RADIOACTIVITY STANDARD REFERENCE MATERIALS

Purpose

The purpose of this Procedure is twofold:

1) To document the quality procedures used to ensure that the NIST Standard Reference Materials (SRMs) for Radioactivity Measurements are of the highest metrological quality, and
2) To document the principles and practices of the production processes of the radioactivity SRMs.

There is a wide range of individual values and protocols that could be used to produce a radioactivity SRM. Hence, the exact values of properties and the exact production details of the current radioactivity SRMs are presented in appendices rather than in the body of this Procedure.

Background

NIST radioactivity SRMs represent the national basis for accurate radioactivity measurements. Several commercial companies provide secondary radioactivity standards for both specific and general needs. These secondary standards are linked to national standards through NIST calibration services. Generally, the radioactivity SRMs that are available from NIST are provided for one of several reasons: (a) they are not available from outside commercial suppliers, (b) commercially-produced standards may not be traceable to national standards, (c) the accuracy of commercially-produced standards is not adequate for a significant number of users, or (d) there are enough requests from the user community for a standard not otherwise available. Radioactivity SRMs can typically be classified into three general categories: (1) environmental and nuclear power, (2) medicine, and (3) basic and applied research using or involving radioactivity in the development of nuclear data and the examination of basic nuclear processes.

NIST issues a wide array of SRMs for radioactivity measurements. Typically, there are 50 to 60 such SRMs in stock; calibrations have been performed on approximately 80 different radionuclides. Expanded uncertainties of these calibrations are typically 1 percent or less. These calibrations are performed using approximately 20 radiometric and a few mass spectrometric methods. The SRMs are issued in several configurations, including acidic solutions of alpha- and beta-particle and gamma-, and x-ray emitting radionuclides, and various matrix materials. The NIST Complex Matrix radioactivity SRMs (see RPD Procedure 16) result from collaboration with national and international environmental laboratories. These SRMs are distributed as ground, homogenized powders of soils, sediments, and organic materials and are characterized for as many as 20 radionuclides at environmental levels.

NIST radioactivity measurements are compared with the primary standards of other National Metrology Institutes (NMIs) through international measurement comparisons, including those organized and evaluated by the International Bureau of Weights and Measures (BIPM). The results of such international comparisons, as well as an extensive data file of NIST Calibration and Measurement Capabilities (CMCs), may be found on the BIPM website at www.bipm.org/kcdb.

Scope

Appendix A1 lists the properties of 48 radioactivity SRMs that are in stock or in preparation as of August 2026. The certified massic activities (activity divided by the total mass of the sample [1]) of the radioactivity SRMs have a range of more than 9 orders of magnitude, from less than 10^{-3} Bq·g^{-1} to more than 10^{6} Bq·g^{-1}. The half-lives have a range of more than 13 orders of magnitude, from less than 10^{-3} years (6 hours) to more than 10^{10} years. Radioactivity SRMs with short half-lives are available only at certain preannounced times. The radionuclides range from hydrogen-3 (Z = 1) to curium-244 (Z = 96), and include solids and liquids.

For such a wide variety of radioactivity SRMs, there is not a single procedure (or even a small number of procedures) that can be used to describe how they are made. There is, however, a sequence of steps that can be used to describe, in general, the production process of an SRM, including a radioactivity SRM. Each of these steps is discussed in greater detail in the Procedures section of this document. The intent will be generally the same within each step, but the exact sequence of the steps and the exact procedure by which each step is carried out may vary from SRM to SRM. Each of the most common procedures within each step will be described in detail in an appendix dedicated to that procedure. These appendices form a collection of "modular building blocks" from which the appropriate ones can be selected and combined to form the complete production procedure for any given radioactivity SRM. See Appendix A1 for the information necessary to construct the complete production procedure for each radioactivity SRM.

Safety

The production processes for the radioactivity SRMs involve working with radioactive materials, sometimes at very high levels of activity and dose rate, with various acids and other chemicals, and with potentially dangerous equipment. Safe work practices are an essential part of the production process. Many of the essential safety processes are documented in the MML Hazard Review system and in the Safety Evaluations (Authorized Use Permits). See step 6 in the procedures section.

Equipment

The production of the NIST radioactivity SRMs involves a large number of different machines and measuring instruments. See step 8 in the Procedures section.

Uncertainty Analysis

A measurement result is complete only when accompanied by a quantitative statement of its uncertainty. The uncertainty often determines the usefulness of the measurement result. The analysis and reporting of measurement uncertainties is an essential step in the production process. See step 19 in the Procedures section.

Records

The data in the production records should be complete enough so that anyone who is reasonably familiar with the SRM production process can reproduce any or all of the calculations that lead to the final measurement results and uncertainties for the SRM (i.e., the certified values) and evaluate and reproduce the production process (e.g., for the next batch of that SRM). See step 22 in the Procedures section.

Filing and Retention

The radioactivity SRM production records are stored in Building 245, C001 SRM Records Storage Room. The production records are retained for as long as the SRM is available for sale to the public, plus at least an additional 10 years. See step 22 in the Procedures section.

The Radiation Physics Division (RPD) Quality Manager shall maintain the original and all past versions of this RPD Procedure.

Procedures

The need for a new SRM largely derives from advice from the radioactivity user community. Interactions

with this community include the annual CIRMS (Council on Ionizing Radiation Measurements and Standards) meeting, interactions with the members of the former NRMAP, Inc., steering committees, focused workshops, and personal interactions with users within other laboratories, academia, and industry. This need is usually identified by the principal investigator responsible for producing, calibrating, and certifying the SRM. A need could also be identified by other Radioactivity Group (RG) members.

RPD-QM-II describes the responsibilities of the Radioactivity Group Leader, SRM Coordinator, and SRM Principal Investigator and the coordination of SRM activities among them.

Below is a sequence of general steps that can be used to describe the production process of a radioactivity SRM.

Step 1. Determine the intended use, the requirements, and the demand for the SRM.

Ensuring that each NIST radioactivity SRM is of the highest metrological quality requires more than having low uncertainty of the certified values. It also requires that the form, chemical composition, size, activity, and packaging of the SRM are such that the user can easily make correct and accurate measurements; the price of the SRM must also be acceptable to the intended customers. In order to help ensure all of these things, the RG seeks the advice of a number of organizations in addition to the requests and suggestions of individual customers.

If this SRM is a renewal (i.e., the production of a new batch of an already existing, but presently out-of-stock, SRM), the previous sales record is also considered. If there is a question about the continued need for a particular radioactivity SRM, previous customers for that SRM are usually consulted to obtain their comments and suggestions.

See Appendix A1 for the (primary) intended use for each radioactivity SRM.

Step 2. Select the chemical and physical properties of the SRM and select the chemical and physical quantities that are to be quantified and/or certified.

There are three basic guidelines for the selection of the chemical and physical properties of a radioactivity SRM:

1. The SRM should be stable (there is no chemical or physical change to the radioactivity SRM, other than the intrinsic radioactive decay, that changes a certified value by more than 25 percent of its stated uncertainty over the stated time period) for a period of at least ten half-lives of the primary radionuclide or for at least 20 years, whichever is less.
2. The SRM should be as similar as is practical to the sample(s) that the customer will measure. This helps reduce or eliminate additional uncertainties due to dilution or due to corrections for different geometries, different photon absorptions, etc.
3. The SRM should be usable by as many customers as possible. For example, at the request of the U.S. Environmental Protection Agency, all new batches of solution radioactivity SRMs that are used as tracers for environmental measurements are made with nitric acid. This is because stainless-steel planchets are widely used to make deposited sources for environmental measurements, and nitric acid does not significantly attack stainless steel (unlike, for example, hydrochloric acid).

There are two basic guidelines for the selection of the chemical and physical properties whose values are to be quantified:

1. All of the properties that are essential to the proper use of the radioactivity SRM must be described quantitatively. For example, some users are able to dispense solution SRMs volumetrically only using

a pipette. Since the solution radioactivity SRMs have certified values of massic activity (activity per unit mass), the solution density must be accurately quantified in order for the SRM to be useful.

2. The precision of contributing measurements should be considered such that the expanded uncertainty of the SRM remains low enough to be satisfactory for the majority of users.

See Appendix A1 for the properties of each radioactivity SRM.

Step 3. Select a suitable container and packaging for the SRM.

The three basic guidelines for selecting a suitable container for a radioactivity SRM are the same as for selecting the chemical and physical properties of the SRM (see step 2).

The containers currently in use for radioactivity SRMs have been selected according to these guidelines. See Appendix A1 for the container used for each radioactivity SRM.

As part of the production process, additional packaging is placed around the radioactivity SRM container. This packaging is designed to protect the SRM during handling and long-term storage and to pass the performance tests for Type-A packages of radioactive material. The packaging currently in use for the radioactivity SRMs has proven satisfactory over decades of use and has been designed to ensure compliance with national and international transport regulations involving hazardous materials

Step 4. Select a measurement model, a suitable sampling and measurement method (experimental design), including the sequence of operations for the production process.

Four possible types of measurement models are considered for the radioactivity SRMs.

1. LMNL = Linear, Multiplicative, Normal, Low Correlation
2. LMNH = Linear, Multiplicative, Normal, High Correlation
3. LMOL = Linear, Multiplicative, Other than Normal, Low Correlation
4. NMNL = Non-Linear, Multiplicative, Normal, Low Correlation

The first type of measurement model has proven to be appropriate for most of the radioactivity SRMs. The measurement model is selected in consultation with the NIST Statistical Engineering Division, as needed.

Measurements are made on one or more samples of the master solution/mixture to determine the values of the properties that are to be quantified. In order for these measurements to be relevant to the SRM solution/mixture, the two solutions or mixtures must be gravimetrically related. In the RPD, only gravimetric measurements are used when dispensing or diluting the master and the SRM solutions.

It is clearly advantageous in terms of production effort (and often in terms of minimizing the measurement uncertainty as well) to have the master solution and the SRM solution be the same, and this is done whenever practical. For most gamma-ray-emitting radioactivity SRMs, the master solution and the SRM solution are the same solution. For the gamma-ray-emitting solutions, both liquids and gases, the unopened SRM ampoule is the sample for measurement.

For alpha-particle-emitting and beta-particle-emitting radioactivity SRMs, the master solution and the SRM solution may or may not be the same solution. For the low-level environmental tracer solutions, the SRM solution is a quantitative dilution of the master solution. Careful and thorough mixing of the solutions is essential if the calibration of the master solution is to be relevant to the SRM solution. The master solution is gravimetrically dispensed to make point sources and/or liquid scintillation sources for measurement. If the master solution is to be diluted to make the SRM solution, this is usually done at the same time.

The selection of primary and confirmatory measurement methods depends primarily on the decay mode of the primary radionuclide and on the activity and physical form of the sample(s) to be measured. The general criteria for the selection of a measurement method are:

1. Non-destructive to the sample (if possible)
2. Ease of measurement
3. Ease of sample preparation
4. Low measurement uncertainty
5. Selectivity (if more than one radionuclide is present)
6. High detection efficiency (especially if the decay rate is low)

There are presently 16 basic methods, some with many variations, that are used for primary, confirmatory, and/or impurity measurements of the radioactivity SRMs. See Appendix A1 for the measurement method(s) used for each radioactivity SRM.

The sequence in which the required steps are to be carried out, and the required facilities, equipment, personnel, supplies, and funding, should be documented in whatever form is satisfactory for the purpose, such as lists, tables, drawings, flow charts, Gantt diagrams, etc.

Step 5. Have the proposed production process reviewed and approved.

The review and approval of the SRM production plan are carried out by the Radioactivity Group Leader and the SRM Coordinator. A record of this review shall be maintained with the SRM documentation.

Step 6. Have the proposed safety measures reviewed and approved by the NIST Office of Safety, Health, and Environment and the Radiation Safety Division

The acquisition and use of radioactive material at NIST must be approved, in advance, by the NIST Radiation Safety Division (RSD), part of the NIST Office of Safety, Health and Environment, in the context of an Ionizing Radiation Safety Committee (IRSC)-approved Safety Evaluation (SE)/Authorized Use Permit (AUP). For the radioactivity SRM production process, this is done by submitting a Proposed Use Request under AUP-0038: Preparation and Calibration of SRMs, along with a properly signed (by the source custodian, the RG Leader, and the RPD Chief) NIST 364 “Radioactive Material Request,” or NIST 365 “Change to Radioactive Material Authorization,” or equivalent online processes, for approval. Once approved by RSD, the proposed use is assigned an identification number and can be referenced in future production processes. For additional OSHE requirements, the MML Hazard review system was used to evaluate the hazards in the SRM production procedures. Relevant hazard reviews include 682.04.0143, 682.04.0142, and 682.04.0144.

Step 7. Obtain the necessary funding.

This step is normally carried out by the radioactivity SRM production Coordinator, together with the RG leader. Funding of a radioactivity SRM production from the SRM Working Capital Fund requires the approval of the RPD Chief and the Office of Reference Materials

Step 8. Arrange for the use of the necessary facilities, equipment, and personnel

A number of suitable general-purpose radiochemistry laboratories are available in the NIST Radiation Physics Division/Radioactivity Group (RPD/RG) for the preparation of radioactivity SRMs and measurement of samples. The production of the NIST radioactivity SRMs involves a large number of different machines and measuring instruments. It is the intent of the RPD/RG that there are enough units

of each type of equipment available so that no one piece of equipment is essential to the production process of any SRM. For example, the preparation of 50 mg radioactive point sources may require a microbalance with a capacity of >7 g, a readability of <5 µg, and a standard uncertainty of <50 µg (relative to the SI). The RPD/RG currently has at least 6 balances that meet these specifications, all of which are serviced and calibrated once per year using NIST-traceable masses.

This step is normally carried out by, or in cooperation with, the coordinator of radioactivity SRM production and with the concurrence of the RG leader.

Step 9. Acquire suitable materials.

As used here, materials include

a. the radioactive material for the radioactivity SRM,
b. chemical reagents and other consumable materials, and
c. SRM containers, glassware, personal protective equipment (PPE), and other laboratory supplies.

Most radionuclides used to produce radioactivity SRMs are available from commercial suppliers. Radionuclidic purity and carrier concentration vary somewhat, but one can usually purchase suitable radioactive starting material that does not require any additional chemical purification. A few radionuclides that are used for radioactivity SRMs are the parent of a radioactive decay chain, and chemical purification may be necessary to improve the calibration accuracy or because of the way in which the SRM is expected to be used.

Chemical reagents used as solvents and non-radioactive carriers are at least Analytical Grade reagents, and each bottle is provided with a lot analysis. Spectroscopic Grade reagents or Trace Element Grade reagents are preferred.

Borosilicate glass or Teflon containers are always used for solution radioactivity SRMs.

Step 10. Prepare and characterize the materials (as necessary).

The SRM containers, glassware, and other laboratory supplies are prepared, as necessary, using standard analytical laboratory techniques for washing, rinsing, drying, labeling, etc.

For most of the radioactivity SRMs, the radioactive starting material is received as a solution. The material is measured for radiological (and sometimes chemical) impurities. This is typically done using gamma-ray spectrometry. If the radioactive material is a pure alpha-particle emitter or a pure beta-particle emitter, a portion of the solution may also be measured using alpha-particle or beta-particle spectrometry. Depending upon the nature and level of the impurities, additional chemical separation may be required.

Step 11. Prepare the master solution (or mixture) and, if different from the master, the SRM solution (or mixture).

The master solution or mixture is the material that is calibrated, and the measurements on this material are used to determine the certified values; it is always gravimetrically related to the SRM solution or mixture. The massic activity of the master solution is optimized for the calibration measurements.

For solution radioactivity SRMs, the density of the SRM solution is measured because some users are able to dispense solution SRMs volumetrically only using a pipette. In the RPD/RG, only gravimetric measurements are used when dispensing or diluting the master and the SRM solutions.

Step 12. Dispense the SRM solution (or mixture) into the SRM containers.

Solution radioactivity SRMs are prepared using a precision liquid dispenser to dispense the SRM solution. For gamma-ray-emitting solution SRMs, the volume of solution is (5.0 ± 0.1) mL in a NIST standard 5 mL borosilicate-glass ampoule (from a NIST ampoule stock reserved for this purpose), and each ampoule is weighed before and after filling (some gamma-ray-emitting solution SRMs are used for measurements as the unopened ampoule). Since the solution radioactivity SRMs have certified values of activity per unit mass, the total mass of the solution in the ampoule must also be measured and included in the certificate.

For alpha-particle-emitting and beta-particle-emitting radioactivity SRMs, the ampoules are also made of borosilicate glass, but need not be NIST standard 5 mL ampoules. The volume of solution is approximately 5.0 mL, and some of the ampoules (usually >10 %) are weighed before and after filling. The mass of the solution may or may not be included in the certificate as alpha-particle and beta-particle measurements cannot be made on the solution in an unopened ampoule.

For gaseous radioactivity SRMs, the borosilicate-glass gas ampoules are filled to a measured pressure, usually somewhat less than atmospheric pressure, using a vacuum rack and a gas transfer system. No attempt is made to measure the exact volume of a gas ampoule. Gas ampoules are certified in terms of the total activity in each ampoule.

Step 13. Seal and inspect the SRM containers.

Ampoules: All ampoules are flame-sealed. Each ampoule is closely inspected and vacuum tested to ensure that the seals are adequate and without defects. Any ampoule with a defective seal is opened and the solution is gravimetrically transferred to a new ampoule with an aspirating pycnometer. The new ampoule is then sealed. All sealed ampoules must be tested to ensure the integrity of the seal. This is performed by inverting the cooled ampoule several times over a wad of tissue paper and visually examining the tissue for the presence of any liquid. The tissue is also surveyed with a portable instrument for contamination. If the ampoule is to be opened immediately after sealing (e.g., as in performing a dilution), it is not required that the ampoule be smeared and further surveyed. All other sealed ampoules must be smeared for possible contamination. Smears of SRM production ampoules must be measured by RSD.

Step 14. Prepare samples for measurement.

For the gamma-ray-emitting solution radioactivity SRMs, the SRM is the sample for measurement.

For the alpha-particle-emitting and beta-particle-emitting radioactivity SRMs, the master solution is the sample for the calibration measurements. The master solution is gravimetrically dispensed to make point sources and/or liquid scintillation sources for measurement. In addition, some of the SRM ampoules (typically the first, middle, and last ampoules filled) are opened, and similar sources are made to check the gravimetric dilution ratio between the master solution and the SRM solution. In general, the uncertainty associated with the direct measurement of the dilution ratio will be much larger than the uncertainty associated with the gravimetric measurements. The direct measurement serves as a check on any serious error in the gravimetric measurements, in the calculations, or in the thoroughness of mixing the solution.

See Appendix A1 for the method of preparing the measurement samples for each radioactivity SRM.

Step 15. Measure the value of each selected property as obtained directly or indirectly from a "primary reference measurement procedure".

For the gamma-ray-emitting solution radioactivity SRMs, both liquids and gases, each ampoule is

measured in the Pressurized Ionization Chamber "A" (PIC "A") and/or Auto Ionization Chamber (AutoIC) to determine the total activity of the primary radionuclide. Corrections are made for the response due to any other photon-emitting radionuclides present.

See Appendix A1 for the measurement method used for each radioactivity SRM.

Step 16. Confirm each measured value using one or more confirmatory measurement methods.

Where possible, independent confirmatory measurement methods are used to verify the results from the primary measurement method. Comparison with samples from one or more of the previous batches of the same SRM is also used when such samples are available. A confirmatory method is also used to measure one or more of the individual radioactivity SRMs when the SRM solution is not the master solution. This serves as an additional check on the dispensing and/or dilution of the master solution.

See Appendix A1 for the confirmatory measurement method(s) used for each radioactivity SRM.

Step 17. Measure the homogeneity among (and possibly within) SRM units.

The homogeneity among radioactivity SRM units is usually confirmed by making measurements on several units within the same batch.

For gamma-ray-emitting solution radioactivity SRMs, the massic activity of the solution in each ampoule can be calculated from the measured activity and the measured solution mass. The massic activities are checked for deviant values and for correlations (such as with dispensing sequence or mass of solution).

For alpha-particle-emitting and pure beta-particle-emitting solution radioactivity SRMs, several ampoules (typically one of the first, middle, and last of the ampoules filled) are opened and the massic activity of each solution is measured. The massic activities are checked for deviant values and for correlations (such as with dispensing sequence).

See Appendix A1 for the homogeneity test(s) used for each radioactivity SRM.

Step 18. Establish traceability.

For solution radioactivity SRMs, the measurements include:

1. Radionuclide(s),
2. Massic Activity(ies),
3. Expanded Uncertainty(ies),
4. Reference Time,
5. Solution Mass, and
6. Solution Density (uncertified) at a reference temperature (usually 20 °C).

For point sources, the measurements include:

1. Radionuclide(s),
2. Total Activity(ies),
3. Expanded Uncertainty(ies), and
4. Reference Time.

The measurements made as part of the calibration of a radioactivity SRM are traceable to NIST as follows:

1. Time

Measurements of clock time are made using internet transmissions from NIST Boulder. Counting time increments obtained with calibration instruments are measured by counting the number of cycles from temperature compensated crystal oscillators whose frequencies are measured using a frequency meter traceable to NIST. A traceable, calibrated clock or timing system, in this case through the computer clock, is used to precisely measure the time over which the decays are counted. This timing instrumentation is synchronized with the national time standard, establishing an unbroken chain of calibration.

2. Mass
   Balances and scales used to measure the mass of the SRM solution (or solid) are serviced and calibrated at least once per year using masses (weight sets) directly traceable to NIST.
3. Length (Volume)
   Volumetric glassware used to determine the solution density is Class A glassware and is gravimetrically calibrated using distilled water and the well-established relationship between the density of pure water and the temperature.

4. Temperature / Pressure / Relative Humidity
   The manufacturer's stated accuracy for instruments used to measure temperature, pressure and relative humidity is sufficient as these are used to ensure that the environmental conditions at which the balances are used are the optimal to provide more consistent and accurate data

The determination of activity requires that the number of radioactive decays that occur during a finite time interval be counted. The time interval can usually be chosen so as to make its uncertainty negligible. The difficulty lies in determining the efficiency of the detector for the radioactive decays. Every radioactivity detector has some intrinsic inefficiency, has a finite size (and hence boundaries), cannot detect radioactive decays that deposit less than some minimum amount of energy in the detector (threshold), and gives some count rate even in the absence of radioactive decays in the source (background count rate). The efficiency of a single detector (decays detected/total decays) cannot be verified without reference to one or more other detectors.

The efficiency of a detector has to be calculated on the basis of one or more theoretical measurement models, each of which has some inherent uncertainty. For radioactive decay, the theoretical measurement models with the lowest uncertainties are those that use multiple detectors, time correlation measurements, and efficiency extrapolations. (See references [4-6].) These measurement models (and the related measurement methods: coincidence and anticoincidence counting with efficiency-extrapolation techniques) cannot be used with all radionuclides or types of decay. But activity calibrations using these models and techniques have become the cornerstone of the international measurement system for radioactivity. The calibration of virtually all radioactivity measurement instruments is based upon them.

Step 19. Evaluate the uncertainty.

Measurement uncertainty is evaluated in accordance with the *Guide to the Expression of Uncertainty in Measurement* [2] and the *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results* [3].

In general, the uncertainty components associated with the instruments and artifacts used to measure time, mass, length (volume), temperature, pressure, and relative humidity, are small and reasonably well known. For most radioactivity SRMs, the largest component of uncertainty arises from the uncertainty in the detection efficiency for the radioactive decays. The uncertainties associated with the detection efficiency (decays detected/total decays) vary with the type of radioactive decay, with the type of detector, and with the measurement method.

See Appendix A1 for the radionuclide, the decay mode(s), the expanded uncertainty, the measurement

method(s), and other data for each radioactivity SRM.

Step 20. Label, package, and store the SRM containers.

As part of the production process, additional packaging is placed around the container for the radioactivity SRM. This packaging is designed to protect the SRM during handling and long-term storage. The packaged SRMs are stored in Building 245, SRM Storage Room (B049) until shipped to the customer.

The US Department of Transportation (USDOT) and the US Nuclear Regulatory Commission (USNRC) require that personnel who label and package radioactive material for shipping be certified to do so. USDOT RAM certification is available through training by the NIST RSD. Shipping of Radioactive SRMs is covered in Procedure 19.

The Office of Reference Material (ORM) provides support services in the production and delivery of SRMs. These services include label research and design, SDS development for the SRMs, pricing for SRMs, order processing, and documentary support necessary for delivering the SRMs

Step 21. Prepare the SRM Certificate and Conduct Technical Review.

The NIST Certificate for a radioactivity SRM contains information about the composition, the properties, and the proper use of the SRM, and additional required information as stated in NIST-QM-I. For an example of previously issued certificates, see Appendix A2.

The certificate undergoes a final technical review prior to issuance. The review must be approved (and signed) at a minimum by the principal investigator, RG leader, RPD chief, and SRM coordinator.

Step 22. Collect and store the production records.

The radioactivity SRM production plan, detailed descriptions of the certification methods and procedures, methods of validation, measurement uncertainty, and sampling plans are archived together in a three-ring binder. These documents and records are stored in Building 245, C001 (SRM Records Storage Room). The production information is retained for as long as the SRM is available for sale to the public, plus at least an additional 10 years.

A list of the typical contents of the Record File is presented below:

Preparatory

- Justification for SRM production. This is a simple statement as to why the SRM is being produced; e.g., reissue of previous one, new demand for new one and justification, etc. The SRM coordinator can assist in the justification.
- Funding request, statement of work, and approval of funds from the SRM Program Office. This is largely handled by the SRM coordinator.
- Approval for acquisition and use of radioactive materials by RSD (NIST 364) or change to radioactive material authorization (NIST 365) documentation.
- Description of the experimental design/plans (i.e., list, table, diagrams, outline, flowchart, etc.), which may include measurement methods, sequence of steps to be used, facilities, equipment, supplies, personnel, counting source preparation details, etc.
- Hazard reviews and any details relevant to the materials used, which may include SDS and key procedure steps relevant to safety.
- Production approval by SRM coordinator, including number to be produced, activity levels, composition, etc.

- Purchase order for radioactive material (if necessary).
- Acquisition of material explanation (if not purchased).

Production (as applicable)

- Any relevant technical information of the material provided by the manufacturer or from previous production.
- Safety Data Sheet (SDS; if material presents a physical, chemical or biological hazard).
- Preparation of carrier solution data.
- Preparation of master solution or mixture data.
- Dispenser test data (if applicable).
- SRM dispensing data (if applicable).
- Statement of SRM sterilization and independent documentation if available (e.g., radiation sterilization for natural matrix SRM).
- Preparation of counting sources/samples data (if applicable).

Data and Analyses (for standardization)

- Hard copies of all original data, including all original hand-written data sheets and all instrument print-outs.
- Notations of any equipment and instruments settings (as needed).
- Hard copies of all data analysis records (electronic version is acceptable to include, but hard copies are needed), including all analysis software output, all spreadsheets, all summary tables, graphs, etc.
- Any calculations performed, e.g., for corrected masses, solution composition, decay corrections, decay-corrected K values for appropriate RRS (see RPD Procedure 01), LS detection efficiencies, etc.
- Explanation of any calculation assumptions.
- An uncertainty analysis page (including basis, assumptions, and derivations as needed).

Certification and Transfer

- Summary statement(s) – in short paragraph or tabular form-- regarding the basis for the certified values and how they were determined.
- Production/calibration schedule of all principal steps (from the initial design and lab set up through the certification) with a listing of the responsible person(s) and dates. There are two versions of this schedule: one that is updated throughout the SRM process as a living document, and the other as a formal checklist to ensure documentary completeness.
- All the drafts of the certificate and revisions (see NIST-QM-I for everything that the certificate must contain at a minimum).
- Packaging information and a sample of the SRM label.
- All packaging inserts; user notes, SDS, etc.
- Technical review sheet (signed).
- Transfer form(s) to SRM stock or inventory control. This is largely handled by the SRM coordinator.

Step 23. Monitoring Stability of SRMs.

The SRMs produced by RPD have indefinite periods of validity since the stability of the solution was a deciding factor in production (see Step 2) which means that there is no direct stability testing for extending expiration dates. However, the stability of the SRMs is monitored by the use of scientific judgement, random inspection, results from interlaboratory comparisons, communications with customers and by establishing links between new and previous calibrations of the radionuclide.

References

The calibration and/or production processes for some of the radioactivity SRMs have been published in the literature.

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[2] *GUM: Guide to the Expression of Uncertainty in Measurement;* JCGM 100:2008 (GUM 1995 with Minor Corrections); with JCGM 101:2008, JCGM104:2009, JCGM 102:2011 and JCGM 106:2012. Joint Committee for Guides in Metrology: BIPM, Sevres Cedex, France (2008); available at https://www.bipm.org/en/publications/guides/gum.html (accessed Oct 2019)

[3] Taylor, B.N.; Kuyatt, C.E.; *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*; NIST Technical Note 1297, U.S. Government Printing Office: Washington, DC (1994); available at http://www.nist.gov/pml/pubs/index.cfm (accessed Mar 2013).

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[5] International Commission on Radiation Units and Measurements (ICRU) Report 52, *Particle Counting in Radioactivity Measurements*, 1994. Available from ICRU Publications, 7910 Woodmont Avenue, Bethesda, MD 20814 U.S.A.

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Appendix A1: Properties and Preparation of the NIST Radioactivity SRMs, as of July 2026.
Certified values are in bold type. Abbreviations and Notes are provided at the end of Appendix A1.

SRM Number	4222d	4226D	4233f	4239a
Radionuclide	**C-14**	**Ni-63**	**Cs-137**	**Sr-90**
Decay Mode(s) (>1%)	BP	BP	BP,GR	BP
Half Life	5.70 ka	100.1 a	30.05 a	28.80 a
Intended Use	CAL(LSC)	CAL(LSC)	CAL(Ge,NaI)	CAL (LSC)
Physical State	Liquid	Liquid	Liquid	Liquid
Chemical Form	n-Hexadecane	$NiCl_2$	CsCl	$SrCl_2$
Solution/Mixture Composition	n-Hexadecane	1.2 $mol \cdot L^{-1}$ HCl	1 $mol \cdot L^{-1}$ HCl	1.02 $mol \cdot L^{-1}$ HCl
Solution/Mixture Mass (g)	~4	5.09	5.067	5.084
Solution density ($g \cdot mL^{-1}$)	0.771	1.014	1.015	1.018
Containment	5AMP	5AMP	5NIST	5NIST
Non-radioactive Carrier	None	$NiCl_2$	CsCl	$SrCl_2$; YCl_3
Carrier Concentration ($mg \cdot L^{-1}$)	-	105	26	45; 74
Massic Activity ($Bq \cdot g^{-1}$)	**54.01 k**	**85.94 k**	**221.1 k**	**29.492 k**
Reference Time	**10 Sep 2014**	**11 Nov 2009**	**04 Aug 2018**	**25 Dec 2019**
Expanded Uncertainty (k=2) (%)	**0.896**	**0.84**	**0.78**	**0.30**
Source of Starting Material(s)	PUR(COM)	PUR(COM)	PUR(COM)	PUR (COM)
Preparation of Starting Material(s)	None	None	None	None
Impurity Measurement Method	GRS0(Ge),LSC2	GRS0&2(Ge)	GRS0&2(Ge)	GRSI(Ge)
Radionuclidic Impurities Detected	None	None	None	Pu-238 and/or Am-241
Relative Activity of the Impurity	-	-	-	< 4E-3
Preparation of Master Solution	DIL	CAR,DIL	CAR,DIL	DIL (4234A)
Preparation of SRM Solution	= Master	= Master	= Master	CAR, QDIL
Preparation of Measurement Samples	GRV2	GRV2	None	GRV2
Measurement Model Type	LMNL	LMNL	LMNL	LMNL
Measurement Method	LSC2+ET(H-3)	LSC2+ET(H-3), CPR	PIC2(CAC)	LSC 2+ET(H-3)
Confirmatory Method(s)	LSC (TDCR)	None	None	LSC (TDCR)
Homogeneity Test	SEQ	SEQ	ALL	RAN
Other Information	-	-	-	-

Appendix A1: Properties and Preparation of the NIST Radioactivity SRMs, as of July 2026.
Certified values are in bold type. Abbreviations and Notes are provided at the end of Appendix A1.

SRM Number	4251d	4274	4288B	4320b
Radionuclide	**Ba-133**	**Ho-166m**	**Tc-99**	**Cm-244**
Decay Mode(s) (>1%)	EC, GR	BP,GR	BP	AP
Half Life	10.52 a	1.20 ka	211 ka	18.1 a
Intended Use	CAL(Ge,NaI)	CAL(Ge,NaI)	CAL,ENV	CAL,ENV
Physical State	Liquid	Liquid	Liquid	Liquid
Chemical Form	$BaCl_2$	$HoCl_3$	$KTcO_4$	$Cm(NO_3)_3$
Solution/Mixture Composition	1 mol·L^{-1} HCl	1 mol·L^{-1} HCl	0.001 mol·L^{-1} KOH	1 M HNO_3
Solution/Mixture Mass (g)	5.063	5.057	4.994	5.170
Solution density (g·mL^{-1})	1.015	1.016	0.997	1.033
Containment	5NIST	5NIST	5AMP	5AMP
Non-radioactive Carrier	$BaCl_2$	$HoCl_3$	None	None
Carrier Concentration (mg·L^{-1})	133	282	-	-
Massic Activity (Bq·g^{-1})	**382.6 k**	**19.3 k**	**31.55 k**	**35.47**
Reference Time	**13 Jul 2018**	**15 Feb 2006**	**01 May 2008**	**01 Sep 2011**
Expanded Uncertainty (k=2) (%)	**1.2**	**0.81 to 2.4**	**0.66**	**1.4**
Source of Starting Material(s)	PUR (COM)	PUR(USDOE)	PUR(USDOE)	PUR(USDOE)
Preparation of Starting Material(s)	None	None	None	SEP
Impurity Measurement Method	GRS0&2(Ge	GRS0&2(Ge)	GRS0&2(Ge)	GRS0(Ge),APS2
Radionuclidic Impurities Detected	None	Tm-170	None	Pu-240;Cm-243, Cm-245
Relative Activity of the Impurity	-	-	-	1.E-2;3.E-4; 8.E-5
Preparation of Master Solution	DIL	DIL	DIL	DIL
Preparation of SRM Solution	CAR, QDIL	= Master	= Master	= Master
Preparation of Measurement Samples	GRV2, QDIL	None	GRV2	GRV1
Measurement Model Type	LMNL	LMNL	LMNL	LMNL
Measurement Method	LSC(CAC)	GRS(Ge)	LSC 2+ET(H-3)	LSC1
Confirmatory Method(s)	LSC 2+ET(H-3), LSC(TDCR), PIC (CAC)	PIC2(CAC)	CAC+ET(Co-60), LSC(TDCR), CPR	GRS(Ge)
Homogeneity Test	ALL	ALL	SEQ	RAN
Other Information	-	-	-	-

Appendix A1: Properties and Preparation of the NIST Radioactivity SRMs, as of July 2026.
Certified values are in bold type. Abbreviations and Notes are provided at the end of Appendix A1.

SRM Number	4321d	4322d	4323c	4324c
Radionuclide	**U-NAT**	**Am-241**	**Pu-238**	**U-232**
Decay Mode(s) (>1%)	AP	AP,GR	AP	AP
Half Life	4.468 Ga	432.6 a	87.74 a	70.6 a
Intended Use	CAL,ENV	CAL,ENV	CAL,ENV	CAL,ENV
Physical State	Liquid	Liquid	Liquid	Liquid
Chemical Form	$UO_2(NO_3)_2$	$Am(NO_3)_3$	$Pu(NO_3)_6$	$UO_2(NO_3)_2$
Solution/Mixture Composition	1 $mol \cdot L^{-1}$ HNO_3	1 $mol \cdot L^{-1}$ HNO_3	3 $mol \cdot L^{-1}$ HNO_3	2 $mol \cdot L^{-1}$ HNO_3
Solution/Mixture Mass (g)	5.284	5.14	5.511	5.313
Solution density ($g \cdot mL^{-1}$)	1.057	1.032	1.102	1.064
Containment	5AMP	5AMP	5AMP	5NIST
Non-radioactive Carrier	None	None	None	None
Carrier Concentration ($mg \cdot L^{-1}$)	-	-	-	-
Massic Activity ($Bq \cdot g^{-1}$)	**459.63 (Total)**	**133.7**	**22.73**	**26.30**
Reference Time	**15 Mar 2017**	**01 Mar 2019**	**11 Oct 2016**	**31 Oct 2022**
Expanded Uncertainty (k=2) (%)	**1.07**	**0.32**	**0.50**	**0.86**
Source of Starting Material(s)	PUR(USDOE)	PUR(COM)	PUR(USDOE)	PUR(COM)
Preparation of Starting Material(s)	DSS	None	DSS	None
Impurity Measurement Method	GRS1(Ge),APS2	GRS0(Ge)	GRS0(Ge),APS2	GRS0(Ge),
Radionuclidic Impurities Detected	None	None	None	None
Relative Activity of the Impurity	-	-	-	-
Preparation of Master Solution	QDIL	DIL	DIL	None
Preparation of SRM Solution	QDIL	QDIL	QDIL	QDIL
Preparation of Measurement Samples	GRV1	GRV1	GRV1	GRV1
Measurement Model Type	LMNL	LMNL	LMNL	LMNL
Measurement Method	WTR0,MS2	LSC1	LSC1	LSC2+ +ET(H-3)
Confirmatory Method(s)	LSC2, APS	None	APS	LS2
Homogeneity Test	ALL	RAN	SEQ	SEQ
Other Information	-	-	-	-

Appendix A1: Properties and Preparation of the NIST Radioactivity SRMs, as of July 2026
Certified values are in bold type. Abbreviations and Notes are provided at the end of Appendix A1.

SRM Number	4326A	4328d	4329a	4330C
Radionuclide	**Po-209**	**Th-229**	**Cm-243**	**Pu-239**
Decay Mode(s) (>1%)	AP	AP,GR	AP,GR	AP
Half Life	125.2 a	7.889 ka	28.9 a	24.110 ka
Intended Use	CAL,ENV	CAL,ENV	CAL,ENV	CAL,ENV
Physical State	Liquid	Liquid	Liquid	Liquid
Chemical Form	$PoCl_4$	$Th(NO_3)_4$	$Cm(NO_3)_3$	$Pu(NO_3)_6$
Solution/Mixture Composition	2 $mol \cdot L^{-1}$ HCl	1.0 $mol \cdot L^{-1}$ HNO_3	1 $mol \cdot L^{-1}$ HNO_3	3.4 $mol \cdot L^{-1}$ HNO_3
Solution/Mixture Mass (g)	5.169	5.149	5.156	2.7707
Solution density ($g \cdot mL^{-1}$)	1.032	1.032	Not given	1.1082
Containment	5AMP	5NIST	5AMP	5AMP
Non-radioactive Carrier	None	None	None	None
Carrier Concentration ($mg \cdot L^{-1}$)	-	-	-	-
Massic Activity ($Bq \cdot g^{-1}$)	**39.01**	**41.19**	**30.54**	**38.41**
Reference Time	**1 Dec 2013**	**14 July 2022**	**15 May 2019**	**1 May 2009**
Expanded Uncertainty (k=2) (%)	**0.46**	**1.0**	**0.20**	**0.46**
Source of Starting Material(s)	PUR(COM)	PUR(USDOE)	PUR(USDOE)	PUR(USDOE)
Preparation of Starting Material(s)	None	DSS	DSS	DSS
Impurity Measurement Method	GRS0(Ge),APS1	GRS0(Ge)	GRS0(Ge),APS2	GRS0(Ge),APS2
Radionuclidic Impurities Detected	None	Th-228	Am-243; Cm-244	None
Relative Activity of the Impurity	-	2.3E-3	3E-5; 5e-4	-
Preparation of Master Solution	DIL	DIL	DIL	DIL
Preparation of SRM Solution	QDIL	QDIL	= Master	QDIL
Preparation of Measurement Samples	GRV1	GRV1	GRV1	GRV1
Measurement Model Type	LMNL	LMNL	LMNL	LMNL
Measurement Method	LSC1	LSC	LSC	LSC1
Confirmatory Method(s)	GCE1,SB1	LSC2+ET(H-3), LSC(TDCR),SB 2, APS, CPR	None	CPR
Homogeneity Test	SEQ	SEQ	None	RAN
Other Information	-	-	-	-

Appendix A1: Properties and Preparation of the NIST Radioactivity SRMs, as of July 2026.
Certified values are in bold type. Abbreviations and Notes are provided at the end of Appendix A1.

SRM Number	4332f	4334j	4337	4338b
Radionuclide	**Am-243**	**Pu-242**	**Pb-210**	**Pu-240**
Decay Mode(s) (>1%)	AP,GR	AP	BP,GR	AP
Half Life	7.367 ka	373.5 ka	22.2 a	6.561 ka
Intended Use	CAL,ENV	CAL,ENV	CAL,ENV	CAL,ENV
Physical State	Liquid	Liquid	Liquid	Liquid
Chemical Form	$Am(NO_3)_3$	$Pu(NO_3)_6$	$Pb(NO_3)_2$	$Pu(NO_3)_6$
Solution/Mixture Composition	1.03 $mol \cdot L^{-1}$ HNO_3	3.1 $mol \cdot L^{-1}$ HNO_3	1 $mol \cdot L^{-1}$ HNO_3	3.08 $mol \cdot L^{-1}$ HNO_3
Solution/Mixture Mass (g)	5.138	5.499	5.133	5.49
Solution density ($g \cdot mL^{-1}$)	1.032	1.1099	1.028	1.099
Containment	5AMP	5AMP	5NIST	5AMP
Non-radioactive Carrier	None	None	$Pb(NO_3)_2$, $Bi(NO_3)_3$,	None
Carrier Concentration ($mg \cdot L^{-1}$)	-	-	17, 39	-
Massic Activity ($Bq \cdot g^{-1}$)	**48.42**	**26.08**	**9.037 k**	**40.81**
Reference Time	**08 Mar 2024**	**09 Aug 2017**	**15 June 2006**	**27 Aug 2019**
Expanded Uncertainty (k=2) (%)	**0.52**	**0.51**	**2.4**	**1.1**
Source of Starting Material(s)	PUR(COM)	PUR(USDOE)	PUR(COM)	PUR(USDOE)
Preparation of Starting Material(s)	None	DSS	None	DSS
Impurity Measurement Method	GRS0(Ge), MS	GRS1(Ge),APS 2	GRS0&2(Ge)	GRS0(Ge),APS 2
Radionuclidic Impurities Detected	Pu-240; Am-241; Pu-241, Pu-239	Pu-241; Am-241	None	Pu-238; Am-241; Pu-241
Relative Activity of the Impurity	-	1.5E-3;8E-5	-	7.5.E-3;3.7.E-4; 2E-3
Preparation of Master Solution	DIL	DIL	DIL	DIL
Preparation of SRM Solution	QDIL	QDIL	QDIL	QDIL
Preparation of Measurement Samples	GRV1	GRV1	GRV1	GRV1
Measurement Model Type	LMNL	LMNL	LMNL	LMNL
Measurement Method	LSC2+ET(H-3)	LSC1	LSC2+ET(H-3)	DSA1,LSC1
Confirmatory Method(s)	TDCR, LTAC, DES	LSC2	GRS2(Ge)	LSC2
Homogeneity Test	RAN	SEQ	RAN	SEQ
Other Information	-	-	-	-

Appendix A1: Properties and Preparation of the NIST Radioactivity SRMs, as of July 2026.
Certified values are in bold type. Abbreviations and Notes are provided at the end of Appendix A1.

SRM Number	4339B	4340B	4341A	4342A
Radionuclide	**Ra-228**	**Pu-241**	**Np-237**	**Th-230**
Decay Mode(s) (>1%)	BP	BP	AP,GR	AP
Half Life	5.75 a	14.33 a	2.14 Ma	75.38 ka
Intended Use	CAL,ENV	CAL,ENV	CAL,ENV	CAL,ENV
Physical State	Liquid	Liquid	Liquid	Liquid
Chemical Form	$Ra(NO_3)_2$	$Pu(NO_3)_6$	$Np(NO_3)_3$	$Th(NO_3)_4$
Solution/Mixture Composition	1.3 $mol \cdot L^{-1}$ HNO_3	2.8 $mol \cdot L^{-1}$ HNO_3	2 $mol \cdot L^{-1}$ HNO_3	1.0 $mol \cdot L^{-1}$ HNO_3
Solution/Mixture Mass (g)	5.180	5.5050	5.320	5.1626
Solution density ($g \cdot mL^{-1}$)	1.034	1.087	1.067	1.032
Containment	5NIST	5AMP	5AMP	5NIST
Non-radioactive Carrier	$Ba(NO_3)_2$	None	None	None
Carrier Concentration ($mg \cdot L^{-1}$)	19.8	-	-	-
Massic Activity ($Bq \cdot g^{-1}$)	**195**	**258.5**	**152.3**	**40.83**
Reference Time	**7 Oct 2010**	**15 June 2007**	**1 Sep 2012**	**1 Apr 2007**
Expanded Uncertainty (k=2) (%)	**7.2**	**3.8**	**0.94**	**0.38**
Source of Starting Material(s)	DON(NIST)	PUR(COM)	PUR(USDOE)	PUR(USDOE)
Preparation of Starting Material(s)	DSS,SEP	None	DSS	DSS,SEP
Impurity Measurement Method	GRS1(Ge)	GRS1(Ge); APS	GRS0(Ge),APS1	GRS1,MS0
Radionuclidic Impurities Detected	Ra-226; Th-232	Am-241;Pu-239+240; Pu-238, Pu-242	Total Alpha	Th-229;Th-232
Relative Activity of the Impurity	2.6E-3; 4E-4	8.8E-4; 4E-4;1.6E-4;7.7E-6	9.9E-6	4E-4;6E-7
Preparation of Master Solution	DIL	DIL	DIL	DIL
Preparation of SRM Solution	QDIL	QDIL	QDIL	QDIL
Preparation of Measurement Samples	GRV1&2	GRV1	GRV1	GRV1
Measurement Model Type	LMNL	LMNL	LMNL	LMNL
Measurement Method	GRS(Ge)	LSC2+ET(H-3)	LSC	LSC1
Confirmatory Method(s)	APS(	LSC2(TDCR)	CAC & Ge	SB2
Homogeneity Test	RAN	RAN	RAN	RAN
Other Information	-	-	-	-

Appendix A1: Properties and Preparation of the NIST Radioactivity SRMs, as of July 2026.
Certified values are in bold type. Abbreviations and Notes are provided at the end of Appendix A1.

SRM Number	4361C	4370d	4401L #	4404L #
Radionuclide	**H-3**	**Eu-152**	**I-131**	**Tl-201**
Decay Mode(s) (>1%)	BP	BP,EC,GR	BP,GR	EC,GR
Half Life	12.312 a	13.517 a	8.02070 d	72.912 h
Intended Use	HYD	CAL(Ge,NaI)	CAL,NM	CAL,NM
Physical State	Liquid	Liquid	Liquid	Liquid
Chemical Form	H_2O	$EuCl_3$	KI	$TlNO_3$
Solution/Mixture Composition	H_2O	1 mol·L^{-1} HCl	0.007 mol·L^{-1} LiOH+	1.2 mol·L^{-1} HNO_3
Solution/Mixture Mass (g)	~500	5.0338	4.9744*	5.2051*
Solution density (g·Ml^{-1})	0.998	Not given	0.999	1.040
Containment	500GB	5NIST	5NIST	5NIST
Non-radioactive Carrier	None	$EuCl_3$	KI	$TlNO_3$
Carrier Concentration (mg·L^{-1})	-	277	70	100
Massic Activity (Bq·g^{-1})	**2.009**	**18.70 k**	**5.365 M**	**5.858 M**
Reference Time	**03 Sep 1998**	**19 Jul 2018**	**every Jan**	**every Apr**
Expanded Uncertainty (k=2) (%)	**0.76**	**1.2**	**0.70**	**0.80**
Source of Starting Material(s)	PUR(COM)	PUR(USDOE)	PUR(COM)	PUR(COM)
Preparation of Starting Material(s)	None	None	None	None
Impurity Measurement Method	GRS0(Ge),BPS1	GRS1(Ge)	GRS1&2(Ge)	GRS1&2(Ge)
Radionuclidic Impurities Detected	None	Eu-154	None	Tl-200;Tl-202
Relative Activity of the Impurity	-	1.2E-3	-	2.E-3;2.E-3
Preparation of Master Solution	= 4926E	CAR,DIL	= 4401H	= 4404H
Preparation of SRM Solution	QDIL	= Master	CAR,QDIL	CAR,QDIL
Preparation of Measurement Samples	GRV2	None	None	None
Measurement Model Type	LMNL	LMNL	LMNL	LMNL
Measurement Method	GCI	PIC1(CPD)	PIC1&2(CAC)	PIC1&2(CAC)
Confirmatory Method(s)	LSC2	CPD2(Ge)	CDP2(Ge)	CPD2(Ge)
Homogeneity Test	SEQ	ALL	ALL	ALL
Other Information	[d]	-	-	-

Appendix A1: Properties and Preparation of the NIST Radioactivity SRMs, as of July 2026.
Certified values are in bold type. Abbreviations and Notes are provided at the end of Appendix A1.

SRM Number	4406L #	4407L #	4410H #	4412L #
Radionuclide	**P-32**	**I-125**	**Tc-99m**	**Mo-99**
Decay Mode(s) (>1%)	BP	EC,GR	IT,GR	BP,GR
Half Life	12.284 d	59.400 d	6.01 h	65.94 h
Intended Use	CAL,NM	CAL,NM	CAL,NM	CAL,NM
Physical State	Liquid	Liquid	Liquid	Liquid
Chemical Form	H_3PO_4	KI	$NaTcO_4$	Na_2MoO_4
Solution/Mixture Composition	0.06 $mol \cdot L^{-1}$ H_3PO_4	0.01 $mol \cdot L^{-1}$ LiOH	0.16 $mol \cdot L^{-1}$ NaCl	3.1 $mol \cdot L^{-1}$ HNO_3
Solution/Mixture Mass (g)	5.1459*	4.9608*	4.9865*	5.5053*
Solution density ($g \cdot Ml^{-1}$)	1.001	0.999	1.005	1.102
Containment	5NIST	5NIST	5NIST	5NIST
Non-radioactive Carrier	None	KI	None	Na_2MoO_4
Carrier Concentration ($mg \cdot L^{-1}$)	-	60	-	90
Massic Activity ($Bq \cdot g^{-1}$)	**3.6 M**	**1.433 M**	**1.408 G**	**15.22 M**
Reference Time	**every Apr**	**every Nov**	**every Aug**	**every Feb**
Expanded Uncertainty (k=2) (%)	**0.42**	**0.78**	**0.64**	**0.72**
Source of Starting Material(s)	PUR(COM)	PUR(COM)	PUR(COM)	PUR(COM)
Preparation of Starting Material(s)	None	None	None	None
Impurity Measurement Method	GRS2(Ge)	GRS1&2(Ge)	GRS2(Ge)	GRS1&2(Ge)
Radionuclidic Impurities Detected	None	None	Mo-99	None
Relative Activity of the Impurity		-	1.E-6	-
Preparation of Master Solution	DIL	= 4407H	DIL	= 4412H
Preparation of SRM Solution	= Master	CAR,QDIL	= Master	CAR,QDIL
Preparation of Measurement Samples	GRV2	GRV2	None	None
Measurement Model Type	LMNL	LMNL	LMNL	LMNL
Measurement Method	LSC	SPC	PIC1(CAC)	PIC1&2(CAC)
Confirmatory Method(s)	None	CDP2(Ge)	CPD2(Ge)	CDP2(Ge)
Homogeneity Test	RAN	ALL	ALL	ALL
Other Information		-	-	-

Appendix A1: Properties and Preparation of the NIST Radioactivity SRMs, as of July 2026.
Certified values are in bold type. Abbreviations and Notes are provided at the end of Appendix A1.

SRM Number	4415L #	4416L #	4417L #	4427L #
Radionuclide	**Xe-133**	**Ga-67**	**In-111**	**Y-90**
Decay Mode(s) (>1%)	BP,GR	EC,GR	EC,GR	BP
Half Life	5.243 d	3.2612 d	2.8047 d	64.0 h
Intended Use	CAL,NM	CAL,NM	CAL,NM	CAL,NM
Physical State	Gas	Liquid	Liquid	Liquid
Chemical Form	Xe	$GaCl_3$	$InCl_3$	YCl_3
Solution/Mixture Composition	Xe	2 $mol \cdot L^{-1}$ HCl	3.2 $mol \cdot L^{-1}$ HCl	1.1 $mol \cdot L^{-1}$ HCl
Solution/Mixture Mass (g)	~7 mg total	5.1523*	5.265*	5.0844*
Solution density ($g \cdot mL^{-1}$)	~25 Kpa	1.033	1.053	1.017
Containment	5GAS	5NIST	5NIST	5NIST
Non-radioactive Carrier	None	$GaCl_3$	$InCl_3$	YCl_3
Carrier Concentration ($mg \cdot L^{-1}$)		800	60	50
Massic Activity ($Bq \cdot g^{-1}$)	**563.8 M total***	**4.688 M**	**6.224 M**	**5.731 M**
Reference Time	**every Sep**	**every May**	**every Jul**	**every Oct**
Expanded Uncertainty (k=2) (%)	**0.78**	**0.60**	**0.54**	**0.72**
Source of Starting Material(s)	PUR(COM)	PUR(COM)	PUR(COM)	PUR(COM)
Preparation of Starting Material(s)	None	None	None	None
Impurity Measurement Method	GRS1&2(Ge)	GRS1&2(Ge)	GRS1&2(Ge)	GRS1&2(Ge)
Radionuclidic Impurities Detected	Kr-85;Xe-131m	None	In-114m	Sr-90
Relative Activity of the Impurity	5.E-6;1.5E-2	-	3.E-4	7.E-8
Preparation of Master Solution	= 4415H	= 4416H	= 4417H	= 4427H
Preparation of SRM Solution	CAR,QDIL	CAR,QDIL	CAR,QDIL	CAR,QDIL
Preparation of Measurement Samples	None	None	None	GRV2
Measurement Model Type	LMNL	LMNL	LMNL	LMNL
Measurement Method	PIC1&2(GCI)	PIC1&2(CAC)	PIC1&2(CAC)	LSC2
Confirmatory Method(s)	CPD2(Ge)	CDP2(Ge)	CPD2(Ge)	PIC2(LSC)
Homogeneity Test	Not applicable	ALL	ALL	ALL
Other Information	-	-	-	-

Appendix A1: Properties and Preparation of the NIST Radioactivity SRMs, as of July 2026.
Certified values are in bold type. Abbreviations and Notes are provided at the end of Appendix A1.

SRM Number	4915F	4919I	4926E	4927G
Radionuclide	**Co-60**	**Sr-90**	**H-3**	**H-3**
Decay Mode(s) (>1%)	BP,GR	BP	BP	BP
Half Life	1925.28 d	28.80 a	12.312 a	12.32 a
Intended Use	CAL(Ge,NaI)	CAL(LSC)	CAL(LSC),HYD	CAL(LSC)
Physical State	Liquid	Liquid	Liquid	Liquid
Chemical Form	$CoCl_2$	$SrCl_2$	H_2O	H_2O
Solution/Mixture Composition	1.1 $mol \cdot L^{-1}$ HCl	1.0 $mol \cdot L^{-1}$ HCl	H_2O	H_2O
Solution/Mixture Mass (g)	5.0595	5.0790	~20	4.99
Solution density ($g \cdot mL^{-1}$)	1.017	1.017	0.998	0.998
Containment	5NIST	5AMP	20SERUM	5AMP
Non-radioactive Carrier	$CoCl_2$	$SrCl_2$;YCl_3	None	None
Carrier Concentration ($mg \cdot L^{-1}$)	130	36;50	-	-
Massic Activity ($Bq \cdot g^{-1}$)	**58.29 k**	**4.261 k**	**5.038 k**	**544.2 k**
Reference Time	**01 Nov 2005**	**25 Dec 2006**	**03 Sep 1998**	**01 May 2015**
Expanded Uncertainty (k=2) (%)	**0.5**	**0.48**	**0.72**	**0.96**
Source of Starting Material(s)	PUR(COM)	PUR(COM)	PUR(COM)	PUR(COM)
Preparation of Starting Material(s)	None	None	None	None
Impurity Measurement Method	GRS2(Ge)	GRS1(Ge)	GRS0(Ge),BPS0	GRS0(Ge),BPS1
Radionuclidic Impurities Detected	Co-57	None	None	None
Relative Activity of the Impurity	3.8E-5	-	-	-
Preparation of Master Solution	CAR,DIL	DIL(4234A)	=4927F	DIL
Preparation of SRM Solution	= Master	CAR,QDIL	QDIL	=Master
Preparation of Measurement Samples	None	GRV2	GRV2	GRV2
Measurement Model Type	LMNL	LMNL	LMNL	LMNL
Measurement Method	PIC2(CAC)	LSC2+ET(H-3)	GCI1	GCI2
Confirmatory Method(s)	None	LSC(TDCR)	LSC2	LSC2
Homogeneity Test	ALL	RAN	SEQ	SEQ
Other Information	-	-	-	-

Appendix A1: Properties and Preparation of the NIST Radioactivity SRMs, as of July 2026.
Certified values are in bold type. Abbreviations and Notes are provided at the end of Appendix A1.

SRM Number	4929F	4943	4949D	4965A
Radionuclide	**Fe-55**	**Cl-36**	**I-129**	**Ra-226**
Decay Mode(s) (>1%)	EC	BP,EC	BP,GR	AP,GR
Half Life	2.737 a	301 ka	15.7 Ma	1.600 ka
Intended Use	CAL(LSC),ENV	CAL(LSC),ENV	ENV,CAL(LSC)	CAL,ENV
Physical State	Liquid	Liquid	Liquid	Liquid
Chemical Form	$FeCl_3$	NaCl	NaI	$RaCl_2$
Solution/Mixture Composition	1 mol·L^{-1} HCl	H_2O	0.01 mol·L^{-1} NaOH + 0.007 mol·L^{-1} Na_2SO_3	1.0 mol·L^{-1} HCl
Solution/Mixture Mass (g)	5.080	~3	5.005	5.087
Solution density (g·mL^{-1})	1.014	Not given	0.999	1.019
Containment	5AMP	5AMP	5AMP	5NIST
Non-radioactive Carrier	$FeCl_2$	NaCl	None	$BaCl_2$
Carrier Concentration (mg·L^{-1})	56	200	-	65
Massic Activity (Bq·g^{-1})	**58.43 k**	**10.95 k**	**2.747 k**	**30.32**
Reference Time	**30 Nov 2005**	**Dec 1984**	**01 Jan 2014**	**01 Jan 2007**
Expanded Uncertainty (k=2) (%)	**1.7**	**0.82**	**1.08**	**1.3**
Source of Starting Material(s)	PUR(COM)	PUR(COM)	PUR(COM)	PUR(COM)
Preparation of Starting Material(s)	None	None	None	None
Impurity Measurement Method	GRS1&2(Ge)	GRS0(Ge),BPS2	GRS1(Ge),BPS2	GRS0&1(Ge)
Radionuclidic Impurities Detected	None	None	None	None
Relative Activity of the Impurity	-	-	-	-
Preparation of Master Solution	CAR,DIL	DIL	DIL	CAR,QDIL
Preparation of SRM Solution	CAR,QDIL	=Master	CAR,QDIL	CAR,QDIL
Preparation of Measurement Samples	GRV2	GRV2	GRV2	GRV2
Measurement Model Type	LMNL	LMNL	LMNL	LMNL
Measurement Method	MC	GCE1	CAC1	WTR0
Confirmatory Method(s)	LSC2, CPR	LSC2	TDCR, GRS(Ge)	LSC2
Homogeneity Test	RAN	SEQ	RAN	PIC2,CPD2
Other Information	-	-	-	-

Appendix A1: Properties and Preparation of the NIST Radioactivity SRMs, as of July 2026.
Certified values are in bold type. Abbreviations and Notes are provided at the end of Appendix A1.

SRM Number	4966A	4967A	4969	4990C
Radionuclide	**Ra-226**	**Ra-226**	**Ra-226**	**C-14**
Decay Mode(s) (>1%)	AP,GR	AP,GR	AP,GR	BP
Half Life	1.600 ka	1.600 ka	1.600 ka	5.70 ka
Intended Use	CAL,ENV	CAL,ENV	CAL,ENV	C14
Physical State	Liquid	Liquid	Liquid	Solid
Chemical Form	$RaCl_2$	$RaCl_2$	$RaCl_2$	Oxalic Acid
Solution/Mixture Composition	1 $mol \cdot L^{-1}$ HCl	1 $mol \cdot L^{-1}$ HCl	1.5 $mol \cdot L^{-1}$ HCl	Powder
Solution/Mixture Mass (g)	5.085	5.086	5.122	28 x 8
Solution density ($g \cdot mL^{-1}$)	1.017	1.017	1.024	-
Containment	5NIST	5NIST	5NIST	60JAR x 8
Non-radioactive Carrier	$BaCl_2$	$BaCl_2$	$BaCl_2$	None
Carrier Concentration ($mg \cdot L^{-1}$)	6376	80	100	-
Massic Activity ($Bq \cdot g^{-1}$)	**287.6**	**2.482 k**	**3.047**	**0.008**
Reference Time	**0 Jan 2007**	**01 Sep 2003**	**15 Sep 1998**	**1980**
Expanded Uncertainty (k=2) (%)	**1.3**	**1.20**	**1.8**	**1.6**
Source of Starting Material(s)	PUR(COM)	PUR(COM)	PUR(COM)	PUR(COM)
Preparation of Starting Material(s)	None	None	None	None
Impurity Measurement Method	GRS0&1(Ge)	GRS0&1(Ge)	GRS0&1(Ge)	GRS0(Ge)
Radionuclidic Impurities Detected	None	None	None	None
Relative Activity of the Impurity	-	-	-	-
Preparation of Master Solution	CAR,QDIL	CAR,QDIL	CAR,QDIL	OA
Preparation of SRM Solution	CAR,QDIL	CAR,QDIL	CAR,QDIL	OA
Preparation of Measurement Samples	GRV2	GRV2	GRV2	OA
Measurement Model Type	LMNL	LMNL	LMNL	LMNL
Measurement Method	RPIC	WTR0	WTR0	GCI2
Confirmatory Method(s)	GRS1(Ge), GRS1(NaI)	LSC2	LSC2	LSC2
Homogeneity Test	PIC2,CPD2	PIC2,CPD2	PIC2,CPD2	RAN
Other Information	-	-	-	[[a],[b]

ABBREVIATIONS AND ACRONYMS

General
* = Representative value; each unit is individually measured and certified.
+ = Solution also contains other components. See the SRM Certificate for more information.
# = Short-lived SRMs. Production suspended

Decay Modes
AP = Alpha-Particle emission
BP = Beta-Particle emission
EC = Electron Capture
GR = Gamma-Ray emission
IT = Internal Transition

Intended Use
AMS = Accelerator Mass Spectrometry
CAL( ) = Calibration of instruments ( ) and procedures
C14 = Carbon-14 dating measurements
ENV = Environmental measurements
GEO = Geological and geochronological measurements
HYD = Hydrological measurements
NM = Nuclear Medicine

Containment
20SERUM = 20 mL glass serum vial
500GB = 500 mL glass bottle
5AMP = 5 mL borosilicate glass ampoule
5GAS = 5 ml gas ampoule [c]
5NIST = 5 mL NIST glass ampoule
60JAR = 60 mL glass jar

Source of Starting Material
COM = Commercial supplier
DON ( ) = Donated by ( )
IAEA = International Atomic Energy Agency
PUR ( ) = Purchased from ( )
USDOE = United States Department of Energy

Preparation of Starting Material(s)
DSS = Dissolution of solid material(s)
SEP = Radiochemical Separation / Purification

Measurement Methods
0 = Starting material
1 = Material from the Master Solution
2 = Material from the SRM container
AC = Atom Counting
APS = Alpha-particle Spectrometry
BPS = Beta-particle Spectrometry
CAC = Coincidence/Anticoincidence Counting
CPD( ) = Calibrated Photon Detection System (Ge, NaI, etc.)

CPR = Compared with previous RSRM
DSA = Defined Solid Angle Counting
ET( ) = Efficiency Tracing using ( ) as the tracing radionuclide
GCE = Gas Counting (External)
GCI = Gas Counting (Internal)
Ge = Germanium photon detector
GRS( ) = Gamma-ray Spectrometry using ( )
LSC = Liquid Scintillation Counting
LTAC = Live-timed anticoincidence
MC = Microcalorimetry
MS = Mass Spectrometry
NaI = Sodium Iodide photon detector
OA = Other Agency. Distributed but not certified by NIST.
PIC( ) = Ionization Chamber calibrated using ( )
RPIC = Pulse Ionization Chamber for Radon Measurements
SB = Surface Barrier alpha-particle detector
SPC = Sum-Peak Counting
TDCR = Triple-to-Double Coincidence Ratio
THE = Theoretically Computed
WTR = Weight of Radionuclide

Preparation of Solutions/Mixtures
BL = Blending
CAR = Addition of non-radioactive carrier
DIL = Dilution
DIL5 = Dilution to (5.0 ± 0.1) mL in a 5 mL NIST ampoule
QDIL = Quantitative dilution

Preparation of Measurement Samples
0 = Starting material
1 = Material from the Master Solution
2 = Material from the SRM container
DIL5 = Dilution to (5.0 ± 0.1) mL in a 5 mL NIST ampoule
GRV = Dispense by mass
QDIL = Quantitative dilution

Measurement Models
LMNL = Linear, Multiplicative, Normal Distribution, Low Correlation
LMNH = Linear, Multiplicative, Normal Distribution, High Correlation
LMOL = Linear, Multiplicative, Other than Normal Distribution, Low Correlation
NMNL = Non-Linear, Multiplicative, Normal Distribution, Low Correlation

Homogeneity Test
ALL = Measure every SRM dispensed
SEQ = Measure sequential samples of the SRM (typically the first, some of the middle, and the last dispensed)
RAN = Measure SRMs randomly selected out of the total dispensed

Other Information
[letter] = Note
[number] = Reference

NOTES

[a] SRM 4990C replaces SRM 4990, which has been in use in radiocarbon dating laboratories since 1958. The material is part of a 450 kg lot of oxalic acid that was prepared by fermentation of French beet molasses from the 1977 spring, summer, and fall harvests. The ratio of the massic activity of SRM 4990C to that of SRM 4990, and the isotopic ratios of carbon-13 to carbon-12 in each, were measured by eleven international carbon dating laboratories in an intercomparison organized by L.M. Cavallo and W.B. Mann. See Proceedings of the 11th International Radiocarbon Dating Conference, M. Stuiver and R. Kra, Editors, *Radiocarbon* **25**, No. 2 (1983).

[b] This standard is not radioactive material for licensing or shipping purposes.

[c] Flame-sealed borosilicate glass ampoule with an outside diameter of 1.5 cm and a length of 4.5 cm.

AppendixA2.

National Institute of Standards and Technology
U.S. Department of Commerce

Date of Issue:
07 November 2023

Standard Reference Material® 4324c
Uranium-232 Radioactivity Standard
CERTIFICATE

Purpose: The certified value delivered by this Standard Reference Material (SRM) is intended primarily for the calibration of instruments that are used to measure radioactivity and for the monitoring of radiochemical procedures.

Description: A unit of SRM 4324c consists of approximately 5 mL of a solution of a standardized and certified quantity of radioactive uranium-232 (in equilibrium with its progeny) in a suitably stable and homogeneous matrix, contained in a flame-sealed borosilicate-glass ampoule [1].

Certified Values: A NIST certified value, as used within the context of this certificate, is a value for which NIST has the highest confidence in its uncertainty assessment. It is a "measurement result" [2] obtained directly or indirectly from a "primary reference measurement procedure" [2]. Uncertainties for the certified quantities are expanded ($k = 2$). The uncertainties are calculated according to the ISO/JCGM and NIST Guides [3,4]. The certified value is traceable to the derived International System of Units (SI) unit, becquerel (Bq).

Table 1. Certified ^{232}U Massic Activity of SRM 4324c

Radionuclide	**Uranium-232 (in equilibrium with its progeny)**
Reference time	**1200 EST, 31 October 2022**
Massic activity of ^{232}U	**26.30 Bq•g^{-1}**
Relative expanded uncertainty ($k = 2$)[(a)]	**0.86 %**

(a) The uncertainties on certified values are expanded uncertainties, $U = ku_c$. The quantity u_c is the combined standard uncertainty calculated according to the ISO/JCGM and NIST Guides [3,4]. The combined standard uncertainty is multiplied by a coverage factor of $k = 2$ and was chosen to obtain an approximate 95 % level of confidence.

Non-Certified Values: Non-certified values and additional information are provided in Appendix A.

Period of Validity: The certification of **SRM 4324c** is valid indefinitely, within the measurement uncertainty specified, provided that the SRM is handled and stored properly and that no evaporation or change in composition has occurred. The certification is nullified if the SRM is damaged, contaminated, or otherwise modified. Periodic recertification of this SRM is not required.

Maintenance of Certification: NIST will monitor this SRM over the period of its validity. If substantive technical changes occur that affect the certification, NIST will issue an amended certificate through the NIST SRM website (https://www.nist.gov/srm) and notify registered users. SRM users can register online from a link available on the NIST SRM website or fill out the user registration form that is supplied with the SRM at the time of purchase. Before making use of any of the values delivered by this material, users should verify they have the most recent version of this documentation, available free of charge through the NIST SRM website.

Alan K. Thompson, Acting Chief
Radiation Physics Division

Steven J. Choquette, Director
Office of Reference Materials

Table 2. Uncertainty Evaluation for the ^{232}U Massic Activity of SRM 4324c

Uncertainty component		Assessment Type[a]	Relative standard uncertainty contribution on massic activity of ^{232}U (%)
1	Liquid scintillation (LS) measurement precision for the CIEMAT/NIST[b] efficiency tracing (CNET) method measurements; relative standard deviation of the mean for the grand mean of two measurement trials using two different LS counters, considering all within-trial and between-trial components of variance. Each trial was based on five measurements using five sources, quench matched with ^{3}H standards. The typical within-trial relative standard deviation (considering the variations for the between five measurements and the between five sources) for each trial was 0.08 %. The between-source relative standard deviation across the six trials was 0.06 %. The individual values for both data sets fit a normal distribution.	A	0.11
2	Background; LS measurement variability, cocktail mismatch effects and cocktail composition stability; wholly embodied in component 1.	A	--
3	Live time determination for LS counting time intervals (includes uncorrected dead time effects)	B	0.07
4	Uncertainty on massic activity of ^{3}H standard used as efficiency detection monitor	B	0.0094
5	Uncertainty on ^{3}H dilution	B	0.02
6	Uncertainty on gravimetric (mass) measurements for preparation of ^{3}H LS sources	B	0.04
7	Uncertainty on gravimetric (mass) measurements for preparation of ^{232}U LS sources	B	0.003
8	Decay Correction for ^{232}U for half-life uncertainty of 1.56 %	B	0.0086
9	Decay Correction for ^{3}H for half-life uncertainty of 0.20 %	B	0.086
10	Computed β detection efficiencies (Model dependencies and computed Beta spectra)[c]	B	0.40
Relative combined standard uncertainty			**0.43**
Relative expanded uncertainty (k = 2)			**0.86**

[a] Letter A denotes evaluation by statistical methods; Letter B denotes evaluation by other methods.
[b] The acronym CIEMAT/NIST refers to the two laboratories that collaborated in developing the protocol for this LS efficiency tracing methodology, i.e., the Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT) and the National Institute of Standards and Technology (NIST).
[c] For ^{212}Pb, ^{212}Bi, and ^{208}Tl, the beta detection efficiencies were obtained using the MICELLE2 code and the simplified decay scheme from Napoli, et al (2020) [5]. All α emitters in the ^{232}U decay chain were assumed to be detected with 100 % efficiency. The short-lived ^{212}Po ((300 ± 2) x 10^{-9} s) daughter and its ^{212}Bi parent were assumed to be detected with a combined efficiency of 100 %.

Safety: Consult the Safety Data Sheet (SDS) enclosed with the SRM shipment, for radiological and chemical hazard information.

Storage and Handling: SRM 4324c should be stored and used at a temperature between 5 °C and 65 °C. The ampoule (or any subsequent container) should always be clearly marked as containing radioactive material. If the ampoule is transported, it should be packed, marked, labeled, and shipped in accordance with the applicable national, international, and carrier regulations. This is **not** a pre-scored ampoule; **the gold color band is only for identification**. The solution in the ampoule is a dangerous good (hazardous material) because of both the radioactivity and the strong acid. The ampoule should be opened only by persons qualified to handle both radioactive material and alkaline and/or acidic solutions. Appropriate shielding and/or distance should be used to minimize personnel exposure. Refer to the SDS for further information.

REFERENCES

[1] NIST Physical Measurement Laboratory; *Storage and Handling of Radioactive Standard Reference Materials, Ampoule Specifications and Opening Procedure*; available at https://www.nist.gov/pml/radiation-physics/ampoule-specifications-and-opening-procedure (accessed Nov 2023). **Note:** This SRM is contained in a generic borosilicate-glass ampoule (identified as NIST-3) and **not** in the standard NIST ampoule (identified as NIST-1) Refer to R. Collé, Ampoules for Radioactivity Standard Reference Materials, NIST Internal Report 8524 (2019) Available at https://www.nist.gov/publications/ampoules-radioactivity-standard-reference-materials (accessed Nov 2023). **This is not a pre-scored ampoule; the gold color band is only for identification.**

[2] JCGM 200:2012; *International Vocabulary of Metrology - Basic and General Concepts and Associated Terms (VIM)*; (2008 version with Minor Corrections), 3rd edition; Joint Committee for Guides in Metrology (JCGM): BIPM, Sevres Cedex, France; p. 19 (2012); available at https://www.bipm.org/en/committees/jc/jcgm/publications (accessed Nov 2023).

[3] JCGM 100:2008; *Guide to the Expression of Uncertainty in Measurement*; (GUM 1995 with Minor Corrections), JCGM: BIPM, Sevres Cedex, France (2008); available at https://www.bipm.org/en/committees/jc/jcgm/publications (accessed Nov 2023).

[4] Taylor, B.N.; Kuyatt, C.E.; *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*; NIST Technical Note 1297, U.S. Government Printing Office: Washington, DC (1994); available at https://www.nist.gov/pml/nist-technical-note-1297 (accessed Nov 2023).

[5] Napoli, E.; Cessna, J.T; Fitzgerald, R.; Pibida, L.; Collé, R.; Laureano-Pérez, L.; Zimmerman, B.E.; Bergeron, D.E.; *Primary Standardization of ^{224}Ra Activity by Liquid Scintillation Counting*, Appl. Radiat. Isotop., Vol. 155, pp. 108933 (2020).

[6] Pearce, A.; *Table of Radionuclides, Recommended Data*; Laboratoire National Henri Becquerel (2008); available at http://www.lnhb.fr/nuclides/U-232_tables.pdf (accessed Nov 2023).

[7] Nichols, A.L.; *Table of Radionuclides, Recommended Data*; Laboratoire National Henri Becquerel (2013); available at http://www.lnhb.fr/nuclides/Th-228_tables.pdf (accessed Nov 2023).

[8] Nichols, A.L.; *Table of Radionuclides, Recommended Data*; Laboratoire National Henri Becquerel (2011); available at http://www.lnhb.fr/nuclides/Ra-224_tables.pdf (accessed Nov 2023).

[9] Nichols, A.L.; *Table of Radionuclides, Recommended Data*; Laboratoire National Henri Becquerel (2011); available at http://www.lnhb.fr/nuclides/Rn-220_tables.pdf (accessed Nov 2023).

[10] Nichols, A.L.; *Table of Radionuclides, Recommended Data*; Laboratoire National Henri Becquerel (2011); available at http://www.lnhb.fr/nuclides/Po-216_tables.pdf (accessed Nov 2023).

[11] Nichols, A.L.; *Table of Radionuclides, Recommended Data*; Laboratoire National Henri Becquerel (2011); available at http://www.lnhb.fr/nuclides/Pb-212_tables.pdf (accessed Nov 2023).

[12] Nichols, A.L.; *Table of Radionuclides, Recommended Data*; Laboratoire National Henri Becquerel (2011); available at http://www.lnhb.fr/nuclides/Bi-212_tables.pdf (accessed Nov 2023).

[13] Nichols, A.L.; *Table of Radionuclides, Recommended Data*; Laboratoire National Henri Becquerel (2011); available at http://www.lnhb.fr/nuclides/Po-212_tables.pdf (accessed Nov 2023).

[14] Nichols, A.L.; *Table of Radionuclides, Recommended Data*; Laboratoire National Henri Becquerel (2016); available at http://www.lnhb.fr/nuclides/Tl-208_tables.pdf (accessed Nov 2023).

Certain commercial equipment, instruments, or materials may be identified in this Certificate to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

Users of this SRM should ensure that the Certificate in their possession is current. This can be accomplished by contacting the Office of Reference Materials 100 Bureau Drive, Stop 2300, Gaithersburg, MD 20899-2300; telephone (301) 975-2200; e-mail srminfo@nist.gov; or the Internet at https://www.nist.gov/srm.

* * * * * * * End of Certificate * * * * * * *

APPENDIX A

This SRM was prepared by the NIST Physical Measurement Laboratory, Radiation Physics Division, under the direction of B.E. Zimmerman, Group Leader of the Radioactivity Group. Overall technical direction and physical measurement leading to certification were provided by R. Collé, L. Laureano-Pérez and M. DiGiorgio of the NIST Radiation Physics Division, Radioactivity Group. Photon-emitting-impurity analyses were provided by L. Pibida of the NIST Radiation Physics Division, Radioactivity Group. Support aspects involved in the issuance of this SRM were coordinated through the NIST Office of Reference Materials.

Non-Certified Values: Non-certified values are suitable for use in method development, method harmonization, and process control but do not provide metrological traceability to the SI or other higher-order reference system. Non-certified values are provided in Table A1.

Table A1. Non-Certified Values for SRM 4324c[a]

Source description	Liquid in a flame-sealed 5 mL borosilicate-glass ampoule [1]
Solution composition	(2.00 ± 0.03) mol•L^{-1} HNO_3[b]
Solution density	(1.064 ± 0.001) g•mL^{-1} at 23.9 °C[b]
Solution mass	(5.313 ± 0.003) g [b]
Photon-emitting impurities	None detected [c]
Half-lives used [d]	^{232}U: (70.6 ± 1.1) a ^{228}Th: (1.9126 ± 0.0009) a ^{224}Ra: (3.631 ± 0.002) d ^{220}Rn: (55.8 ± 0.3) s ^{216}Po: (0.148 ± 0.004) s ^{212}Pb: (10.64 ± 0.01) h ^{212}Bi: (60.54 ± 0.06) m ^{212}Po: (300 ± 2) x 10^{-9} s ^{208}Tl: (3.058 ± 0.006) m
Calibration methods (and instruments)	The certified massic activity for ^{232}U was obtained by 4παβ LS spectrometry with two commercial LS counters. The beta detection efficiencies for the ^{232}U daughters were calculated using the MICELLE2 code for the CIEMAT/NIST[e] efficiency tracing (CNET) method with composition matched LS cocktails of a ^{3}H standard as the efficiency detection monitor. Confirmatory measurements were performed by LS counting comparative measurements against SRM 4324b[f], using two different LS measurement systems (with varying operating systems) and two different LS cocktail compositions, and by gamma – ray spectrometry [g].

[a] References on page 3.
[b] The stated uncertainty is two times the standard uncertainty [4].
[c] The estimated limits of detection for photon-emitting impurities as of November 2022, expressed as massic photon emission rates (numbers of photons per second per gram), are:
0.12 s^{-1}•g^{-1} for energies between 40 keV and 75 keV,
0.097 s^{-1}•g^{-1} for energies between 80 keV and 1450 keV (skipping over main gamma-ray energies from the ^{232}U decay), and
0.05 s^{-1}•g^{-1} for energies between 1470 keV and 2000 keV,
provided that the photons are separated in energy by 4 keV or more from photons emitted in the decay chain of ^{232}U.
[d] The stated uncertainty is the standard uncertainty. See references 6–14.
[e] The acronym CIEMAT/NIST refers to the two laboratories that collaborated in developing the protocol for this LS efficiency tracing methodology, i.e., the Centro de Invenstigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT) and the National Institute of Standards and Technology (NIST).
[f] SRM 4324b was standardized in 2002 by live-timed anticoincidence counting. A re-standardization of 4324b by CNET as part of this work was in agreement with the decay corrected certified value by 0.66 %.
[g] Confirmatory values by LS comparative measurements and gamma-ray spectrometry were in agreement with the CNET certified value by 0.30 % and 0.84 %, respectively.

Maintenance of Non-Certified Values: NIST will monitor this material to the end of its period of validity. If substantive technical changes occur that affect the non-certified values during this period, NIST will update this Appendix and notify registered users. SRM users can register online from a link available on the NIST SRM website or fill out the user registration form that is supplied with the SRM. Registration will facilitate notification. Before making use of any of the values delivered by this material, users should verify they have the most recent version of this documentation, available through the NIST SRM website (https://www.nist.gov/srm).

* * * * * * * * * * * End of Appendix A * * * * * * * * * * *