.1E-02	1.3E-08	3.1E-02
6	4.7E-07	1.2E-02	9.4E-08	1.2E-02	9.4E-09	1.2E-02
7	3.6E-07	4.4E-03	7.1E-08	4.4E-03	7.1E-09	4.4E-03
8	2.8E-07	1.6E-03	5.5E-08	1.6E-03	5.5E-09	1.6E-03
9	2.2E-07	6.0E-04	4.4E-08	6.0E-04	4.4E-09	6.0E-04
10	1.8E-07	2.2E-04	3.6E-08	2.2E-04	3.6E-09	2.2E-04

**Annex E**  
**(informative)**

**Committed effective dose coefficient and annual intake limit and derived air concentration**

See Table E.1 and Table E.2 for the committed effective dose coefficient  $e$  (Sv Bq<sup>-1</sup>), annual intake limit ALI(Bq) and derived air concentration DAC (Bq m<sup>-3</sup>) of <sup>238</sup>Pu, <sup>239</sup>Pu and <sup>240</sup>Pu inhalation route respectively. See Table E.3 for the committed effective dose coefficient  $e$  and annual intake limit ALI of digestion route. See Table E.4 for the committed effective dose coefficient  $e$  and annual intake limit ALI of direct blood inflow route. ALI and DAC are calculated with formula E.1 and formula E.2 respectively:

$$ALI=0.02/e \dots \dots \dots (E. 1)$$

$$DAC=ALI/(2000 \times 1.2) \dots \dots \dots (E. 2)$$

Note: The data in Table E.1, Table E.2, Table E.3 and Table E.4 are calculated according to the committed effective dose coefficient  $e$  published by ICRP through website by using formulas E.1 and E.2.

Table E.1  $e$ , ALI and DAC for Inhalation of <sup>238</sup>Pu

AMAD(μm)	Type M			Type S		
	$e$ (SvBq <sup>-1</sup> )	ALI (Bq)	DAC(Bqm <sup>-3</sup> )	$e$ (SvBq <sup>-1</sup> )	ALI (Bq)	DAC(Bqm <sup>-3</sup> )
0.3	5.4E-05	3.7E+02	1.5E-01	2.0E-05	1.0E+03	4.2E-01
1.0	4.3E-05	4.7E+02	1.9E-01	1.5E-05	1.3E+03	5.7E-01
3.0	3.8E-05	5.3E+02	2.2E-01	1.2E-05	1.7E+03	7.1E-01
5.0	3.0E-05	6.7E+02	2.8E-01	1.1E-05	1.8E+03	7.9E-01
10.0	1.8E-05	1.1E+03	4.5E-01	6.0E-06	3.3E+03	1.4E+00

Table E.2  $e$ , ALI and DAC for Inhalation of <sup>239</sup>Pu and <sup>240</sup>Pu

AMAD(μm)	Type M			Type S		
	$e$ (SvBq <sup>-1</sup> )	ALI (Bq)	DAC(Bqm <sup>-3</sup> )	$e$ (SvBq <sup>-1</sup> )	ALI (Bq)	DAC(Bqm <sup>-3</sup> )
0.3	5.9E-05	3.4E+02	1.4E-01	2.0E-05	1.0E+03	4.1E-01
1.0	4.7E-05	4.3E+02	1.8E-01	1.5E-05	1.3E+03	5.7E-01
3.0	4.1E-05	4.9E+02	2.1E-01	1.1E-05	1.8E+03	7.3E-01
5.0	3.2E-05	6.3E+02	2.6E-01	8.3E-06	2.4E+03	1.0E+00
10.0	2.0E-05	1.0E+03	4.2E-01	5.9E-06	3.4E+03	1.4E+00

Table E.3  $e$  and ALI for Ingestion of <sup>238</sup>Pu, <sup>239</sup>Pu and <sup>240</sup>Pu

fI Value	<sup>238</sup> Pu		<sup>239</sup> Pu		<sup>240</sup> Pu	
	$e$ (SvBq <sup>-1</sup> )	ALI(Bq)	$e$ (SvBq <sup>-1</sup> )	ALI(Bq)	$e$ (SvBq <sup>-1</sup> )	ALI(Bq)
1E-05	8.8E-09	2.3E+06	9.0E-09	2.2E+06	9.0E-09	2.2E+06
1E-04	4.9E-08	4.1E+05	5.3E-08	3.8E+05	5.3E-08	3.8E+05
5E-04	2.3E-07	8.9E+04	2.5E-07	8.0E+04	2.5E-07	8.0E+04

Table E.4  $e$  and ALI for Entry through wounds or intact skin of <sup>238</sup>Pu, <sup>239</sup>Pu

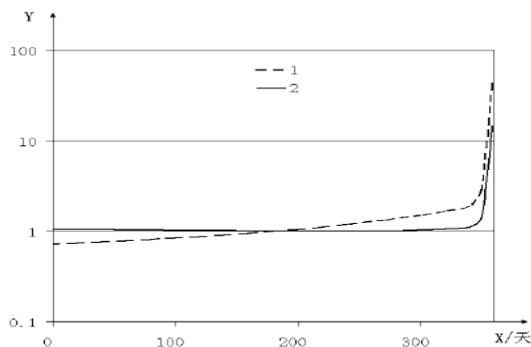
fI Value	<sup>238</sup> Pu		<sup>239</sup> Pu		<sup>240</sup> Pu	
	$e$ (SvBq <sup>-1</sup> )	ALI(Bq)	$e$ (SvBq <sup>-1</sup> )	ALI(Bq)	$e$ (SvBq <sup>-1</sup> )	ALI(Bq)
5E-04	4.5E-04	4.5E+01	4.9E-04	4.1E+01	4.9E-04	4.1E+01

## Annex F (informative)

### Uncertainty data of estimated dose due to uncertainty at the time of acute intake

**F.1** When estimating the dose of inhaled  $^{238}\text{Pu}$  through urine sample analysis, the ratio of the estimated dose data at the time of assumed acute intake to the estimated dose data at the time of actual acute intake is shown in Chart F.1.

Note: Chart F.1 and Chart F.2 are drawn with reference to Chart 4 in ISO 27048: *Radiation Protection - Dose Estimation for Internal Exposure Monitoring of Workers*. The original data are from ICRP 78.



In the figure:

X—Actual time of intake, day

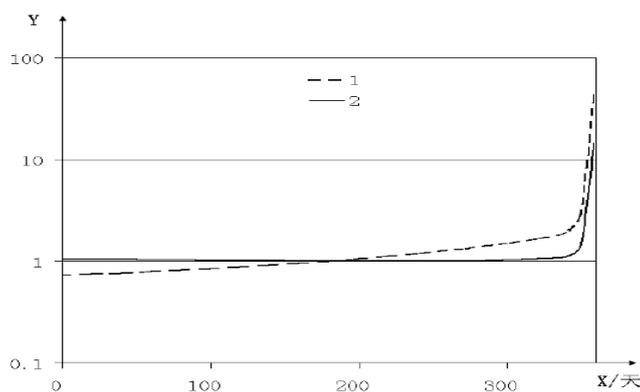
Y—Estimated dose/ actual dose

1—Type M  $^{238}\text{Pu}$

2—Type S  $^{238}\text{Pu}$

Chart F.1 Ratio of calculated dose data at the time of assumed acute intake to that at the time of actual acute intake under  $^{238}\text{Pu}$  inhalation and 24h urine sample analysis

**F.2** When estimating the dose of inhaled  $^{239}\text{Pu}$  or  $^{240}\text{Pu}$  through urine sample analysis, the ratio of the estimated dose data at the time of assumed acute intake to the estimated dose data at the time of actual acute intake is shown in Chart F.2.



In the figure:

X—Actual time of intake, day

Y—Estimated dose/ actual dose

1—Type M  $^{239}\text{Pu}$  or  $^{240}\text{Pu}$

2—Type S  $^{239}\text{Pu}$  or  $^{240}\text{Pu}$

Chart F.2 Ratio of calculated dose data at the time of assumed acute intake to that at the time of actual acute intake under  $^{239}\text{Pu}$  or  $^{240}\text{Pu}$  inhalation and 24h urine sample analysis

**Annex G**  
**(informative)**

**Typical values of coefficient of dispersion in logarithmic normal distribution  $K_{SF}$**

**G.1** The typical values of coefficient of dispersion in logarithmic normal distribution  $K_{SF}$  in the in vivo monitoring of Pu are shown in Table G.1.

Note: The data in Table G.1 and Table G.2 are from Table B.1 “Typical values of logarithmic normal uncertainty distribution in in vivo measurements of emission of low energy, medium energy and high energy photonic radiation” and Table B.3 “Default values of logarithmic normal dispersion coefficient  $K_{SF}$  for different types of measurements from different studies” in Annex B of ISO 27048: *Radiation Protection - Dose Estimation for Internal Exposure Monitoring of Workers*. Formula G.1 is from Formula B.1 in ISO 27048.

Table G.1 Typical values of coefficient of dispersion in logarithmic normal distribution  $K_{SF}$  in the in vivo monitoring of Pu

Source of uncertainty (Type)	Coefficient of dispersion in logarithmic normal distribution	
	Low energy photon (E<20keV)	Medium energy photon (20keV<E<100keV)a
Counting statistics (A)	1.5	1.3
Change of probe position (B)	1.2	1.05
Change of background signal (B)	1.5	1.1
Change of body shape (B)	1.5	1.12
Change of lung outer covering (B)	1.3	1.15
Change of activity distribution (B)	1.3	1.05
Scale <sup>(3)</sup>	1.05	1.05
Spectrum calculation <sup>b</sup> (B)	1.15	1.05

<sup>a</sup>Calculation of plutonium dose through measurement of <sup>241</sup>Am.  
<sup>b</sup>High-purity germanium probe measurement spectrum.

The total dispersion coefficient is calculated with formula (G.1):

$$K_{SF} = \exp\left[\sqrt{\sum_i \ln^2(K_{SF_i})}\right] \dots\dots\dots (G.1)$$

Wherein:

$K_{SF}$  -- Total dispersion coefficient;

$K_{SF_i}$  -- Dispersion coefficient of component i.

**G.2** Typical values of Class B uncertainty of biological samples are listed in Table G.2.

Table G.2 Typical values of coefficient of dispersion in logarithmic normal distribution  $K_{SF}$  of class B errors in Pu biological sample analysis

Source of uncertainty (Type)	Class B coefficient of dispersion in logarithmic normal distribution
24h urine sample	1.1
Single urine sample	2.0
24h fecal sample	3.0
72h fecal sample	1.9

## Annex H (informative)

### Example of intake and dose estimation

#### H.1 Example of estimation through PAS/SAS monitoring

##### H.1.1 Exposure scenario

In a workplace involving  $^{239}\text{Pu}$  operation, fixed air samplers were installed on site and workers did not wear masks or take other protective measures when working. According to the data summary at the end of the year, it was found that the average air concentration measured by the fixed air sampler was  $0.001\text{Bq/m}^3$  and the aerosol particle size was  $2.8\mu\text{m}$ . It was proved that the ratio of the air concentration measured by personal respiratory sampler to that measured by fixed air sampler was 8:1 and the inhaled materials were type M materials.

##### H.1.2 Intake and dose estimation

With the ratio of the air concentration measured by a personal respiratory sampler to that measured by a stationary air sampler, it was calculated the air concentration at the position of the breathing zone of on-site personnel was  $0.008\text{Bq/m}^3$ . With the formula (6), it was calculated the annual intake of on-site personnel was  $19.2\text{Bq}$  (the intake time  $t$  was taken as  $2000\text{h}$ ). Through the calculation of the dose coefficient of radioactive aerosol particles with different particle sizes, it can be obtained the dose coefficient of type M  $^{239}\text{Pu}$  aerosol particles with activity-median aerodynamic diameter (AMAD) of  $2.8\mu\text{m}$  is  $4.16\text{E-}05\text{Sv/Bq}$ . By multiplying the annual intake by corresponding committed effective dose coefficient, it can be calculated that the committed effective dose caused by the annual intake of  $^{239}\text{Pu}$  in the year was about  $0.8\text{mSv}$ .

#### H.2 Case of estimation through urine sample analysis

##### H.2.1 Exposure scenario

A worker was engaged in Pu operations 345d to 255d (91d of exposure period) and 55d to 5d (51d of exposure period) before taking its urine samples and inhaled  $^{239}\text{Pu}$  aerosol particles. The operating conditions were normal during the operation. The results of urine analysis showed that the net urine  $^{239}\text{Pu}$  daily excretion was  $1.5\text{mBq}$  (excluding the natural living urine plutonium background and the contribution of plutonium intake before that year). It was assumed that the AMAD of aerosol particles is  $5\mu\text{m}$  and the inhaled materials were type M materials.

##### H.2.2 Intake estimation

###### H.2.2.1 Simplified estimation

Assume that the intake of the year is a single intake at the midpoint of the year. It can be seen from Table A.1 that  $m(360/2)$  is  $5.4 \times 10^{-6}$ . With formula (4), the annual intake of  $^{239}\text{Pu}$  is calculated as  $278\text{Bq}$ .

###### H.2.2.2 Precise method

Take the intake of a year in two intakes and keep the intake per day the basically same. Take the first intake at the mid-point between 345d and 255d, i.e. calculating by taking the intake at the time of 300d (the intake is the daily intake times the number of days taken). Take the second intake at the mid-point between 55d and 5d, i.e. calculating by taking the intake at the time of 30d.  $m(300)$  and  $m(30)$  can be respectively calculated as  $4.2 \times 10^{-6}$  and  $9.5 \times 10^{-6}$ . Daily intake can be calculated with the formula (H.1) by the method of solving equation.

$$D_1 \times \dot{I} \times m(t_1) + D_2 \times \dot{I} \times m(t_2) = M \dots\dots\dots \text{(H.1)}$$

Wherein:

$D_1$  -- Duration of first intake (days), in this example,  $D_1=345-255+1=91$  (days);

$\dot{I}$  -- Daily intake. This method assumes daily intake is the same.

$m(t_1)$  -- intake excretion fraction at the time of  $t_1$ , in this example,  $t_1=(345+255)/2=300$ ,  $m(t_1)=m(300)=4.2 \times 10^{-6}$ ;

$D_2$  -- Duration of second intake (days), in this example,  $D_2=55-5+1=51$  (days);

$m(t_2)$  -- intake excretion fraction at the time of  $t_2$ , in this example,  $t_2=(55+5)/2=30$ ,  $m(t_2)=m(30)=9.5 \times 10^{-6}$ ;

$M$  -- Net urine plutonium daily excretion, in this example,  $M=0.0015\text{Bq}$ .

Put relevant data in formula H.1 and calculate daily  $^{239}\text{Pu}$  intake  $\dot{I}$  as 1.73Bq. Then, multiply by total exposure days  $D_1+D_2=142$  and calculate annual  $^{239}\text{Pu}$  intake as 246Bq.

### H.2.2.3 More precise method

Assume the intake of a year is taken every day during the exposure period and the daily intake  $\dot{I}$  is basically the same. Daily intake can be calculated with the formula (H.2) by the method of solving equation. Put relevant data in formula H.2 and calculate annual  $^{239}\text{Pu}$  intake as 220.3Bq. The daily intake  $\dot{I}$  is calculated with formula (H.2).

$$\dot{I} \sum_{t=5}^{55} m(t) + \dot{I} \sum_{t=255}^{345} m(t) = M \dots\dots\dots \text{(H.2)}$$

Wherein:

$\dot{I}$  -- Daily intake. This method assumes daily intake is the same.

$m(t)$  -- Intake excretion fraction at the time of  $t$ ;

$M$  -- Net urine plutonium daily excretion, in this example,  $M=0.0015\text{Bq}$ .

### H.2.3 Dose estimation

Assume to take the annual intake of  $^{239}\text{Pu}$  as 278Bq and take AMAD as the default value recommended by ICRP for workers, i.e.  $5\mu\text{m}$ , the committed effective dose coefficient can be calculated as  $3.2 \times 10^{-5}\text{Sv} \cdot \text{Bq}^{-1}$  with E.2. By multiplying the annual intake by committed effective dose coefficient, it can be calculated that the committed effective dose caused by the annual intake of  $^{239}\text{Pu}$  in the year was about 8.9mSv.

## Annex I (informative)

### Example of dose uncertainty estimation

#### I.1 Exposure scenario

A worker was engaged in Pu operation throughout the year and inhaled  $^{239}\text{Pu}$  aerosol particles. The operating conditions were normal during the operation. The results of urine analysis showed that the net urine  $^{239}\text{Pu}$  daily excretion was 1.5mBq (excluding the natural living urine plutonium background and the contribution of plutonium intake before that year). Aerosol particle size measurement was not conducted and the inhaled materials were estimated to be type M materials, but it was also possible that there were some type S materials mixed.

#### I.2 Intake estimation

Assume that the intake of the year is a single intake at the midpoint of the year. It can be seen from Table A.1 that  $m(360/2)$  is  $5.4 \times 10^{-6}$ . With formula (4), the annual intake of  $^{239}\text{Pu}$  is calculated as 278Bq.

#### I.3 Dose estimation

Take the annual intake of  $^{239}\text{Pu}$  as 278Bq. Take AMAD as the default value recommended by ICRP for workers, i.e.  $5\mu\text{m}$ , the committed effective dose coefficient of intaken  $^{239}\text{Pu}$  can be calculated as  $3.2 \times 10^{-5}\text{Sv}\cdot\text{Bq}^{-1}$  with E.2. By multiplying the annual intake by corresponding committed effective dose coefficient, it can be calculated that the committed effective dose caused by the annual intake of  $^{239}\text{Pu}$  in the year was about 8.9mSv.

#### I.4 Uncertainty estimation

##### I.4.1 Uncertainty of estimated dose from uncertainty at the time of intake

In the calculations above, it was assumed that the intake of a year occurred at the midpoint of the year, i.e., a single intake at the time of the 180th day. But in fact, it can be intaken on any day from the 1st to the 360th day. By calculating the intake on every day, it can be got the biggest possible underestimate occurred on the first day of the intake. At that time, the net urine  $^{239}\text{Pu}$  daily excretion was the daily excretion on the 360th day,  $m(360)$  was  $3.86 \times 10^{-6}$ , and the corresponding intake can be calculated as 389Bq with formula (1). The biggest possible overestimate occurred on the last day of the intake, i.e. the day before the measurement. At that time, the net urine  $^{239}\text{Pu}$  daily excretion was the daily excretion on the first day,  $m(1)$  was  $2.32 \times 10^{-4}$ , and the corresponding intake can be calculated as 6.47Bq with formula (1).

Notes: In most cases, the biggest possible overestimate occurs on the last day of the intake and the biggest possible underestimate occurs on the first day of the intake. But this is not always the case. Intake at all possible intake time shall be calculated. And the result shall be accurate to day.

It can be seen that, considering the uncertainty of intake time, the actual annual intake of the worker is between 6.47Bq~389Bq and the actual annual dose is between 0.21mSv~12.4mSv.

##### I.4.2 Uncertainty of estimated dose from measurement results

For urine sample analysis, the Class A uncertainty of the measurement results (i.e., the uncertainty caused by the randomness of the counting) can be ignored and considered to be 0. The Class B uncertainty of the measurement results (i.e., the uncertainty of the measurement results caused by the measurement system) can be analyzed as follows:

For urine sample analysis, when 24h urine sample sampling is carried out, the Class B coefficient of dispersion in logarithmic normal distribution is 1.1 according to Table G.2. According to formula (G.1) and statistical theory, when the measured quantity is 1.5mBq, the confidence level of 2.5% is 1.24mBq and the confidence level of 97.5% is 1.81mBq. At this time, if the intake occurs at the mid-point of one year, the

corresponding intake is 231Bq and 338Bq. Considering the uncertainty of estimated dose caused by the uncertainty of the measurement results, the actual annual dose ranges from 7.4mSv to 10.8mSv.

### **I.4.3 Uncertainty of estimated dose from characteristics of intaken materials**

#### **I.4.3.1 Uncertainty of estimated dose from uncertainty of particle size**

In this example, no information about AMAD is given and the AMAD value is taken as 5 $\mu$ m. According to the ICRP's recommendation, the corresponding geometric standard deviation is 2.5. According to statistical theory, the confidence interval of 95% is 1.35 $\mu$ m~14.25 $\mu$ m. It can be obtained through calculation that when AMAD=1.35 $\mu$ m,  $m(360/2)=1.03\times 10^{-5}$  and the dose coefficient is  $5.69\times 10^{-5}\text{Sv}\cdot\text{Bq}^{-1}$ . Then, the intake is calculated as 146Bq and the dose is 8.29mSv. When AMAD=14.25 $\mu$ m,  $M(360/2)=1.32\times 10^{-6}$  and the dose coefficient is  $9.39\times 10^{-6}\text{Sv}\cdot\text{Bq}^{-1}$ . Then, the intake is calculated as 1140Bq and the dose is calculated as 10.7mSv. Considering the uncertainty of estimated dose caused by the uncertainty of particle size, the actual annual dose ranges from 8.29mSv to 10.7mSv.

#### **I.4.3.2 Uncertainty of estimated dose from uncertainty of material type**

As it can not be confirmed whether the material contains type S material or how many type S materials it contains, calculation can be conducted by taking the proportion of type M materials in total materials from 0 to 1 (groups other than type M are classified as type M). It can be got that the annual dose corresponding to the daily urine excretion per mBq/d at 180d is 5.56mSv at the minimum and 142mSv at the maximum. As the measured daily urine excretion is 1.5mBq/d, the actual dose of the worker may be between 8.33mSv and 213mSv.

### **I.4.4 Discussion of dose uncertainty data**

From the calculations above, the following conclusions can be drawn:

- The largest source of uncertainty for the estimated dose in this example is the uncertainty of the material type. If it can be confirmed the inhaled material is type M material, it can be basically confirmed that the dose inhaled by the worker is below the annual dose limit. Otherwise there is the possibility of a high dose, even more than 200mSv. Further measurements shall be carried out to confirm whether there are obvious type S materials in inhaled plutonium. If yes, dose estimation shall be carried out after content measurement.
- The dose inhaled by the worker is recorded as 8.9mSv. If only the uncertainty at the time of intake is taken into account, the value may be an underestimate with less underestimation. But it may also be a serious overestimate. Considering the actual intake may occur on 1d among 1d~359d, the actual annual dose of the worker may be 0.21mSv~12.4mSv. If the value (8.9mSv) is considered as an serious overestimate and it is necessary to get a data closer to the true value, measurement can be conducted for this worker again after several days. Then, the uncertainty of the estimated dose caused by the uncertainty of the intake time can be significantly lowered.
- The effect of the uncertainty of measurement results on the dose estimate is acceptable.
- If urine sample analysis method is adopted, the effect of AMAD on dose uncertainty is acceptable. The measurement of AMAD is important if monitored aerosol value is used for dose estimation.

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