IRRADIATION OF PASSIVE DOSIMETERS

Purpose

The purpose of this document is to describe the setup, measurement, and procedures for irradiating passive dosimeters such as Thermo-Luminescent Dosimeters (TLDs) in terms of air kerma using gamma-ray beams from the NIST ^{137}Cs and ^{60}Co sources.

Scope

The measurement service described in this document is listed as NIST service code 46020C. The document starts by describing the physical quantities air kerma and exposure and provides a brief background describing the rationale behind the irradiation process. It later describes the equipment and systems used and the procedures followed in performing the irradiations. Appendix B includes a copy of a sample irradiation certificate.

Definitions and Background

Description of Service

The Dosimetry Group of the NIST Radiation Physics Division receives passive dosimeters for irradiation to specified radiation levels. This service is assigned test number 46020C (for a single setup) and 46021C (for multiple setups). The total exposure or air kerma delivered is provided for each of the passive dosimeters irradiated.

The Quantities Air Kerma and Exposure

The quantity kerma characterizes a beam of photons or neutrons in terms of the energy transferred to any material. For the calibration service described in this document, consideration is limited to photon beams in air. Air kerma is the total energy per unit mass transferred from a photon beam to air. Air kerma, K_{air}, is the quotient of dE_{tr} by dm, where dE_{tr} is the sum of the initial kinetic energies of all electrons liberated by photons in a volume element of air, and dm is the mass of air in that volume element. Then

$$K_{air} = \frac{dE_{tr}}{dm}$$

The SI unit of air kerma is the gray (Gy), which equals one joule per kilogram; the special unit of air kerma is the rad, which equals 0.01 Gy.

The quantity exposure characterizes an x-ray or gamma-ray beam in terms of the electric charge liberated through the ionization of air. Exposure is defined as the total charge per unit mass liberated in air by a photon beam and is represented by the equation:

$$\boldsymbol{X} = \frac{\boldsymbol{dQ}}{\boldsymbol{dm}}$$

where *dQ* is the sum of the electrical charges on all the ions of one sign produced in air when all the electrons liberated by photons in a volume element of air, whose mass is *dm*, are completely stopped in air. The SI unit of exposure is the coulomb per kilogram (C/kg); the special unit of exposure, the roentgen (R), is equal to exactly 2.58×10^{-4} C/kg. The ionization arising from the absorption of bremsstrahlung emitted by the secondary electrons is not included in *dQ*. Except for this small difference, significant only at high energies, the exposure as defined above is the ionization equivalent of air kerma. The relationship between air kerma and exposure can be expressed as a simple equation:

$$\boldsymbol{K} = \boldsymbol{X}\ 2.58 \cdot 10^{-4} \left(\frac{\boldsymbol{W}}{\boldsymbol{e}} \right) \left(\frac{1}{1 - \boldsymbol{g}} \right)$$

where *W/e* is the mean energy per unit charge expended in air by electrons, and *g* is the fraction of the initial kinetic energy of secondary electrons dissipated in air through radiative processes. The value currently accepted by the NIST for *W/e* is 33.97 J/C. The currently accepted *g* values for ^{60}Co and ^{137}Cs beams are 0.32 % and 0.16 %, respectively.

<u>Characterization of the NIST Gamma-Ray Beams in Terms of Air Kerma</u>

There are four NIST gamma-ray irradiator sources that produce the ^{137}Cs and ^{60}Co gamma-ray beams that are typically used for irradiating passive dosimeters in terms of air-kerma and exposure. The air-kerma rates and exposure rates at given distances are very well-known for all of these sources. The values for the air kerma and exposure at these distances are determined by using the primary standard instruments, which are a suite of graphite-wall, air-ionization, Bragg-Gray cavity chambers developed at NIST.

The value of the exposure rate measured with the primary standard instrument is decay corrected to provide the value of the exposure rate (and air-kerma rate) at a given distance from the source for any given date and time of the year.

Generalities of the Irradiation of Passive Dosimeters in Terms of Air Kerma and Exposure

Passive dosimeters sent to the NIST are irradiated in terms of air kerma and exposure. The goal of the irradiation is to deliver a well-known value of exposure or air kerma to the dosimeters sent for irradiation. The value is reported to the customer in an “air kerma dosimeter irradiation certificate,” a copy of which can be found in Appendix B of this report.

Equipment

Gamma-Ray Irradiator Sources

All NIST irradiators generate a collimated beam of gamma rays. The orientation of each of these beams is listed in the table below.

Radionuclide	Nominal Rates as of 2021-01-01 (Gy/s)	Orientation
^{60}Co	4.5×10^{-8}	Horizontal
^{60}Co	5.0×10^{-9}	Horizontal
^{137}Cs	8.2×10^{-6}	Horizontal
^{137}Cs	8.5×10^{-7}	Horizontal

Console

For each of the four irradiators in this facility, there is a console or control unit from which the individual irradiators can be operated. The control unit has an expose button and a return button, which allow opening the source shutter or returning it to its safe position. The console has a timer that can be set to the desired exposure time.

Reference Scale

In each room there is a metallic scale that is used to measure the distance between the source and the detector.

Other Equipment

There is a detector-alignment system consisting of a telescope, movable cart and a stand for positioning detectors at a fixed distance from the source, a laser for positioning the detectors along the beam-centerline, and an acrylic phantom.

Temperature and Pressure probes

The ambient temperature and pressure during the customer's dosimeter irradiations are recorded and later reported in the irradiation certificate. However, neither the temperature nor the pressure is a quantity that influences the air kerma delivered to the dosimeters. A list of all the thermometers and barometers used in the gamma calibration facilities is maintained in an Excel sheet that can be accessed by the facility computer from L:\internal\846.02\Gamma-Chamber-Cal. The Excel sheet includes: the identity of the item (and its software when applicable), the manufacturer's name, the model number, the serial number, and the use location. It also includes the calibration of all thermometers and barometers used in the facilities against the Dosimetry Group reference standard Thermometer and Barometer.

To perform the quality check of the air kerma rate delivered at the irradiation distance where the dosimeters are placed, a NIST reference standard chamber (aka NIST check chamber or NIST QA chamber) is used as discussed in the sections ahead. In brief, the QA procedure consists of comparing the response of one of the NIST check chambers with its historical value. Any change in the reproducibility above 0.5 % to 1 % of a typical chamber response, depending on the chamber type and history, may require an investigation into the support equipment used for the NIST check chamber calibration. If any of the support equipment were found to be out of calibration or damaged, it would be disconnected, and its condition clearly marked on the instrument. A calibrated, identical model replacement instrument would be used for calibrations to continue.

Procedure

Communication with the Customer

Customers can request calibration services in a variety of ways. Typically, a new or first-time customer will establish contact with the Dosimetry Group by telephone and/or e-mail requesting information regarding techniques offered, charges, backlog time, turnaround time, and shipping/mailing information. At this stage, there is generally an opportunity to discuss with the prospective customer appropriate technical and/or logistics aspects of the service. Technical aspects may include discussions on the beam qualities, air kerma rates, conditions under which the instruments are used, etc. Logistics aspects may include discussions about how to submit purchase orders through the NIST storefront, how to ship instruments to NIST, and any accessories that the customer may need to include in the shipment, depending on the type of instrument being calibrated or irradiated. The customer is informed that a purchase order must be received at NIST before an official calibration is performed. The customer is instructed to make use of the NIST storefront, which can be found on https://shop.nist.gov/. Through the storefront, the customer will shop for the desired calibration service and will also be able to upload all necessary documentation, which includes a type of payment, such as a purchase order. The purchase order should include a detailed description of the calibration request, including beam quality codes, instrument model, and serial numbers, and the name and telephone number of a technical contact. If an incomplete purchase order is received, every effort is made to get a detailed description of the service requested.

Initiation of Paperwork and Inspection of Instruments sent to NIST for Calibration

Once an order for a calibration service is placed on the NIST storefront and both a payment confirmation and the instruments have been received at NIST, every effort is made to start the calibration process as soon as possible. This process consists of two stages:

- Handling of the administrative portion of the calibration,
- Handling of the instruments and their calibration/ irradiation.

Regarding the administrative portion of the calibration, after an order is received at NIST through the NIST storefront, a NIST order number consisting of 10 digits is generated with the following format: O-0000000000. The NIST technical contact (person performing the calibration) is then notified by email. The technical contact is able to review the order placed through the NIST calibration e-commerce platform called Salesforce. Information submitted by the customer through Salesforce includes the model and serial number of the instruments to be calibrated, the radiation beam qualities (Cs-137 or Co-60) to which each instrument needs to be calibrated, and the purchase order from the customer. Once this information is reviewed by the technical contact, if any information is missing from the customer, every effort is made to get the information needed by contacting the customer. All documentation associated with the calibration is stored under the NIST order number assigned to the calibration being requested. This includes the summary sheet on Salesforce, a copy of the purchase order submitted by the customer, the shipping document, copies of the calibration reports and all calibration data and corresponding data analysis sheets. A unique identifier named the Dosimetry Group (DG) number is used to identify the services for a given set of dosimeters. This identifier is used by several members of the Dosimetry Group and consists of a 5-digit number followed by the fiscal year as DGN: 00000-00. Both the NIST order number and the DG number are included on the cover of the calibration report.

Regarding the handling of dosimeters, dosimeters arriving for calibration are unpacked and inspected for damage. Shipping damage is reported to the NIST shipping department. When an instrument arrives in a state of disrepair that is obvious by visual inspection, the customer is notified, and a decision is made whether to return the instrument to the customer; if the repair is minor, NIST personnel may perform the repair.

Source Setup for Irradiation Facilities

1. Sign in using the logbook for operating the source. This logbook is located in the control room for operating the sources. Log-in the information requested in the logbook: date, operator name, time, shutter elapsed time, room, use, etc.

2. After filling in the logbook, get the key for unlocking the mechanical safe lock and unlock the source. **ATTENTION**: It is extremely important to unlock the source before operating it. Failure to do so can damage the irradiator unit.

3. Turn on the main power to the console.

4. Enter the room to make sure no people are in it. Exit the room and close the door.

5. A check of the safety-interlock system and other visible indicators must be performed. The interlock system is checked by opening the source shutter and later opening the door to the room containing the irradiator units. The source shutter must close immediately upon opening the door. This is verified only once at the start of the day.

6. The source shutter is opened by pressing the “EXPOSE” button. In the shutter open position, radiation is present in the room. By pressing the “RETURN” button, the source shutter closes, and there is no radiation present in the room.

7. When opening the source for the first time on the day of measurement, also verify that all safety light indicators change color from GREEN to RED when the source is exposed.

8. After all safety checks outlined above have been performed, one can enter the room and set up the dosimeters for irradiation.

Preparation

1. Previous to setting up the dosimeters, they are grouped according to the total exposure they will receive.

2. The dosimeter type, models and serial numbers are written in a worksheet created with Microsoft Excel and saved later in a calibration folder prepared exclusively for filing purposes. The folder is identified with the corresponding DG number.

3. In determining the preset time, the timer offset must be taken into account by subtracting its value from the ideal preset time.

4. The timer offset can be measured by setting the timer for a given time, for example 60.00 seconds. The source shutter is opened and when it closes the actual time is recorded. The timer offset is the difference between the actual time and the preset time. This is typically a fraction of a second for all of the sources.

5. Once the preset times for all the dosimeters are determined and recorded, the dosimeters can be placed on the phantom inside the room after the steps outlined in the section entitled “Source Setup” have been followed.

Setup of Dosimeters

The irradiation of dosimeters using gamma-ray beams are performed by using a previously determined value of the air-kerma rate obtained by decaying the initial value to the date and time of the irradiation.

For all customer irradiations, a NIST reference-class transfer ionization chamber is calibrated in the beam for quality assurance. The NIST chamber should have a previous calibration for the reference radiation qualities selected by the customer.

Irradiations are typically performed at a distance of 300 cm from the source. The setup of dosimeters is described in the steps below:

1. Each gamma-ray facility has a metallic scale that is used to set the source-to-detector distance. The source-to-detector distance is set by sighting the telemicroscope on the appropriate scale distance.

2. An acrylic phantom is placed on top of the table.

3. The height of the phantom is adjusted to the beam center-line using the laser beam associated with each source.

4. A mirror is placed on the rear face of the phantom that allows the laser beam to be reflected onto itself to ensure that the phantom is placed perpendicular to the photon beam.

5. The front face of the phantom is then centered in the telemicroscope-scale reticule.

6. A maximum of six passive dosimeters can be placed on the front face of the phantom using double sided adhesive tape. An effort is made in minimizing the gap between the dosimeter and the front face of the phantom. Ideally the dosimeter should be in direct contact with the phantom.

7. Once the dosimeters are mounted on the phantom, exit the room and close the door. The dosimeters are ready to be exposed.

8. Set the preset time on the touch screen display of the console.

9. Open the source shutter.

10. Record the time the exposure started. The timer should be running at this time. The source shutter will close automatically when it reaches the preset time.

11. Once the timer stops (the source shutter is now closed), record the actual time in the worksheet.

12. The total exposure delivered is calculated in the worksheet by multiplying the actual time by the exposure rate.

13. Enter the room and remove the dosimeters. If there is a new batch of dosimeters, repeat the procedure described above.

14. Shut down the power to the console. Remove the key from the irradiator unit and place it in the drawer in the control room. Sign out in the lab logbook. Turn all lasers off.

Quality Control

An in-house check of the irradiation system is performed by calibrating a NIST chamber at the same source-to-detector distance where the dosimeters were placed. The NIST chamber must have a calibration history in order to be used for this purpose.

For all NIST reference-class chambers, a record is maintained of all calibrations, calibration results, calibration dates, and the previous calibrations are compared with the current calibration to detect any trend or measurement discrepancy. The calibration history and record for all NIST reference chambers can be accessed by the facility computer from L:\internal\846.02\Gamma-Chamber-Cal. Any discrepancy arising with a NIST check chamber greater than 0.5 % gives rise to a thorough investigation of the calibration and irradiation systems previous to exposing the customer dosimeters.

Documentation/Irradiation Certificates/Storage

After the dosimeters have been irradiated, the irradiation certificate is generated. Currently, certificates are generated in Microsoft Word. Templates are available to simplify this procedure and to ensure consistency in the reporting format. A sample certificate is found in Appendix B. *All results reported relate only to the dosimeters, instruments or items tested and/or calibrated for this irradiation. This statement is also included in the irradiation certificate.*

All irradiation certificates are signed by personnel explicitly authorized to do so. The review and signing process can be summarized as follows: the final copy of the irradiation certificate is reviewed and initialed by the preparer. An authorized Dosimetry Group calibration staff member later reviews the report and suggests any modifications that need to be made to the preparer, who needs to address these comments prior to sending it to the Group Leader for further review. After the Group Leader approves and initials the report, it is sent to the Division Chief for approval. Once all reviewers have approved and initialed/signed the report, the report is sent by the technical contact to the customer electronically. If the report is completed prior to the instruments being shipped, a hard copy of the report is also included in the box with the instruments.

After all the requested work is completed, the technical contact informs the accounting office that the calibration work has been completed and that the instruments need to be returned to the customer. The instruments are packed either in the original container or in a more suitable one if necessary. A shipping document is available on Salesforce, which is printed and attached to the box of instruments for shipping. After shipment, all documents associated with the irradiation of dosimeters are kept in the facility computer and are backed up routinely to L:\internal\846.02\Gamma-Chamber-Cal. The calibration is identified by the NIST order number and by the DG number described previously. Calibration records and reports are typically kept for at least 3 years but not more than 7 years.

Assessment of Uncertainties

The assessment of uncertainties of the air kerma delivered to the dosimeters as well as the uncertainty components of other measured quantities relevant to the realization of the air kerma are made by following the guideline for evaluating and expressing uncertainties in measurements outlined in the NIST Technical Note 1297. As stated in the NIST Technical Note 1297: "*the result of a measurement is only an approximation or estimate of the value of the specific quantity subject to measurement, that is, the* ***measurand*** *and thus the result is complete only when accompanied by a quantitative statement of its uncertainty*", thus the importance of evaluating the uncertainties in these measurements.

The convention is to categorize the uncertainties in Type A and Type B according to how the evaluation of these uncertainties is performed. A Type A evaluation of uncertainty is carried out using statistical analysis of a series of observations, for example, by calculating the standard deviation of the mean of a series of observations. A Type B evaluation of uncertainty is carried out using methods other than statistical analysis for a series of observations and it is usually based on scientific judgement using all the relevant information available which for example may include (but not limited to) previous measurement data, manufacturer's specifications, data provided in a calibration certificate, etc. Whether the various uncertainty components that contribute to the uncertainty of the **measurand** (for example, the air kerma) are of Type A or Type B, they will need to be combined in order to give a single value of uncertainty of the measurand. This is known as the *combined standard* uncertainty and is obtained by calculating the quadratic sum of the relative standard uncertainties. Without getting into the details of statistical analysis, it is important to note that despite the fact that Type B uncertainty evaluations are non-statistical, they need to be expressed in the form of a standard deviation so that they can be combined with Type A uncertainty components. So, for example, in the case that a Type B uncertainty component is given by the limits of a range of observations, a rectangular distribution can be used to obtain a standard deviation of the distribution, which will serve as the estimated Type B uncertainty.

An important feature of the combined uncertainty of the measurand (and thus the importance of calculating this) is that it takes the form of a normal distribution, which is expressed in terms of one standard deviation. Because of this property, it is known that there is a 68% confidence that the value of the measurand lies within the stated limits of the combined uncertainty. In practice, though, a higher level of confidence is preferred in most applications, which is why an expanded uncertainty has been defined as the combined uncertainty multiplied by a coverage factor of k=2. The expanded uncertainty is considered to have the approximate significance of a 95 % confidence limit, meaning that there is a 95% confidence that the value of the measurand lies within the stated limits of the expanded uncertainty. The coverage factor of k=2 used to define the expanded uncertainty is derived by assuming that all uncertainty components follow approximately a normal distribution, which is mostly the case for the measurements involved in this calibration service. However, it is important to note that for other applications, where a normal distribution cannot be assumed, a different coverage factor may be needed to obtain a coverage probability of approximately 95%.

Appendix A lists the details of the assessment of uncertainty in the air-kerma rates determined for the different gamma-ray beams. The details of the assessment of uncertainty in the irradiation of passive dosimeters are also listed in Appendix A.

Safety

The main safety consideration is radiation protection. As described below, every effort is made to avoid any possibility of radiation exposure, even though it would be highly unlikely that serious exposures could occur accidentally. All radiation areas in the building are marked with appropriate signage and dosimeters must be worn by all personnel in these areas. Radiation safety training and assessment services are provided by the NIST Radiation Safety Division (RSD).

Radiation Safety

All doors permitting access to the gamma-ray calibration ranges have interlocks, as required by the Nuclear Regulatory Commission. Safety indicator lights are available in each gamma calibration range. At each entrance to a gamma-ray calibration range, there is a light stack that is GREEN when there is no radiation and turns RED if there is radiation in the room.

International Comparisons

International comparisons have been made with other National Metrology Institutes around the world. During these international comparisons, a reference class chamber is calibrated at both facilities, and the values of the calibration coefficients obtained at both institutions are compared. The reference section lists comparisons made in the last few years using the same ^{137}Cs and ^{60}Co gamma-ray beams that are used for the calibration service described in this procedure.

Filing and Retention

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

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Appendix A: Uncertainty Analysis for the NIST Air Kerma Rate for the ^{137}Cs beams (values in %)

	Std 1		Std 10		Std 30		Std 50-1		Std 50-2		Std 50-3	
Physical Constants	Type A	Type B	Type A	Type B	Type A	Type B	Type A	Type B	Type A	Type B	Type A	Type B
Density of dry air at T=0C and P=1atm (kg/m3)		0.02		0.02		0.02		0.02		0.02		0.02
ratio of mean photon energy-absorption coefficients, air/graphite		0.06		0.06		0.06		0.06		0.06		0.06
product of W_{air}/e and ratio of stopping powers, graphite/air		0.11		0.11		0.11		0.11		0.11		0.11
(1-g), radiative loss correction.		0.02		0.02		0.02		0.02		0.02		0.02
Correction Factors												
humidity correction (corrects to dry air)		0.06		0.06		0.06		0.06		0.06		0.06
ksat, loss of ionization due to recombination	0.05	0.10	0.05	0.10	0.05	0.10	0.05	0.10	0.05	0.10	0.05	0.10
stem scatter		0.05		0.05		0.05		0.05		0.05		0.05
kwall, zero wall thickness		0.17		0.17		0.17		0.17		0.17		0.17
axial nonuniformity		0.02		0.05		0.05		0.05		0.05		0.05
radial nonuniformity		0.01		0.01		0.01		0.01		0.01		0.01
air density correction (temperature and pressure)		0.03		0.03		0.03		0.03		0.03		0.03
chamber volume/ cm3	0.10	0.10	0.16	0.10	0.06	0.05	0.06	0.05	0.06	0.05	0.06	0.05
Charge/ C	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
time/ s		0.05		0.05		0.05		0.05		0.05		0.05
distance (axial)/ m		0.02		0.02		0.02		0.02		0.02		0.02
Relative Standard Uncertainty												
quadratic sums	0.15	0.29	0.20	0.30	0.13	0.28	0.13	0.28	0.13	0.28	0.13	0.28
relative combined standard uncertainty of Ki for all 6 probes	0.33		0.35		0.31		0.31		0.31		0.31	
relative combined standard uncertainty of K	**0.29**											
relative expanded uncertainty of K (k=2)	0.59											

Appendix B: Sample irradiation certificate

National Institute of Standards and Technology

Air Kerma Dosimeter Irradiation Certificate

FOR

The Dosimetry Center
100 Dosimetry Road
Gaithersburg, MD 20899

Dosimeter Type: TLD Badge Model DT-1000

Irradiations performed by Ronaldo Minniti

Report reviewed by Ronald Tosh

Report approved by Michael Mitch, Leader
Dosimetry Group

Alan K. Thompson
Chief of the Radiation Physics Division
Physical Measurement Laboratory
For the Director of the National Institute of Standards and Technology

Information on technical aspects of this report may be obtained from Dr. Ronaldo Minniti, National Institute of Standards and Technology, 100 Bureau Drive Stop 8460, Gaithersburg, MD 20899, (301) 975-5586, ronnie.minniti@nist.gov.

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

DG: 00000-00
CALIBRATION SERVICE 46020C/ 46021. ORDER NUMBER: 682.02/O-0000000000
MONTH, DAY, YEAR

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National Institute of Standards and Technology

Air Kerma Dosimeter Irradiation Certificate

FOR

The Dosimetry Center
100 Dosimetry Road
Gaithersburg, MD 20899

Dosimeter Type: TLD Badge Model DT-1000

Badge Orientation: The front face was normal to the incident radiation.
Date of Exposure: Month Day, YYYY
Beam Code: ^{137}Cs
Air Kerma Rate: 0.00 x10^{-00} Gy/s
Beam Radius: 62 cm
Setup Conditions: All thermoluminescent dosimeters (TLDs) were exposed on a 30 cm × 30 cm × 15 cm polymethylmethacrylate (PMMA) slab phantom. The irradiation distance listed in the table below corresponds to the distance between the gamma ray source and the front face of the phantom. The average environmental measured values of temperature and pressure during irradiations were 295.5 K and 99.9 kPa.
Control dosimeter labels: Control 1 to Control 12

TLD Identification		Total Air Kerma Delivered (mGy)	Irradiation Distance (cm)
Model	Number		
DT-702	1-5	4.13	300
DT-702	6-10	4.14	300
DT-702	11-15	4.13	300
DT-702	16-20	4.13	300
DT-702	21-25	4.13	300
DT-702	26-30	4.13	300
DT-702	31-35	4.13	300
DT-702	36-40	4.13	300
DT-702	41-42	4.13	300

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Explanation of Terms

Reference Air Kerma Rate: The air kerma rate at NIST is realized at the calibration position by a free-air ionization chamber for x radiation and by graphite cavity ionization chambers for ^{60}Co and ^{137}Cs gamma radiation, and is expressed in units of grays per second (Gy/s). This realization of the radiation quantity of air kerma establishes the National standard, which can in turn be transferred to other measurement facilities through a suitable measuring instrument, thus enabling traceability to the National standard. The gamma-ray air kerma rates are corrected to the date of calibration (from previously measured values) by decay corrections based on half-lives of 5.27 years for ^{60}Co and 30 years for ^{137}Cs. For a free-air ionization chamber with measuring volume V, the air kerma rate is determined by the relation

$$\dot{K} = \frac{I}{\rho_{\text{air}} V} \frac{W_{\text{air}}}{e} \frac{1}{1 - g_{\text{air}}} \prod_i k_i \ ,$$

where

$I / (\rho_{\text{air}} V)$ is the ionization current, measured by the standard, divided by the mass of air in the measuring volume

W_{air} is the mean energy expended by an electron of charge e to produce an ion pair in dry air, the value used at NIST is W_{air}/e = 33.97 J/C

g_{air} is the fraction of the initial kinetic energy of secondary electrons dissipated in air through radiative processes, the values used at NIST are 0.0032 for ^{60}Co, 0.0016 for ^{137}Cs and 0.0 (negligible) for x rays with energies less than 300 keV, and

$\Pi \ k_i$ is the product of the correction factors to be applied to the standard.

Air kerma in grays (Gy) is related to exposure (X) in roentgens (R) by the equation:

$$K = 2.58E - 04 \ \frac{W_{\text{air}}}{e} \frac{X}{1 - g_{\text{air}}} \ .$$

To obtain exposure in roentgens, divide air kerma in grays by 8.79 x 10^{-3} for ^{60}Co gamma rays, 8.78 x 10^{-3} for ^{137}Cs gamma rays, and 8.76 x 10^{-3} for x rays with energies less than 300 keV.

Irradiation Distance: The irradiation distance is that between the radiation source and front face of the phantom.

Total Air Kerma Delivered: The total air kerma delivered shown in this report corresponds to the total air kerma delivered to the dosimeters provided by the customer which may include thermoluminescent dosimeters (TLDs), optically stimulated luminescence dosimeters (OSLDs) or other dosimeter types. The total air kerma delivered is obtained by irradiating the dosimeters for a preset amount of time to the NIST reference air kerma rate established for the irradiation distance shown in this report. The dosimeters may be irradiated free in air or on a 30 cm × 30 cm × 15 cm polymethylmethacrylate (PMMA) slab phantom.

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Potential use of the irradiated dosimeters by customers may include the calibration of the customer's dosimeter readout units, such as for example a TLD reader and/or OSLD reader. Other uses for the irradiated dosimeters may be to verify or test the capability of a dosimetry system to measure accurately dose values and to ensure traceability of those measurements to the national standard.

Uncertainty: The expanded, combined uncertainty of the irradiation described in this report is 1.0 %. The expanded, combined uncertainty is formed by taking two times the square root of the sum of the squares of the standard deviations of the mean for component uncertainties obtained from replicate determinations, and assumed approximations of standard deviations for all other uncertainty components; it is considered to have the approximate significance of a 95 % confidence limit. Examples of uncertainty analyses are given in the following reference: P. J. Lamperti and M. O'Brien, "Calibration of X-Ray and Gamma-Ray Measuring Instruments," NIST Special Publication 250-58 (2001).

Measurement Results: The results relate only to the instrument calibrated and/or tested in this report.

References

[1] P. J. Lamperti and M. O'Brien, "Calibration of X-Ray and Gamma-Ray Measuring Instruments," NIST Special Publication 250-58 (2001).

[2] R. Minniti and S. Seltzer, "Calibration of a ^{137}Cs Gamma-Ray Beam Irradiator using Large Size Chambers," Applied Radiation Isotopes, 65 (2007) 401-406.

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Changes in NIST Air Kerma Primary Standards for Gamma-Ray Beams

The National Institute of Standards and Technology (NIST) has revised the primary standards for air kerma (and exposure) from ^{137}Cs and ^{60}Co gamma-ray beams. ***The new standards are effective 1 May 2023.*** The change in the air kerma standard is due to the adoption of the recommendations published in the International Commission on Radiation Units and Measurements Report No. 90 *Key data for ionizing-radiation dosimetry: measurement standards and applications* (ICRU 2016). The ICRU makes certain recommendations that, when adopted, may result in changes to the realization of air kerma made by National Metrology Institutes worldwide.

As a result of the ICRU recommendations, the air kerma standard for ^{137}Cs gamma-ray beams has been reduced by 0.60 % while the air kerma standard for ^{60}Co gamma-ray beams was reduced by 0.80 %. Ionization chambers and all types of radiation measurement devices sent to NIST for calibration after ***1 May 2023***, include this change, which will be reflected in the value of the Calibration Coefficient or Calibration Factor reported in all *Reports of Air Kerma Calibration* issued by NIST after this date.

Calibration coefficients and calibration factors that have been reported prior to ***1 May 2023*** for instruments sent to NIST for calibration in gamma-ray beams should be revised to account for the changes as described below.

^{137}Cs Beams: If an instrument was calibrated at NIST prior to 1 May 2023, the calibration coefficient or calibration factor should be multiplied by **0.994** to account for the change in the standard.

^{60}Co Beams: If an instrument was calibrated at NIST prior to 1 May 2023, the calibration coefficient or calibration factor should be multiplied by **0.992** to account for the change in the standard.

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References

[1] ICRU Report No. 90 vol 14 (2016), "Key Data for ionizing-radiation dosimetry: measurement standards and applications"

[2] M. McEwen, D. Burns, M. Darienzo, J. de Pooter, M. Pinto, B. Rapp, "Report presented to the Consultative Committee for Ionizing Radiation (CCRI) Section I of the International Bureau of Weights and Measures (BIPM) on the recommendations of ICRU Report 90". Report CCRI(I)/17-07, BIPM, Sèvres (2017)

[3] C. Kessler, D. Burns and R. Minniti, "Key comparison BIPM.RI(I)-K1 of the air-kerma standards of the NIST, USA, and the BIPM". Metrologia 62 06002 (2025). https://www.bipm.org/documents/d/guest/bipm-ri-i-k1_nist_2023

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