



Cite this: *J. Anal. At. Spectrom.*, 2024, 39, 1665

An isotope dilution mass spectrometry overview: tips and applications for the measurement of radionuclides†‡

Alexandre Quemet,^a Amélie Hubert,^b Alkiviadis Gourgiotis,^c Ana María Sánchez Hernández,^d Marielle Crozet,^e Guillaume Bailly,^e Andrew Dobney,^f Georges Duhamel,^g Joe Hiess,^g Urska Repinc,^g Sébastien Mialle,^h Béatrice Boulet,ⁱ Raphaëlle Escoube,^c Céline Bouvier-Capely,^c Fabien Pointurier^b and Sébastien Picart^a

This article proposes a practical guide including good laboratory practices followed by a critical review about the application of isotope dilution mass spectrometry (ID-MS) measurement to radionuclide analyses. Several national and international scientific institutions (French Alternative Energies and Atomic Energy Commission, French Radioprotection and Nuclear Safety Institute, European Commission, International Atomic Energy Agency, and Belgian Nuclear Research Centre) participated in this review by sharing their good laboratory practices. ID-MS is one of the primary ratio methods of measurement in the International System of Units. It can produce highly accurate results, as potential sources of bias can be controlled. Many hints are given to obtain the best performance. In addition, a script written with the open source software Octave is provided to calculate the optimal parameters of the {sample–spike} mixture easily. Radionuclide analysis by ID-MS applies to many different fields (environmental, biological, reference materials, irradiated samples, process control, nuclear safeguards and nuclear forensics).

Received 26th January 2024
Accepted 18th April 2024

DOI: 10.1039/d4ja00029c

rsc.li/jaas

1. Introduction

Radionuclides are unstable radioactive nuclides which emit radiation during their decay to gain more stability. They can be naturally occurring such as ¹⁴C or ¹²⁹I that come from cosmogenic processes or ²¹⁰Pb or ²³⁰Th that are decay products of uranium isotopes. However, the majority of radionuclides are artificial, being end-products or by-products. For example,

^{99m}Tc or ¹³¹I isotopes are used in medicine. ^{99m}Tc, ⁹⁰Sr and ¹³⁷Cs are fission products generated by nuclear fission in reactors or during nuclear weapons tests, while Pu and Am isotopes are produced in nuclear reactors.

The accurate assay of radionuclides is essential for various reasons. For example, U and Pu are the main elements of interest in the nuclear fuel cycle as some of their isotopes are used as fissile materials. As such, U and Pu accountancy is of prime importance in the nuclear fuel cycle and for safeguards purposes.^{1,2} Pu is present in common spent fuel at 1% by weight, in Mixed OXide fuel (MOX) at 5–10% by weight for use in pressurized water reactors and at 20–30% by weight for use in fast-neutron reactors.³ Its measurement with high accuracy (*i.e.* measurement trueness and precision^{4–6}) is essential to manage criticality issues, to verify fuel pellet conformity and for nuclear material accountancy. Am is also an important element in the nuclear fuel cycle as it is the major contributor to the long-term radiotoxicity coming from the waste, once Pu has been removed. Its reliable analysis is required for waste management and is also important for safeguards and nuclear forensics as it acts as a clock since the last separation of Pu.⁷

Age dating of nuclear materials is also an area of growing interest for safeguards and nuclear forensics purposes. The main radio-chronometers that are subject to analytical developments are ²³⁰Th–²³⁴U and ²³¹Pa–²³⁵U for uranium and ²⁴¹Am–²⁴¹Pu, ²³⁶U–²⁴⁰Pu and ²³⁵U–²³⁹Pu for plutonium.^{8–11} The

^aCEA, DES, ISEC, DMRC, Univ Montpellier, Marcoule, France. E-mail: alexandre.quemet@cea.fr

^bCEA, DAM, DIF, 91297 Arpajon, France

^cInstitut de Radioprotection et de Sécurité Nucléaire (IRSN), PSE-ENV/SPDR/LT2S, PSE-SANTE/SESANE/LRSI, Fontenay-aux-Roses, F-92260, France

^dEuropean Commission, Joint Research Centre (JRC), Hermann-von-Helmholtz-Platz 1, Eggenstein-Leopoldshafen, Karlsruhe, 76344, Germany

^eCEA, DAM, Valduc, Is-sur-Tille, 21120, France

^fSCK-CEN, Boeretang 200, Mol, 2400, Belgium

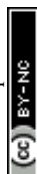
^gOffice of Safeguards Analytical Services, Department of Safeguards, International Atomic Energy Agency, IAEA Laboratories, Friedensstrasse 1, A-2444 Seibersdorf, Austria

^hUniversité Paris-Saclay, CEA, Service de Physico-Chimie, Gif-sur-Yvette, 91191, France

ⁱInstitut de Radioprotection et de Sécurité Nucléaire (IRSN), PSE-ENV/SAME/LMRE, Orsay, F-91400, France

† In memoriam: René Brennetot

‡ Electronic supplementary information (ESI) available. See DOI: <https://doi.org/10.1039/d4ja00029c>



accurate measurement of radionuclides is necessary to decrease the uncertainty of the calculated material age. Radionuclides are typically measured by radiometric counting methods (alpha, beta and gamma spectrometry) and mass spectrometry techniques (Inductively Coupled Plasma Mass Spectrometry (ICP-MS), accelerator mass spectrometry, Thermal Ionization Mass Spectrometry (TIMS), Resonance Ionization Mass Spectrometry, Secondary Ion Mass Spectrometry or Glow Discharge Mass Spectrometry).^{12–14}

The isotope dilution (ID) method is used for quantification purposes and is based on the internal calibration principle. The origin of ID is not well known. ID is similar to the mark-recapture method used in ecology to estimate animal population size.¹⁵ The mark-recapture method is based on reintroducing a small number of marked animals to an original population considered as a closed system. Later a group of animals is captured and the proportion of marked animals helps to estimate the total number of animals. This method was first used in 1896 by Petersen to estimate plaice¹⁵ and may have been used to estimate rare bird species living on islands.¹⁶ An assumption of this method, fundamental also to ID, is the perfect mixing of the animals.

The principle of ID is also very simple. A sample of an element with a known isotope composition but unknown number of atoms is mixed with a spike solution containing a known number of atoms of the same element enriched in an isotope and with a known isotope composition. After isotope equilibrium, the isotope ratio of the {sample-spike} mixture reflects the sample analyte amount. The application of ID was invented by Hevesy and Paneth in 1913 to determine the solubility of lead sulfide in water.¹⁷ In the 1950s, ID was extended to actinides.^{18,19} As it is based on isotope ratio determination, an accurate technique for isotope ratio measurements must be preferred to reach the best performance for ID. Measurements by TIMS have been mostly used since 1950 for this purpose due to its highly accurate measurement of isotope ratios.²⁰ Since the 1990s, the use of ID applied to mass spectrometric measurement (ID-MS) has grown considerably due to the widespread application of ICP-MS and the availability of certified reference materials (CRMs) from different institutes.

ID-MS has been listed as a primary method, together with coulometry or gravimetry.²¹ The definition of the Consultative Committee for Amount of Substance (CCQM) of a primary method of measurement in the International System of Units (SI) is a method having the highest metrological qualities, for which a mathematical model and realization are completely described and understood in terms of SI units.²² Two concepts are defined: a primary direct method and a primary ratio method. A primary direct method measures the value of an unknown quantity without reference to a standard of the same quantity, such as coulometry or gravimetry. A primary ratio method measures the value of an unknown to a standard of the same quantity; its operation must be completely described by a measurement equation, such as ID-MS.²¹ In both cases, the results must be accompanied by a complete uncertainty statement.²² From the list of primary methods, ID-MS is the most

widely used one in U and Pu amount determination inter-laboratory comparisons (ILCs).²³ Furthermore, the International Atomic Energy Agency (IAEA) considers ID-MS as one of the most accurate methods in terms of the International Target Values (ITVs) for measurement uncertainties applied on safeguarding nuclear materials.^{24,25} TIMS and ICP-MS are the techniques of choice to measure the isotope ratio of most elements,²⁶ for example radionuclides such as Sr,²⁷ Cs,^{28–30} Nd,^{31–34} Th,^{35,36} U,^{33,37–41} Pu,^{3,33,38,40,42–45} Am,^{7,31,38} and Cm.^{31,46} ID-MS is a versatile tool for radionuclide quantity measurement and the “gold standard” for nuclear safeguards.

Several reviews have described ID-MS for CRM characterization,²⁰ element speciation,^{47,48} proteomics⁴⁹ and geochemical analysis.⁵⁰ Some articles have discussed the general concept of ID-MS.^{26,51–54} To our knowledge no general reviews on radionuclide measurement by ID-MS have been published.

The Commission for the Establishment of Analytical Methods (CETAMA) is a unit of the French Alternative Energies and Atomic Energy Commission (CEA), which has a goal of measurement quality improvement within the nuclear field.^{23,55–58} The main activities of CETAMA are to develop and provide CRMs for nuclear analysis laboratories worldwide, to organize ILCs and to participate in the standardization of analytical methods. One of the CETAMA's working groups is dedicated to ID-MS which gathers several national and international scientific bodies (CEA, French Institute for Radiation Protection and Nuclear Safety (IRSN), Joint Research Centres (Europe), IAEA, Belgian Nuclear Research Centre (SCK)) that share their know-how in radionuclide analysis by ID-MS.

This review describes the good laboratory practices of the ID-MS working group members and proposes a critical review about the applications of ID-MS to radionuclide measurement. After a brief theoretical description of ID, the uncertainty budget expression is explained in more detail, including how to minimize it. The implementation and good laboratory practices of ID-MS are further described. The review covers the application of ID in different fields: environment, biology, reference material production, irradiated sample analysis, process control, nuclear safeguards and nuclear forensics. The final chapter is dedicated to the description of different ILCs available for testing the performance of radionuclide measurement by ID-MS.

2. Theory

2.1. General formula

The principle of ID is illustrated in Fig. 1. Isotope “A” is the major isotope of the element “E” in the sample. Isotope “B” is the major isotope of the element “E” in the spike. For clarity and conciseness, the following nomenclature is used throughout the manuscript:

- Subscripts:
 - Mix refers to the {sample-spike} mixture;
 - T refers to the spike (or tracer);
 - S refers to the sample.
- R is the B/A ratio in mol mol^{-1} .



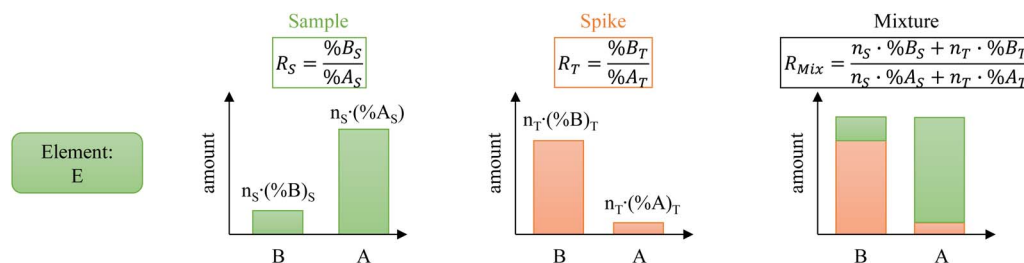


Fig. 1 Illustration of the isotope dilution principle.

- R' is the A/B ratio in mol mol^{-1} .
- %A refers to the isotope abundance in percent of mol mol^{-1} of A.
- %B refers to the isotope abundance in percent of mol mol^{-1} of B.
- n refers to the amount of substance (mol).
- w refers to the mass fraction in g g^{-1} .
- M refers to the molar mass in g mol^{-1} .
- m refers to the mass in g.
- u is the standard uncertainty with a coverage factor of $k = 1$.
- u_r is the relative standard uncertainty with a coverage factor of $k = 1$.
- α refers to the sample amount; spike amount ratio ($\alpha = n_S/n_T$) in mol mol^{-1} .
- LOD is the limit of detection.

The mixture isotope ratio (R_{Mix}) can be calculated from the atom number or number of moles of an element and the isotope abundance of isotopes A and B.

$$R_{\text{Mix}} = \frac{n_S \cdot \%B_S + n_T \cdot \%B_T}{n_S \cdot \%A_S + n_T \cdot \%A_T} \quad (1)$$

Introducing $\%B_S = \%A_S \cdot R_S$ and $\%B_T = R_T \cdot \%A_T$ in eqn (1) leads to the general form of the isotope dilution equation (eqn (2)).

$$n_S = n_T \cdot \frac{\%A_T}{\%A_S} \cdot \frac{R_T - R_{\text{Mix}}}{R_{\text{Mix}} - R_S} \quad (2)$$

Eqn (2) can be converted into mass fractions by taking into account the masses of the sample and spike, and the atomic masses of the element in the sample and spike (eqn (3)).

$$w_S = w_T \cdot \frac{m_T}{m_S} \cdot \frac{M_S}{M_T} \cdot \frac{\%A_T}{\%A_S} \cdot \frac{R_T - R_{\text{Mix}}}{R_{\text{Mix}} - R_S} \quad (3)$$

Another form is also commonly used to show the major isotopes in the spike and in the sample ($\%B_T$ and $\%A_S$) in the ID formula (eqn (4)). Eqn (2) and (4) correspond to each other and will give the same results.

$$n_S = n_T \cdot \frac{\%B_T}{\%A_S} \cdot \frac{R'_{\text{Mix}} - R'_T}{1 - R'_{\text{Mix}} \cdot R_S} \quad (4)$$

2.2. Formula used for environmental samples

A single (eqn (5)) and a double isotope dilution equation (eqn (6)) are commonly used in environmental samples for the mass fraction determination of ^{238}U using a spike enriched in the ^{236}U isotope and the $^{230}\text{Th}/^{238}\text{U}$ ratio using a spike enriched in the ^{229}Th and ^{236}U isotopes. Obviously, these equations can be applied for other target radionuclides by using the appropriate spike and the respective atomic masses.

$$w_S(^{238}\text{U}) = \left(\frac{^{238}\text{U}}{^{236}\text{U}} \right)_{\text{Mix}} \cdot \frac{M(^{238}\text{U})}{M(^{236}\text{U})} \cdot w_T(^{236}\text{U}) \cdot \frac{m_T}{m_S} \quad (5)$$

$$\frac{w_S(^{230}\text{Th})}{w_S(^{238}\text{U})} = \left(\frac{^{230}\text{Th}}{^{229}\text{Th}} \right)_{\text{Mix}} \cdot \left(\frac{^{236}\text{U}}{^{238}\text{U}} \right)_{\text{Mix}} \cdot \frac{w_T(^{229}\text{Th})}{w_T(^{236}\text{U})} \cdot \frac{M(^{236}\text{U}) \cdot M(^{230}\text{Th})}{M(^{238}\text{U}) \cdot M(^{229}\text{Th})} \quad (6)$$

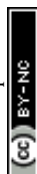
The mass fraction and mass fraction ratio are then converted into activity ratios by considering the radionuclide atomic masses and their respective half-lives ($t_{1/2}$). It should be noted that the double isotope dilution in combination with a double spike (*i.e.* ^{229}Th – ^{236}U) is a powerful tool that helps to minimize weighing errors and eliminate errors due to differential evaporation of spike solutions. Indeed, the spike weight does not play a role in eqn (6).⁵⁹

It should be noticed that spikes usually contain isotopic impurities (for instance, a ^{236}U spike usually contains traces of ^{234}U , ^{235}U and ^{238}U isotopes). In many cases, especially for the less abundant isotopes at ultra-trace levels, eqn (5) and (6) must be modified to include and correct for the contribution of these isotopic impurities.

2.3. Estimation of the limit of detection

The LOD is the minimum concentration or quantity of an analyte that can be detected with a reasonable certainty for a given analytical procedure.⁶⁰ Eqn (7) can be used to obtain a conservative estimate of the LOD of the element E using ID ($\text{LOD}_{\text{ID}}(E)$) for a specific spike.⁶¹

$$\text{LOD}_{\text{ID}}(E) = \frac{\sqrt{\text{LOD}(\text{B})^2 + R_T \times \text{LOD}(\text{A})^2}}{\left| \frac{\%B_S}{100} - R_T \times \frac{\%A_S}{100} \right|} \quad (7)$$



where LOD(B) and LOD(A) are the LOD for B and A isotopes, respectively. LOD_{ID}(E), LOD(B) and LOD(A) units must be identical.

3. Implementing isotope dilution

A careful implementation is needed to obtain the best performance for ID-MS. The highest level of quality can be reached when a weighed aliquot of the sample is mixed with a weighed aliquot of the spike. Volumetric mixing can only achieve a lower level of uncertainty. The uncertainty will also be minimum when an optimal ratio between the sample and the spike is reached.

Successful ID requires achieving complete isotope equilibration between the sample and spike. This is practically only possible when the mixture is in solution. Due to isobaric interferences in many instances a separation step to obtain the pure element is needed. Theoretically this separation does not introduce a source of error since after isotope equilibration, losses of the substance have no influence on the final result, an important advantage compared to other methods. In all cases, the appropriate ID-MS spike should be added to the sample aliquots before starting the sample preparation and should be added before the separation protocol. It is therefore also clear that any loss of substance before reaching full equilibrium is a source of error and to be avoided. Another advantage is the compensation of matrix effects as any factor influencing the sensitivity of the analyte is the same for the sample and spike nuclide.

The main disadvantages of the method are its destructive nature and that the preparation steps consume time and resources. The disadvantages are generally balanced out by the advantages. The spike availability is for most elements no issue as the laboratories produce their own spikes or procure them from CRM producers.

The weighing procedure, the preparation of the {sample-spike} mixture, the choice of the spike, spike management, and isotopic homogenization are the main criteria to be taken into consideration when implementing ID-MS. These various influencing parameters are discussed in the ensuing paragraphs. Isotope ratio measurements by MS are also an important parameter to take into account and are largely described in the literature.^{12,62–68}

3.1. Weighing procedure

3.1.1. General recommendations. An accurate weighing and mass determination of the sample and the spike are essential for a correct ID-MS assay with low uncertainties. There are many weighing techniques, but in this section those most commonly used for radionuclide analyses are presented.

In the case of solid samples, the material is normally dissolved taking a sample quantity sufficiently large to obtain a representative sample of the material. The mass of the dissolved sample generally exceeds 0.1 g to optimize the uncertainty contribution from mass measurements (see Section 4.2). The solution is diluted, if needed, to match the target sample/spike ratio (see Section 3.2). For mass spectrometric measurements, typically picogram to microgram amounts of spike are used. Therefore, a similar quantity of the sample is required for

assay determination by ID-MS. The mass of the sample and of the spike used to prepare the mixture solution should also exceed 0.1 g for the same reasons.

For ID-MS, the amounts of spike and sample are typically small. Thus, the uncertainties in the mass determination contribute significantly to the overall uncertainty budget. Therefore, it is important to consider the different effects that can lead to a significant bias, some of which are related to the weighing itself (buoyancy, electrostatic effects), some to the sample preparation (evaporation, moisture content and stability, type and mass of vials) and others to effects that might happen during aliquoting such as cross-contamination.

The availability of a high-precision analytical balance is a prerequisite, typically with a resolution of at least 0.1 mg. The balance must be assessed before use with appropriate standard weights to ensure proper balance function.

Electrostatic effects can be avoided when needed by using specific tools to prevent or eliminate electrostatic charges. Moreover, properly trained analysts and good analytical practices can improve the mass determination, for instance performing daily check weighings prior to using the balance for critical measurements, and ensuring the correct placement of vials on the balance.⁶⁹

3.1.2. Weighing by difference. The most common weighing technique for radionuclide measurement is weighing by difference: *i.e.* placing a container on the balance, noting the mass, and then adding the sample or spike to it and noting the mass again. The difference between the two masses is the mass of the sample or spike added to the container.

The weighing procedure can be summarized as follows: the balance is tared with the vial and the cap, then the sample is added and the cap placed on the vial to avoid evaporation, and the mass displayed is the sample aliquot, m_s .⁷⁰ After another tare of the balance, the spike is added and weighed with the cap on the vial. The mass displayed is the spike aliquot, m_t .

A different procedure, employing the technique of weighing by difference, was established in the nuclear safeguards laboratories of the Joint Research Centre (JRC) Karlsruhe, the double-weighing method.⁷¹ In this procedure, the aliquot mass of the sample, or spike, is determined twice:

1. The mass dispensed from a Pasteur pipette determined by the mass difference between a filled and an emptied pipette (eqn (8)):

$$m_{ip} = m_{pf} - m_{pe} \quad (8)$$

where m_{ip} is the mass of the sample or the spike ($i = S$ or T), m_{pf} is the mass of the filled pipette and m_{pe} is the mass of the emptied pipette.

2. The mass received into a vessel, the mass difference between the spike vial with and without the aliquot (eqn (9)):

$$m_{iv} = m_{vf} - m_{ve} \quad (9)$$

where m_{iv} is the mass of the sample or the spike ($i = S$ or T), m_{vf} is the mass of the filled vial with the sample or spike and m_{ve} is the mass of the empty vial.



Once the consistency between the two mass determinations has been demonstrated, they should not differ from one another by a laboratory determined limit, and the mass dispensed from the pipette (eqn (8)) is taken as the true aliquot mass. This procedure can minimize the impact of some of the undesirable effects encountered during weighing, and offers a built-in consistency check so that a bad weighing can be detected before mass spectrometric measurements.

3.1.3. The substitution method. For very accurate determinations, *e.g.* preparation or characterization of certified reference materials, the substitution method (also known as ABBA or SUUS) is used. In this method, the mass is determined through comparison with mass standards of similar nominal value.⁷² The substitution method consists of weighing the mass reference standard A and the mass to be determined B, one after another on the same load carrier according to the weighing cycle A–B–B–A or also in the sequence B–A–A–B. The balance is used as a comparator eliminating possible linear drifts of the balance. The mass of the sample or spike is determined using the mass of the standard (S) and the difference between the readings, ΔX (eqn (10)):

$$m_i = S + \Delta X$$

$$\Delta X = \frac{X_{B1} + X_{B2} - X_{A1} - X_{A2}}{2} \quad (10)$$

Uncertainties on the order of tens of μg can be achieved with the substitution method.^{73,74} However, this method requires many standards and is time consuming, and hence is usually restricted to metrological labs and is not routinely used in analytical labs.

3.1.4. Air buoyancy and electrostatic effects. The air buoyancy effect is well known and corrections can be applied,⁷⁵ see eqn (11), although for many nuclear applications the effect can be negligible:

$$m_{\text{true}} = (\Delta X - \delta) + a \left(\frac{1}{r} - \frac{1}{r_0} \right) \Delta X \quad (11)$$

where m_{true} is the true mass, $\Delta X = X - X_0$ the read mass between the in-load and the no-load indications of the balance, δ is the correction for the bias, a is the air density, and r and r_0 are the densities of the sample and of the standard used for calibration, respectively.

The need to correct for air buoyancy depends on how accurate the results must be and on the density of the samples. It is particularly critical when the target total uncertainty is less than 1% (metrological purposes for example) and for aqueous solutions with a density close to 1000 kg m^{-3} , because such a density is far removed from that ($8000\text{--}8100 \text{ kg m}^{-3}$) of the stainless steel calibration standards.

The expression for the correction factor, K , for air buoyancy is given in eqn (12)

$$K = \frac{\left(1 - \frac{\rho_{\text{air}}}{\rho_{\text{std}}}\right)}{\left(1 - \frac{\rho_{\text{air}}}{\rho_{\text{sol}}}\right)} \text{ with } m_{\text{corrected}} = K \times m_{\text{as read}} \quad (12)$$

If the requirement in terms of weighing uncertainty is 0.1%, it is not necessary to measure the air density experimentally in order to calculate the K factor for an aqueous sample with a density of 1000 kg m^{-3} . Knowing the density of the sample, the conventional value, 1.2 kg m^{-3} , for the density of air is sufficient to express K and correct the read mass. For solid samples and the same requirement in terms of the uncertainty level, corrections are not necessary.

In the case of ID-TIMS, the weights are expressed in the equation in the form of a ratio, $\frac{m_T}{m_S}$. If the solutions are alike (*e.g.* same nitric acid concentrations), their densities and K factors will be identical and the ratio of the masses as read will correspond to the ratio of true masses (corrected masses). No corrections will be needed. The same conclusions can be drawn if serial dilutions are made using solutions with similar characteristics.

If higher accuracy is required, corrections for air buoyancy should be considered throughout the entire preparation of sample. For example, when a solid is dissolved, the K factor for the solid is 1; whereas for a solution is greater than 1. By considering a density solution of 1100 kg m^{-3} ($\approx 3 \text{ mol L}^{-1}$ nitric acid solution), the K factor for this solution can be written as in eqn (13)

$$K = \frac{\left(1 - \frac{1.2}{8000}\right)}{\left(1 - \frac{1.2}{1100}\right)} = 1.0009 \quad (13)$$

The relative mass correction of the solution is approximately +0.1%. The mass fraction for the dissolved solid should then be corrected inversely by -0.1% . In other words, not taking the air buoyancy into account would lead to an overestimation of the mass fraction of the sample.

3.2. Optimization of the {sample-spike} mixture

ID-MS requires an optimum spiking ratio to obtain the best accuracy (*i.e.* the minimum relative uncertainty of n_s , eqn (2)). Several studies have been reported in the literature.^{37,52,76–80} Here, three different methods are detailed. The first derives the error multiplication factor (F) as a function of the mixture isotope ratio, leading to a very simple formula to derive the optimal isotope ratio for the mixture. The second derives the F factor as a function of the ratio between the amount of sample and the amount of spike which makes it straightforward to prepare the mixture experimentally. The third method is broader, in that it considers all isotope ratio uncertainties. Lastly, the choice of the spike isotope and examples are discussed.

The three methods have been implemented in a script written with the open source software Octave,^{81,82} version 8.3.0. The method calculating the LOD as a function of the spike's isotope ratio (eqn (7)) was also implemented. To start the script, download the “startup_ID.m” file available in the ESI.† Start the Octave software and set the browser directory to the appropriate folder where the file “startup_ID.m” is located. Starting the



script is performed by typing “startup_ID” in the Octave command window. The script then prompts the user to select an optimization method. All parameters must be selected. Once the calculation has been completed, the optimum parameters are displayed in the Octave command windows. The plot is also displayed. The plot can be saved as an 8 cm × 8 cm “.png” file. The results and the raw data can be saved as a “.txt” file.

3.2.1. Error multiplication factor as a function of the mixture isotope ratio. This method helps calculate the F factor as a function of the mixture isotope ratio.^{76–79,83} Using the law of error propagation, the n_s uncertainty can be calculated by considering the R_{Mix} contribution only (eqn (14)). The contributions of R_s and R_T are considered as negligible.

$$\left| \frac{dn_s}{n_s} \right| = F \left| \frac{dR_{\text{Mix}}}{R_{\text{Mix}}} \right| \quad (14)$$

The F factor is obtained from eqn (15).

$$F = \frac{(R_s - R_T) \cdot R_{\text{Mix}}}{(R_{\text{Mix}} - R_s) \cdot (R_T - R_{\text{Mix}})} \quad (15)$$

Finding the optimal value of R_{Mix} is simply a matter of locating the minimum F factor in the function $F = f(R_{\text{Mix}})$. The minimum of a function is obtained when the derivative is equal to zero (eqn (16)).

$$\frac{dF}{dR_{\text{Mix}}} = \frac{R_s - R_T \cdot (R_{\text{Mix}}^2 - R_s \cdot R_T)}{((R_{\text{Mix}} - R_s) \cdot (R_T - R_{\text{Mix}}))^2} = 0 \quad (16)$$

Eqn (16) is equal to zero if the numerator is equal to zero. After rearrangement, eqn (17) is obtained. The optimum mixture ratio ($R_{\text{Mix,opt}}$) can be calculated using the square root of the product of R_s and R_T .

$$R_{\text{Mix,opt}} = \sqrt{R_s \cdot R_T} \quad (17)$$

Eqn (17) is a very simple equation for deriving the optimum mixture isotope ratio. However, one prerequisite is the lower R_s and R_T uncertainties compared to R_{Mix} uncertainties. This condition is generally true: R_T uncertainty is usually very low as coming from the CRM certificate or can be accurately measured in the case of an in-house spike; R_s can be measured several times to decrease its uncertainty.

The blue curve in Fig. 2 shows the F factor as a function of R_{Mix} (eqn (15)) for a sample with 3.0% of ^{235}U and 97% of ^{238}U ($\%A_s = 97\%$, $\%B_s = 3.0\%$, $R_s = 0.0309$) using a spike enriched with the ^{235}U isotope such as IRMM-054 CRM (93.2% of ^{235}U and 5.4% of ^{238}U ; $R_T = 17.3$). Using this raw data, the optimum isotope ratio of the mixture is $R_{\text{Mix,opt}} = 0.73$. In this example, the parameters are robust since the F factor varies little in the region around the optimum value.

When the major spike isotope is absent from the sample ($R_s = 0$), eqn (17) can be simplified (eqn (18)).

$$F = \frac{R_T}{R_{\text{Mix}} - R_T} \quad (18)$$

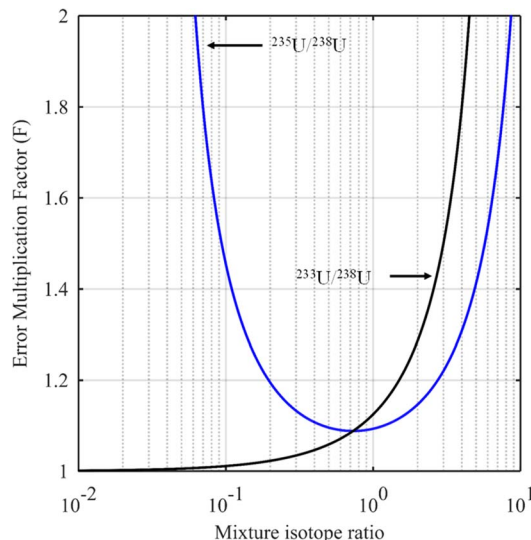


Fig. 2 Error multiplication factor as a function of the $^{235}\text{U}/^{238}\text{U}$ mixture isotope ratio (blue curve) for a sample with $^{235}\text{U}/^{238}\text{U} = 0.0309$ and for a spike enriched with the ^{235}U isotope ($^{235}\text{U}/^{238}\text{U} = 17.3$), and as a function of the $^{233}\text{U}/^{238}\text{U}$ mixture isotope ratio (black curve) for a sample with $^{233}\text{U}/^{238}\text{U} = 0$ and for a spike enriched with a ^{233}U isotope ($^{233}\text{U}/^{238}\text{U} = 9$).

Evaluation of the optimum isotope ratio of the mixture can be done graphically. An example is shown in Fig. 2 (black curve), for a uranium sample with $^{233}\text{U}/^{238}\text{U} = R_s = 0$ and a spike enriched at 90% in the ^{233}U isotope ($^{233}\text{U}/^{238}\text{U} = R_T = 9$). The F factor tends to 1 as R_{Mix} gets closer to R_s and becomes larger as R_{mix} approaches R_T . The best choice would appear to be $R_{\text{Mix}} = R_s$ (i.e. when no spike is used), but this makes no sense for an ID measurement. A compromise needs to be reached between the minimum F factor and spike addition. In the example in Fig. 2 (black curve), mixture isotope ratios in the range 0.1 to 1 seem to provide an interesting compromise between a low F factor and needing to add a spike.

3.2.2. Error multiplication factor as a function of the ratio between the amount of sample and amount of spike. This method calculates the F factor as a function of the ratio between the amount of sample and the amount of spike.⁵² It is essentially eqn (15), rewritten, by introducing α (n_s/n_T atomic ratio) into eqn (1), which leads to eqn (19)

$$R_{\text{Mix}} = \frac{\alpha \cdot \%B_s + \%B_T}{\alpha \cdot \%A_s + \%A_T} \quad (19)$$

By combining eqn (15) and (19), the F factor as a function of α can be calculated (eqn (20)).

$$F = f(\alpha) = \frac{(R_s - R_T) \cdot \frac{\alpha \cdot \%B_s + \%B_T}{\alpha \cdot \%A_s + \%A_T}}{\left(\frac{\alpha \cdot \%B_s + \%B_T}{\alpha \cdot \%A_s + \%A_T} - R_s \right) \cdot \left(R_T - \frac{\alpha \cdot \%B_s + \%B_T}{\alpha \cdot \%A_s + \%A_T} \right)} \quad (20)$$

Determining the α optimum value is simply a matter of locating the minimum F value. To understand how the F factor



varies around the optimum α value, the F factor can be plotted as a function of α (eqn (20)). This plot is useful for illustrating how robust the optimal value is. In practice, the sample amount is generally not accurately known. It is therefore difficult to mix the sample and spike in the exact optimal proportions.

Combining eqn (4) and (17) helps to quickly obtain the optimal sample amount over spike amount ratio (α_{opt} , eqn (21)).

$$\alpha_{\text{opt}} = \frac{\% A_T \cdot \sqrt{R_S \cdot R_T} - B_T}{\% B_S - \% A_S \cdot \sqrt{R_S \cdot R_T}} \quad (21)$$

This way of expressing the F factor provides the analyst with a simple way to derive the {sample-spike} mixture. As for the previous method, one prerequisite is that the uncertainties of R_S and R_T are lower than that of R_{Mix} . In cases where the major isotope of the spike is absent from the sample ($R_S = 0$), eqn (20) cannot be applied. In this case, the optimum ratio of sample amount to spike amount can be determined graphically.

The curves in Fig. 3 show the F factor as a function of α (eqn (20)) for a sample with 3.0% of ^{235}U and 97.0% of ^{238}U using a spike enriched with the ^{235}U isotope such as IRMM-054 CRM (blue curve, 93.2% of ^{235}U and 5.4% of ^{238}U , same example as for Fig. 2) and for a sample with 70.0% of ^{239}Pu and 1.0% of ^{242}Pu using a spike enriched with a ^{242}Pu isotope like the IRMM-049d CRM (black curve, 0.2% of ^{239}Pu and 94.7% of ^{242}Pu). Using these raw data, the optimal α values are 1.3 and 0.5 for uranium and plutonium samples respectively. In these examples, the F factor varies little in the region around the optimum value of α .

3.2.3. Optimal mixture isotope ratio by taking into account all isotope ratio uncertainties. This method derives the optimum mixture isotope ratio by taking into account all isotope ratio uncertainties.³⁷ In this method, the uncertainties

of R_S and R_T are taken into account. Considering eqn (2), n_T , $\%A_T$ and $\%B_T$ terms have no effect on the optimum ratio. From the uncertainty point of view, eqn (4) can be simplified and become eqn (22): using this equation and the law of propagation of uncertainty, eqn (23) is obtained.

$$n_S \Leftrightarrow \frac{R_T - R_{\text{Mix}}}{R_{\text{Mix}} - R_S} \quad (22)$$

$$u^2(n_S) = \left(-\frac{R_T - R_{\text{Mix}}}{(R_{\text{Mix}} - R_S)^2} \right)^2 \cdot u^2(R_S) + \left(\frac{1}{R_{\text{Mix}} - R_S} \right)^2 \cdot u^2(R_T) + \left(\frac{R_S - R_T}{(R_{\text{Mix}} - R_S)^2} \right)^2 \cdot u^2(R_{\text{Mix}}) \quad (23)$$

The optimum spiking should minimize the relative uncertainty of n_S , which can be expressed as a function of R_{Mix} (eqn (24)).

$$u_r(n_S) = \frac{u(n_S)}{n_S} = f(R_{\text{Mix}}) \quad (24)$$

Determining the optimal value of R_{Mix} is simply a matter of locating the minimum relative uncertainty of n_S ($u_{r,\min}(n_S)$). To understand how the F factor varies around the R_{Mix} optimal value, the error of the relative uncertainty as a function of R_{Mix} can be plotted (eqn (25)).

$$\frac{u_r(n_S)}{u_{r,\min}(n_S)} - 1 = f(R_{\text{Mix}}) \quad (25)$$

If the uncertainties of R_S and R_T are equal to zero, then this solution is identical to that obtained by using method 1 (eqn (15)).

To illustrate this method, a sample with 3% of ^{235}U and 97% of ^{238}U was considered: $\%A_S = 97\%$, $\%B_S = 3\%$, $R_S = 0.0309$ and $u_r(R_S) = 0.5\%$. A spike, enriched in the ^{235}U isotope (such as the IRMM-054 CRM), was used: $R_T = 17.3$ and $u_r(R_T) = 0.03\%$. The R_{Mix} relative uncertainty was fixed at 0.07%, corresponding to the ITV value.²⁴ In this example, the optimum isotope ratio of the mixture is $R_{\text{Mix,opt}} = 1.03$. It should be noted that the optimum isotope ratio of the mixture (1.03) determined by taking into account all uncertainties is slightly different from, but not dissimilar to, the value (0.73) when not taking into account uncertainties of the isotope ratio R_S and R_T (eqn (15)).

Just as for the previous two methods, in cases where the major isotope of the spike is absent from the sample ($R_S = 0$), the optimum isotope ratio of the mixture can be determined graphically.

3.2.4. Choice of the spike isotope. Isotope selection of the spike is a key step. A good choice will simplify the preparation of the {sample-spike} mixture and improve the quality of the measurement as well as minimize the uncertainty. It is recommended to follow a few rules for the selection of the spike isotope:^{52,66}

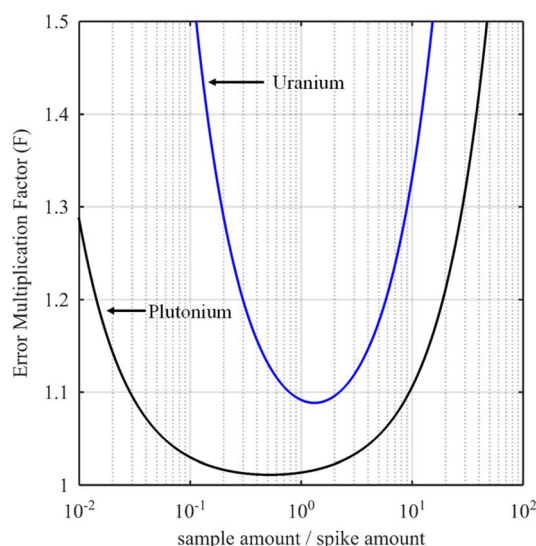


Fig. 3 Error multiplication factor as a function of the sample over spike amount for uranium (blue curve, sample with 3% of ^{235}U and 97% of ^{238}U using a spike enriched with 93.2% of ^{235}U) and plutonium (black curve, sample with 70% of ^{239}Pu and 1% of ^{242}Pu using a spike enriched with 94.7% ^{242}Pu).



- It is better if the spike isotope is absent from the sample or has the lowest isotopic abundance in the sample.

- A spike enrichment higher than 90% is recommended, allowing the accuracy of the ID to be practically independent of the mixture preparation.

- It is better if the spike isotope has no isobaric interference.

For uranium, the most common spikes are ^{233}U , ^{235}U or ^{236}U , since the main uranium isotope in most samples is generally ^{238}U (excluding highly enriched uranium material). For plutonium, ^{240}Pu , ^{242}Pu or ^{244}Pu spike isotopes are commonly used, since ^{239}Pu is usually the main major isotope in most samples. For americium, since the samples have ^{241}Am as the major isotope, a spike enriched in the ^{243}Am isotope is a good option.⁵⁶ In the case of U, Pu and Am, the choice is easy as the sample has one major isotope and spikes highly enriched in minor isotopes are commercially available. It is worth noting, for the radioactive spike, the isotope abundance and mass fraction must be updated for the day of analysis to correct for the radioactive decay.

For certain other elements, the choice of the spike isotope is not as straightforward. For example, in the case of neodymium measurement with natural isotopic composition, several choices are possible. In theory, the best choice of reference isotope in the sample is the ^{142}Nd isotope since it is the most abundant isotope in such a sample. However, since ^{142}Ce can be an isobaric interference on the ^{142}Nd isotope, the ^{144}Nd isotope is generally preferred as a sample isotope.³¹ Fig. 4 shows the F factor as a function of the sample/spike amount ratio for different Nd isotopes as the major isotope in the spike. The curves for ^{148}Nd and ^{150}Nd lie close together and overlap each other, as shown in Fig. 4. Since ^{148}Nd and ^{150}Nd are the two least abundant isotopes, in a sample with natural neodymium isotopic composition, a spike enriched in either ^{148}Nd or ^{150}Nd

is the best choice to obtain the lowest uncertainty (*i.e.* minimum F factor) and the easiest to implement (because the plot of the F factor is almost flat in the region around the optimum value). Since all other Nd isotopes in such a sample have higher abundances, choosing an isotope other than ^{148}Nd or ^{150}Nd as the spike isotope will generate a higher minimum F factor and a narrower range around the optimal F factor. Fig. 5 shows the F factor as a function of the sample/spike amount ratio for different spike enrichments when using a spike enriched in the ^{150}Nd isotope. The higher the spike enrichment is, the smaller the optimal F factor is. Moreover, the region around the optimal F factor value is relatively flat for spikes with $R_T > 9$ (*i.e.* spike enrichment higher than 90%), which makes it easier to implement ID. The LOD, in arbitrary units, as a function of the spike isotope ratio is presented in Fig. 6 for different major isotopes of the spike, assuming the LOD of A and B isotopes is equal to 1 in arbitrary units (eqn (7)). The curves for ^{148}Nd and ^{150}Nd isotopes overlap in Fig. 6. The LOD decreases from $R_T = R_S$, tending towards lower LOD values at higher spike enrichments. It should be noted that the choice of spike isotope has no significant influence on the LOD when R_T is high enough. In this example, all LODs are similar irrespective of the spike isotope chosen when $R_T > 6$. In this way, for the measurement of natural Nd by ID-MS, a judicious choice is a spike enriched in ^{148}Nd or ^{150}Nd isotopes with an enrichment greater than 90%. The optimal sample/spike amount ratio in the mixture is then calculated as a function of the spike enrichment (Fig. 5).

Some laboratories do not calculate the optimal parameters for every new sample when measuring U or Pu. Instead, the mixture is prepared in such a way as to obtain a 1/1 ratio between the amounts of spike and sample. This method works well if the conditions for the selection of the spike are fulfilled: the spike isotope is absent from the sample or has the lowest

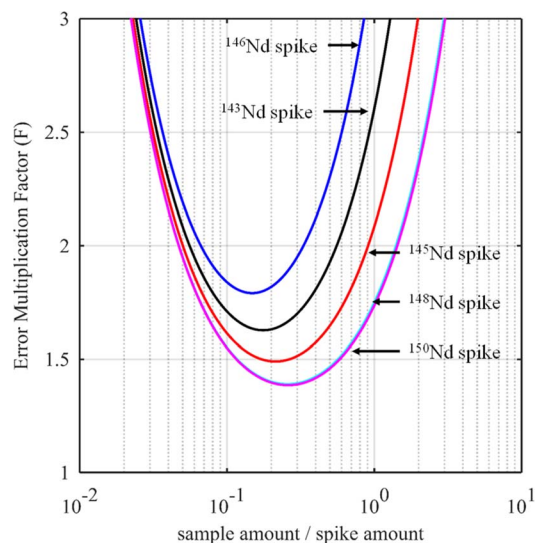


Fig. 4 Error multiplication factor as a function of the sample/spike amount ratio for ^{143}Nd (black line), ^{145}Nd (red line), ^{146}Nd (blue line), ^{148}Nd (cyan line) and ^{150}Nd (purple line) spikes ($R_T = 9$ for all spikes) with a neodymium sample of natural isotopic composition. The ^{144}Nd isotope is used as a reference sample isotope.

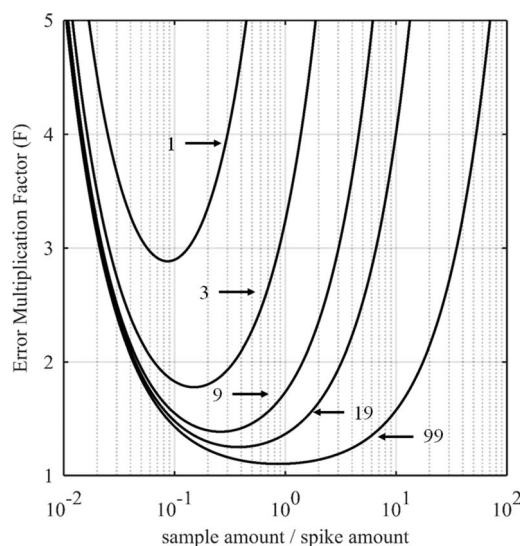


Fig. 5 Error multiplication factor as a function of the sample/spike amount ratio for different $^{150}\text{Nd}/^{144}\text{Nd}$ spike isotope ratios ($R_T = 1, 3, 9, 19$ or 99) for measuring natural neodymium.



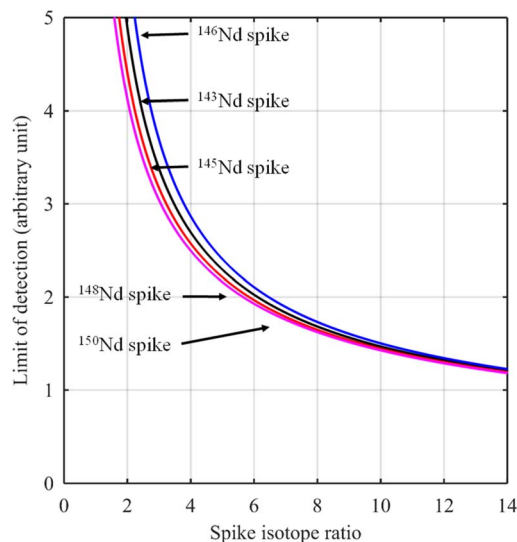


Fig. 6 Limit of detection (arbitrary unit) for a natural sample of neodymium as a function of the spike isotope ratio for spikes enriched in ^{143}Nd (black line), ^{145}Nd (red line), ^{146}Nd (blue line), ^{148}Nd (cyan line) and ^{150}Nd (purple line) isotopes.

isotopic abundance in the sample and the spike enrichment is high enough (Fig. 3). In these examples, the optimal n_s/n_T ratio is found to be 1.3 (F factor = 1.088) for the uranium sample and 0.5 (F factor = 1.011) for the plutonium sample. However, at values around $n_s/n_T = 1$, the F factor (1.093 for uranium and 1.014 for plutonium) is very similar to that at the optimum ratio. In these cases, employing a 1/1 ratio between the amount of the spike and the sample instead of the optimal amount ratio will have no impact on the ID-MS accuracy.

3.3. Spike monitoring

Assessment of the spike stability and homogeneity of liquid spike materials is crucial to ensure the quality of the ID analysis results and their reliability. The behavior of spike materials is difficult to predict reliably solely from stability studies over short periods. Due to evaporation, the observed differences in element mass fraction can be higher than 0.1% after several weeks, which is generally larger than the element mass fraction uncertainty of the spike. To overcome this issue, several solutions are presented in this section.

When using liquid spikes in the form of ampoules, it is recommended to consume the spike solution immediately after opening, or alternatively to dry the prepared aliquots as small-size dried spikes for later use, eliminating the need to correct evaporation effects and additional uncertainty due to dilution. However, due to the scarcity and costs of commercially available spikes, this option is not often applied.

IRMM-1027 Large-Sized Dried (LSD) and LSD spikes produced by the IAEA, prepared from U and Pu metal CRMs, are applied to measure the uranium and plutonium content of dissolved fuels in reprocessing plants.^{73,84–86} LSD spike vials have certified masses of uranium (^{235}U and ^{238}U) and ^{239}Pu and isotopic composition with associated uncertainty. The main

advantage is that they are to be used on an undiluted sample solution containing mg amounts of U and Pu. A further advantage is that cross-contamination is limited precisely because of the large amounts of the analyte in both the spike and the sample. However, they are prepared for a specific and single use, and until the spikes were in a dried nitrate form, it was not easy to maintain their integrity over longer periods. Nowadays, organic stabilizing substances are used to prolong shelf-life and guarantee stability during shipment.⁷³

Liquid spikes are often used after dilution to prolong the operational lifetime of the spike and to adjust the spike solution mass fraction. In this case, not only spike solution evaporation but also the associated uncertainty of performing gravimetric dilution needs to be considered. Spike solutions in glass ampoules with a screw-cap were introduced by JRC-Geel to replace the flame sealing of ampoules, and are a good choice to reduce the evaporation effects during use. The storage in glass ampoules for U, Pu or Am spikes shows glass-solution interactions have no effect on the spike concentration. Due to safety reasons ampoule sealing by a flame or laser is not commonly applied in analytical laboratories, but with the use of screw-capped ampoules it is possible to verify the evaporation of the spike solution by weighing.

The Atalante Analysis Laboratory of the CEA (CEA/LAAT) and the JRC-Karlsruhe adapted a similar system,⁸⁷ where the CRM spike is first gravimetrically diluted to a known mass fraction suitable for mass spectrometry, at the $\mu\text{g g}^{-1}$ level. Approximately 10 mL aliquots of this diluted spike solution are then stored in sealed borosilicate glass ampoules. Upon opening a sealed ampoule of a diluted spike, the diluted spike solution is divided into several vials with caps, each containing a known amount (*i.e.* mass) of spike. The vials can be stored in racks for up to several weeks before use. Any evaporation of this solution will affect the mass fraction of the spike in the vials but not the amount (*i.e.* mass) of spike in the vials. The sample is added to the vials to produce the {sample-spike} mixture. This entire mixture is then evaporated to dryness, thereby eliminating any influence of potential changes in the spike mass fraction due to evaporation during storage. This step ensures the trueness of the isotope ratio in the mixture. The dried {sample-spike} mixture is then dissolved in nitric acid medium for ID-MS measurement (*e.g.* mass spectrometric measurement or separation step). The dilution of the CRM spike is verified annually by means of inter-laboratory comparison exercises.

3.4. Isotopic homogenization of the sample-spike mixture

Essential for correct ID analysis is the isotopic equilibrium in the mixture which may be defined as the homogeneous distribution between the isotopes coming from the sample and the spikes in the mixtures.⁸⁸

In the nuclear field, most of the samples and spikes are in the same strong acidic media. The isotope homogenization is therefore quite easy and fast for most of the radionuclides (U, Th, Am, Cm, lanthanides...). Manual or mechanical shaking of the mixture is carried out for several seconds or minutes to ensure the homogenization.⁵⁴ Some laboratories may also heat



overnight under reflux to homogenize the mixture or dry the mixture and re-dissolve it in nitric acid.

The analyte in the sample and the spike should be in the same form or species to reach an isotopic equilibrium. For example, in case of Pu ID-MS measurements, the Pu contained in the spike and the Pu coming from the sample may not have the same oxidation state due to the multiple possible redox states of Pu in aqueous solution (+III, +IV, +V, +VI). The Pu in the mixture may be discriminated if a redox cycle is not performed before a separation step to adjust the Pu to a unique valency. Different redox reagents can be used: hydrogen peroxide, an iron II solution, sodium nitrite, potassium metabisulfite or titanium(III) chloride.^{89–93} The optimum time to reach the Pu valency adjustment is variable: the Fe(II)/NaNO₂ method requires a waiting time of 20 min whereas the hydrogen peroxide requires a minimum waiting time of 2 h.⁵⁸

4. Uncertainty evaluation

4.1. Weighing uncertainty

4.1.1. Expression of the true mass uncertainty. For the true mass (m_{true}), the measurand expression that takes into account the bias in trueness and the correction for air buoyancy is described in eqn (11). The uncertainty associated with m_{true} is derived by propagating the uncertainties of the terms in eqn (11) according to the Guide to the Expression of Uncertainty in Measurement (GUM, eqn (26)).

$$u^2(m_{\text{true}}) = u^2(\Delta X) + u^2(\delta) + \left(\frac{\Delta X}{r} - \frac{\Delta X}{r_0}\right)^2 u^2(a) + \left(\Delta X \frac{a}{r^2}\right)^2 u^2(r) \quad (26)$$

The term $u^2(\Delta X)$, described as the weighing result component, depends on parameters such as the resolution of the balance and the repeatability of the measurement. The term $u^2(\delta)$ is the trueness component, which is also dependent on the resolution and repeatability of the balance, but also on the uncertainty of the standard used for calibration and the uncertainty of its durability. It also takes into account (i) the effect of the air density variation, (ii) the effect of temperature variation and (iii) the effect of eccentricity on the trueness of measurement during calibration.⁷² The final terms of the equation, $\left(\frac{\Delta X}{r} - \frac{\Delta X}{r_0}\right)^2 u^2(a) + \left(\Delta X \frac{a}{r^2}\right)^2 u^2(r)$, concern the uncertainty on the corrections for air buoyancy and the effects of variation in air density and that of the sample density under the measurement conditions. It is evident that, even for one measurement, evaluating the uncertainty of a weighing is quite tedious and time consuming.

4.1.2. Expression of the weighing uncertainty from the maximum permissible deviation. In practice, the calibration of the balance consists of determining the δ and the $u(\delta)$ terms for a series of standard masses that are representative of the range of the balance. A specification of performance in accuracy is defined for the balance in the form of a maximum permissible

deviation (MPE) according to its class, its range and its resolution.

A metrological confirmation of the balance is then carried out (calibration + verification) to ensure the following inequality after calibration of the balance (eqn (27)).

$$|\delta| + 2u(\delta) \leq \text{MPE}(\Delta X) \quad (27)$$

If this condition is respected over the entire considered mass range, the balance is metrologically confirmed and the MPE can be used for the expression of the weighing uncertainty in a simpler manner.

Assuming that the statistical distribution of weighing measurements follows a continuous uniform law with a span of 2 MPE, the standard uncertainty equals half the span of the distribution (MPE) divided by the square root of 3 (eqn (28)).

$$u(m_{\text{true}}) = \frac{\text{MPE}}{\sqrt{3}} \quad (28)$$

For example, a class 1 balance having a range of 200 g and a resolution of 0.1 mg would traditionally be assigned an MPE of 1 mg, resulting in a standard uncertainty of 0.6 mg according to eqn (28). The mass weight of 0.5 g would then be associated with an expanded uncertainty of 1.2 mg at a confidence level of 95%, corresponding to a relative uncertainty of 0.24%. For such a balance, in order to guarantee a weighing uncertainty on the order of 0.1%,⁶⁹ it is recommended to weigh only masses greater than 1 g.

4.1.3. Uncertainty with the substitution method. This method of weighing consists of comparing the sample mass to that of a standard having an almost identical mass, according to a specific scheme, usually an ABBA or SUUS scheme (see Section 3.1 and eqn (10)). The true mass expression becomes eqn (29), with m_{std} the mass of the standard.

$$m_{\text{true}} = m_{\text{std}} + (\Delta X - \delta) + a\left(\frac{1}{r} - \frac{1}{r_0}\right)m_{\text{std}} \approx m_{\text{std}} + \Delta X + a\left(\frac{1}{r} - \frac{1}{r_0}\right)m_{\text{std}} \quad (29)$$

The uncertainty of m_{true} (eqn (30)) is derived from eqn (29).

$$u^2(m_{\text{true}}) = u^2(m_{\text{std}}) + u^2(\Delta X) + u^2(\delta) + \left(\frac{m_{\text{std}}}{r} - \frac{m_{\text{std}}}{r_0}\right)^2 u^2(a) + \left(m_{\text{std}} \frac{a}{r^2}\right)^2 u^2(r) \approx u^2(m_{\text{std}}) + u^2(\Delta X) \quad (30)$$

This method is not sensitive to balance drift if weighing measurements are spaced regularly over time and if the drift is linear. The trueness error δ is then reduced drastically, because ΔX – the difference between the sample and the standard mass – is very small. The trueness error can then be neglected, as well as its uncertainty contribution when calculating the weighing uncertainty. In practice, only the contributions from standard mass uncertainty and from repeatability are retained, and



hence very low uncertainties on the order of tens of μg can be achieved.^{73,74}

4.2. Isotope dilution uncertainty

The various ways of estimating measurement uncertainty can be divided into two main categories: inter-laboratory and intra-laboratory approaches.⁵ The result of an ID-MS measurement (*i.e.* w_s) can be expressed as a function of various parameters which makes it well suited to be used as an intra-laboratory approach with measurement modelling. Uncertainty estimation of the measurement model must be taken into account, at all the stages of the measurement process and for all input parameters coming from certified values or measured values. Here, we apply this approach to an example: the measurement result for the U mass fraction from CEA/LAAT during the 2022 “Nuclear Material Round Robin” (NMRoRo) ILCs organized by the IAEA. For this measurement LAAT used the IRMM-054 spike, which was first diluted in nitric acid to obtain a known mass fraction of approximately $10 \mu\text{g g}^{-1}$. The NMRoRo ILC sample (a uranium oxide powder) was dissolved, after which the solution was diluted three times consecutively to produce a diluted sample. Three {diluted sample-spike} mixtures were gravimetrically prepared. The measurement model is reported in eqn (31). The different steps of spike dilution, sample dissolution and dilutions have been taken into account and only measured or certified data are used as inputs.

$$w_s = \frac{1}{M_T} \cdot \left(\frac{R_{48s}}{R_{48s} + R_{58s} + R_{68s} + 1} \cdot M_4 + \frac{R_{58s}}{R_{48s} + R_{58s} + R_{68s} + 1} \cdot M_5 + \frac{R_{68s}}{R_{48s} + R_{58s} + R_{68s} + 1} \cdot M_6 + \frac{1}{R_{48s} + R_{58s} + R_{68s} + 1} \cdot M_8 \right) \cdot w_T \cdot \frac{m_T}{m_s} \cdot \frac{A_{8T}}{1} \cdot \frac{1/R_{85T} - R_{58\text{Mix}}}{R_{58\text{Mix}} - R_{58s}} \cdot \frac{m_{4\text{fS}}}{m_{4\text{iS}}} \cdot \frac{m_{3\text{fS}}}{m_{3\text{iS}}} \cdot \frac{m_{2\text{fS}}}{m_{2\text{iS}}} \cdot \frac{m_{1\text{fS}}}{m_{1\text{iS}}} \cdot \frac{m_{1\text{fT}}}{m_{1\text{iT}}} \quad (31)$$

where the measured quantities are: R_{48s} , R_{58s} , and R_{68s} , the $^{234}\text{U}/^{238}\text{U}$, $^{235}\text{U}/^{238}\text{U}$, and $^{236}\text{U}/^{238}\text{U}$ ratios in the sample, respectively (mol mol^{-1}); $R_{58\text{Mix}}$, the $^{235}\text{U}/^{238}\text{U}$ ratio in the mixture (mol mol^{-1}); m_T , mass of the diluted spike used (g); m_s , mass of the sample used (after dissolution and dilutions) (g); $m_{1\text{iS}}$, $m_{2\text{iS}}$, $m_{3\text{iS}}$, and $m_{4\text{iS}}$, mass of the sample before dissolution and sample solution before each of the three dilution steps (g), respectively; $m_{1\text{fS}}$, $m_{2\text{fS}}$, $m_{3\text{fS}}$, and $m_{4\text{fS}}$, mass of the sample dissolution solution and of the solution after each of the dilution steps of the sample dissolution solution (g); $m_{1\text{iT}}$, mass of the spike before dilution (g); $m_{1\text{fT}}$, mass of the spike solution after dilution (g); and where the certified quantities are: M_4 , M_5 , M_6 , and M_8 , the molar mass of ^{234}U , ^{235}U , ^{236}U and ^{238}U (g mol^{-1}) respectively;⁹⁴ M_T , molar mass of U in the spike (g mol^{-1}) from the IRMM-054 certificate;⁹⁵ w_T , the U mass fraction certified value in the spike (g kg^{-1}) from the IRMM-054 certificate;⁹⁵ A_{8T} , isotope abundance of ^{238}U in the spike (mol mol^{-1}) from the IRMM-054 certificate;⁹⁵ R_{58T} , the $^{235}\text{U}/^{238}\text{U}$ ratio in the spike (mol mol^{-1}) from the IRMM-054 certificate.⁹⁵

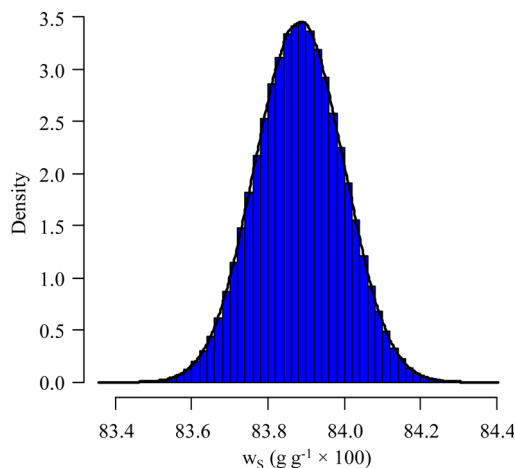


Fig. 7 Distribution law of w_s by MCM – LAAT measurement on the NMRoRo 2022 sample.

From the measurement process model, the uncertainty is estimated by propagating the uncertainty of the input data. This can be done using the Monte Carlo method (MCM), as recommended in supplement 1 of the GUM.⁹⁶ This approach requires no assumptions to be made about the distribution of the result, nor about any correlation between the input parameters. However, for each of the input parameters in the NMRoRo example, a particular distribution needs to be chosen, a most

probable value and a standard deviation are required before performing the Monte Carlo simulation on the model (eqn (31)).

Using the information provided by the LAAT about the parameter values and their standard uncertainties, and assuming a uniform distribution for each of the masses and a normal distribution for the other parameters, a standard measurement uncertainty of 0.15% (probability density function (pdf) of w_s in Fig. 7) is obtained.

The simulated pdf of w_s is not significantly different from a normal law. The uncertainty budget can be established using the sensitivity indices (first-order and total Sobol indices):⁹⁷ the budget obtained for this example is illustrated in Fig. 8.

The contributions to the uncertainty of parameters R_{48s} , R_{58s} , R_{68s} , M_4 , M_5 , M_6 , M_8 , and M_T are not significant and therefore the uncertainty calculation can be simplified here by treating these inputs as constants. Although some contributions from

§ All the calculations presented in this paragraph were made using R software (free to use).⁹⁹



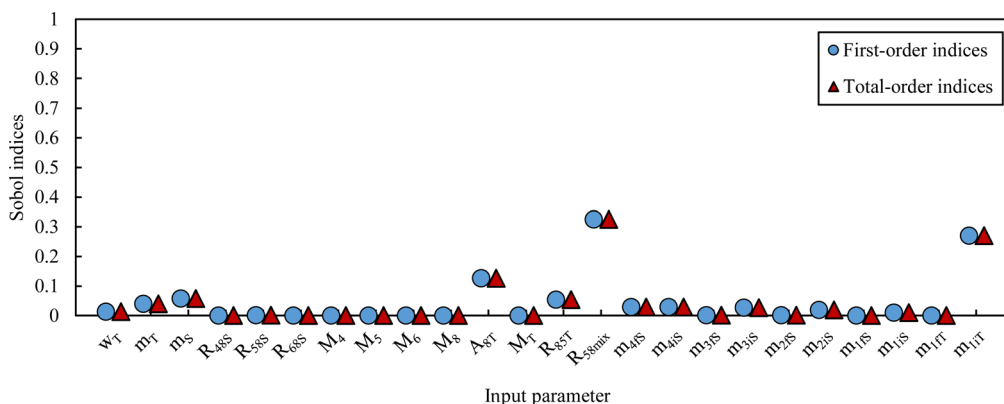


Fig. 8 Sobol indices – LAAT measurement on the NMRoRo 2022 sample.

masses weighed during dissolution or dilution are small, they have been retained in order to maintain the overall dissolution/dilution process, the total contribution of which is not negligible. The measurement model (eqn (31)) then becomes a simplified model (eqn (32)).

$$w_S = w_T \cdot \frac{m_T}{m_S} \cdot \frac{M_S}{M_T} \cdot \frac{A_{8T}}{A_{8S}} \cdot \frac{1/R_{85T} - R_{58Mix}}{R_{58Mix} - R_{58S}} \cdot \frac{m_{4IS}}{m_{4IS}} \cdot \frac{m_{3IS}}{m_{3IS}} \cdot \frac{m_{2IS}}{m_{2IS}} \cdot \frac{m_{1IS}}{m_{1IS}} \cdot \frac{m_{1IT}}{m_{1IT}} \quad (32)$$

where M_S is the molar mass of U in the sample (g mol^{-1} , eqn (33)) and A_{8S} is the isotope abundance of ^{238}U in the sample (mol mol^{-1}).

$$M_S = \frac{R_{48S}}{R_{48S} + R_{58S} + R_{68S} + 1} \cdot M_4 + \frac{R_{58S}}{R_{48S} + R_{58S} + R_{68S} + 1} \cdot M_5 + \frac{R_{68S}}{R_{48S} + R_{58S} + R_{68S} + 1} \cdot M_6 + \frac{1}{R_{48S} + R_{58S} + R_{68S} + 1} \cdot M_8 \quad (33)$$

From this equation, we can conclude that (1) the result distribution is not significantly different from a normal distribution; (2) several influencing parameters contribute to the uncertainty, and (3) the first-order and total Sobol indices are very similar, meaning there is no correlation between the influencing parameters (Fig. 8). These findings mean that, if desired, the GUM approach⁹⁸ (quadratic cumulation method) without covariance can also be applied to the simplified model (eqn (32)). This approach leads to the same standard uncertainty on w_S as the MCM approach, *i.e.* 0.15%. The similarity between uncertainty budgets estimated with the MCM (recommended in GUM-S1) and by the quadratic cumulation method (recommended in GUM) for the NMRoRo sample at LAAT is illustrated in Fig. 9. For this measurement, the main contributors to the uncertainty are R_{58Mix} (33%), m_{1IT} (28%), A_{8T} (13%), m_S (6%), R_{85T} (5%), and m_T (4%).

In conclusion, the measurement uncertainty of ID-MS is estimated in several stages:

(1) The measurement process is modelled on the basis of eqn (31) or taking into account all the stages in the process (dissolution, dilution, *etc.*) and using input parameters with certified values or measured values (avoiding input parameters that are mathematical expressions).

(2) The propagation of the uncertainty by using the MCM, preferably, and assess the uncertainty budget (sensitivity indices).

(3) If needed or desired, simplify the measurement model by reducing the number of variables and considering other parameters as constants.

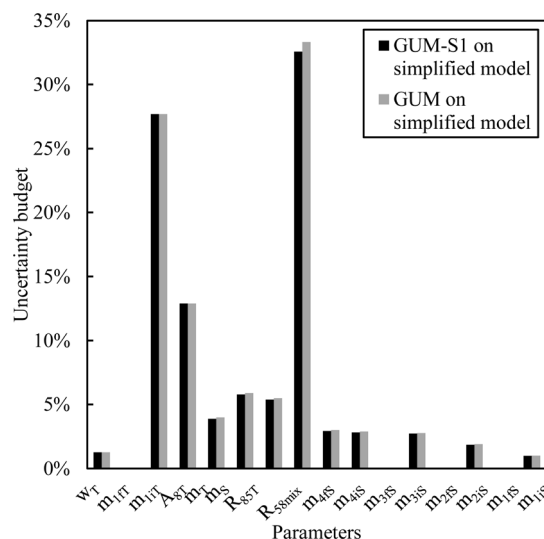


Fig. 9 Sensitivity indices obtained by the MCM or quadratic cumulation method – LAAT measurement on the NMRoRo 2022 sample.



(4) If needed or desired, in the case where (i) the result distribution does not differ significantly from a normal distribution, (ii) more than one parameter contributes to the uncertainty, and (iii) the first-order and total Sobol indices are very similar, we can apply the quadratic cumulation method (GUM) without covariance terms to the model.

Note: As calculations are easy and quick with R,⁹⁹ we recommend using the MCM approach (GUM-S1).

5. Application for radionuclide measurement

5.1. Environmental applications

5.1.1. Application in Earth sciences

5.1.1.1. U-series disequilibrium. The ID-MS technique plays a key role in the U-series disequilibrium studies in environmental and Earth sciences. U-series geochemistry provides a profound understanding of fundamental processes in wide-spread disciplines as diverse as geomorphology,¹⁰⁰ weathering and erosion of geological formations,¹⁰¹ oceanography,¹⁰² and environmental pollution science.^{103,104} A wide range of U-series geochemistry applications to the Earth sciences was thoroughly summarized in *“Uranium-series Disequilibrium, Applications to Earth, Marine and Environmental Sciences”*.¹⁰⁵ The uranium and thorium decay-series contain radioactive isotopes of many elements (in particular, ²³⁴U, ²³⁵U, ²³⁸U, ²³⁰Th, ²³²Th, ²³¹Pa, ²²⁶Ra and ²²⁷Ac) with varied physicochemical properties leading to a fractionation (mainly elemental fractionation) within the chain in different geological environments during geochemical processes. The accurate measurement of these radionuclides and more specifically their elemental ratios (*i.e.*, ²³⁰Th/²³⁸U, ²³⁸U/²³²Th, ²³¹Pa/²³⁵U, ²²⁶Ra/²³⁰Th) allows the investigation of processes occurring on time scales from a hundred years to ~600 000 years. To this end, radionuclide concentrations are accurately determined in environmental samples by ID-MS. It is worth mentioning that isotopic compositions (*i.e.*, ²³⁴U/²³⁸U and ²³⁰Th/²³²Th) are also mandatory for disequilibrium studies, however this topic will not be addressed in this section, as it does not fall under the scope of ID-MS.

Sample preparation is a crucial step that strongly influences the quality of analytical results. Generally, natural solid samples undergo total dissolution in Teflon bombs or beakers. The digestion protocol is adapted according to the sample matrix. Usually for rocks, sediments and soils, concentrated HNO₃, HF, or HClO₄ (ref. 106 and 107) or alkaline fusion¹⁰⁸ is used. After sample digestion, separation protocols for U/Th,^{106,109–114} Ra,^{111,112,115–121} Pa^{111,113,122,123} and Ac^{124,125} extraction are used. An exhaustive review for Ra separation protocols can be found in Boudias *et al.*¹²⁶ Radionuclide separation helps concentrating the radionuclides of interest, minimizing matrix effects and reducing or removing polyatomic interferences.

For the determination of U concentrations in natural samples two kinds of spikes are commonly used: a single spike (²³³U or ²³⁶U) or a double spike (²³³U–²³⁶U) certified in both concentration and isotope ratio. The ²³³U–²³⁶U double spike method was first introduced by Dietz *et al.*¹²⁷ and thanks to this

technique it is possible to proceed to ID by internally correcting the instrumental mass fractionation using the certified ratio ²³³U/²³⁶U (*i.e.* to correct the ²³⁸U/²³⁶U ratio).^{106,128,129} If a single isotope is used for spiking, the standard-bracketing method should be employed to externally correct for the instrumental mass fractionation or the total evaporation method may be employed in the case of TIMS measurement to overcome the isotope fractionation.^{37,130} With a new generation multi-collector-ICP-MS (MC-ICP-MS) equipped with high-efficiency desolvation systems, it is possible to achieve LODs of ~10^{−7} and ~10^{−8} ng g^{−1} for ²³³U and ²³⁶U, respectively.¹³¹

The ²³⁰Th dating (based on the radioactive decay: ²³⁸U ⇒ ²³⁴U ⇒ ²³⁰Th) method has become one of the most important dating methods for quaternary research,¹³² radiocarbon calibration¹³³ and also for weathering and erosion studies.¹³⁴ A major source of uncertainty for the ²³⁰Th/²³⁸U ratio is the accurate measurement of the amount of ²³⁰Th. More commonly, ²³⁰Th is measured by using an isotopically enriched ²²⁹Th material as a spike.^{135–138} This ²²⁹Th spike can be an “in-house” standard or certified ²²⁹Th standards such as the standard reference material (SRM) 4328C^{139,140} and reference materials provided by the National Physical Laboratory (NPL)¹⁴¹ or the Eckert and Ziegler company. However, to use an “in-house” spike, the analyst must expend considerable effort in producing, calibrating, and, if possible, establishing traceability. Recently, a new high purity ²²⁹Th (²³⁰Th/²²⁹Th = 5.18 × 10^{−5} and ²³²Th/²²⁹Th = 3.815 × 10^{−4}) reference solution was commercialized by the National Institute of Standards and Technology (NIST).³⁶ This spike is ideal for measuring samples with very low ²³⁰Th, ²³²Th content (*i.e.* young carbonates, *etc.*). For the correction of the instrumental mass fractionation on the ²³⁰Th/²²⁹Th or ²³²Th/²²⁹Th (for ²³²Th determination) ratios, the IRMM-035 CRM¹⁴² and the standard-bracketing method are used. Thanks to the double isotope dilution method (eqn (6)), the ²³⁰Th/²³⁸U concentration ratio can also be accurately determined by using a double (²²⁹Th–²³⁶U or ²³³U) or a triple spike (²²⁹Th–²²³U–²³⁶U). A triple spike was used in U migration studies in marine sediments¹⁴³ and for environment pollution purposes.¹⁰³ The LODs of ²³⁰Th for seawater samples are close to 0.15 fg kg^{−1}.¹⁴⁴ For analytical purposes, it is preferable in certain cases to measure the ²³⁰Th/²³⁵U ratio (as ²³⁰Th is closer in terms of abundance to ²³⁵U compared to ²³⁸U), and subsequently calculate the ²³⁰Th/²³⁸U ratio by taking into account the natural ²³⁸U/²³⁵U ratio (137.818 ± 0.045).¹⁴⁵

For ²²⁶Ra determination in natural samples, a spike such as ²²⁸Ra is used. It is worth mentioning that the natural ²²⁸Ra contribution is considered negligible due to its very low natural abundance and its very short half-life (*t*_{1/2} = 5.75 years¹⁴⁶) compared to that of ²²⁶Ra (*t*_{1/2} = 1600 years¹⁴⁶). However, in some specific cases for solid samples containing a high concentration of ²³²Th, a pre-analysis before spiking for the determination of the ²²⁸Ra/²²⁶Ra ratio is mandatory to correct for the contribution of natural ²²⁸Ra. The ²²⁸Ra spike is commercially provided (*i.e.* NIST-SRM 4339B, NPL, *etc.*), but generally in geosciences, an enriched ²²⁸Ra spike is prepared by milking the Ra fraction from an old pure thorium nitrate material (*i.e.* Th(NO₃)₄). The ²²⁸Ra fraction can be used directly



after its separation from $^{232}\text{Th}^{120,121,147}$ or the ^{232}Th solution is purified from Ra ($^{226,228}\text{Ra}$) and then the purified thorium solution is set aside, and ^{228}Ra grows in through ^{232}Th decay.¹⁴⁸ As ^{226}Ra (impurities of $^{230}\text{Th} \Rightarrow ^{226}\text{Ra}$) grows much more slowly than ^{228}Ra , at the beginning of ^{232}Th decay (some months or years) a high $^{228}\text{Ra}/^{226}\text{Ra}$ ratio suitable for ID-MS can be obtained. The ^{228}Ra spike concentrations were calibrated against certified ^{226}Ra solutions (*i.e.* provided by NIST and NPL) or by using the Harwell Uraninite (HU-1)¹¹⁹ that is known to be close to secular equilibrium.¹²⁸ Typical values of LOD of ^{226}Ra are close to $\sim 0.1 \text{ fg g}^{-1}$ (3 mBq kg^{-1}).^{149,150}

The $^{231}\text{Pa}/^{235}\text{U}$ radiochronometer is complementary to that of $^{230}\text{Th}/^{238}\text{U}$ and can be used to obtain more reliable age estimates, especially for samples with complex histories. Moreover, the $^{231}\text{Pa}/^{230}\text{Th}$ ratio is a very useful paleoproductivity and scavenging ocean tracer.^{151,152} The measurement of ^{231}Pa concentration is performed by ID-MS with ^{233}Pa as the spike isotope.^{153,154} Due to the short half-life of ^{233}Pa ($t_{1/2} = 26.98 \text{ days}^{155}$), no certified ^{233}Pa spike exists. Rather, the ^{233}Pa spike is prepared by milking the Pa fraction from a ^{237}Np solution immediately prior to use and calibrated for ^{233}Pa concentration for its working-lifetime of approximately 3–4 months. The ^{233}Pa spike is calibrated using commercially available¹⁵⁶ or “in-house” ^{231}Pa standard solutions calibrated against the HU-1. Recent developments allow the measurement of quantities as low as 0.1 fg of ^{231}Pa by MC-ICP-MS.^{102,157} TIMS protocols for ^{231}Pa analysis allow the determination of as little as a few tens of fg to a few ag.^{153,158} Moreover, high resolution ICP-MS (HR-ICP-MS) reported LOD values were close to 0.02 fg kg^{-1} .¹⁴⁴

Recently, the analysis of ^{227}Ac by ID-MS was developed for nuclear forensic purposes.¹²⁵ However, this technique has found important applications in environmental studies mainly in oceanography.¹²⁴ As there is no commercial spike for Ac, the method for isotope dilution measurement of ^{227}Ac uses a ^{229}Th standard to provide ^{225}Ac , which is used as the spike. ^{227}Ac determination by MC-ICP-MS in seawater makes reliable measurements with 10 L samples with ^{227}Ac concentrations of $\sim 2 \text{ ag kg}^{-1}$ with a LOD of around 0.7 ag kg^{-1} .¹²⁴

5.1.1.2. Other radiogenic elements: ^{87}Rb – ^{87}Sr method. The ^{87}Rb – ^{87}Sr method stands out as one of the earliest dating techniques in geology. It has been widely used, particularly since the introduction of the Sr evolution diagram which enabled the determination of both the age and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for sets of co-genetic samples.^{159,160} Contrary to U-series applications where non-naturally occurring tracers could be used, in this case isotopically enriched tracers of natural isotopes (*e.g.*, ^{84}Sr or ^{86}Sr , ^{87}Rb at purities higher than 96%) are commonly used.¹⁶¹ It should be noted that before analysis, Rb and Sr are chemically separated to avoid isobaric interference at m/z 87.

5.1.2. Application to environmental monitoring of nuclear facilities. Monitoring of the environment is a major concern for the nuclear industry. The main sources of anthropogenic radionuclides in the environment are fallout from nuclear weapons tests, releases during nuclear accidents, waste reprocessing and authorized discharges. In this context, ID is used both to quantify the activity of the radionuclides and to

determine the isotopic ratios characteristic of the source of the deposit. When available, a known quantity of a certified spike is added in the beginning of the analysis, as specified in the norms for the analysis of radioactivity in the environment for isotopes of uranium¹⁶² and plutonium^{163,164} for example.

A good candidate spike for ID-MS has a half-life large enough to limit the activity handled, be readily available and contain few isotopic impurities. If the isotopic composition of the radioelement that is suspected to be present as a contaminant in the environmental sample is not known, it is important to ensure that the radioactive tracer added for ID is not already present in the sample. In such a case, the measured elemental concentration of the radioelement will be wrong. If suspected, an analysis without the addition of the spike is mandatory to correct for the presence of the isotope used as an ID spike in the environmental sample. If ID-MS is done with an isotope naturally present in the environmental sample, an analysis of the sample without and with the spike needs to be done. In any case, the purity of the spike has to be verified before use, to check that it does not contain the isotopes of interest in the sample, and if present to carry out the appropriate corrections. In many cases, the isotope composition of the spike, including impurities, is mentioned in the certificate. Otherwise, abundances of isotope impurities must be quantified with an appropriate technique, for instance by direct measurement of a significant amount of spike with the most accurate mass spectrometer available.

In the following, we describe the implementation of ID to the most common radioelements that can be measured by mass spectrometry and that may be the subject of environmental monitoring of nuclear facilities.

5.1.2.1. Uranium. The isotopes of interest for the survey of uranium in the environment are ^{234}U , ^{235}U , ^{236}U and ^{238}U . The measurement of the abundances of these isotopes (or isotope ratios with respect to ^{238}U) helps to distinguish an anthropogenic contribution from naturally occurring uranium. In particular, the abundance of ^{235}U is characteristic of the industrial origin of uranium and shows a significant difference with respect to that of natural uranium. Indeed, the abundance of ^{235}U in man-modified uranium ranges from $\sim 0.2\%$ in depleted U to more than 20% for highly enriched U, reaching abundances higher than 90% in nuclear weapons.¹⁶⁵ By contrast, ^{235}U abundance in naturally occurring uranium shows very small variations around an average value of 0.725% (isotopic abundance). The ^{236}U isotope is also an excellent fingerprint of anthropogenic nuclear activities. Indeed, this isotope does not exist in measurable abundance in the environment ($^{236}\text{U}/^{238}\text{U} < 10^{-12}$), but it is produced in a nuclear reactor through neutron capture by ^{235}U nuclei. For instance, $^{236}\text{U}/^{238}\text{U}$ isotope ratios can reach 10^{-3} in spent fuel. So the detection of a significant abundance of ^{236}U by mass spectrometry is also characteristic of environmental marking through nuclear activities.¹⁶⁶ As a consequence, use of ^{236}U as an ID spike is not recommended when the presence of irradiated uranium is suspected. By contrast, ^{233}U is generally not present in nuclear materials (except in a few cases, for instance when ^{232}Th is irradiated) and so is absent in environmental samples.



Thus, the spike recommended for ID-MS is ^{233}U .¹⁶² It can be provided with a good purity by NPL or JRC (IRMM-057) for example. Mass bias factor correction, and gain calibration of the detectors in the case of measurements with a multiple-collector mass spectrometer, can be performed with certified reference materials whose isotope ratios are certified (for example NBL CRM U030-A or IRMM-186).

5.1.2.2. Plutonium. Plutonium isotopes are produced in nuclear reactors through successive neutron captures: ^{239}Pu by capture of a neutron by a ^{238}U nuclei, ^{240}Pu by capture of a neutron by a ^{239}Pu nuclei, *etc.* The most common plutonium isotopes measured in environmental samples by ID-MS are ^{239}Pu , ^{240}Pu , ^{241}Pu and ^{242}Pu . It should be mentioned that extremely low concentrations of plutonium are present in soil samples, although they are measurable by combining thorough radiochemical separations with the most sensitive mass spectrometry techniques.¹⁶⁷ This is a worldwide marking which originates from the global fallouts of thermonuclear atmospheric nuclear weapons tests. So quantification of plutonium is not sufficient to identify a recent, man-made origin: measurement of isotope ratios is mandatory for that. Indeed, isotope ratio compositions of plutonium from global fallout and from various nuclear activities (separation of military or civilian plutonium, reprocessing, *etc.*) show significant differences. For example, the $^{240}\text{Pu}/^{239}\text{Pu}$ and $^{241}\text{Pu}/^{239}\text{Pu}$ atomic ratios of the global fallout of atmospheric nuclear weapons tests are respectively 0.182 and 9.7×10^{-4} ,¹⁶⁸ whereas the ratio of $^{240}\text{Pu}/^{239}\text{Pu}$ in environmental samples from nuclear weapons test sites at the atolls of Mururoa is 0.018 ± 0.005 (at./at. $\pm 2\sigma$).¹⁶⁹ In the fuel cycle facilities, isotope ratios of Pu are slightly different. In the pressured water reactor using oxide enriched uranium fuel, the isotope ratios of $^{240}\text{Pu}/^{239}\text{Pu}$ and $^{241}\text{Pu}/^{239}\text{Pu}$ are around 0.4 and 0.2 (w_i/w_j) respectively, and in MOX fuel the ratios are around 0.9 and 0.4 (w_i/w_j) respectively.¹⁷⁰ The $^{240}\text{Pu}/^{239}\text{Pu}$ ratio is the easiest ratio to measure in the environment as ^{239}Pu and ^{240}Pu are generally the most abundant isotopes. ^{241}Pu is a short-lived isotope ($t_{1/2} = 14.325$ years¹⁷¹) whose abundance can be correlated with that of its decay product ^{241}Am .¹⁷² However, ^{238}Pu is generally measured by alpha spectrometry because of the non-negligible interference of ^{238}U at the same mass and its relatively short radioactive period ($t_{1/2} = 87.74$ years¹⁷³). The spike commonly used for ID-MS is ^{242}Pu in water¹⁶³ and solid matrices,¹⁷² but ^{244}Pu can also be chosen if ^{242}Pu is expected in the sample.^{163,174} A ^{242}Pu spike can be provided with a very high purity by NIST (SRM 4334) or JRC (IRMM-049) and a ^{244}Pu spike by IRMM (IRMM-042a). ^{242}Pu can also be used as a spike for alpha spectrometry measurements.¹⁶⁴ Mass bias can be corrected with a $^{235}\text{U}/^{238}\text{U}$ certified ratio.

5.1.2.3. Americium. Traditionally, ^{241}Am ($t_{1/2} = 432.6$ years¹⁴⁶) was measured by alpha spectrometry. In the past few decades, ICP-MS has been more and more widely used as a fast and highly sensitive technique for the measurement of ^{241}Am .¹⁷⁵ Indeed, new generations of ICP-MS/MS are more sensitive and help to better remove the interferences. For example, for 1 g of ash sediment sample, the measurement of ^{241}Am with an ICP-MS/MS coupled with the APEX Ω sample introduction system

and the addition of O_2/He gas to remove the ^{241}Pu interference, allows a LOD of ^{241}Am of 20 mBq kg^{-1} to be reached.¹⁷⁵ The most suitable long-lived americium isotope suitable for the determination of the ^{241}Am mass fraction in environmental samples by ID-MS is ^{243}Am ($t_{1/2} = 7370$ years¹⁴⁶).¹⁷⁶ The ^{243}Am spike can be provided by NPL (A14063), CETAMA (STAM CRM) or JRC (IRMM-0243) with good purity.⁵⁶

5.1.2.4. Technetium-99. ^{99}Tc is a long-life fission product ($t_{1/2} = 2.115 \times 10^5$ years¹⁴⁶). For ^{99}Tc , the best candidates for ID-MS are ^{97}Tc ($t_{1/2} = 2.6 \times 10^6$ years¹⁷⁷) and ^{98}Tc ($t_{1/2} = 4.2 \times 10^6$ years¹⁷⁸) due to their long half-life. Unfortunately, they are not commercially available.¹⁷⁹ However, natural $^{185,187}\text{Re}$ is commonly used, as an analog of Tc, to estimate the radiochemical recovery, or the short-lived $^{99\text{m}}\text{Tc}$ ($t_{1/2} = 6.00660 \text{ h}$ ¹⁸⁰) measured by gamma spectrometry. Another point to consider is that interferences such as $^{98,99,100}\text{Ru}$ and $^{97,98,100}\text{Mo}$ may still be present even after a high decontamination factor of the sample. Thus, even with the use of ^{97}Tc for ID-MS, interferences have to be corrected by calculation or eliminated by the introduction of an appropriate gas into the collision-reaction cell of an ICP-MS. For instance, Yang *et al.* implemented an ICP-MS/MS with O_2 , as a reaction gas, to remove Mo.¹⁷⁹

5.1.2.5. Radio-caesium. The $^{135}\text{Cs}/^{137}\text{Cs}$ ratio is a new relevant anthropogenic signature in environmental samples that emerged after the Fukushima accident, thanks to the new possibilities offered by ICP-MS/MS. Both are fission products with half-lives of $t_{1/2}(^{135}\text{Cs}) = 2.3 \times 10^6$ years and $t_{1/2}(^{137}\text{Cs}) = 30.018$ years.¹⁴⁶ The $^{135}\text{Cs}/^{137}\text{Cs}$ ratio is useful for identifying the origin of radio-caesium. It can be determined after a high purification of the sample and the use of gas in the collision-reaction cell for ICP-MS measurement.^{28,29} However, no radioactive spike is available for ID-MS and no certified solutions of the $^{135}\text{Cs}/^{137}\text{Cs}$ ratio are available commercially to correct the mass bias effect. Then, the chemical yield can be estimated by gamma measurement of the intrinsic ^{137}Cs of the sample before and after purification of the sample as an internal isotope dilution standard. Moreover, a solution qualified by a more accurate method (TIMS for example) can be used to correct for the mass bias effect. In addition, reference materials such as IAEA-330, IAEA-375 and IAEA-385 can be analyzed to validate the analysis.^{28,29}

5.1.2.6. Iodine-129. Recent publications present the possibility of measuring ^{129}I , a very long-life decay product ($t_{1/2} = 1.614 \times 10^7$ years¹⁸¹), by mass spectrometry in environmental samples with a lower LOD than γ -spectrometry.¹⁸² However, even if its long half-life is favorable for MS measurement, its volatility and the numerous interferences can be challenging. Also, an important memory effect of I in ICP-MS has been reported.¹⁸³ The quantification of ^{129}I is usually based on the isotopic dilution technique using stable ^{127}I as an internal standard and the mass shift mode of the ICP-MS/MS. The initial amount of ^{127}I is then quantified with an external calibration.¹⁸² The use of ^{125}I present in certified NIST SRMs 4407H and 4407L is also mentioned to quantify ^{129}I by ID because the abundance of ^{129}I in the CRMs is negligible.¹⁸³

5.1.2.7. Neptunium-237. The measurement of Np by ID-MS is difficult. In radioactive samples originating from the



nuclear fuel cycle, the ^{237}Np isotope is the only isotope of Np with a long half-life. The only other isotope of Np with a long half-life is the ^{236}Np isotope ($t_{1/2} = 1.55 \times 10^5$ years¹⁴⁶) which might permit the determination of ^{237}Np by ID-MS. However, ^{236}Np is not commercially available and its production is difficult.^{184,185} If a laboratory happens to have a ^{236}Np solution, it is possible to create an in-house spike by measuring the ^{236}Np amount fraction by ID-MS using a commercially available ^{237}Np material. The in-house ^{236}Np spike can then be used to measure the ^{237}Np in a sample by ID-MS.¹⁸⁶ In the absence of a ^{236}Np spike, a ^{242}Pu spike can be used to measure the ^{237}Np by ID-MS.^{184,187} In that case, measurements must be made by ICP-MS, and not by TIMS, due to the different behaviors to sublimation between Pu and Np during the measurements.

5.2. Nuclear forensics

In the framework of nuclear forensic investigations, seized materials are characterized as completely as possible by complementary techniques, to carry out physical characterization (size and weight) and determine the chemical, elemental, and isotopic compositions, as well as concentrations of non-radioactive and radioactive impurities. It is the combination of all these parameters that provides clues to determine the origin or the processing history of the nuclear material intercepted outside regulatory control.^{188–190} Of all these analyses, age dating measurement gives an indication of the time elapsed since a nuclear material last underwent chemical purification. The date of the purification (also called “model age”) is obtained by measuring the ratio between a nuclide and its daughter product. The “model age” is calculated by using the equation derived from Bateman's equations (eqn (34)). This equation is valid provided that all the daughter products have been removed during the last chemical operation on the material (at the production stage), and the system has been kept closed ever since (no contamination, no elemental segregation).

$$t = \frac{1}{\lambda_p - \lambda_d} \ln \left(1 - \frac{n_d}{n_p} \times \frac{\lambda_d - \lambda_p}{\lambda_p} \right) \quad (34)$$

with λ_p and λ_d being the decay constants of the parent and daughter products, and n_d/n_p being the atomic ratio of the daughter nuclide to its parent nuclide.

This n_d/n_p ratio is derived from the concentration measurement of each nuclide in the nuclear material. The accuracy of the age calculation depends directly on the accuracy of these concentrations and the accuracy of the half-lives involved in the calculation. To this end, ID-MS is the method that can achieve the best results, provided there is rigor in the choice of the isotopic spikes, in the chemical purification of the material and in the mass spectrometric measurements. The uncertainties of the half-lives of the parent nuclides and of the daughter products (mainly ^{234}U – ^{230}Th , ^{235}U – ^{231}Pa , ^{234}U – ^{238}Pu , ^{235}U – ^{239}Pu , ^{236}U – ^{240}Pu , ^{238}U – ^{242}Pu and ^{241}Pu – ^{241}Am) are very low (between less than 0.01% and 0.4% (for ^{231}Pa)) and their contribution to the global uncertainty is generally negligible.

In the preceding decade, there has been a large international effort made to improve the methods for uranium age dating

measurements, through the development of reference materials or round robin exercises.^{8,10,191,192} Uranium has two commonly used chronometers: $^{230}\text{Th}/^{234}\text{U}$ and $^{231}\text{Pa}/^{235}\text{U}$. To quantify the different uranium isotopes, most laboratories use a ^{233}U spike. For ^{230}Th quantification, a spike enriched in the ^{229}Th isotope can be used.³⁶ The method used to calibrate an ID spike can influence the uncertainty. For example, ^{229}Th spikes are often calibrated by means of alpha spectrometry, which leads to a large relative uncertainty (>1%) in the determination of the ^{230}Th concentration and the necessity to convert the certified ^{229}Th specific activity to molality using the ^{229}Th half-life. Bias in this half-life value will affect the accuracy of the results. Production of a new ^{229}Th reference material certified by mass spectrometric measurements³⁶ in combination with the publication of coherent values for ^{229}Th half-life^{193–196} have enabled the development of uranium age dating with the ^{230}Th – ^{234}U chronometer.

The ^{231}Pa – ^{235}U chronometer is not as widely used. One of the main reasons for this is the difficulty in obtaining a calibrated isotopic dilution spike. ^{233}Pa is obtained by milking a ^{237}Np solution. The short half-life of ^{233}Pa ($t_{1/2} = 26.98$ days¹⁵⁵) makes it difficult to have a commercially available certified spike. Laboratories must prepare it, when required, for immediate use. The ^{233}Pa solution can be calibrated by various methods: gamma measurement, ID-MS with a rock at secular equilibrium,¹⁹⁷ ID-MS with a ^{231}Pa solution or after decay of the ^{233}Pa , by measuring the concentration of the decay product (^{233}U).¹⁹⁸ ^{233}Pa and its decay product (^{233}U) are isobars. The chemical purification has to be optimized to eliminate U from the Pa fraction, and the Pa measurements have to be performed immediately after purification. If the measurement is delayed, a correction for ingrowth of ^{233}U has to be included in the calculation, which increases the measurement uncertainty.

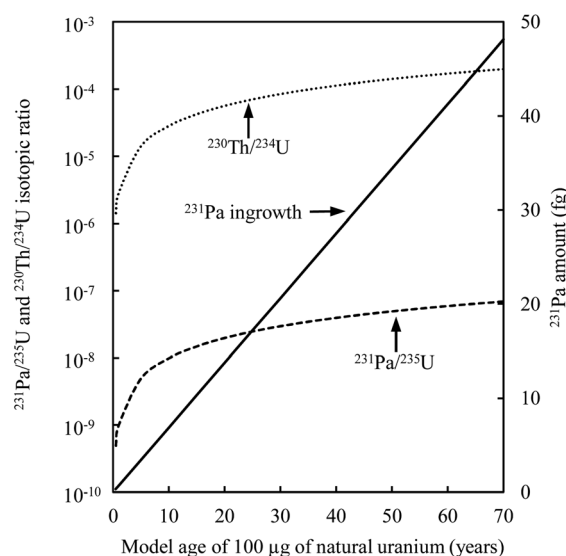


Fig. 10 Temporal evolution of the daughter/parent isotopic ratio for 100 µg of natural uranium. The dotted line is for the ^{230}Th – ^{234}U chronometer, dashed line is for the ^{231}Pa – ^{235}U chronometer and solid line is for the ingrowth of ^{231}Pa in fg.



As illustrated with Pa, the decay of the spike is important for age dating measurement. This is also the case for thorium, where ^{229}Th is the daughter product of ^{233}U . If ^{233}U is used as a spike for U ID-MS, the aliquot for Th ID-MS must be prepared separately.

Another difficulty with U age dating is the variability in the atomic abundance of the parent nuclide compared to its daughter product (Fig. 10). The amount of sample to be analyzed has to be carefully defined before spiking the different aliquots and starting the analyses. The laboratory environment must be considered. The use of a large amount of spike or sample will affect the laboratory and instrumental background, thereby leading to biases in the measurement. When the chemical purification is optimized and if the instrument is very sensitive, it is possible to date small masses of nuclear materials,⁹ thereby economizing on reagents and the amount of precious spike.

It should be noted that, in the case of plutonium, although five radio-chronometers are potentially measurable, ^{234}U – ^{238}Pu , ^{235}U – ^{239}Pu , ^{236}U – ^{240}Pu , ^{241}Am – ^{241}Pu and ^{238}U – ^{242}Pu , only three different spikes are required, ^{233}U for U ID-MS, ^{244}Pu for Pu ID-MS and ^{243}Am for Am ID-MS. The use of the ^{244}Pu isotope enables one to determine the concentration of all the Pu isotopes from ^{239}Pu to ^{242}Pu . Due to the isobaric interference at mass 238 from ^{238}U , it is preferable to measure the ^{238}Pu by alpha spectrometry. Also simultaneous measurements of ^{238}U and ^{238}Pu are reportedly possible by TIMS.^{199,200} The impact of the minor isotopes in the ^{244}Pu spike depends on the composition of such spike. A new ^{244}Pu reference material has been released recently,⁴³ which is really pure (the main impurity is ^{242}Pu with $^{242}\text{Pu}/^{244}\text{Pu} < 10^{-4}$). With such spike the ID-MS has no impact on the spike's minor Pu isotopes on the final uncertainties. If the level of minor isotopes is around the percent level, it is then recommended to do an independent isotopic measurement of the material, and to use ID-MS to quantify only the major Pu isotope.

For completeness, it should also be mentioned that grand-daughter–parent chronometers (such as ^{226}Ra – ^{234}U and ^{227}Ac – ^{235}U) can be used for age dating determination. However, this is not very common.¹²⁵

5.3. Safeguards

Destructive analysis of safeguards samples is used to independently verify fuel cycle facility operators' nuclear material accountancy declarations and the quality of the operator's measurement systems. ID-MS is one of the most accurate analytical technique to determine the uranium/plutonium content in safeguards samples. Furthermore, the ITVs for measurement uncertainties in safeguarding nuclear materials provide state-of-practice uncertainty limits for ID-MS measurements.^{24,25} The safeguards laboratories of the IAEA and the JRC-Karlsruhe use ID-MS for analysis of nuclear safeguards samples. These laboratories use ID-MS for the production of reference materials, for external verification activities in the production of LSD spikes,^{84,201} for the verification of spike solutions and in-house working standards, as well as for the preparation of

reference solutions that are needed for the calibration of instruments.

LSD spikes are used for fissile material control of irradiated nuclear spent fuel by operators, as well as regulatory and safeguards authorities, for instance the IAEA safeguards laboratories at the Rokkasho On-Site laboratory (OSL) and at the EURATOM OSL in the Orano nuclear fuel reprocessing facilities at La Hague. LSD spikes are provided by JRC-Geel,^{84,201} the IAEA⁸⁶ and the Japan Atomic Energy Agency (JAEA)^{202,203} and they are typically prepared from Pu and U metal CRMs. They are verified using independent analysis techniques and ID-MS. LSD spikes typically contain 2 mg Pu (90–98 wt% ^{239}Pu) and 10–50 mg of enriched uranium (20–93 wt% ^{235}U). The IAEA LSD spikes are prepared as glassy dried nitrates deposited on the bottom of penicillin vials. The JRC-Geel IRMM-1027 series are commercially available⁸⁴ and they are also prepared as dried nitrates deposited on the bottom of penicillin vials, although a stabilizing matrix is used to improve the mechanical stability of the spike, carboxymethyl cellulose sodium salt (CMC) or cellulose acetate butyrate (CAB).^{73,204,205} The stability of spikes, which can be affected by transportation or storage conditions in the OSLs, is essential for the quality of the ID-MS analysis. In analogy to the IRMM-1027 spikes,²⁰⁶ the IAEA is investigating the use of CMC to create foam-like LSD-type spike materials to increase stability and extend the life-time of the LSD spikes. For quality control and instrument calibrations for primary assay measurement techniques applied in the Rokkasho OSL (HKED or Spectrophotometry), with the current status of operations of a reprocessing facility, the Office of Safeguards Analytical Services Nuclear Material Laboratory (SGAS-NML) prepares approximately 500 units of LSD spike vials every two years. For analysis of highly active liquid waste materials, small size ^{233}U and ^{242}Pu spikes are used containing mg amounts of U and μg amounts of ^{242}Pu .

In SGAS-NML and in the safeguards laboratory at the JRC-Karlsruhe there is a wider range of spike materials available for analysis of safeguards samples. At the SGAS-NML milligram-sized dried U/Pu samples are spiked directly in the vials as received. Mono-element spike solutions, containing major isotopes ^{238}U , ^{235}U , or ^{233}U , and ^{239}Pu or ^{242}Pu , are selected, depending on the declared isotopic composition of the samples that are used for ID-MS analysis. High abundance ^{240}Pu spike solutions have been used in the past, but their use has been abandoned due to safety concerns (pressure build-up in ampoules during storage), with ^{242}Pu spikes being used instead. In general, most of the spike materials used for analysis of those samples are liquid solutions, produced in-house from metal CRMs, commercially available spike solutions, or custom-made materials provided to the IAEA through the Member States Support Programmes (MSSPs), that allow us to establish the traceability to reference materials produced by NBL, CETAMA or JRC-Geel. At the JRC-Karlsruhe small spike mono-elemental solutions containing major isotopes ^{238}U or ^{233}U and ^{239}Pu or ^{242}Pu are used for ID-MS analyses.⁸⁷ These small spikes are prepared with a concentration suitable for mass spectrometry and they are characterized against standards prepared from CRMs.⁸⁷



For analysis of environmental samples in the environmental sample laboratory (ESL) of SGAS (mostly swipe and hot cotton swipe samples), two categories are distinguished, low-level and high-level samples, with total 10 pg Pu and 1000 ng U considered to be high-level samples. After sample digestion and pre-screening, sample splitting is done followed by spiking with enriched ^{242}Pu , ^{244}Pu , ^{233}U and ^{243}Am spikes for isotope dilution analysis, using $^{242}\text{Pu}/\text{Pu}$ or $^{244}\text{Pu}/\text{Pu}$ amount ratios between 1 and 10, and $^{233}\text{U}/\text{U}$ of around 100. Spike solutions used are prepared by step-wise dilutions from mother solutions, and therefore the concentration needs to be corrected for evaporation loss during storage. U and Pu analysis is performed by MC-ICP-MS following the methods outlined in ref. 45,131 and 207.

ID-MS is performed on nuclear material samples by TIMS applying the total evaporation method.^{208,209} After purification when needed,⁵⁸ appropriate amounts of uranium and plutonium solutions are deposited onto a filament for each measurement of safeguards samples, CRMs and process control materials. By making duplicate analyses of both the spiked aliquots and unspiked sample aliquots the isotopic composition and elemental concentrations can be calculated and compared with defined control and warning limits.

As an alternative to traditional ID-MS when both pure and spiked sample aliquots are measured by TIMS, a combination of techniques can be used. In the OSL, High Resolution Gamma Spectrometry (HRGS) is combined with TIMS to determine the isotopic composition²¹⁰ of samples that are subsequently subjected to spiking to perform the plutonium assay in pure plutonium solutions or mixed U and Pu solutions (free of strong beta gamma emitters, U/Pu ratio greater than two). For timeliness considerations, this method has the merit of skipping the chemical separation of the {sample-spike} fractions for isotope and ID analysis. In this case, values for isotope ratios of $^{241}\text{Pu}/^{239}\text{Pu}$ and $^{238}\text{Pu}/^{239}\text{Pu}$ in the ID-MS assay equation are replaced by ones obtained by HRGS Multi-Group Analysis Software (MGA) codes. For U containing samples with complex matrices and unknown declarations (also Pu materials containing traces of U), acceptable performance is achievable by using over-spiking (high spike-to-sample amounts) with highly enriched ^{233}U spikes to determine the uranium amount and isotopic composition of the material from TIMS measurements of spiked sample aliquots. This so-called isotope stripping approach has also been used for the determination of traces of U in Pu materials.²¹¹

5.4. Irradiated samples

Irradiated samples, for which ID-MS is commonly applied, typically originate from the nuclear fuel cycle (definition of NFC in ref. 212). Nuclear fuels, for generation of electricity in a Nuclear Power Plant (NPP), are based predominantly on uranium (e.g. uranium oxide (UOX) fuels) or mixtures of uranium with other elements (e.g. Pu in MOX fuels). The so-called major actinide elements, U and Pu, possess fertile isotopes. These are isotopes which can be converted into a fissile isotope by neutron absorption: for example, the ^{238}U isotope can be converted into ^{239}Pu or ^{242}Pu can be converted

into ^{243}Am . The major actinide elements also possess fissile isotopes, so it is possible that an actinide nucleus splits into two smaller nuclei, which are referred to as fission products: most of the lanthanides, cesium, and metallic fission products. Therefore, a nuclear fuel can contain a wide range of chemical elements once it has been irradiated. The isotopic composition of a fission product element can differ substantially from the naturally occurring isotopic composition of that same element: certain stable isotopes of an element might not be formed by fission. The amount of particular fission products (e.g. specific isotopes of Cs, Ce and Nd) present in an irradiated fuel can be very indicative of how much fission has taken place, and hence such isotopes can be used as fission burn-up monitors.²¹³ Information about the extent of fission in a particular fuel (rod) is very useful knowledge for the safe and correct operation of an NPP. In the case of non-power reactors, which are used for material testing, R&D, and training purposes for example, the trend to switch from highly enriched uranium (HEU) to low enriched uranium (LEU) fuels (an anti-proliferation measure) has involved the testing of a range of fuels that differ quite substantially, in chemical and physical form, and enrichment, from those used in NPPs. Irradiated samples received by a radiochemical analysis laboratory can therefore differ widely in terms of matrices, their chemical composition (oxide based fuels to metallic or silicide fuels) and homogeneity, their enrichment (from LEU to HEU), and their physical form (a segment from an oxide fuel or a segment from a plate fuel).

Despite the variety of irradiated samples, the determination of the U, Pu and Nd isotopic and elemental mass fractions by means of ID-MS can already provide considerable information. This is a common analysis as part of post irradiation examination. This gives information about the residual heavy metal atoms (the major actinides) and the concentration of the burn-up monitor (in this case the Nd fission product) can be used in the estimation of the fuel burn-up. Such information can be fed back into areas such as the assessment of fuel performance/qualification, validation of nuclear codes for criticality or for long-term storage of nuclear waste.^{31,38,130,214,215} Crucially, these rely on the low measurement uncertainties ID-MS can provide.

The irradiated sample first has to be brought into solution, before spiking can occur. Dissolution of spent fuels for analysis is detailed elsewhere,^{216–221} but in general terms an irradiated fuel is often dissolved quantitatively by heating (under reflux) under strong acidic conditions over several days inside a shielded hot cell. Only then can spikes be added to an aliquot of the dissolved sample, but crucially before any separations are started. Separations of lanthanides and actinides are discussed elsewhere.^{31–33,58,222–228} Van Winckel *et al.*²²⁰ provide a useful summary of the situations in which off-line and on-line separations are used for spent nuclear fuels.

Many practical details of the radiochemical analyses of the major actinides and Nd (amongst other actinides and fission products) to enable determination of the burn-up of an irradiated fuel are described elsewhere.^{229–232} The methodology reported by Roach *et al.*²³¹ relies on on-line separation hyphenated to an MC-ICP-MS for isotopic vectors and Pu and Nd concentration or Davies & Gray titration for U concentration, all with



calibration by ID-MS to provide results much more rapidly than off-line separations combined with an analytical technique such as TIMS.

The ASTM E321-20 method²³³ uses the ^{148}Nd concentration as the fission burn-up monitor, due to the small difference between the fission yield of the two dominant fissile isotopes (^{235}U and ^{239}Pu). Govers *et al.*²³⁴ reported that this approach works well for NPPs, but that in high-flux reactors (non-power reactors) the $^{147}\text{Nd}(n)^{148}\text{Nd}$ (*i.e.* short form for the $^{147}\text{Nd} + n \rightarrow ^{148}\text{Nd}$ formula) capture reaction may no longer be insignificant. In such cases, a correction needs to be applied to avoid an overestimation of the burn-up when using the ^{148}Nd concentration. If it is not possible to correct the ^{148}Nd for such capture by ^{147}Nd an alternative is to measure the entire Nd vector. Data from the other Nd isotopes can provide estimates of the burn-up value.

The isotopic composition of stable or long-lived Nd isotopes formed during fission in irradiated fuels, including the absence of ^{142}Nd , differs from that of natural Nd. Data from almost 40 different irradiated fuel samples at the SCK laboratories indicate the isotopic abundances of ^{146}Nd and ^{150}Nd are rather similar to their natural abundances whilst those of ^{145}Nd and ^{148}Nd are approximately doubled. For ^{143}Nd and ^{144}Nd the abundances can deviate more widely from their natural isotopic abundances. Roach *et al.*²³¹ give examples of such data from three samples. The choice of the spike isotope for the quantification of Nd formed during fission is different than for Nd with natural isotopic composition due to their different isotopic compositions. A spike enriched in the ^{146}Nd isotope can be an alternative to ^{148}Nd and ^{150}Nd isotopes^{33,38} if the entire Nd vector is to be measured. The amount of spike to be added depends on the concentration in the sample, and to some extent this depends on the laboratory's operating license. Some laboratories perform spiking inside a glovebox and others under a fumehood, the difference being the amount of U, Pu or Nd in the sample to be spiked. To perform spiking under a fumehood, an aliquot of diluted mother solution is required as the mother solution is too active, which in turn requires an appropriately lower spike concentration to avoid overspiking and to avoid spike masses with too high an uncertainty.

Cesium can also be used as an alternative fission burn-up monitor to neodymium.^{235–239} After irradiation of the fuel, the sample contains ^{133}Cs , ^{134}Cs , ^{135}Cs and ^{137}Cs . Cesium is naturally monoisotopic (^{133}Cs), which makes it a good spike for such sample. The difficulties of cesium measurement by ID-MS come from the lack of reference materials to estimate the mass fractionation. Different methods can be used, such as a combination of TIMS and gamma spectrometry or intertechnique comparison.^{235,240}

5.5. Biological applications

Radionuclide analysis in biological samples became important considering their intensive use in industry and medicine, and for some of them, their natural presence in the environment, such as Th and U (also named NORM, for Naturally Occurring Radioactive Material). Therefore, monitoring human exposure

is crucial for evaluating the risks to the wider population and to workers. In addition, in case of a nuclear crisis or radiological exposure, such analyses are crucial to identify each individual's contamination. The most common matrices in which radionuclides are analyzed are urine and feces, but others biological tissues can also be considered in the research field.

The ICP-MS technique has become increasingly popular in recent years for measuring those radionuclides with a sufficiently long half-life ($t_{1/2} > 10\,000$ years).²⁴¹ The performance of ICP-MS, in terms of limits of detection and analysis time (several minutes), offers considerable advantages, even for complex matrices, over nuclear techniques such as alpha spectrometry.^{242,243} Furthermore, in addition to activity concentration determination, the isotopic composition can be determined by means of ICP-MS, which enables the origin of a contamination to be traced.^{242,244}

For urine samples, diluted samples can be measured directly by means of ICP-MS with external calibration, if their concentrations are high enough.^{245,246} However, for urine samples with extremely low radionuclide concentrations and/or for other biological matrices such as feces, blood, nail and hair, a radiochemical purification and pre-concentration may be necessary before measurement by ICP-MS (urinary U,^{247,248} urinary Pu²⁴⁹). The ID technique is, in this case, highly recommended: (i) to evaluate the chemical yield and (ii) to use as an internal standard to measure the concentrations accurately by means of ICP-MS. Therefore, ID coupled to ICP-MS permits proper characterization by more accurate matrix effect corrections in case of high matrix or low concentration measurements.

ICP-MS is widely used for actinide (U, Pu, Am) analyses of biological samples^{241,246,247,249–270} with calibration methods that rely on an actinide isotope that is absent from the sample, such as ^{233}U for U isotopes (^{234}U , ^{235}U , ^{236}U and ^{238}U), ^{242}Pu for Pu isotopes (^{239}Pu , ^{240}Pu , and ^{241}Pu) or ^{243}Am for ^{241}Am analysis. Ni *et al.* developed a protocol for the rapid determination of ultra-trace plutonium isotopes in small volumes of urine.²⁴⁹ This method is based on a chemical treatment of the urine samples (acid digestion, co-precipitation, extraction chromatography) before plutonium measurement by means of HR-ICP-MS. A ^{242}Pu spike is used as a yield tracer to characterize the Pu isotopes. The method allows a high ^{238}U decontamination factor (3.8×10^6), which is essential to limit the polyatomic interference of $^{238}\text{UH}^+$ during ^{239}Pu measurement. An average value of $72.7 \pm 5.5\%$ was achieved for ^{242}Pu recovery for 20 mL or 100 mL urine bioassays. For 100 mL urine samples, the limits of detection (LODs) of ^{239}Pu , ^{240}Pu and ^{241}Pu were 0.003 fg mL^{-1} , 0.002 fg mL^{-1} , and 0.003 fg mL^{-1} , corresponding to 0.006 mBq L^{-1} , 0.015 mBq L^{-1} and 9.8 mBq L^{-1} , respectively. The current LODs of ^{239}Pu and ^{240}Pu by means of ICP-MS are more than 100 times lower than those usually achieved by means of the alpha spectrometry method (1 mBq L^{-1}). In another study, Wang *et al.* developed an online separation and pre-concentration method coupled with ICP-MS/MS for measurement of ^{90}Sr , ^{234}U , ^{239}Pu and ^{241}Am isotopes using ^{233}U , ^{242}Pu and ^{86}Sr tracers to correct for column recovery and matrix effects.²⁷¹ This method required small sample volumes (10 mL) and offered rapid analysis times (46 min per sample for the full



process) and was applied to various liquid matrices (lake water, seawater, and urine samples). The limits of detection were 1.48 pg L^{-1} (8257 mBq L^{-1}) for ^{90}Sr , 1.75 pg L^{-1} (0.40 mBq L^{-1}) for ^{234}U , 0.65 pg L^{-1} (77.65 mBq L^{-1}) for ^{241}Am , and 0.56 pg L^{-1} (1.25 mBq L^{-1}) for ^{239}Pu . In this work, no specific spike was used for ^{241}Am analysis. The authors mentioned that high recoveries were obtained for ^{241}Am in samples analyzed by means of this protocol. Therefore, it may be suspected that no recovery correction was applied for the determination of ^{241}Am . To a limited extent, spike addition has been used to trace another radioelement, *e.g.* the use of ^{242}Pu to trace ^{237}Np , for which no suitable tracer is available, during quantification of ^{237}Np by means of ICP-MS.²⁵⁴ In this study, the authors showed that ^{242}Pu can serve as the recovery monitor for ^{237}Np in the separation and pre-concentration procedure developed.

It should be noted that, in all these publications, no ID equation was detailed. Furthermore, the use of spikes is often mentioned in these papers as a yield tracer. Consequently, it may be suspected that these spikes are used more as internal tracers for recovery correction than as spikes for ID.

Clases *et al.*²⁷² suggested an “isobaric dilution analysis” (IBDA) method as a “new quantitative method for long-lived radionuclides” by means of ICP-MS. The technique relies on using a spike of a different element, but which contains an isobaric isotope and has similar chemical properties to those of the analyte. Demonstration of IBDA has been performed on the determination of gadolinium concentration using a certified dysprosium solution spike by measuring the $^{157}\text{Gd}/^{160}\text{Dy}$ ratio. The same authors applied IBDA for technetium, for which no safe standard, in terms of radioprotection, is available. They demonstrated that the IBDA technique can also be applied on an element with monoisotopic abundance such as ^{99}Tc using a ruthenium solution as a spike solution. The determination of ^{99}Tc in the ^{99}Tc -MAG3 drug is therefore obtained using the $^{99}\text{Tc}/^{101}\text{Ru}$ ratio. This technique could be extended to ^{41}Ca , ^{60}Co and ^{90}Sr using K, Ni and Zr, respectively and applied in various application fields such as industry, environment, cosmochemistry and medicine.²⁷²

Furthermore, understanding the behavior, biokinetics and excretion of radionuclides from the human body increases even more in priority due to the increase of their medical applications. Therefore, radionuclide quantification by ID-ICP-MS is a promising tool for investigating the partitioning and behavior of radionuclides in organ tissues, such as the use of ^{242}Pu and ^{243}Am spikes to determine ^{239}Pu , ^{240}Pu and ^{241}Am isotopes in brain tissues.²⁷³

Enriched spikes have also been used to trace specific speciation into the organism.⁴⁷ However, this technique has not yet been applied to radionuclides.

ID-MS is a promising technique for quantifying low radionuclide concentration and/or in complex matrices for radiation protection purposes and also for investigating the behavior of radionuclides in biological tissues. However, this technique has not been used widely with well-described ID equations. This is perhaps due to the limited number of laboratories performing radioisotope quantification in biological samples by means of ICP-MS. Nevertheless, developments in ID-MS can be anticipated in the coming years.

5.6. Reference material

For CRM certification, reference measurement techniques that provide metrological traceability are required. ID-MS is a very accurate technique for the determination of element mass fraction and provides results with low uncertainties: it can be applied as a primary ratio method when suitable CRMs and calibrators are available. The challenges associated with the development of reference measurement systems for clinical analytes, and in particular for ID-MS, are highlighted in ref. 274. The role of ID-MS in the certification of CRMs is presented in ref. 20 and 21. ID-MS is commonly used by nuclear CRM producers either for characterization or for verification of the assigned certified values determined by means of other techniques.^{43,56,71,201} Facility operator laboratories and other laboratories performing nuclear material analyses use ID-MS for the characterization of laboratory CRMs for quality management, process or instrument control and preparation of spikes.^{86,201,275} ID-MS was used in the last few years to certify several CRMs: ^{243}Am spike,^{7,56,276} LSD spike,^{73,201} ^{229}Th spike,³⁶ ^{231}Pa spike,¹⁵⁶ ^{242}Pu spike,²⁷⁷ ^{244}Pu spike⁴³ or uranium oxide particle CRM.²⁷⁸

On the other hand, CRMs play a crucial role in the performance of ID-MS measurements. Using high quality CRMs in ID-MS provides accurate and traceable measurement results. For instance, in nuclear safeguards spikes are a metrological quality tool to meet the existing requirements indicated by the ITVs for reliable accountancy and verification measurements.^{24,25} Considering modern instrumentation and state-of-the-practice methods, uncertainties of the CRM isotope ratios often significantly dominate the uncertainty budgets for the assay values of U and Pu. Several studies conducted by the IAEA for evaluating the fitness for purpose of CRMs in use²⁷⁹ have concluded that the certified uncertainties of some CRMs were larger than the estimated intermediate precision of the TIMS measurements. Thus, the need for re-certification for better uncertainty is to be addressed by CRM producers. For this important metrology mission, the IAEA and the JRC-Geel organize technical meetings among the safeguards community to discuss the current requirements of the CRMs.

5.7. Process control

ID is a method of choice for process control applications that require an especially high accuracy, granted that appropriate spikes are available for the measured elements. ID comes with a significant advantage over almost all other methods, as it is not affected by sample losses, as long as the loss occurs after the preparation of the {sample-spike} mixture. This is a great feature of ID for trace and ultra-trace analysis that is very sensitive to any sample loss during preparation steps such as separation, dilution, evaporation, *etc.* Another actual advantage of ID is its very low sensitivity to matrix effects, because the spike and sample both share the same matrix and valency after mixture homogenization.

However, it comes with a rather complex setup that complicates and extends the sample preparation, which may be an issue for routine analysis. This is mainly due to the spiking step, where each sample is carefully spiked with an accurately



weighed amount of spike. Automated systems based on highly accurate volumetric dispensers have been developed to solve this issue, helping to prepare a definite number of containers loaded with a known, accurately weighed amount of spike.²⁸⁰ These automated systems are particularly effective for process control, where the analyst has generally access to a decent estimation of expected sample concentrations.

For applications where speciation is important, various reports have demonstrated the compatibility of the ID method with techniques such as laser ablation (LA)-ICP-MS, gas chromatography (GC)-MS, high-performance liquid chromatography (HPLC)-ICP-MS, gamma spectrometry, *etc.*^{281–285}

6. Inter-laboratory comparisons involving ID-MS

ILCs can be divided into three categories: those involving expert laboratories participating in the certification of a CRM (such as that organized for STAM CRM ²⁴³Am certification²⁷⁶), those involving laboratories validating a new measurement method, and finally those testing the proficiency of laboratories/methods for measurement (Proficiency Test, PT). These last two types of ILC are efficient tools to monitor the quality of measurement of analytical laboratories and, in particular, for those using ID-MS. Usually, PTs are organized on a regular basis to evaluate the ability of the laboratory to measure one or several quantities called measurands.²⁸⁶ PTs also play an important role in a laboratory quality system and are increasingly recognized by national accreditation bodies and are part of the ISO17025 standard requirements for the competence of analytical laboratories.²⁸⁷ The benefit for a laboratory of participating in PTs is to evaluate the accuracy of its measurements and to take corrective actions if necessary. The evaluation procedure consists of providing performance scores, such as the z-score or the zeta-score.

The z-score (eqn (35)) compares the difference between the laboratory measurement result (y_{lab}) and the PT assigned value (y_{PT} , certified or consensual value) to the PT standard deviation (S_{PT} , usually determined by robust statistics).

$$z\text{-score} = \frac{y_{\text{lab}} - y_{\text{PT}}}{S_{\text{PT}}} \quad (35)$$

The zeta-score compares the same numerator to the uncertainty of the difference between the laboratory measurement value (u_{lab}) and assigned value (u_{PT} , eqn (36)).

$$\text{zeta-score} = \frac{y_{\text{lab}} - y_{\text{PT}}}{\sqrt{u_{\text{lab}}^2 + u_{\text{PT}}^2}} \quad (36)$$

According to z or zeta-score values, results are classified as:

- Satisfactory if $|z|$ or $|\text{zeta}| < 2$.
- Questionable if $2 < |z|$ or $|\text{zeta}| < 3$.
- Unsatisfactory if $|z|$ or $|\text{zeta}| > 3$.

The z-score indicates the number of PT standard deviations between the laboratory measurement value and the PT assigned value. The zeta-score determines whether the measurement

uncertainty value claimed by the laboratory allows the laboratory's measurement value and the assigned value to be considered identical. Action is then encouraged if unsatisfactory performance is indicated.

In the field of radionuclide analysis, several international PTs are organized annually by different institutions (IAEA, CETAMA, NBL, JRC, *etc.*) in different fields ranging from environmental concerns to safeguards or nuclear mining/enrichment/reprocessing activities.

Laboratories using ID techniques are generally concerned with PTs for the measurement of radionuclide mass fractions (or amount content) in solids or solutions. For example, CETAMA offers PTs, called EQRAIN U, EQRAIN Pu and EQRAIN (U + Pu), for the determination of U or/and Pu mass fractions in solution. These PTs are typically organized every 18 months.²³ The content values lie in the ranges of 1 to 6 g kg⁻¹ for Pu and 50 to 200 g kg⁻¹ for U, and are designed for laboratories connected with the mining or reprocessing industries, institutions for safeguards or institutions dealing with reference materials.

The IAEA regularly organizes NMROro PTs and ILCs to assist the members of the IAEA network analytical laboratories (NWAL), as well as nuclear facility operators and other relevant laboratories, in the assessment of their nuclear material analyses (PTs) and environmental sample analyses (ILCs). During the last two exercises, the goal of NMROro was to determine uranium mass and uranium isotopic ratios in uranium oxide powder, and uranium and plutonium masses and uranium and plutonium isotopic ratios in a dried mixed Pu-U nitrate sample.²⁸⁸ The goals of another ILC organized by the IAEA every two years are to measure the uranium and plutonium masses and isotopic abundances in cotton wipe samples (referred to as "swipe sample") thanks to "bulk analysis" methods (swipe dissolution, uranium and plutonium purifications and ID-MS measurements).

7. Conclusion

This article reviews isotope dilution analysis and its application for radionuclide measurements in different contexts. ID-MS is a primary ratio method that helps to measure radionuclide mass fraction, in solids or liquids, with high accuracy. The ID-MS analysis process is well understood and the ID-MS measurement uncertainty is well controlled and quantified. An uncertainty estimation is calculated considering all stages in the ID-MS process. MCM or quadratic cumulation methods can be used for uncertainty calculation: both approaches yield identical results. To obtain the most accurate measurement, implementation is needed for all stages: weighing process, mixture preparation, spike monitoring, isotopic homogenization, and mass spectrometry measurements.

The excellent performance of ID-MS for radionuclide characterization has been demonstrated in a wide variety of fields: environmental, biological analysis, irradiated sample characterization, certified reference material production, safeguards and nuclear forensics. The ability to evaluate ID-MS measurement performance by using a wide range of ILCs is essential for guaranteeing measurement reliability and demonstrates that



ID-MS has the potential to satisfy current and future needs in radioanalytical chemistry.

List of acronyms

CAB	Cellulose Acetate Butyrate
CCQM	Consultative Committee for Amount of Substance
CEA	French Alternative Energy and Atomic Energy Commission
CETAMA	Commission for the Establishment of Analytical Methods
CMC	CarboxyMethyl Cellulose sodium salt
CRM	Certified Reference Material
<i>F</i>	Error Multiplication Factor
HEU	Highly Enriched Uranium
HKED	Hybrid K-Edge Densitometry
HRGS	High Resolution Gamma Spectrometry
HR-ICP-MS	High Resolution-Inductively Coupled Plasma Mass Spectrometry
HU-1	Harwell Uraninite
IAEA	International Atomic Energy Agency
IBDA	Isobaric Dilution Analysis
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
ID	Isotope Dilution
ID-MS	Isotope Dilution Mass Spectrometry
ILCs	Inter-Laboratory Comparisons
IRSN	French Institute for Radiation Protection and Nuclear Safety
ITVs	International Target Values
IAEA	Japan Atomic Energy Agency
JRC	Joint Research Centre
LAAT	Atalante Analysis Laboratory
LEU	Low Enriched Uranium
LOD	Limit Of Detection
LSD	Large-Sized Dried
MC-ICP-MS	Multi-Collector-Inductively Coupled Plasma Mass Spectrometry
MCM	Monte Carlo Method
MOX	Mixed OXide
MPE	Maximum Permissible Deviation
MSSP	Member States Support Programme
MGA	Multi-Group Analysis
NBL	New Brunswick Laboratory
NFC	Nuclear Fuel Cycle
NIST	National Institute of Standards and Technology
NMRoRo	Nuclear Material Round Robin
NORM	Naturally Occurring Radioactive Material
NPL	National Physical Laboratory
NPP	Nuclear Power Plant
NWAL	IAEA Network Analytical Laboratories
OSL	On-Site Laboratory
PT	Proficiency Test
<i>R</i>	Isotope Ratio
SCK	Belgian Nuclear Research Centre
SGAS	Office of Safeguards Analytical Services
SGAS-ESL	Environmental Sample Laboratory of SGAS

SGAS-NML	Nuclear Material Laboratory of SGAS
SI	International System of Units
SRM	Standard Reference Material
$t_{1/2}$	Half-life
TIMS	Thermal Ionization Mass Spectrometry
<i>u</i>	Standard Uncertainty
UOX	Uranium Oxide
u_r	Relative Standard Uncertainty

Author contributions

Alexandre Quemet: conceptualization, writing – original draft (Introduction, Theory, Optimization of the {sample-spike} mixture, Spike monitoring, and Conclusion parts) and review, supervision. Amélie Hubert: conceptualization, writing – original draft (Nuclear forensics part). Alkiviadis Gourgiotis: conceptualization, writing – original draft (Environmental applications: natural radionuclides: U-series disequilibrium part). Ana María Sánchez Hernández: writing – original draft (Weighing procedure and Reference material parts) and review. Marielle Crozet: writing – original draft (Isotope dilution uncertainty part) and review. Guillaume Bailly: writing – original draft (Process control part). Andrew Dobney: writing – original draft (Irradiated samples part) and review. Georges Duhamel: writing – original draft (Safeguards part). Joe Hiess: writing – original draft (Safeguards part) and review. Urska Repinc: writing – original draft (Safeguards part) and review. Sébastien Mialle: writing – original draft (Isotopic homogenization of the sample-spike mixture and Irradiated samples part). Béatrice Boulet: writing – original draft (Application to environmental monitoring of nuclear facilities part). Raphaëlle Escoubé: writing – original draft (Biological applications part). Céline Bouvier-Capely: writing – original draft (Biological applications part). Fabien Pointurier: writing – review & editing. Sébastien Picart: writing – original draft (Weighing uncertainty and Interlaboratory comparison involving ID-MS parts) and review, supervision.

Conflicts of interest

There are no conflicts to declare.

References

- 1 M. L. D. P. Godoy, J. M. Godoy, L. A. Roldão and L. Tauhata, Determination of total content and isotopic compositions of plutonium and uranium in environmental samples for safeguards purposes by ICP-QMS, *J. Environ. Radioact.*, 2009, **100**, 613–625.
- 2 S. Boulyga, S. Konegger-Kappel, S. Richter and L. Sangély, Mass spectrometric analysis for nuclear safeguards, *J. Anal. At. Spectrom.*, 2015, **30**(7), 1469–1489.
- 3 A. Quemet, E. Buravand, B. Catanese, P. Huot, V. Dalier and A. Ruas, Monitoring the plutonium depletion in dissolution residues of a spent fuel solution using a surrogate and



- plutonium isotope ratio measurements, *J. Radioanal. Nucl. Chem.*, 2020, **326**(1), 255–260, DOI: [10.1007/s10967-020-07311-5](https://doi.org/10.1007/s10967-020-07311-5).
- 4 BIPM, *International vocabulary of metrology – Basic and general concepts and associated terms (VIM)*, 3rd edn, 2008, vol. 3, Available from: http://www.bipm.org/utis/common/documents/jcgm/JCGM_200_2008.pdf.
 - 5 M. Désenfant and M. Priel, Road map for measurement uncertainty evaluation, *Measurement*, 2006, **39**(9), 841–848. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0263224106000789>.
 - 6 ISO 5725-1:2023, *Accuracy (Trueness and Precision) of Measurement Methods and Results — Part 1: General Principles and Definitions*.
 - 7 A. Quemet, A. Ruas, V. Dalier and C. Rivier, Americium isotope analysis by Thermal Ionization Mass Spectrometry using the Total Evaporation Method, *Int. J. Mass Spectrom.*, 2018, **431**, 8–14.
 - 8 A. M. Gaffney, A. Hubert, W. S. Kinman, M. Magara, A. Okubo, F. Pointurier, *et al.*, Round-robin 230Th–234U age dating of bulk uranium for nuclear forensics, *J. Radioanal. Nucl. Chem.*, 2016, **307**(3), 2055–2056, DOI: [10.1007/s10967-015-4334-8](https://doi.org/10.1007/s10967-015-4334-8).
 - 9 F. Pointurier, A. Hubert and G. Roger, A method for dating small amounts of uranium, *J. Radioanal. Nucl. Chem.*, 2013, **296**(2), 593–598, DOI: [10.1007/s10967-012-2198-8](https://doi.org/10.1007/s10967-012-2198-8).
 - 10 Z. Varga, K. Mayer, C. E. Bonamici, A. Hubert, I. Hutcheon, W. Kinman, *et al.*, Validation of reference materials for uranium radiochronometry in the frame of nuclear forensic investigations, *Appl. Radiat. Isot.*, 2015, **102**, 81–86, DOI: [10.1016/j.apradiso.2015.05.005](https://doi.org/10.1016/j.apradiso.2015.05.005).
 - 11 P. van Calsteren and L. Thomas, Uranium-series dating applications in natural environmental science, *Earth Sci. Rev.*, 2006, **75**(1–4), 155–175. <https://linkinghub.elsevier.com/retrieve/pii/S0012825205001418>.
 - 12 X. Hou and P. Roos, Critical comparison of radiometric and mass spectrometric methods for the determination of radionuclides in environmental, biological and nuclear waste samples, *Anal. Chim. Acta*, 2008, **608**(2), 105–139.
 - 13 P. P. Povinec, Ultra-sensitive radionuclide analyses: new frontiers in radioanalytics, *J. Radioanal. Nucl. Chem.*, 2019, **322**(3), 1247–1255, DOI: [10.1007/s10967-019-06707-2](https://doi.org/10.1007/s10967-019-06707-2).
 - 14 S. Díez-Fernández, H. Isnard, A. Nonell, C. Bresson and F. Chartier, Radionuclide analysis using collision–reaction cell ICP-MS technology: a review, *J. Anal. At. Spectrom.*, 2020, **35**(12), 2793–2819. Available from: <http://xlink.rsc.org/?DOI=D0JA00211A>.
 - 15 T. R. E. Southwood and P. A. Henderson, *Ecological Methods*, Blackwell, 2015.
 - 16 E. Roth, Critical evaluation of the use and analysis of stable isotopes (Technical Report), *Pure Appl. Chem.*, 1997, **69**(8), 1754–1813.
 - 17 G. V. Hevesy and F. Paneth, Die Löslichkeit des Bleisulfids und Bleichromats, *Zeitschrift für Anorg Chemie.*, 1913, **82**(1), 323–328.
 - 18 P. Goris, W. E. Duffy and F. H. Tingey, Uranium Determination by the Isotope Dilution Technique, *Anal. Chem.*, 1957, **29**(11), 1590–1592.
 - 19 G. R. Tilton, L. T. Aldrich and M. G. Inghram, Mass Spectrometric Determination of Thorium, *Anal. Chem.*, 1954, **26**(5), 894–898, DOI: [10.1080/18811248.1967.9732709](https://doi.org/10.1080/18811248.1967.9732709).
 - 20 J. Vogl, Characterisation of reference materials by isotope dilution mass spectrometry, *J. Anal. At. Spectrom.*, 2007, **22**(5), 475–492.
 - 21 M. J. T. Milton and T. J. Quinn, Primary methods for the measurement of amount of substance, *Metrologia*, 2001, **38**(4), 289–296.
 - 22 BIPM, *Consultative Committee for Amount of Substance (CCQM) — 5th Meeting (February 1999)*, 1999.
 - 23 M. Crozet, D. Roudil, C. Rigaux, C. Bertorello, S. Picart and C. Maillard, EQRAIN: uranium and plutonium interlaboratory exercises from 1997 to 2016—comparison to ITVs-2010, *J. Radioanal. Nucl. Chem.*, 2019, **319**(3), 1013–1021, DOI: [10.1007/s10967-018-6399-7](https://doi.org/10.1007/s10967-018-6399-7).
 - 24 International Atomic Energy Agency, *International Target Values 2010 for Measurement Uncertainties in Safeguarding Nuclear Materials - STR368*, Vienna, Austria, 2010.
 - 25 International Atomic Energy Agency, *International Target Values for Measurement Uncertainties in Safeguarding Nuclear Materials - STR368 (Revision 1.1)*, Vienna, Austria, 2022.
 - 26 J. Irrgeher, J. Vogl, J. Santner and T. Prohaska, *Sector Field Mass Spectrometry for Elemental and Isotopic Analysis*, ed. T. Prohaska, J. Irrgeher, A. Zitek and N. Jakubowski, Royal Society of Chemistry, Cambridge, 2014. pp. 126–151, New Developments in Mass Spectrometry, Available from: DOI: [10.1039/9781849735407](https://doi.org/10.1039/9781849735407).
 - 27 G. Cavazzini, D. Roccato and A. Fasson, The determination of the isotopic composition of strontium, *Int. J. Mass Spectrom.*, 2022, **471**, 116757, DOI: [10.1016/j.ijms.2021.116757](https://doi.org/10.1016/j.ijms.2021.116757).
 - 28 L. Zhu, C. Xu, X. Hou, J. Qiao, Y. Zhao and G. Liu, Determination of Ultratrace Level 135 Cs and 137 Cs Ratio in Small Volume Seawater by Chemical Separation and Thermal Ionization Mass Spectrometry, *Anal. Chem.*, 2020, **92**, 6709–6718, DOI: [10.1021/acs.analchem.0c00688](https://doi.org/10.1021/acs.analchem.0c00688).
 - 29 A. Magre, B. Boulet, H. Isnard, S. Mialle, O. Evrard and L. Pourcelot, Innovative ICP-MS/MS Method To Determine the 135 Cs/137 Cs Ratio in Low Activity Environmental Samples, *Anal. Chem.*, 2023, **95**(17), 6923–6930, DOI: [10.1021/acs.analchem.3c00207](https://doi.org/10.1021/acs.analchem.3c00207).
 - 30 Y. Shibahara, S. Nakamura, A. Uehara, T. Fujii, S. Fukutani, A. Kimura, *et al.*, Measurement of cesium isotopic ratio by thermal ionization mass spectrometry for neutron capture reaction studies on 135Cs, *J. Radioanal. Nucl. Chem.*, 2020, **325**(1), 155–165, DOI: [10.1007/s10967-020-07198-2](https://doi.org/10.1007/s10967-020-07198-2).
 - 31 A. Quemet, M. Angenieux and A. Ruas, Nd, Am and Cm isotopic measurements after simultaneous separation in transmutation irradiated samples, *J. Anal. At. Spectrom.*, 2021, **36**(8), 1758–1767. Available from: <http://xlink.rsc.org/?DOI=D1JA00165E>.



- 32 N. N. Wanna, K. Van Hoecke, A. Dobney, M. Vasile, T. Cardinaels and F. Vanhaecke, Determination of the lanthanides, uranium and plutonium by means of on-line high-pressure ion chromatography coupled with sector field inductively coupled plasma-mass spectrometry to characterize nuclear samples, *J. Chromatogr. A*, 2020, **1617**, 460839. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S002196731931310X>.
- 33 N. N. Wanna, A. Dobney, K. Van Hoecke, M. Vasile and F. Vanhaecke, Quantification of uranium, plutonium, neodymium and gadolinium for the characterization of spent nuclear fuel using isotope dilution HPIC-SF-ICP-MS, *Talanta*, 2021, **221**(September 2020), 121592, DOI: [10.1016/j.talanta.2020.121592](https://doi.org/10.1016/j.talanta.2020.121592).
- 34 L. Vio, G. Crétier, F. Chartier, V. Geertsens, A. Gourgiotis, H. Isnard, *et al.*, Separation and analysis of lanthanides by isotachopheresis coupled with inductively coupled plasma mass spectrometry, *Talanta*, 2012, **99**, 586–593.
- 35 A. Quemet, J. Sevilla and R. Vauchy, A combined TIMS and ICP-MS study for Th0.5Np0.5O₂ thorium neptunium mixed oxide analysis, *Int. J. Mass Spectrom.*, 2021, **460**, 116479, DOI: [10.1016/j.ijms.2020.116479](https://doi.org/10.1016/j.ijms.2020.116479).
- 36 R. M. Essex, J. L. Mann, R. W. Williams, W. S. Kinman, A. Hubert, M. E. Bennett, *et al.*, A new thorium-229 reference material, *Appl. Radiat. Isot.*, 2018, **134**(July 2017), 23–31, DOI: [10.1016/j.apradiso.2017.07.050](https://doi.org/10.1016/j.apradiso.2017.07.050).
- 37 A. Quemet, A. Ruas, E. Esbelin, V. Dalier and C. Rivier, Development and comparison of two high accuracy methods for uranium concentration in nuclear fuel: ID-TIMS and K-edge densitometry, *J. Radioanal. Nucl. Chem.*, 2019, **321**(3), 997–1004, DOI: [10.1007/s10967-019-06670-y](https://doi.org/10.1007/s10967-019-06670-y).
- 38 A. Quemet, E. Buravand, J.-G. Peres, V. Dalier and S. Bejaoui, Irradiated UAmO₂ transmutation discs analyses: from dissolution to isotopic analyses, *J. Radioanal. Nucl. Chem.*, 2022, **331**(2), 1051–1061, DOI: [10.1007/s10967-021-08156-2](https://doi.org/10.1007/s10967-021-08156-2).
- 39 H. Jaegler, A. Gourgiotis, P. Steier, R. Golser, O. Diez and C. Cazala, Pushing Limits of ICP-MS/MS for the Determination of Ultralow ²³⁶U/²³⁸U Isotope Ratios, *Anal. Chem.*, 2020, **92**(11), 7869–7876.
- 40 A. Gourgiotis, M. Granet, H. Isnard, A. Nonell, C. Gautier, G. Stadelmann, *et al.*, Simultaneous uranium/plutonium separation and direct isotope ratio measurements by using CO₂ as the gas in a collision/reaction cell based MC-ICPMS, *J. Anal. At. Spectrom.*, 2010, **25**(12), 1939–1945.
- 41 C. Venchiarutti, G. Stadelmann, R. Middendorp, Z. Mácsik and A. Venzin, Determination of picogram amounts of uranium in micrometre-sized particles by isotope dilution mass spectrometry, *J. Anal. At. Spectrom.*, 2021, **36**(3), 548–560.
- 42 P.-A. Chaboche, F. Pointurier, P. Sabatier, A. Foucher, T. Tiecher, J. P. G. Minella, *et al.*, ²⁴⁰Pu/²³⁹Pu signatures allow refining the chronology of radionuclide fallout in South America, *Sci. Total Environ.*, 2022, **843**(April), 156943. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0048969722040402>.
- 43 R. M. Essex, R. W. Williams, K. C. Treinen, A. Hubert, M. A. Humphrey, J. D. Inglis, *et al.*, A highly-enriched ²⁴⁴Pu reference material for nuclear safeguards and nuclear forensics measurements, *J. Radioanal. Nucl. Chem.*, 2020, **324**(1), 257–270, DOI: [10.1007/s10967-020-07075-y](https://doi.org/10.1007/s10967-020-07075-y).
- 44 A. M. Sánchez Hernández, J. Horta Domenech, D. Wojnowski and E. Zuleger, Improvement of the ²⁴¹Pu/²³⁹Pu isotope ratio measurement by thermal ionisation mass spectrometry - An approach to account for the ²⁴¹Am in-growth after plutonium purification, *Int. J. Mass Spectrom.*, 2021, **468**, 116660. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S1387380621001408>.
- 45 G. R. Eppich, Z. Mácsik, R. Katona, S. Konegger-Kappel, G. Stadelmann, A. Köpf, *et al.*, Plutonium assay and isotopic composition measurements in nuclear safeguards samples by inductively coupled plasma mass spectrometry, *J. Anal. At. Spectrom.*, 2019, **34**(6), 1154–1165. Available from: <http://xlink.rsc.org/?DOI=C9JA00047J>.
- 46 A. Gourgiotis, H. Isnard, M. Aubert, E. Dupont, I. AlMahamid, G. Tiang, *et al.*, Accurate determination of Curium and Californium isotopic ratios by inductively coupled plasma quadrupole mass spectrometry (ICP-QMS) in ²⁴⁸Cm samples for transmutation studies, *Int. J. Mass Spectrom.*, 2010, **291**(3), 101–107, DOI: [10.1016/j.ijms.2010.02.002](https://doi.org/10.1016/j.ijms.2010.02.002).
- 47 P. Rodríguez-González, J. M. Marchante-Gayón, J. I. García Alonso and A. Sanz-Medel, Isotope dilution analysis for elemental speciation: A tutorial review, *Spectrochim. Acta Part B At. Spectrosc.*, 2005, **60**(2), 151–207.
- 48 P. Rodríguez-González and J. I. García Alonso, Recent advances in isotope dilution analysis for elemental speciation, *J. Anal. At. Spectrom.*, 2010, **25**(3), 239–259.
- 49 J. Villanueva, M. Carrascal and J. Abian, Isotope dilution mass spectrometry for absolute quantification in proteomics: Concepts and strategies, *J. Proteonomics*, 2014, **96**, 184–199, DOI: [10.1016/j.jpro.2013.11.004](https://doi.org/10.1016/j.jpro.2013.11.004).
- 50 C. Pin and B. Le Fèvre, Isotope Dilution with Matrix Element Removal: A Key for High-Precision, High-Accuracy Trace Analysis of Geological Samples Using Inductively Coupled Plasma-Mass Spectrometry, *Geostand. Geoanal. Res.*, 2002, **26**(2), 135–148, DOI: [10.1111/j.1751-908X.2002.tb00882.x](https://doi.org/10.1111/j.1751-908X.2002.tb00882.x).
- 51 J. D. Fassett and P. J. Paulsen, Isotope Dilution Mass Spectrometry for Accurate Elemental Analysis, *Anal. Chem.*, 1989, **61**(10), 643A–649A.
- 52 F. Vanhaecke and P. Degryse, *Isotopic Analysis*, ed. F. Vanhaecke and P. Degryse, Wiley, 2012, Available from: DOI: [10.1002/9783527650484](https://doi.org/10.1002/9783527650484).
- 53 P. J. De Bièvre and G. H. Debus, Precision mass spectrometric isotope dilution analysis, *Nucl. Instrum. Methods*, 1965, **32**(2), 224–228. Available from: <https://linkinghub.elsevier.com/retrieve/pii/0029554X65905161>.
- 54 P. Rodríguez-González and J. Ignacio García Alonso, Mass spectrometry | Isotope dilution mass spectrometry, *Encycl Anal Sci*, 2019, **6**, 411–420.



- 55 D. Roudil, C. Rigaux, C. Rivier, J. C. Hubinois and L. Aufore, CETAMA Contribution to Safeguards and Nuclear Forensic Analysis based on Nuclear Reference Materials, *Procedia Chem.*, 2012, 7, 709–715, DOI: [10.1016/j.proche.2012.10.108](https://doi.org/10.1016/j.proche.2012.10.108).
- 56 R. Jakopič, A. Fankhauser, Y. Aregbe, S. Richter, M. Crozet, C. Maillard, *et al.*, 243Am certified reference material for mass spectrometry, *J. Radioanal. Nucl. Chem.*, 2021, 327(1), 495–504, DOI: [10.1007/s10967-020-07521-x](https://doi.org/10.1007/s10967-020-07521-x).
- 57 G. Canciani, Y. Davrain, M. Crozet, D. Roudil and S. Picart, Controlled Potential Coulometry for the accurate determination of plutonium in the presence of uranium: The role of sulfate complexation, *Talanta*, 2021, 222, 121490, DOI: [10.1016/j.talanta.2020.121490](https://doi.org/10.1016/j.talanta.2020.121490).
- 58 C. Maillard, D. Maloubier, O. Boulay, V. Savigny and A. Quemet, U and Pu separation with U/TEVA resin : Influence of some parameters on chromatographic cycle performances, *J. Radioanal. Nucl. Chem.*, 2021, (0123456789, DOI: [10.1007/s10967-021-07986-4](https://doi.org/10.1007/s10967-021-07986-4).
- 59 A. Quemet and S. Baghdadi, Optimization of double isotope dilution, *J. Anal. At. Spectrom.*, 2022, 37(2), 240–248. Available from: <http://pubs.rsc.org/en/Content/ArticleLanding/2022/JA/D1JA00322D>.
- 60 IUPAC. The IUPAC Compendium of Chemical Terminology, *The IUPAC Compendium of Chemical Terminology*, ed. V. Gold, NC: International Union of Pure and Applied Chemistry (IUPAC), Research Triangle Park, 2019, p. 1670, Available from: <https://goldbook.iupac.org/terms/view/L03540>.
- 61 L. L. Yu, J. D. Fassett and W. F. Guthrie, Detection Limit of Isotope Dilution Mass Spectrometry, *Anal. Chem.*, 2002, 74(15), 3887–3891, DOI: [10.1021/ac011254l](https://doi.org/10.1021/ac011254l).
- 62 L. Yang, Accurate and precise determination of isotopic ratios by MC-ICP-MS: A review, *Mass Spectrom. Rev.*, 2009, 28(6), 990–1011. Available from: <https://apps.who.int/iris/bitstream/handle/10665/254610/WHO-MSD-MER-2017-2-eng.pdf?sequence=1%0Ahttp://apps.who.int/iris/bitstream/handle/10665/254610/WHO-MSD-MER-2017-2-eng.pdf;jsessionid=F9A3B620D10ECFAF8498AC0E08EFCBC8?sequence=1%0Ahttp://apps.who.int/>.
- 63 M. E. Wieser, D. Buhl, C. Bouman and J. Schwieters, High precision calcium isotope ratio measurements using a magnetic sector multiple collector inductively coupled plasma mass spectrometer, *J. Anal. At. Spectrom.*, 2004, 19(7), 844. Available from: <http://xlink.rsc.org/?DOI=b403339f>.
- 64 L. Yang and R. E. Sturgeon, Comparison of mass bias correction models for the examination of isotopic composition of mercury using sector field ICP-MS, *J. Anal. At. Spectrom.*, 2003, 18(12), 1452. Available from: <http://xlink.rsc.org/?DOI=b307973b>.
- 65 P. Lindahl, G. Olzowski and M. Eriksson, Performance and optimisation of triple quadrupole ICP-MS for accurate measurement of uranium isotopic ratios, *J. Anal. At. Spectrom.*, 2021, 14–16.
- 66 S. K. Aggarwal, Thermal ionisation mass spectrometry (TIMS) in nuclear science and technology – a review, *Anal. Methods*, 2016, 8(1996), 942–957.
- 67 T. Prohaska, J. Irrgeher, A. Zitek and N. Jakubowski, Sector Field Mass Spectrometry for Elemental and Isotopic Analysis, *New Developments in Mass Spectrometry*, ed. T. Prohaska, J. Irrgeher, A. Zitek and N. Jakubowski, The Royal Society of Chemistry, 2014. Available from: <https://books.rsc.org/books/book/996/Sector-Field-Mass-Spectrometry-for-Elemental-and->.
- 68 F. Albarède, P. Telouk, J. Blichert-Toft, M. Boyet, A. Agranier and B. Nelson, Precise and accurate isotopic measurements using multiple-collector ICPMS, *Geochim. Cosmochim. Acta*, 2004, 68(12), 2725–2744. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0016703703008871>.
- 69 C. E. Mathew, V. K. Rai, C. Ottenfeld and R. Keller, Effect of weighing uncertainty on assay values by isotope dilution mass spectrometry, *J. Radioanal. Nucl. Chem.*, 2021, 328(1), 235–243, DOI: [10.1007/s10967-021-07646-7](https://doi.org/10.1007/s10967-021-07646-7).
- 70 ASTM C1380-04 - Standard Test Method for Determination of Uranium Content and Isotopic Composition by Isotope Dilution Mass Spectrometry.
- 71 P. van Belle, E. Zuleger and L. Duinslaeger, An improved self-checking weighing practice and a method for contamination detection for use in IDMS nuclear material assay, *INMM Rep*, 2008.
- 72 OIML, International Recommendation OIML R 111-1 Edition 2004 (E), *Int. Organ. Leg. Metrol.*, 2004, 2004, 1–78. Available from: https://www.oiml.org/en/files/pdf_r/r111-1-e04.pdf.
- 73 K. Toth, R. Jakopic, J. Bauwens, C. Hennessy, F. Kehoe, U. Jakobsson, *et al.*, Preparation and Certification of Large-Sized Dried (LSD) Spike: IRMM-1027w, *JRC Ref. Mater. Rep.*, 2022, DOI: [10.2760/817757](https://doi.org/10.2760/817757).
- 74 S. Belz, I. Bianchi, C. Cella, H. Emteborg, F. Fumagalli, O. Geiss, *et al.*, Current Status of the Quantification of Microplastics in Water - Results of a JRC/BAM Inter-laboratory Comparison Study on PET in Water, EUR 30799 EN, Publications Office of the European Union, 2021.
- 75 OIML R 33, 1979 International Organization of Legal Metrology - Conventional Value of the Result of Weighing in Air, 1979.
- 76 M. Ohata, T. Ichinose, N. Furuta, A. Shinohara and M. Chiba, Isotope Dilution Analysis of Se in Human Blood Serum by Using High-Power Nitrogen Microwave-Induced Plasma Mass Spectrometry Coupled with a Hydride Generation Technique, *Anal. Chem.*, 1998, 70(13), 2726–2730.
- 77 R. Hoelzl, C. Hoelzl, L. Kotz and L. Fabry, The optimal amount of isotopic spike solution for ultratrace analysis by isotope dilution mass spectrometry, *Accredit. Qual. Assur.*, 1998, 3(5), 185–188.
- 78 P. Bedson, Guidelines for Achieving High Accuracy in Isotope Dilution Mass Spectrometry (IDMS), *Guidelines for Achieving High Accuracy in Isotope Dilution Mass Spectrometry (IDMS)*, Royal Society of Chemistry,



- Cambridge, 2002, pp. 1–34, Available from: DOI: [10.1039/9781847559302](https://doi.org/10.1039/9781847559302).
- 79 B. N. Colby, A. E. Rosecrance and M. E. Colby, Measurement parameter selection for quantitative isotope dilution gas chromatography/mass spectrometry, *Anal. Chem.*, 1981, **53**(12), 1907–1911.
 - 80 C. J. Park and J. K. Suh, Determination of Trace Elements in Rice Flour by Isotope Dilution Inductively Coupled Plasma Mass Spectrometry, *J. Anal. At. Spectrom.*, 1997, **12**(5), 573–577. Available from: <http://xlink.rsc.org/?DOI=a607393j>.
 - 81 J. W. Eaton, GNU Octave and reproducible research, *J. Process Control*, 2012, **22**(8), 1433–1438, DOI: [10.1016/j.jprocont.2012.04.006](https://doi.org/10.1016/j.jprocont.2012.04.006).
 - 82 J. W. Eaton, D. Bateman, S. Hauberg and R. Wehbring, {GNU Octave} version 8.3.0 manual: a high-level interactive language for numerical computations, 2023, Available from: <https://www.gnu.org/software/octave/doc/v8.3.0/>.
 - 83 J. Irrgeher, J. Vogl, J. Santner and T. Prohaska, Chapter 8 Measurement Strategies, In *Sector Field Mass Spectrometry for Elemental and Isotopic Analysis*, The Royal Society of Chemistry, 2015, pp. 126–151.
 - 84 R. Jakopič, K. Toth, J. Bauwens, R. Buják, C. Hennessy, F. Kehoe, *et al.*, 30 years of IRMM-1027 reference materials for fissile material accountancy and control: development, production and characterisation, *J. Radioanal. Nucl. Chem.*, 2021, **330**(1), 333–345, DOI: [10.1007/s10967-021-07927-1](https://doi.org/10.1007/s10967-021-07927-1).
 - 85 N. Surugaya, T. Hiyama, A. Verbruggen and R. Wellum, Preparation, Certification and Validation of a Stable Solid Spike of Uranium and Plutonium Coated with a Cellulose Derivative for the Measurement of Uranium and Plutonium Content in Dissolved Nuclear Fuel by Isotope Dilution Mass Spectrometry, *Anal. Sci.*, 2008, **24**(2), 247–252, DOI: [10.2116/analsci.24.247](https://doi.org/10.2116/analsci.24.247).
 - 86 G. Bagliano, J. Cappis, N. Doubek, G. Jammet, W. Raab and A. Zoigner, *Preparation and Validation of a Large Size Dried Spike: Batch SAL-9924*, 1989, IAEA/AL/02.
 - 87 A.-M. Sanchez-Hernandez, C.-L. Andor, R. Buda, L. Commin, F. D'Amati, J. Domenech, *et al.*, Optimising the use of reference materials for destructive analysis in nuclear safeguards, In *Proceedings of 41st ESARDA Symposium*, 2019, pp. 188–199.
 - 88 J. Meija and Z. Mester, Paradigms in isotope dilution mass spectrometry for elemental speciation analysis, *Anal. Chim. Acta*, 2008, **607**(2), 115–125. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0003267007019253>.
 - 89 W. Men, J. Zheng, H. Wang, Y. Ni, Y. Kumamoto, M. Yamada, *et al.*, Pu isotopes in the seawater off Fukushima Daiichi Nuclear Power Plant site within two months after the severe nuclear accident, *Environ. Pollut.*, 2019, **246**(July 2013), 303–310, DOI: [10.1016/j.envpol.2018.12.007](https://doi.org/10.1016/j.envpol.2018.12.007).
 - 90 H. Wang, Y. Ni, W. Men, Z. Wang, M. Liu, D. Xiao, *et al.*, Distributions of fallout ¹³⁷Cs, ²³⁹⁺²⁴⁰Pu and ²⁴¹Am in a soil core from South Central China, *J. Environ. Radioact.*, 2022, **251–252**, 106971, DOI: [10.1016/j.jenvrad.2022.106971](https://doi.org/10.1016/j.jenvrad.2022.106971).
 - 91 Y. Fan, H. Jiang, J. Ren, X. Liu, J. Lan, P. Cheng, *et al.*, Plutonium-based radiometric dating of rapidly accumulated sediments in the Sanyuan sinkhole, southern Chinese Loess Plateau, *Sci. Total Environ.*, 2023, **864**(December 2022), 160937, DOI: [10.1016/j.scitotenv.2022.160937](https://doi.org/10.1016/j.scitotenv.2022.160937).
 - 92 C. Maillard and J.-M. Adnet, Plutonium(IV) peroxide formation in nitric medium and kinetics Pu(VI) reduction by hydrogen peroxide, *Radiochim. Acta*, 2001, **89**(8), 485–490, DOI: [10.1524/ract.2001.89.8.485/html](https://doi.org/10.1524/ract.2001.89.8.485/html).
 - 93 A. Brunstad, Oxidation of Plutonium (III) by Sodium Nitrite, Niskayuna, NY (United States), 1957, Available from: <http://www.osti.gov/servlets/purl/4345806/>.
 - 94 J. Meija, T. B. Coplen, M. Berglund, W. A. Brand, P. De Bièvre, M. Gröning, *et al.*, Atomic weights of the elements 2013 (IUPAC Technical Report), *Pure Appl. Chem.*, 2016, **88**(3), 265–291.
 - 95 EC-JRC, IRMM-054 Uranium-235 spike, nitrate solution, [cited 2023 Jul 21], Available from: <https://crm.jrc.ec.europa.eu/p/40454/40475/By-application-field/Nuclear/IRMM-054-URANIUM-235-SPIKE-NITRATE-SOLUTION/IRMM-054>.
 - 96 Joint Committee for Guides in Metrology, *JCGM 101:2008 Evaluation of Measurement Data — Supplement 1 to the “Guide to the Expression of Uncertainty in Measurement” — Propagation of Distributions Using a Monte Carlo Method*, Jcgmg, 2008, vol. 101:2008.
 - 97 A. Saltelli, Making best use of model evaluations to compute sensitivity indices, *Comput. Phys. Commun.*, 2002, **145**(2), 280–297. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0010465502002801>.
 - 98 Joint Committee for Guides in Metrology, *JCGM 100:2008 GUM 1995 Evaluation of Measurement Data — Guide to the Expression of Uncertainty in Measurement*, Jcgmg, 2008, vol. 100, 2008.
 - 99 R Core Team, *R: A Language and Environment for Statistical Computing*, Vienna, Austria, 2023, <https://www.R-project.org>.
 - 100 K. W. W. Sims, S. Pichat, M. K. Reagan, P. R. Kyle, H. Dulaiova, N. W. Dunbar, *et al.*, On the Time Scales of Magma Genesis, Melt Evolution, Crystal Growth Rates and Magma Degassing in the Erebus Volcano Magmatic System Using the ²³⁸U, ²³⁵U and ²³²Th Decay Series, *J. Petrol.*, 2013, **54**(2), 235–271, DOI: [10.1093/petrology/egs068](https://doi.org/10.1093/petrology/egs068).
 - 101 F. Chabaux, E. Blaes, P. Stille, R. di Chiara Roupert, E. Pelt, A. Dosseto, *et al.*, Regolith formation rate from U-series nuclides: Implications from the study of a spheroidal weathering profile in the Rio Icacos watershed (Puerto Rico), *Geochim. Cosmochim. Acta*, 2013, **100**, 73–95. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0016703712005431>.
 - 102 S. Gdaniec, M. Roy-Barman, M. Levier, O. Valk, M. R. van der Loeff, L. Foliot, *et al.*, ²³¹Pa and ²³⁰Th in the Arctic Ocean: Implications for boundary scavenging and



- 231Pa/230Th fractionation in the Eurasian Basin, *Chem. Geol.*, 2020, **532**(April 2019), 119380. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0009254119305091>.
- 103 A. Beaumais, A. Mangeret, D. Suhard, P. Blanchart, M. Neji, C. Cazala, *et al.*, Combined U-Pb isotopic signatures of U mill tailings from France and Gabon: A new potential tracer to assess their fingerprint on the environment, *J. Hazard Mater.*, 2022, **430**(February), 128484. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0304389422002722>.
- 104 A. Gourgiotis, A. Mangeret, G. Manhès, P. Blanchart, L. Stetten, G. Morin, *et al.*, New Insights into Pb Isotope Fingerprinting of U-Mine Material Dissemination in the Environment: Pb Isotopes as a Memory Dissemination Tracer, *Environ. Sci. Technol.*, 2020, **54**(2), 797–806, DOI: [10.1021/acs.est.9b04828](https://doi.org/10.1021/acs.est.9b04828).
- 105 M. Ivanovich and R. S. Harmon, Uranium-series disequilibrium: applications to earth, *Marine & Environ. Sci.*, 1992, **2**, 910.
- 106 J. H. Chen and G. J. Wasserburg, Isotopic Determination of Uranium in Picomole and Subpicomole Quantities, *Anal. Chem.*, 1982, **54**(2), 350, DOI: [10.1021/ac00239a601](https://doi.org/10.1021/ac00239a601).
- 107 T. Yokoyama, A. Makishima and E. Nakamura, Evaluation of the coprecipitation of incompatible trace elements with fluoride during silicate rock dissolution by acid digestion, *Chem. Geol.*, 1999, **157**(3–4), 175–187. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S000925419800206X>.
- 108 P. Lindahl, G. Olszewski and M. Eriksson, Total dissolution of environmental samples for the determination of uranium and thorium by ICP-MS and alpha-particle spectrometry, *Appl. Radiat. Isot.*, 2022, **181**(October 2021), 110103, DOI: [10.1016/j.apradiso.2022.110103](https://doi.org/10.1016/j.apradiso.2022.110103).
- 109 E. Douville, E. Sallé, N. Frank, M. Eisele, E. Pons-Branchu and S. Ayrault, Rapid and accurate U–Th dating of ancient carbonates using inductively coupled plasma-quadrupole mass spectrometry, *Chem. Geol.*, 2010, **272**(1–4), 1–11, DOI: [10.1016/j.chemgeo.2010.01.007](https://doi.org/10.1016/j.chemgeo.2010.01.007).
- 110 G. Yang, H. Tazoe and M. Yamada, Determination of 236 U in environmental samples by single extraction chromatography coupled to triple-quadrupole inductively coupled plasma-mass spectrometry, *Anal. Chim. Acta*, 2016, **944**, 44–50, DOI: [10.1016/j.aca.2016.09.033](https://doi.org/10.1016/j.aca.2016.09.033).
- 111 O. Alhassanieh, A. Abdul-Hadi, M. Ghafar and A. Aba, Separation of Th, U, Pa, Ra and Ac from natural uranium and thorium series, *Appl. Radiat. Isot.*, 1999, **51**(5), 493–498. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0969804399000688>.
- 112 C. Dalencourt, M. N. Chabane, J.-C. Tremblay-Cantin and D. Larivière, A rapid sequential chromatographic separation of U- and Th-decay series radionuclides in water samples, *Talanta*, 2020, **207**(May 2019), 120282, DOI: [10.1016/j.talanta.2019.120282](https://doi.org/10.1016/j.talanta.2019.120282).
- 113 A. W. Knight, E. S. Eitrheim, A. W. Nelson, S. Nelson and M. K. Schultz, A simple-rapid method to separate uranium, thorium, and protactinium for U-series age-dating of materials, *J. Environ. Radioact.*, 2014, **134**, 66–74, DOI: [10.1016/j.jenvrad.2014.02.010](https://doi.org/10.1016/j.jenvrad.2014.02.010).
- 114 G. Manhès, C. Allegre and A. Provost, U-Th-Pb systematics of the eucrite “Juvinas”: Precise age determination and evidence for exotic lead, *Geochim. Cosmochim. Acta*, 1984, **48**(11), 2247–2264. Available from: <https://linkinghub.elsevier.com/retrieve/pii/0016703784902217>.
- 115 M. Verlinde, J. Gorny, G. Montavon, S. Khalfallah, B. Boulet, C. Augeray, *et al.*, A new rapid protocol for 226Ra separation and preconcentration in natural water samples using molecular recognition technology for ICP-MS analysis, *J. Environ. Radioact.*, 2019, **202**(February), 1–7, DOI: [10.1016/j.jenvrad.2019.02.003](https://doi.org/10.1016/j.jenvrad.2019.02.003).
- 116 D. Larivière, V. N. Epov, R. D. Evans and R. J. Cornett, Determination of radium-226 in environmental samples by inductively coupled plasma mass spectrometry after sequential selective extraction, *J. Anal. At. Spectrom.*, 2003, **18**(4), 338–343. Available from: <http://xlink.rsc.org/?DOI=b212361d>.
- 117 D. Larivière, V. N. Epov, K. M. Reiber, R. J. Cornett and R. D. Evans, Micro-extraction procedures for the determination of Ra-226 in well waters by SF-ICP-MS, *Anal. Chim. Acta*, 2005, **528**(2), 175–182. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0003267004013030>.
- 118 C. Dalencourt, A. Michaud, A. Habibi, A. Leblanc and D. Larivière, Rapid, versatile and sensitive method for the quantification of radium in environmental samples through cationic extraction and inductively coupled plasma mass spectrometry, *J. Anal. At. Spectrom.*, 2018, **33**(6), 1031–1040. Available from: <http://xlink.rsc.org/?DOI=C8JA00060C>.
- 119 B. Ghaleb, E. Pons-Branchu and P. Deschamps, Improved method for radium extraction from environmental samples and its analysis by thermal ionization mass spectrometry, *J. Anal. At. Spectrom.*, 2004, **19**(7), 906. Available from: <http://xlink.rsc.org/?DOI=b402237h>.
- 120 A. S. Cohen and R. K. O’Nions, Precise determination of femtogram quantities of radium by thermal ionization mass spectrometry, *Anal. Chem.*, 1991, **63**(23), 2705–2708, DOI: [10.1021/ac00023a008](https://doi.org/10.1021/ac00023a008).
- 121 F. Chabaux, D. B. Othman and J. L. Birck, A new Ra-Ba chromatographic separation and its application to Ra mass-spectrometric measurement in volcanic rocks, *Chem. Geol.*, 1994, **114**(3–4), 191–197. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0009254194900523>.
- 122 A. P. Fleer and M. P. Bacon, In *Notes on Some Techniques of Marine Particle Analysis Used at Whoi*, 2013, pp. 223–226, Available from: DOI: [10.1029/GM063p0223](https://doi.org/10.1029/GM063p0223).
- 123 R. A. Mortlock, R. G. Fairbanks, T. Chiu and J. Rubenstone, 230Th/234U/238U and 231Pa/235U ages from a single fossil coral fragment by multi-collector magnetic-sector inductively coupled plasma mass spectrometry, *Geochim. Cosmochim. Acta*, 2005, **69**(3), 649–657. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0016703704005216>.



- 124 M. Levier, M. Roy-Barman, C. Colin and A. Dapoigny, Determination of low level of actinium 227 in seawater and freshwater by isotope dilution and mass spectrometry, *Mar. Chem.*, 2021, **233**(March), 103986, DOI: [10.1016/j.marchem.2021.103986](https://doi.org/10.1016/j.marchem.2021.103986).
- 125 T. M. Kayzar and R. W. Williams, Developing 226Ra and 227Ac age-dating techniques for nuclear forensics to gain insight from concordant and non-concordant radiochronometers, *J. Radioanal. Nucl. Chem.*, 2016, **307**(3), 2061–2068, DOI: [10.1007/s10967-015-4435-4](https://doi.org/10.1007/s10967-015-4435-4).
- 126 M. Boudias, A. Gourgiotis, G. Montavon, C. Cazala, V. Pichon and N. Delaunay, 226Ra and 137Cs determination by inductively coupled plasma mass spectrometry: state of the art and perspectives including sample pretreatment and separation steps, *J. Environ. Radioact.*, 2022, **244–245**, 106812. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0265931X22000029>.
- 127 L. A. Dietz, C. F. Paghugki and G. A. Land, Internal Standard Technique for Precise Isotopic Abundance Measurements in Thermal Ionization Mass Spectrometry, *Anal. Chem.*, 1962, **34**(6), 709–710, DOI: [10.1021/ac60186a001](https://doi.org/10.1021/ac60186a001).
- 128 H. Cheng, R. Edwards, J. Hoff, C. Gallup, D. Richards and Y. Asmerom, The half-lives of uranium-234 and thorium-230, *Chem. Geol.*, 2000, **169**(1–2), 17–33. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0009254199001576>.
- 129 S. Richter, A. Alonso-Munoz, R. Eykens, U. Jacobsson, H. Kuehn, A. Verbruggen, *et al.*, The isotopic composition of natural uranium samples—Measurements using the new n(233U)/n(236U) double spike IRMM-3636, *Int. J. Mass Spectrom.*, 2008, **269**(1–2), 145–148. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S1387380607003855>.
- 130 A. Quemet, V. Dalier and C. Rivier, Americium isotope analysis by TIMS using the total evaporation method: investigation of method accuracy using a new CETAMA/EC-JRC certified reference material, In *International Conference on Radioanalytical and Nuclear Chemistry, 5-10 Mai 2019*, Budapest, Hongrie, 2019.
- 131 S. F. Boulyga, A. Koepf, S. Konegger-Kappel, Z. Macsik and G. Stadelmann, Uranium isotope analysis by MC-ICP-MS in sub-ng sized samples, *J. Anal. At. Spectrom.*, 2016, **31**(11), 2272–2284. Available from: <http://xlink.rsc.org/?DOI=C6JA00238B>.
- 132 T.-Y. Li, X. Wang, C.-J. Chen, M. Tan and Y. Wu, Testing the initial 230Th/232Th for “Known Age Carbonate” and its significance for 230Th dating and paleoclimate research, *Quat. Int.*, 2022, **607**(2021), 113–119, DOI: [10.1016/j.quaint.2021.07.020](https://doi.org/10.1016/j.quaint.2021.07.020).
- 133 T.-C. Chiu, R. G. Fairbanks, R. A. Mortlock, L. Cao, T. W. Fairbanks and A. L. Bloom, Redundant 230Th/234U/238U, 231Pa/235U and 14C dating of fossil corals for accurate radiocarbon age calibration, *Quat. Sci. Rev.*, 2006, **25**(17–18), 2431–2440. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0277379106000667>.
- 134 F. Chabaux, U-Th-Ra Fractionation During Weathering and River Transport, *Rev. Mineral. Geochem.*, 2003, **52**(1), 533–576. Available from: <https://pubs.geoscienceworld.org/rimg/article/52/1/533-576/87464>.
- 135 K. R. Ludwig, K. R. Simmons, B. J. Szabo, I. J. Winograd, J. M. Landwehr, A. C. Riggs, *et al.*, Mass-Spectrometric 230 Th- 234 U- 238 U Dating of the Devils Hole Calcite Vein, *Science*, 1992, **258**(5080), 284–287, DOI: [10.1126/science.258.5080.284](https://doi.org/10.1126/science.258.5080.284).
- 136 G. Hall, Uranium age determination by measuring the 230Th/234U ratio, *J. Radioanal. Nucl. Chem.*, 2005, **264**(2), 423–427, DOI: [10.1007/s10967-005-0732-7](https://doi.org/10.1007/s10967-005-0732-7).
- 137 R. W. Williams and A. M. Gaffney, 230 Th- 234 U model ages of some uranium standard reference materials, *Proc. Radiochem.*, 2011, **1**(1), 31–35, DOI: [10.1524/repr.2011.0005/html](https://doi.org/10.1524/repr.2011.0005/html).
- 138 S. Rihs, E. Lascar, L. Pourcelot, P. Calmon, P. O. Redon, C. Galy, *et al.*, U- and Th- series disequilibria in separated soil mineral fractions: Insight into the mechanism and timescale of U, Th and Ra redistribution, *Chem. Geol.*, 2021, **583**, 120455. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0009254121003983>.
- 139 R. Fitzgerald, R. Collé, L. Laureano-Pérez, L. Pibida, M. M. Hammond, S. Nour, *et al.*, A new primary standardization of 229Th, *Appl. Radiat. Isot.*, 2010, **68**(7–8), 1303–1308. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0969804310000230>.
- 140 NIST, *Standard Reference Material 4328C Thorium-229 Radioactivity Standard*, National Institute of Standards and Technology, Gaithersburg, 2013.
- 141 P. de Lavison, L. J. Husband, S. M. Jerome, J. D. Keightley, A. P. Woodman, D. H. Woods, *et al.*, The standardisation of for an environmental yield tracer, *Appl. Radiat. Isot.*, 2000, **53**(1–2), 243–249. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0969804300001779>.
- 142 K. W. W. Sims, J. B. Gill, A. Dosseto, D. L. Hoffmann, C. C. Lundstrom, R. W. Williams, *et al.*, An Inter-Laboratory Assessment of the Thorium Isotopic Composition of Synthetic and Rock Reference Materials, *Geostand. Geoanal. Res.*, 2008, **32**(1), 65–91, DOI: [10.1111/j.1751-908X.2008.00870.x](https://doi.org/10.1111/j.1751-908X.2008.00870.x).
- 143 A. Gourgiotis, J. L. Reyss, N. Frank, A. Guihou and C. Anagnostou, Uranium and radium diffusion in organic-rich sediments (sapropels), *Geochem., Geophys., Geosyst.*, 2011, **12**(9), 1–15, DOI: [10.1029/2011GC003646](https://doi.org/10.1029/2011GC003646).
- 144 M. Choi, R. Francois, K. Sims, M. Bacon, S. Brown-Leger, A. Fleer, *et al.*, Rapid determination of 230Th and 231Pa in seawater by desolvated micro-nebulization Inductively Coupled Plasma magnetic sector mass spectrometry, *Mar. Chem.*, 2001, **76**(1–2), 99–112. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0304420301000500>.
- 145 J. Hiess, D. J. Condon, N. McLean and S. R. Noble, 238 U/ 235 U Systematics in Terrestrial Uranium-Bearing Minerals, *Science*, 2012, **335**(6076), 1610–1614. Available from: https://www.cambridge.org/core/product/identifier/CBO9781139167291A041/type/book_part.



- 146 LNHB, Atomic and nuclear data - Table of radionuclides, [cited 2023 Nov 14], Available from: <http://www.lnhb.fr/nuclear-data/nuclear-data-table/>.
- 147 D. Larivière, D. K. Brownell, V. N. Epov, R. J. Cornett and R. D. Evans, Determination of ²²⁶Ra in sediments by ICP-MS: A comparative study of three sample preparation approaches, *J. Radioanal. Nucl. Chem.*, 2007, **273**(2), 337–344, DOI: [10.1007/s10967-007-6870-3](https://doi.org/10.1007/s10967-007-6870-3).
- 148 A. M. Volpe, J. A. Olivares and M. T. Murrell, Determination of radium isotope ratios and abundances in geological samples by thermal ionization mass spectrometry, *Anal. Chem.*, 1991, **63**(9), 913–916, DOI: [10.1021/ac00009a015](https://doi.org/10.1021/ac00009a015).
- 149 Z. Varga, Ultratrace-level radium-226 determination in seawater samples by isotope dilution inductively coupled plasma mass spectrometry, *Anal. Bioanal. Chem.*, 2008, **390**(2), 511–519, DOI: [10.1007/s00216-007-1394-9](https://doi.org/10.1007/s00216-007-1394-9).
- 150 Y.-T. Hsieh and G. M. Henderson, Precise measurement of ²²⁸Ra/²²⁶Ra ratios and Ra concentrations in seawater samples by multi-collector ICP mass spectrometry, *J. Anal. At. Spectrom.*, 2011, **26**(7), 1338. Available from: <http://xlink.rsc.org/?DOI=c1ja10013k>.
- 151 L. I. Bradtmiller, J. F. McManus and L. F. Robinson, ²³¹Pa/²³⁰Th evidence for a weakened but persistent Atlantic meridional overturning circulation during Heinrich Stadial 1, *Nat. Commun.*, 2014, **5**(1), 5817. Available from: <https://www.nature.com/articles/ncomms6817>.
- 152 M. Levier, M. Roy-Barman, L. Foliot, A. Dapigny and F. Lacan, Distribution of Pa in the Atlantic sector of the Southern Ocean: Tracking scavenging during water mass mixing along neutral density surfaces, *Deep-Sea Res. Part I Oceanogr. Res. Pap.*, 2023, **194**, 103951. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0967063722002643>.
- 153 D. A. Pickett, M. T. Murrell and R. W. Williams, Determination of Femtogram Quantities of Protactinium in Geologic Samples by Thermal Ionization Mass Spectrometry, *Anal. Chem.*, 1994, **66**(7), 1044–1049, DOI: [10.1021/ac00079a020](https://doi.org/10.1021/ac00079a020).
- 154 M. Regelous, S. Turner, T. Elliott, K. Rostami and C. Hawkesworth, Measurement of Femtogram Quantities of Protactinium in Silicate Rock Samples by Multicollector Inductively Coupled Plasma Mass Spectrometry, *Anal. Chem.*, 2008, **80**(1), 344, DOI: [10.1021/ac702316r](https://doi.org/10.1021/ac702316r).
- 155 V. P. Chechev and N. K. Kuzmenko, Decay Data Evaluation Project (DDEP): Evaluation of the main ²³³Pa decay characteristics, *Appl. Radiat. Isot.*, 2006, **64**(10–11), 1403–1411. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0969804306001072>.
- 156 R. M. Essex, R. W. Williams, K. C. Treinen, R. Collé, R. Fitzgerald, R. Galea, *et al.*, Preparation and calibration of a ²³¹Pa reference material, *J. Radioanal. Nucl. Chem.*, 2019, **322**(3), 1593–1604, DOI: [10.1007/s10967-019-06711-6](https://doi.org/10.1007/s10967-019-06711-6).
- 157 M. Roy-Barman, L. Foliot, E. Douville, N. Leblond, F. Gazeau, M. Bressac, *et al.*, Contrasted release of insoluble elements (Fe, Al, rare earth elements, Th, Pa) after dust deposition in seawater: a tank experiment approach, *Biogeosciences*, 2021, **18**(8), 2663–2678. Available from: <https://bg.copernicus.org/articles/18/2663/2021/>.
- 158 C.-C. Shen, H. Cheng, R. L. Edwards, S. B. Moran, H. N. Edmonds, J. A. Hoff, *et al.*, Measurement of Attogram Quantities of ²³¹Pa in Dissolved and Particulate Fractions of Seawater by Isotope Dilution Thermal Ionization Mass Spectroscopy, *Anal. Chem.*, 2003, **75**(5), 1075–1079, DOI: [10.1021/ac026247r](https://doi.org/10.1021/ac026247r).
- 159 A. Beranoguirre, C. Pin, M. E. Sanchez-Lorda, S. García de Madinabeitia and J. I. Gil Ibarguchi, An evaluation of Rb-Sr isotope dilution analyses with a ⁸⁶Sr-enriched tracer and Multiple Collection-ICP-MS, *Int. J. Mass Spectrom.*, 2019, **435**, 234–240. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S1387380618302574>.
- 160 L. O. Nicolaysen, Graphic interpretation of discordant age measurements on metamorphic rocks, *Ann. N. Y. Acad. Sci.*, 1961, **91**(2), 198–206, DOI: [10.1111/j.1749-6632.1961.tb35452.x](https://doi.org/10.1111/j.1749-6632.1961.tb35452.x).
- 161 C. Pin, S. Joannon, C. Bosq, B. Le Fèvre and P.-J. Gauthier, Precise determination of Rb, Sr, Ba, and Pb in geological materials by isotope dilution and ICP-quadrupole mass spectrometry following selective separation of the analytes, *J. Anal. At. Spectrom.*, 2003, **18**(2), 135–141. Available from: <http://xlink.rsc.org/?DOI=b211832g>.
- 162 ISO 17294-2:2023 “Water Quality - Application of Inductively Coupled Plasma Mass Spectrometry (ICP-MS) - Part 2: Determination of Selected Elements Including Uranium Isotopes, 2023.
- 163 ISO 20899:2018 “Water Quality - Plutonium and Neptunium - Test Method Using ICP-MS, 2018.
- 164 ISO 18589-4:2019 “Measurement of Radioactivity in the Environment-Soil - Part 4: Plutonium 238 and Plutonium 239 + 240, 2019.
- 165 L. Pourcelot, O. Masson, L. Saey, S. Conil, B. Boulet and N. Cariou, Empirical calibration of uranium releases in the terrestrial environment of nuclear fuel cycle facilities, *J. Environ. Radioact.*, 2017, **171**, 74–82. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0265931X16305586>.
- 166 Y. Shao, J. Zhang, M. Luo, D. Xu and L. Ma, A review of anthropogenic radionuclide ²³⁶U: Environmental application and analytical advances, *J. Environ. Radioact.*, 2022, 251–252:106944. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0265931X22001357>.
- 167 J. M. Kelley, L. A. Bond and T. M. Beasley, Global distribution of Pu isotopes and ²³⁷Np, *Sci. Total Environ.*, 1999, 237–238, 483–500. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0048969799001606>.
- 168 United Nations Scientific Committee on the Effects of Atomic Radiation, *Sources and Effects of Ionizing Radiation Volume I: Source*, United Nations Scientific Committee on the Effects, 2000, vol. I, pp. 1–654.
- 169 E. Hrnccek, P. Steier and A. Wallner, Determination of plutonium in environmental samples by AMS and alpha spectrometry, *Appl. Radiat. Isot.*, 2005, **63**(5–6), 633–638.



- Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0969804305001417>.
- 170 H. Yamana, T. Yamamoto and H. Moriyama, Isotopic ratio of Pu released from fuel cycle facilities — importance of radiochemically pure ^{236}Pu as a tracer, *Radioact. Environ.*, 2001, **1**, 31–46. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S156948600180005X>.
 - 171 R. Wellum, A. Verbruggen and R. Kessel, A new evaluation of the half-life of ^{241}Pu , *J. Anal. At. Spectrom.*, 2009, **24**(6), 801. Available from: <http://xlink.rsc.org/?DOI=b819584f>.
 - 172 P. Bouisset, M. Nohl, C. Cossonnet, B. Boulet, S. Thomas, N. Cariou, *et al.*, Contribution of close-in fallout from the French atmospheric tests in inventories of ^{137}Cs , ^{241}Am and plutonium (238 , 239 , 240) in Gambier Islands (French Polynesia) – Signatures of stratospheric fallout in the Southern Hemisphere, *J. Environ. Radioact.*, 2021, **235–236**, 106624. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0265931X21000965>.
 - 173 V. P. Chechev, Standard Reference Data on the Nuclear Characteristics of the Alpha-Radiating Radionuclides ^{226}Ra , ^{233}U , ^{238}Pu , and ^{239}Pu , *Meas. Tech.*, 2001, **44**(11), 1134–1137.
 - 174 H. Jaegler, F. Pointurier, Y. Onda, A. Hubert, J. P. Laceby, M. Cirella, *et al.*, Plutonium isotopic signatures in soils and their variation (2011–2014) in sediment transiting a coastal river in the Fukushima Prefecture, Japan, *Environ. Pollut.*, 2018, **240**, 167–176. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0269749117347875>.
 - 175 K. Xiong, W. Bu, Y. Ni, X. Liu, J. Zheng, T. Aono, *et al.*, Rapid monitoring of ^{241}Am in small amount of sediment samples by combining extraction chromatography for highly efficient separation of interfering and matrix elements and ICP-MS/MS measurement, *Microchem. J.*, 2023, **190**, 108581. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0026265X23001996>.
 - 176 H. Zhang, X. Hou, J. Qiao and J. Lin, Determination of ^{241}Am in Environmental Samples: A Review, *Molecules*, 2022, **27**(14), 4536. Available from: <https://www.mdpi.com/1420-3049/27/14/4536>.
 - 177 B. Salbu and E. Holm. Radiochemical methods | Technetium, in *Encyclopedia of Analytical Science*, Elsevier, 2005, pp. 24–32. Available from: <https://linkinghub.elsevier.com/retrieve/pii/B0123693977005197>.
 - 178 T. Hayakawa, H. Ko, M.-K. Cheoun, M. Kusakabe, T. Kajino, M. D. Usang, *et al.*, Short-Lived Radioisotope ^{98}Tc Synthesized by the Supernova Neutrino Process, *Phys. Rev. Lett.*, 2018, **121**(10), 102701, DOI: [10.1103/PhysRevLett.121.102701](https://doi.org/10.1103/PhysRevLett.121.102701).
 - 179 L. Yang, W. Bu, K. Xiong, Y. Yang and T. Yang, Determination of ^{99}Tc in solid environmental samples by combining alkali fusion and rapid separation using TRans Uranium elements resin in alkali medium to triple quadrupole inductively coupled plasma mass spectrometry, *Spectrochim. Acta Part B At. Spectrosc.*, 2022, **198**, 106564. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0584854722002087>.
 - 180 S. Pommé, J. Paepen and R. Van Ammel, Linearity check of an ionisation chamber through 99 mTc half-life measurements, *Appl. Radiat. Isot.*, 2018, **140**, 171–178. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0969804318302148>.
 - 181 E. García-Toraño, T. Altizoglou, P. Auerbach, M.-M. Bé, C. Bobin, P. Cassette, *et al.*, The half-life of ^{129}I , *Appl. Radiat. Isot.*, 2018, **140**, 157–162. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0969804318303348>.
 - 182 C. Carrier, H. Azza, A. Michelle, A. Celine, B. Didier, M. Denis, *et al.*, Mass-shift mode to quantify low level ^{129}I in environmental samples by ICP-MS/MS, *J. Anal. At. Spectrom.*, 2022, **37**(6), 1309–1317. Available from: <http://xlink.rsc.org/?DOI=D2JA00128D>.
 - 183 J. Kim, J. Y. Kim, S. E. Bae, K. Song and J. H. Park, Review of the development in determination of ^{129}I amount and the isotope ratio of $^{129}\text{I}/^{127}\text{I}$ using mass spectrometric measurements, *Microchem. J.*, 2021, **169**, 106476, DOI: [10.1016/j.microc.2021.106476](https://doi.org/10.1016/j.microc.2021.106476).
 - 184 B. S. Matteson, S. K. Hanson, J. L. Miller and W. J. J. Oldham, Concurrent determination of ^{237}Np and Pu isotopes using ICP-MS: Analysis of NIST environmental matrix standard reference materials 4357, 1646a, and 2702, *J. Environ. Radioact.*, 2015, **142**, 62–67, DOI: [10.1016/j.jenvrad.2015.01.007](https://doi.org/10.1016/j.jenvrad.2015.01.007).
 - 185 S. Zhang, Z. Liu, G. Yang, J. Zheng, S. Pan, T. Aono, *et al.*, Rapid Method To Determine ^{137}Cs , ^{237}Np , and Pu Isotopes in Seawater by SF-ICP-MS, *Anal. Chem.*, 2023, **95**(46), 16892–16901.
 - 186 S. J. Goldstein, A. A. Price, K. A. Hinrichs, S. P. Lamont, A. J. Nunn, R. S. Amato, *et al.*, High-precision measurement of U-Pu-Np-Am concentrations and isotope ratios in environmental reference materials by mass spectrometry, *J. Environ. Radioact.*, 2021, **237**(June), 106689, DOI: [10.1016/j.jenvrad.2021.106689](https://doi.org/10.1016/j.jenvrad.2021.106689).
 - 187 N. Qin, J. Zheng, G. Yang and K. Tagami, A comprehensive survey of reference materials for their use in quality assurance for the determination of Np-237 in environmental samples, *J. Environ. Radioact.*, 2024, **271**(August 2023), 107328, DOI: [10.1016/j.jenvrad.2023.107328](https://doi.org/10.1016/j.jenvrad.2023.107328).
 - 188 K. Mayer, M. Wallenius and Z. Varga, Nuclear Forensic Science: Correlating Measurable Material Parameters to the History of Nuclear Material, *Chem. Rev.*, 2013, **113**(2), 884–900, DOI: [10.1021/cr300273f](https://doi.org/10.1021/cr300273f).
 - 189 M. J. Kristo, A. M. Gaffney, N. Marks, K. Knight, W. S. Cassata and I. D. Hutcheon, Nuclear Forensic Science: Analysis of Nuclear Material Out of Regulatory Control, *Annu. Rev. Earth Planet Sci.*, 2016, **44**(1), 555–579. Available from: <https://www.annualreviews.org/doi/10.1146/annurev-earth-060115-012309>.
 - 190 Z. Varga, M. Wallenius, M. Krachler, N. Rauff-Nisthar, L. Fongaro, A. Knott, *et al.*, Trends and perspectives in Nuclear Forensic Science, *Trac. Trends Anal. Chem.*, 2022, **146**, 116503, DOI: [10.1016/j.trac.2021.116503](https://doi.org/10.1016/j.trac.2021.116503).
 - 191 Z. Varga, C. Venchiarutti, A. Nicholl, J. Krajčó, R. Jakopič, K. Mayer, *et al.*, IRMM-1000a and IRMM-1000b uranium



- reference materials certified for the production date. Part I: methodology, preparation and target characteristics, *J. Radioanal. Nucl. Chem.*, 2016, **307**(2), 1077–1085, DOI: [10.1007/s10967-015-4227-x](https://doi.org/10.1007/s10967-015-4227-x).
- 192 C. Venchiarutti, Z. Varga, S. Richter, A. Nicholl, J. Krajko, R. Jakopič, *et al.*, IRMM-1000a and IRMM-1000b: uranium reference materials certified for the production date based on the $^{230}\text{Th}/^{234}\text{U}$ radiochronometer. Part II: certification, *J. Radioanal. Nucl. Chem.*, 2016, **308**(1), 105–111, DOI: [10.1007/s10967-015-4368-y](https://doi.org/10.1007/s10967-015-4368-y).
- 193 S. J. Goldstein, M. T. Murrell and R. W. Williams, Half-life of ^{229}Th , *Phys. Rev. C*, 1989, **40**(6), 2793–2795, DOI: [10.1103/PhysRevC.40.2793](https://doi.org/10.1103/PhysRevC.40.2793).
- 194 H. Kikunaga, T. Suzuki, M. Nomura, T. Mitsugashira and A. Shinohara, Determination of the half-life of the ground state of ^{229}Th by using ^{232}U and ^{233}U decay series, *Phys. Rev. C*, 2011, **84**(1), 014316, DOI: [10.1103/PhysRevC.84.014316](https://doi.org/10.1103/PhysRevC.84.014316).
- 195 Z. Varga, A. Nicholl and K. Mayer, Determination of the ^{229}Th half-life, *Phys. Rev. C*, 2014, **89**(6), 064310, DOI: [10.1103/PhysRevC.89.064310](https://doi.org/10.1103/PhysRevC.89.064310).
- 196 R. M. Essex, J. L. Mann, R. Collé, L. Laureano-Perez, M. E. Bennett, H. Dion, *et al.*, New determination of the ^{229}Th half-life, *J. Radioanal. Nucl. Chem.*, 2018, **318**(1), 515–525.
- 197 G. R. Eppich, R. W. Williams, A. M. Gaffney and K. C. Schorzman, ^{235}U – ^{231}Pa age dating of uranium materials for nuclear forensic investigations, *J. Anal. At. Spectrom.*, 2013, **28**(5), 666. Available from: <http://xlink.rsc.org/?DOI=c3ja50041a>.
- 198 K. C. Treinen, A. M. Gaffney, J. M. Rolison, K. M. Samperton, K. C. McHugh, M. L. Miller, *et al.*, Improved protactinium spike calibration method applied to ^{231}Pa – ^{235}U age-dating of certified reference materials for nuclear forensics, *J. Radioanal. Nucl. Chem.*, 2018, **318**(1), 209–219, DOI: [10.1007/s10967-018-6149-x](https://doi.org/10.1007/s10967-018-6149-x).
- 199 S. K. Aggarwal and D. Alamelu, A novel approach for the determination of ^{238}Pu by thermal ionization mass spectrometry (TIMS) using interfering element correction methodology, *Int. J. Mass Spectrom.*, 2005, **241**(1), 83–88. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S1387380604004300>.
- 200 D. Alamelu, P. S. Khodade, P. M. Shah and S. K. Aggarwal, Investigations on atomic and oxide ion formation of plutonium and uranium in thermal ionization mass spectrometry (TIMS) for determination of ^{238}Pu , *Int. J. Mass Spectrom.*, 2004, **239**(1), 51–56. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S1387380604003756>.
- 201 R. Jakopič, Y. Aregbe, S. Richter, E. Zuleger, S. Mialle, S. D. Balsley, *et al.*, Verification measurements of the IRMM-1027 and the IAEA large-sized dried (LSD) spikes, *J. Radioanal. Nucl. Chem.*, 2017, **311**(3), 1781–1791, DOI: [10.1007/s10967-016-5123-8](https://doi.org/10.1007/s10967-016-5123-8).
- 202 M. Sumi, K. Abe, T. Kageyama, H. Nakazawa, A. Kurosawa, M. Yamamoto, *et al.*, Verification of LSD spikes prepared in Japan from a MOX source material, in *Proceedings of INMM 51st Annual Meeting (CD-ROM)*, Baltimore, USA, 2010.
- 203 M. Sumi, K. Abe, T. Kageyama and P. Mason, Pu standard material preparation in Japan, In *INMM 55th Annual Meeting*, Atalante, USA, 2014.
- 204 A.-M. Sanchez-Hernandez, K. Toth, Y. Aregbe, N. Banik, J. Bauwens, R. Buda, *et al.*, Alternative nuclear certified reference materials for safeguards and industry, In *ESARDA 39th Annual Meeting 2017 Symposium*, Duesseldorf, Germany, 2017, Available from: <https://publications.jrc.ec.europa.eu/repository/handle/JRC110509>.
- 205 K. Toth, A.-M. S. Hernández, J. Bauwens, R. Buják, R. C. Marquez, R. Jakopič, *et al.*, Embedding matrices to extend the shelf life of reference materials 1: Cellulose acetate butyrate, *Polym. Degrad. Stabil.*, 2022, **202**, 110024. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0141391022002075>.
- 206 K. Toth, R. Buják, A. M. S. Hernández, J. Bauwens, R. C. Marquez, R. Buda, *et al.*, Research on long-term stability of mixed U and Pu large-sized dried (LSD) spikes for fissile material control, *Prog. Nucl. Sci. Technol.*, 2018, **5**, 48–51. Available from: https://www.aesj.net/document/pnst005/data/048_051.pdf.
- 207 S. Konegger-Kappel, A. Koepf, R. Katona, M. R. Kilburn and S. F. Boulyga, A new era of plutonium assay and isotope ratio measurements at ultra-low levels in IAEA safeguards environmental swipe samples by isotope dilution MC-ICP-MS using a ^{244}Pu spike, *J. Radioanal. Nucl. Chem.*, 2023, **332**(7), 2887–2904, DOI: [10.1007/s10967-023-08880-x](https://doi.org/10.1007/s10967-023-08880-x).
- 208 ASTM C1672-17 - Standard Test Method for Determination of Uranium or Plutonium Isotopic Composition or Concentration by the Total Evaporation Method Using a Thermal Ionization Mass Spectrometer.
- 209 S. Bürger, S. D. Balsley, S. Baumann, J. Berger, S. F. Boulyga, J. A. Cunningham, *et al.*, Uranium and plutonium analysis of nuclear material samples by multi-collector thermal ionisation mass spectrometry: Quality control, measurement uncertainty, and metrological traceability, *Int. J. Mass Spectrom.*, 2012, **311**, 40–50. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S1387380611004702>.
- 210 C.-K. Kim, A. Bosko, D. Nakazawa, G. Duhamel, K. Mise, S. Hara, *et al.*, A Combined Method of TIMS and HRGS for Rapid Determination of Pu Concentrations in Safeguards Samples at the On-Site Laboratory in the Rokkasho Reprocessing Plant, Symposium on International Safeguards: Building Future Safeguards Capabilities, In *Symposium on International Safeguards: Building Future Safeguards Capabilities*, Vienna, Austria, 2018, vol. 5–8.
- 211 U. Repinc, Application of strip isotope dilution analysis to safeguards samples containing low levels of uranium and plutonium, In *International Conference on Radioanalytical and Nuclear Chemistry (RANC-2023)*, Budapest from 7 – 12 May 2023.



- 212 M. H. A. Piro and K. Lipkina, Mining and milling, In *Advances in Nuclear Fuel Chemistry*, Elsevier, 2020, pp. 315–329. Available from: <https://linkinghub.elsevier.com/retrieve/pii/B9780081025710000094>.
- 213 A. Beaumais, A. Nonell, C. Caussignac, S. Mialle, G. Stadelmann, M. Janin, *et al.*, Determination of the 144 Ce/238 U atomic ratio in spent nuclear fuel using double spike isotope dilution mass spectrometry, *J. Anal. At. Spectrom.*, 2022, **37**, 1288–1297, DOI: [10.1039/D2JA00052K](https://doi.org/10.1039/D2JA00052K).
- 214 A. Quemet, C. Maillard and A. Ruas, Determination of zirconium isotope composition and concentration for nuclear sample analysis using Thermal Ionization Mass Spectrometry, *Int. J. Mass Spectrom.*, 2015, **392**, 34–40.
- 215 S. Baghdadi, A. Quemet, E. Esbelin, Y. Manidren, S. Gracia, V. Dalier, *et al.*, Zr precipitation kinetics in irradiated fuel dissolution solution by TIMS and ICP-MS: a combined study, *J. Radioanal. Nucl. Chem.*, 2017, 1–6.
- 216 A. Inoue, Mechanism of the oxidative dissolution of UO₂ in HNO₃ solution, *J. Nucl. Mater.*, 1986, **138**(1), 152–154. Available from: <https://linkinghub.elsevier.com/retrieve/pii/0022311586902710>.
- 217 N. Desigan, N. Bhatt, M. A. Shetty, G. K. P. Sreekumar, N. K. Pandey, U. Kamachi Mudali, *et al.*, Dissolution of nuclear materials in aqueous acid solutions, *Rev. Chem. Eng.*, 2019, **35**(6), 707–734, DOI: [10.1515/revce-2017-0063/html](https://doi.org/10.1515/revce-2017-0063/html).
- 218 V. N. Momotov, E. A. Erin and D. E. Tikhonova, Dissolution of Spent Nuclear Fuel Samples for Analytical Purposes, *Radiochemistry*, 2022, **64**(5), 551–580, DOI: [10.1134/S1066362222050010](https://doi.org/10.1134/S1066362222050010).
- 219 F. Liu, T. H. Yan, B. Li and G. A. Ye, Dissolution behavior of irradiated fuels in nitric acid and characteristics of insoluble residue, *J. Radioanal. Nucl. Chem.*, 2020, **326**(1), 337–341, DOI: [10.1007/s10967-020-07350-y](https://doi.org/10.1007/s10967-020-07350-y).
- 220 S. Van Winckel, R. Alvarez-Sarandes, D. Serrano Purroy and L. Aldave de las Heras, Assay data of spent nuclear fuel: the lab-work behind the numbers, *Front. Energy Res.*, 2023, **11**, DOI: [10.3389/fenrg.2023.1168460](https://doi.org/10.3389/fenrg.2023.1168460).
- 221 M. Crozet and C. Rivier, Impact of dissolution on the uncertainty of spent fuel analysis, *J. Radioanal. Nucl. Chem.*, 2013, **298**(1), 325–336, DOI: [10.1007/s10967-013-2518-7](https://doi.org/10.1007/s10967-013-2518-7).
- 222 S. Röllin, Z. Kopatjtjic, B. Wernli and B. Magyar, Determination of lanthanides and actinides in uranium materials by high-performance liquid chromatography with inductively coupled plasma mass spectrometric detection, *J. Chromatogr. A*, 1996, **739**(1–2), 139–149.
- 223 M. Betti, Use of ion chromatography for the determination of fission products and actinides in nuclear applications, *J. Chromatogr. A*, 1997, **789**(1–2), 369–379.
- 224 S. F. Wolf, D. L. Bowers and J. C. Cunnane, Analysis of high burnup spent nuclear fuel by ICP-MS, *J. Radioanal. Nucl. Chem.*, 2005, **263**(3), 581–586.
- 225 A. Morgenstern, C. Apostolidis, R. Carlos-Marquez, K. Mayer and R. Molinet, Single-column extraction chromatographic separation of U, Pu, Np and Am, *Radiochim. Acta*, 2002, **90**(2), 81–85.
- 226 J. W. Grate, M. J. O'Hara, A. F. Farawila, M. Douglas, M. M. Haney, S. L. Petersen, *et al.*, Extraction chromatographic methods in the sample preparation sequence for thermal ionization mass spectrometric analysis of plutonium isotopes, *Anal. Chem.*, 2011, **83**, 9086–9091.
- 227 K. Van Hoecke, J. Bussé, M. Gysemans, L. Adriaensen, A. Dobney and T. Cardinaels, Isolation of lanthanides from spent nuclear fuel by means of high performance ion chromatography (HPIC) prior to mass spectrometric analysis, *J. Radioanal. Nucl. Chem.*, 2017, **314**(3), 1727–1739.
- 228 H. Isnard, M. Aubert, P. Blanchet, R. Brennetot, F. Chartier, V. Geertsens, *et al.*, Determination of 90Sr/238U ratio by double isotope dilution inductively coupled plasma mass spectrometer with multiple collection in spent nuclear fuel samples with in situ 90Sr/90Zr separation in a collision-reaction cell, *Spectrochim. Acta Part B At. Spectrosc.*, 2006, **61**(2), 150–156. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0584854705003435>.
- 229 P. Regge and R. Boden, Determination of neodymium isotopes as burnup indicator of highly irradiated (U, Pu) O₂ Imfbr fuel, *J. Radioanal. Chem.*, 1977, **35**(1), 173–184, DOI: [10.1007/BF02518224](https://doi.org/10.1007/BF02518224).
- 230 E. A. Erin, V. N. Momotov, A. Y. Volkov, M. I. Khamdeev, V. N. Kupriyanov, A. Y. Shadrin, *et al.*, Radiochemical analysis of a sample of mixed uranium–plutonium nitride fuel, *Radiochemistry*, 2017, **59**(4), 372–378, DOI: [10.1134/S1066362217040099](https://doi.org/10.1134/S1066362217040099).
- 231 B. D. Roach, K. T. Rogers, N. A. Zirakparvar, J. S. Delashmitt, S. C. Metzger, B. T. Manard, *et al.*, The need for speed – Burnup determination of spent nuclear fuel, *Talanta Open*, 2022, **6**, 100152. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S2666831922000698>.
- 232 J. S. Kim, Y. S. Jeon, S. D. Park, Y. K. Ha and K. Song, Analysis of high burnup pressurized water reactor fuel using uranium, plutonium, neodymium, and cesium isotope correlations with burnup, *Nucl. Eng. Technol.*, 2015, **47**(7), 924–933, DOI: [10.1016/j.net.2015.08.002](https://doi.org/10.1016/j.net.2015.08.002).
- 233 ASTM International, *ASTM E321-20 - Standard Test Method for Atom Percent Fission in Uranium and Plutonium Fuel (Neodymium-148 Method)*, West Conshohocken, PA, USA, 2021.
- 234 K. Govers, L. Adriaensen, A. Dobney, M. Gysemans, C. Cachoir and M. Verwerft, Evaluation of the irradiation-averaged fission yield for burnup determination in spent fuel assays, *EPJ Nucl. Sci. Technol.*, 2022, **8**, DOI: [10.1051/epjn/2022018](https://doi.org/10.1051/epjn/2022018).
- 235 H. Isnard, M. Granet, C. Caussignac, E. Ducarme, A. Nonell, B. Tran, *et al.*, Comparison of thermal ionization mass spectrometry and Multiple Collector Inductively Coupled Plasma Mass Spectrometry for cesium isotope ratio measurements, *Spectrochim. Acta Part B At. Spectrosc.*, 2009, **64**(11–12), 1280–1286, DOI: [10.1016/j.sab.2009.10.004](https://doi.org/10.1016/j.sab.2009.10.004).
- 236 V. Bulovič, J. Krtil, F. Sus, Z. Maksimovic and E. Klosova, Determination of the balance of the nuclear reactor fuel



- burn-out process by gamma-spectrometry of fission products III, *J. Radioanal. Chem.*, 1983, **80**(1–2), 199–207, DOI: [10.1007/BF02517663](https://doi.org/10.1007/BF02517663).
- 237 J. R. Phillips, B. K. Barnes and T. R. Bement, Correlation of the Cesium-134/Cesium-137 Ratio to Fast Reactor Burnup, *Nucl. Technol.*, 1979, **46**(1), 21–29, DOI: [10.13182/NT46-21](https://doi.org/10.13182/NT46-21).
- 238 L. Pibida, C. A. McMahon and B. A. Bushaw, Laser resonance ionization mass spectrometry measurements of cesium in nuclear burn-up and sediment samples, *Appl. Radiat. Isot.*, 2004, **60**(2–4), 567–570. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0969804303002975>.
- 239 A. P. Smirnov-Averin, V. I. Galkov, I. G. Sheinker, V. P. Meshcheryakov, L. A. Stabenova and B. S. Kir'yanov, Determining burn-up in spent fuel elements, *Sov. J. At. Energy*, 1962, **11**(5), 1102–1104, DOI: [10.1007/BF01490500](https://doi.org/10.1007/BF01490500).
- 240 M. Granet, A. Nonell, G. Favre, F. Chartier, H. Isnard, J. Moureau, *et al.*, Cs-Ba separation using N₂O as a reactant gas in a Multiple Collector-Inductively Coupled Plasma Mass Spectrometer collision-reaction cell: Application to the measurements of Cs isotopes in spent nuclear fuel samples, *Spectrochim. Acta Part B At. Spectrosc.*, 2008, **63**(11), 1309–1314.
- 241 J. S. Becker, R. S. Soma, K. L. Sutton, J. A. Caruso and H.-J. Dietze, Determination of long-lived radionuclides by inductively coupled plasma quadrupole mass spectrometry using different nebulizers, *J. Anal. At. Spectrom.*, 1999, **14**(6), 933–937. Available from: <http://xlink.rsc.org/?DOI=a809252d>.
- 242 S. F. Boulyga, Mass spectrometric analysis of long-lived radionuclides in bio-assays, *Int. J. Mass Spectrom.*, 2011, **307**(1–3), 200–210, DOI: [10.1016/j.ijms.2011.02.012](https://doi.org/10.1016/j.ijms.2011.02.012).
- 243 C. Bouvier-Capely, J. Ritt, N. Baglan and C. Cossonnet, Potentialities of mass spectrometry (ICP-MS) for actinides determination in urine, *Appl. Radiat. Isot.*, 2004, **60**(5), 629–633. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0969804304000132>.
- 244 I. T. Platzner, J. S. Becker and H. Dietze, Stability Study of Isotope Ratio Measurements for Uranium and Thorium by ICP-QMS, *At. Spectr.*, 1999, **20**(February), 6–12.
- 245 W. S. Kinman, S. P. Lamont and R. E. Steiner, A rapid isotope dilution inductively coupled plasma mass spectrometry procedure for uranium bioassay, *J. Radioanal. Nucl. Chem.*, 2009, **282**(3), 1027–1030, DOI: [10.1007/s10967-009-0204-6](https://doi.org/10.1007/s10967-009-0204-6).
- 246 J. G. Arnason, C. N. Pellegrini and P. J. Parsons, Determination of uranium isotope ratios in human urine by sector field inductively coupled plasma mass spectrometry for use in occupational and biomonitoring studies, *J. Anal. At. Spectrom.*, 2013, **28**(9), 1410. Available from: <http://xlink.rsc.org/?DOI=c3ja50151e>.
- 247 C. Li, K. Benkhedda, S. Tolmachev, L. Carty, R. Ko, D. Moir, *et al.*, Measurement of ²³⁶U in human tissue samples using solid phase extraction coupled to ICP-MS, *J. Anal. At. Spectrom.*, 2010, **25**(5), 730. Available from: <http://xlink.rsc.org/?DOI=b923909j>.
- 248 H. Kurosaki, A. A. Tucker, S. E. Iden, S. M. Sexton, B. D. Gonzalez and G. R. Rao, Use of chromatographic pre-concentration for routine uranium bioassay analysis by ICP-MS, *J. Radioanal. Nucl. Chem.*, 2013, **298**(2), 1017–1022, DOI: [10.1007/s10967-013-2437-7](https://doi.org/10.1007/s10967-013-2437-7).
- 249 Y. Ni, J. Zheng, Q. Guo, W. Men, K. Tagami and S. Uchida, Rapid determination of ultra-trace plutonium isotopes (²³⁹Pu, ²⁴⁰Pu and ²⁴¹Pu) in small-volume human urine bioassay using sector-field inductively coupled plasma mass spectrometry, *Anal. Chim. Acta*, 2018, **1000**, 85–92, DOI: [10.1016/j.aca.2017.10.012](https://doi.org/10.1016/j.aca.2017.10.012).
- 250 E. Werner, P. Roth, I. Wendler, P. Schramel, H. Hellmann and U. Kratzel, Feasibility of ICP-MS for the assessment of uranium excretion in urine, *J. Radioanal. Nucl. Chem.*, 1997, **226**(1–2), 201–203, DOI: [10.1007/BF02063647](https://doi.org/10.1007/BF02063647).
- 251 E. J. Wyse, J. A. MacLellan, C. W. Lindenmeier, J. P. Bramson and D. W. Koppelaar, Actinide bioassays by ICPMS, *J. Radioanal. Nucl. Chem.*, 1998, **234**(1–2), 165–170, DOI: [10.1007/BF02389766](https://doi.org/10.1007/BF02389766).
- 252 Y. Shi, X. Dai, R. Collins and S. Kramer-Tremblay, Rapid determination of uranium isotopes in urine by inductively coupled plasma-mass spectrometry, *Health Phys.*, 2011, **101**(2), 148–153. Available from: <https://journals.lww.com/00004032-201108000-00008>.
- 253 Y. Shi, R. Collins and C. Broome, Determination of uranium, thorium and plutonium isotopes by ICP-MS, *J. Radioanal. Nucl. Chem.*, 2013, **296**(1), 509–515, DOI: [10.1007/s10967-012-2128-9](https://doi.org/10.1007/s10967-012-2128-9).
- 254 Y. Shi, X. Dai, C. Li, R. Collins, S. Kramer-Tremblay, R. Riopel, *et al.*, ICP-MS method for Pu and Np isotopes in population monitoring by a micro-flow injection sample introduction system, *J. Anal. At. Spectrom.*, 2014, **29**(9), 1708–1713. Available from: <http://xlink.rsc.org/?DOI=C4JA00105B>.
- 255 P. J. Gray, L. Zhang, H. Xu, M. McDiarmid, K. Squibb and J. A. Centeno, Determination of ²³⁶U/²³⁸U and ²³⁵U/²³⁸U isotope ratios in human urine by inductively coupled plasma mass spectrometry, *Microchem. J.*, 2012, **105**, 94–100, DOI: [10.1016/j.microc.2012.07.004](https://doi.org/10.1016/j.microc.2012.07.004).
- 256 H. Hernández-Mendoza, E. Chamizo, A. Delgado, M. García-León and A. Yllera, Comparison of methods and application of alpha spectrometry and mass spectrometry techniques for ²³⁹Pu determination in biological samples, *J. Anal. At. Spectrom.*, 2011, **26**(7), 1509. Available from: <http://xlink.rsc.org/?DOI=c0ja00093k>.
- 257 A. A. Reinhard, J. D. Inglis, R. E. Steiner, S. P. LaMont, A. R. Cardon, A. M. Wende, *et al.*, An improved method for uranium separation from urine for rapid bioassay by inductively coupled plasma mass spectrometry, *J. Radioanal. Nucl. Chem.*, 2020, **326**(1), 611–619, DOI: [10.1007/s10967-020-07335-x](https://doi.org/10.1007/s10967-020-07335-x).
- 258 D. Clases and R. Gonzalez de Vega, Facets of ICP-MS and their potential in the medical sciences—Part 1: fundamentals, stand-alone and hyphenated techniques, *Anal. Bioanal. Chem.*, 2022, **414**(25), 7337–7361, DOI: [10.1007/s00216-022-04259-1](https://doi.org/10.1007/s00216-022-04259-1).



- 259 D. Clases and R. Gonzalez de Vega, Facets of ICP-MS and their potential in the medical sciences—Part 2: nanomedicine, immunochemistry, mass cytometry, and bioassays, *Anal. Bioanal. Chem.*, 2022, **414**(25), 7363–7386, DOI: [10.1007/s00216-022-04260-8](https://doi.org/10.1007/s00216-022-04260-8).
- 260 Y. Liu, G. Xiao and R. L. Jones, High-Throughput Determination of Ultratrace Actinides in Urine by In-Line Extraction Chromatography Combined with Quadrupole Inductively Coupled Plasma Mass Spectrometry (EC-ICP-MS), *Anal. Chem.*, 2022, **94**(51), 18042–18049, DOI: [10.1021/acs.analchem.2c04458](https://doi.org/10.1021/acs.analchem.2c04458).
- 261 G. Xiao and J. Button, Rapid determination of $^{235}\text{U}/^{238}\text{U}$ in urine using Q-ICP-MS by a simple dilute-and-shoot approach, *J. Radioanal. Nucl. Chem.*, 2023, **332**(1), 185–191, DOI: [10.1007/s10967-022-08713-3](https://doi.org/10.1007/s10967-022-08713-3).
- 262 B. C. Russell, P. E. Warwick, H. Mohamud, O. Pearson, Y. Yu, H. Thompkins, *et al.*, Development of a single method for direct measurement of multiple radionuclides using ICP-MS/MS, *J. Anal. At. Spectrom.*, 2023, **38**(1), 97–110. Available from: <http://xlink.rsc.org/?DOI=D2JA00174H>.
- 263 V. N. Epov, K. Benkhedda, R. J. Cornett and R. D. Evans, Rapid determination of plutonium in urine using flow injection on-line preconcentration and inductively coupled plasma mass spectrometry, *J. Anal. At. Spectrom.*, 2005, **20**(5), 424–430.
- 264 P. Schramel, I. Wendler, P. Roth and E. Werner, Method for the determination of thorium and uranium in urine by ICP-MS, *Mikrochim. Acta*, 1997, **126**(3–4), 263–266, DOI: [10.1007/BF01242331](https://doi.org/10.1007/BF01242331).
- 265 R. S. Pappas, B. G. Ting, J. M. Jarrett, D. C. Paschal, S. P. Caudill and D. T. Miller, Determination of uranium-235, uranium-238 and thorium-232 in urine by magnetic sector inductively coupled plasma mass spectrometry, *J. Anal. At. Spectrom.*, 2002, **17**(2), 131–134. Available from: <http://xlink.rsc.org/?DOI=b108414c>.
- 266 J. W. Ejnik, T. I. Todorov, F. G. Mullick, K. Squibb, M. A. McDiarmid and J. A. Centeno, Uranium analysis in urine by inductively coupled plasma dynamic reaction cell mass spectrometry, *Anal. Bioanal. Chem.*, 2005, **382**(1), 73–79, DOI: [10.1007/s00216-005-3173-9](https://doi.org/10.1007/s00216-005-3173-9).
- 267 J. Qiao, X. Hou, P. Roos and M. Miró, Bead injection extraction chromatography using high-capacity lab-on-valve as a front end to inductively coupled plasma mass spectrometry for urine radiobioassay, *Anal. Chem.*, 2013, **85**(5), 2853–2859.
- 268 S. Baghdadi, G. Cote, C. Beyaert, B. Mane, A. Peroux, L. Masclet, *et al.*, Coupling between a calix[6]arene-based chromatography column and ICP-MS for on-line actinide analysis, *J. Anal. At. Spectrom.*, 2016, **31**(7), 1406–1413. Available from: <http://xlink.rsc.org/?DOI=C6JA00063K>.
- 269 G. Yang, J. Zheng, E. Kim, S. Zhang, H. Seno, M. Kowatari, *et al.*, Rapid analysis of ^{237}Np and Pu isotopes in small volume urine by SF-ICP-MS and ICP-MS/MS, *Anal. Chim. Acta*, 2021, **1158**, 338431, DOI: [10.1016/j.aca.2021.338431](https://doi.org/10.1016/j.aca.2021.338431).
- 270 D. Larivière, T. A. Cumming, S. Kiser, C. Li and R. J. Cornett, Automated flow injection system using extraction chromatography for the determination of plutonium in urine by inductively coupled plasma mass spectrometry, *J. Anal. At. Spectrom.*, 2008, **23**(3), 352–360. Available from: <http://xlink.rsc.org/?DOI=B714135A>.
- 271 H. Wang, Y. Ni, J. Zheng, Z. Huang, D. Xiao and T. Aono, Low-temperature fusion using NH_4HSO_4 and NH_4HF_2 for rapid determination of Pu in soil and sediment samples, *Anal. Chim. Acta*, 2019, **1050**, 71–79, DOI: [10.1016/j.aca.2018.10.065](https://doi.org/10.1016/j.aca.2018.10.065).
- 272 D. Clases, M. Birka, M. Sperling, A. Faust and U. Karst, Isobaric dilution analysis as a calibration tool for long lived radionuclides in ICP-MS, *J. Trace Elem. Med. Biol.*, 2017, **40**, 97–103, DOI: [10.1016/j.jtemb.2017.01.002](https://doi.org/10.1016/j.jtemb.2017.01.002).
- 273 D. L. Arbova, S. Y. Tolmachev and J. D. Brockman, ICP-MS analysis of actinides in brain tissue of an occupationally exposed individual, *J. Radioanal. Nucl. Chem.*, 2022, **331**(12), 5147–5151, DOI: [10.1007/s10967-022-08460-5](https://doi.org/10.1007/s10967-022-08460-5).
- 274 D. M. Bunk, Reference materials and reference measurement procedures: an overview from a national metrology institute, *Clin. Biochem. Rev.*, 2007, **28**(4), 131–137. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/18392127?0Ahttp://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC2282405>.
- 275 C. Venchiarutti, R. Jakopič, C. Hennessy and K. Toth, Preparation and characterisation of uranium and plutonium quality control samples for isotope dilution mass spectrometry measurements and uncertainty estimation, *J. Radioanal. Nucl. Chem.*, 2021, **327**(3), 1305–1316, DOI: [10.1007/s10967-020-07593-9](https://doi.org/10.1007/s10967-020-07593-9).
- 276 M. Crozet, D. Roudil, C. Maillard, C. Rivier, R. Jakopič, A. Fankhauser, *et al.*, Contribution of an interlaboratory comparison to the certification of the STAM/IRMM-0243 ^{243}Am reference material, *J. Radioanal. Nucl. Chem.*, 2019, **319**(3), 717–725, DOI: [10.1007/s10967-018-06404-6](https://doi.org/10.1007/s10967-018-06404-6).
- 277 C. Venchiarutti, C. Hennessy, R. Jakopič, Y. Aregbe, S. Richter and U. Jacobsson, Preparation and certification of a new batch of ^{242}Pu spike IRMM-049e, *JRC Ref. Mater. Rep.*, 2017, DOI: [10.2760/115196](https://doi.org/10.2760/115196).
- 278 S. Richter, J. Truyens, C. Venchiarutti, Y. Aregbe, R. Middendorp, S. Neumeier, *et al.*, Certification of the First Uranium Oxide micro-particle reference materials for Nuclear Safety and Security, IRMM-2329P and IRMM-2331P, *J. Radioanal. Nucl. Chem.*, 2022, 1–5, DOI: [10.1007/s10967-022-08255-8](https://doi.org/10.1007/s10967-022-08255-8).
- 279 K. J. Mathew, F. E. Stanley, M. R. Thomas, K. J. Spencer, L. P. Colletti and L. Tandon, Critical need for plutonium and uranium isotopic standards with lower uncertainties, *Anal. Methods*, 2016, **8**, 7289–7305.
- 280 A. A. Specht and D. Beauchemin, Automated On-Line Isotope Dilution Analysis with ICP-MS Using Sandwich Flow Injection, *Anal. Chem.*, 1998, **70**(5), 1036–1040, DOI: [10.1021/ac9710691](https://doi.org/10.1021/ac9710691).
- 281 K. G. Heumann, S. M. Gallus, G. Raedlinger and J. Vogl, Accurate determination of element species by on-line coupling of chromatographic systems with ICP-MS using



- isotope dilution technique, *Spectrochim. Acta Part B At. Spectrosc.*, 1998, **53**(2), 273–287.
- 282 G. Centineo, P. Rodríguez-González, E. B. González, J. I. García Alonso, A. Sanz-Medel, N. F. Cardona, *et al.*, Isotope dilution GC-MS routine method for the determination of butyltin compounds in water, *Anal. Bioanal. Chem.*, 2006, **384**(4), 908–914, DOI: [10.1007/s00216-005-0061-2](https://doi.org/10.1007/s00216-005-0061-2).
- 283 N. Tretyakova, M. Goggin, D. Sangaraju and G. Janis, Quantitation of DNA Adducts by Stable Isotope Dilution Mass Spectrometry, *Chem. Res. Toxicol.*, 2012, **25**(10), 2007–2035, DOI: [10.1021/tx3002548](https://doi.org/10.1021/tx3002548).
- 284 S. F. Boulyga, D. Desideri, M. A. Meli, C. Testa and J. S. Becker, Plutonium and americium determination in mosses by laser ablation ICP-MS combined with isotope dilution technique, *Int. J. Mass Spectrom.*, 2003, **226**(3), 329–339. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S1387380603000241>.
- 285 S. Paul, A. Sarkar, D. Alamelu, R. V. Shah and S. K. Aggarwal, Isotope dilution gamma spectrometry for Pu using low energy photons, *Radiochim. Acta*, 2012, **100**(5), 291–296, DOI: [10.1524/ract.2012.1919/html](https://doi.org/10.1524/ract.2012.1919/html).
- 286 M. H. Ramsey, S. L. R. Ellison, H. Czichos, W. Hässelbarth, H. Ischi, W. Wegscheider, *et al.*, Quality in Measurement and Testing, In *Springer Handbook of Metrology and Testing*, Berlin, Heidelberg, Springer Berlin Heidelberg, 2011, pp. 39–141. Available from: DOI: [10.1007/978-3-642-16641-9_3](https://doi.org/10.1007/978-3-642-16641-9_3).
- 287 ISO/CASCO Committee on conformity assessment, *General Requirements for the Competence of Testing and Calibration Laboratories*, ISO/IEC 17025:2017, 2017.
- 288 IAEA, *Technical Meeting on Nuclear Material Round Robin*, [cited 2023 Oct 3], Available from: <https://nucleus.iaea.org/sites/SGAS-TM/SGASTMS/NMRORO>.

