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Standard Test Method for Isotopic Abundance Analysis of Uranium Hexafluoride and Uranyl Nitrate Solutions by Multi-Collector, Inductively Coupled Plasma-Mass Spectrometry¹

This standard is issued under the fixed designation C1477; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the isotopic abundance analysis of ^{234}U , ^{235}U , ^{236}U , and ^{238}U in samples of hydrolysed uranium hexafluoride (UF_6) by inductively coupled plasma source, multicollector, mass spectrometry (ICP-MC-MS). The method applies to material with ^{235}U abundance in the range of 0.2 to 6 % mass. This test method is also described in ASTM STP 1344.

1.2 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.4 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 ASTM Standards:²

[C761 Test Methods for Chemical, Mass Spectrometric, Spectrochemical, Nuclear, and Radiochemical Analysis of Uranium Hexafluoride](#)

[C787 Specification for Uranium Hexafluoride for Enrichment](#)

[C859 Terminology Relating to Nuclear Materials](#)

¹ This test method is under the jurisdiction of ASTM Committee C26 on Nuclear Fuel Cycle and is the direct responsibility of Subcommittee C26.05 on Methods of Test.

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² For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[C996 Specification for Uranium Hexafluoride Enriched to Less Than 5 % \$^{235}\text{U}\$](#)

[D1193 Specification for Reagent Water](#)

[2.2 ASTM Manual](#).²

[STP 1344 Applications of Inductively Coupled Plasma-Mass Spectrometry \(ICP-MS\) to Radionuclide Determinations](#)

3. Terminology

3.1 Definitions:

3.1.1 For definitions of terms relating to the nuclear fuel cycle, refer to Terminology [C859](#).

3.2 Abbreviations:

3.2.1 *amu*—atomic mass unit.

3.3 Acronyms:

3.3.1 *ICP-MC-MS*—Inductively Coupled Plasma Multi-Collector Mass Spectrometer.

3.3.2 *ICP-MS*—Inductively Coupled Plasma Mass Spectrometer.

3.3.3 *UIRM*—Uranium Isotopic Reference Material.

4. Summary of Test Method

4.1 Samples are received either in the form of uranium hexafluoride (UF_6) or aqueous uranic solution. The UF_6 samples are hydrolysed, diluted and acidified with nitric acid. Uranic solution samples are diluted and acidified with nitric acid. If required, an internal reference of thorium isotopes can be subsequently added to each diluted sample. As detailed in Section 8, isotope pairs of elements other than thorium could be used for an internal reference.

4.2 The samples are contained in polypropylene tubes that are inserted into the auto-sampler rack of the mass spectrometer. Sample details are input to the computer and the instrument is prepared for measurement. The automatic measuring sequence is initiated.

4.3 Uranium Isotopic Reference Materials (UIRMs) are used to calibrate the instrument. Each UIRM is prepared in aqueous solution (acidified with nitric acid) and if required spiked with the same internal reference as the samples. This

calibration solution is measured and a mass bias parameter is calculated that is stored and subsequently imported into each of the sample measurements³ to correct the measured uranium isotopic ratios.

4.4 Measurements of isotopic ratios in the calibration solution and the subsequent samples are initiated by customised software. The mass bias factor is computed from the measured isotopic ratios in the calibration solution. This parameter is then exported to correct the measured isotopic ratios of the samples for mass bias. The corrected isotopic abundances are expressed as % atomic and are converted to % mass prior to reporting. Details of the mass bias correction are presented in [Appendix X1](#).

5. Significance and Use

5.1 The test method is capable of measuring uranium isotopic abundances of ²³⁴U, ²³⁵U, ²³⁶U, and ²³⁸U as required by Specifications [C787](#) and [C996](#).

6. Interferences

6.1 *Mass Bias*—Electrostatic repulsion between uranium ions causes a so-called “mass bias” effect. Mass bias is observed as an enhancement in the number of ions detected at the collectors from the heavier uranium isotopes relative to the lighter uranium isotopes. A calibration procedure is used to correct the mass spectrometer for mass bias.

6.2 *Adjacent Isotopic Peaks*—There is potential for interference between adjacent isotope peaks depending on the sensitivity of the instrument used. The abundance sensitivity of the ICP-MC-MS used to generate the results reported in this test method is specified at mass 237 to be less than 0.5 ppm of the ²³⁸U ion beam. The method is limited to the measurement of the ²³⁵U isotopic abundances below 6 %, consequently interference effects with the ²³⁴U and the ²³⁶U ion beams are negligible.

6.3 *Isobaric Molecular Interferences*—A molecular interference exists at mass 236 between ²³⁶U and a hydride of ²³⁵U, which is formed in the plasma. This interference can be corrected by measuring the beam height of the ²³⁸U hydride at mass 239, and applying the correction defined in [Eq 1](#), to the measured ²³⁶U ion beam:⁴

$$^{236}\text{U}_c = ^{236}\text{U}_m - \left(^{235}\text{U} \times \frac{^{238}\text{UH}}{^{238}\text{U}} \right) \quad (1)$$

where:

- ²³⁶U_c = the corrected ²³⁶U ion beam,
- ²³⁶U_m = the measured ²³⁶U ion beam,
- ²³⁵U = the measured ²³⁵U ion beam,
- ²³⁸UH = the measured ²³⁸U hydride ion beam, and
- ²³⁸U = the measured ²³⁸U ion beam.

6.4 Memory Effects:

6.4.1 Contamination of the sample introduction system from previous samples produces memory interference effects.

³ The uranium isotopic precision of measurement, limit of detection, and uncertainty of measurement are listed in [Section 15](#) and [Appendix X1](#).

⁴ This correction can only be applied to samples which do not contain ²³⁹Pu (or any other nuclides with mass 239).

Such effects are accentuated when samples that are depleted in ²³⁵U are measured after enriched samples. Memory effects can be readily assessed by aspirating a 0.3 M nitric acid solution and measuring the background ²³⁸U ion beam. The sample introduction system should be periodically disassembled and cleaned, to minimise the background ²³⁸U ion beam.

6.4.2 A background correction is performed during the measurement run by monitoring the analyte signals of the 0.3 M nitric acid rinse solution. The background correction is measured prior to the mass calibration and is re-measured before each subsequent sample.

7. Apparatus

7.1 Mass Spectrometer:

7.1.1 The mass spectrometer has an inductively coupled plasma (ICP) source and a double focusing electrostatic/magnetic sector analyser equipped with twelve Faraday detectors and two ion counters.⁵

7.1.2 The mass spectrometer is fully computer controlled using customised software and is equipped with an auto-sampler.

7.2 *Polypropylene Sample Tubes, Screw-cap*, 50 mL.

7.3 *Polypropylene Sample Tubes, Screw-cap*, 10 mL.

7.4 *Positive Displacement Pipette, and Tips to Suit*, 0.01 mL.

7.5 *Positive Displacement Pipette, and Tips to Suit*, 1 mL.

7.6 *Variable-Volume Dispenser*, 1 to 5 mL, fitted to a 1 L glass storage bottle.

8. Reagents and Materials

8.1 *Purity of Water*—Demineralised water as defined by Type I of Specification [D1193](#).

8.2 *High Purity 0.3 M Nitric Acid Solution* (~x 50 dilution of the concentrated acid).

8.3 *Uranium Isotopic Reference Material (UIRMs)*—UIRMs are used to calibrate the instrument for multi-collection measurements. The Institute for Reference Materials and Measurements⁶ (IRMM) reference material IRMM-024 has been found to be suitable for enriched samples and the New Brunswick Laboratory⁷ Certified Reference Material CRM U005-A has been found suitable for samples of natural or depleted ²³⁵U abundances. Other reference materials may be used. The UIRMs are prepared as uranyl nitrate solutions containing 0.4 µg/mL of uranium.

8.4 *Optional—Internal Reference Solution* containing ²³⁰Th and ²³²Th isotopes (or isotopes of another suitable element).

⁵ The data presented in the paper was obtained using a ‘Nu Plasma’ mass spectrometer, manufactured by Nu Instruments (Nu Instruments Ltd, Unit 74 Clywedog Road South, Wrexham LL13 9XS, North Wales, UK). The Nu Plasma was supplied with the (optional) BIG80 vacuum pumping system to achieve optimum sensitivity.

⁶ Institute for Reference Materials and Measurement, Retieseweg, B-2440 Geel, Belgium.

⁷ New Brunswick Laboratory, D-350, 9800 South Cass Avenue, Argonne, Illinois 60439.

TABLE 1 Zoom Lens Configuration Achieved Under Software Control

Collector	L6	L5	L4	IC1	L3	IC0	L2	L1	Ax	H1	H2	H3	H4	H5
Separation Ion Beam	²³⁰ Th	²³² Th	1U	1U	²³⁴ U	²³⁵ U	²³⁶ U	²³⁸ U	²³⁸ UH	1U	1U	1U	2U	2U

where:

- Ax = Axial Faraday collector,
- L and H = low and high mass Faraday collectors (with respect to the Axial collector),
- IC = ion counters, and
- U = unit mass dispersion for uranium isotopes.

8.4.1 It has been found that the stability of the modern ICP-MC-MS can be such that it is not necessary to use an internal reference to monitor variations in mass bias. The data presented in this paper was obtained without the use of an internal reference. However, if the addition of an internal reference is deemed necessary then isotopes of thorium (230 and 232) can be used as a suitable internal reference material. The internal reference must contain at least one pair of isotopes in a fixed ratio. It is not necessary for this isotopic ratio to be accurately known as the same reference is added to both the calibration material and the subsequent samples. Minor fluctuations in instrument calibration (mass bias) are reflected in the measured ratio of the internal reference in the samples. Subsequent correction of the mass bias parameter using the measured ratio of the internal reference provides the necessary adjustment to the mass bias factor prior to result calculation.

8.4.2 The internal reference material should be prepared with a dilution appropriate to the sensitivity of the mass spectrometer. If thorium is used as the internal reference then a thorium to uranium ratio of approximately 1:2 should be adequate.

NOTE 1—If an internal reference is added, then the uranic concentration of the samples should be adjusted so that the uranic concentration required for the mass spectrometer is achieved following the addition of the internal reference.

NOTE 2—The decay of ²³⁴U to ²³⁰Th may present a problem with the analysis of aged-uranic solutions. This should not present a problem with uranium hexafluoride samples that are taken in the gaseous phase, as gaseous UF₆ separates from any non-volatile thorium compounds.

9. Hazards

9.1 A number of the materials used in this procedure are radioactive, toxic, corrosive or any combination of the three. Adequate laboratory facilities and safe handling procedures must be used. A detailed discussion of all safety procedures is beyond the scope of this method. Site specific practices for the handling of radioactive materials and hazardous chemicals should be followed.

10. Sampling, Test Specimens, and Test Units⁸

10.1 Samples Received as UF₆:

10.1.1 Transfer between 0.2 and 0.25 g of UF₆ gas into a glass sample tube cooled by liquid nitrogen.⁹

⁸ The sample dilutions specified in this section can be varied according to instrument requirements.

⁹ Subsampling of UF₆ is detailed in Test Method C761.

10.1.2 Working in a fume cupboard, hydrolyse the UF₆ using demineralised water from a wash bottle. The operator should keep the sample tube pointed away at all times since some toxic HF gas is produced.

10.1.3 Pour the hydrolysed UF₆ into a 50 mL screw-cap polypropylene tube and dilute so that the final concentration of UF₆ is 5 mg/mL. For example, if the weight of UF₆ transferred is 0.2 g, dilute to 40 mL with demineralised water.

10.1.4 Using a positive displacement pipette, take a 0.01 mL aliquot of solution and transfer to a clean 50 mL screw-cap polypropylene tube. Dilute to a volume of 42 mL using a 0.3 M nitric acid solution. The resulting solution contains 1.2 µg/mL of UF₆ which is equivalent to 0.8 µg/mL of uranium.

10.1.5 Pour 2 mL of solution into a 10 mL polypropylene tube and double the volume to 4 mL using 0.3 M nitric acid solution, to reduce the uranic concentration to 0.4 µg/mL.

10.1.6 If required, add an aliquot of the thorium internal reference and mix the solution thoroughly (see 8.4).

10.1.7 Place the tube in the designated rack position in accordance with Section 13.

10.2 Samples Received as Aqueous Uranyl Nitrate Solutions of Known Uranic Concentration:

10.2.1 Dilute the sample with a 0.3 M nitric acid solution so that the uranium concentration is 0.8 µg/mL.

10.2.2 Proceed in accordance with 10.1.5 – 10.1.7.

11. Preparation of Apparatus

11.1 Many ICP-MC-MS designs require the Faraday collectors to be mechanically positioned to align with the ion beams. The instrument used for this work adopts a different approach, where a “zoom lens” which alters the dispersion of the instrument is used to focus the beams onto a fixed array of detectors. The zoom lens settings were adjusted under software control to achieve the configuration shown in Table 1.

11.2 To minimise measurement uncertainty, minor isotope (²³⁴U and ²³⁶U) abundances are measured with ion counters. The analyser magnet must be calibrated across the mass range 230 to 238, however, the instrument manufacturer recommends calibrating across the mass range 80 to 238 (achieved using the beam from the Argon dimer). The magnet should be re-calibrated if the calibration drifts by more than 0.2 atomic mass units.