CALIBRATION OF RADIATION DETECTORS IN TERMS OF AIR-KERMA USING GAMMA-RAY BEAMS

Purpose

The purpose of this document is to describe the setup, measurement and procedures for calibration of instruments in terms of air kerma using gamma-ray beams from ^{137}Cs and ^{60}Co irradiator sources.

Scope

The measurement service described in this document is listed as NIST service code 46010C. Appendix C of this document also includes a description of the associated air kerma proficiency test (from gamma-ray beams) listed as NIST service 46050S. The document starts by describing the physical quantities air kerma and exposure and provides a brief background describing the rationale behind the calibration process. It later describes the calibration systems used and the procedures that are typically followed in performing a calibration, analyzing the data, and reporting the results of the calibration. The appendix includes a copy of a sample of the current calibration reports used for the different types of instruments submitted for calibration.

Definitions and Background

Description of Service

The Dosimetry Group of the NIST Radiation Physics Division receives a variety of instruments for calibration in gamma-ray beams. Calibration coefficients or calibration factors are provided for the radiation detectors sent to NIST for calibration. Calibrations are performed in terms of the physical quantities air kerma and exposure.

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 old unit of air kerma, the rad, 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:

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

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:

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

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 current value 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.

Characterization of the NIST Gamma-Ray Beams in Terms of Air Kerma

There are a total of seven gamma-ray sources that produce the ^{137}Cs and ^{60}Co gamma-ray beams that are used for calibrating instruments in terms of air kerma and exposure. The air kerma rates and exposure rates in these facilities are realized by using the NIST primary standard instruments, a suite of six graphite-wall, air ionization, Bragg-Gray cavity chambers developed at NIST.

The reference air kerma rate that is realized with the primary standard instrument is later decay corrected to provide the value of the air kerma rate at a given distance from the source for any given date and time of the year.

The rates are readily available on the console of the data acquisition system used to perform the calibration of instruments.

Generalities of the Calibration of an Instrument in Terms of Air Kerma and Exposure

Instruments that are sent to the NIST are calibrated in terms of air kerma and exposure. The goal of the calibration is to determine either a calibration coefficient or a calibration factor depending on the type of instrument to be calibrated. Determination of these parameters requires the measurement of an ionization current, or the direct measurement of a radiation dose quantity obtained from the display reading of an electrometer. In addition, the temperature and the pressure of the air surrounding the detector must be measured for the case of ionization chambers that are open to the atmosphere.

Calibration Coefficient: The calibration coefficient is defined as the quotient of the air kerma and the charge generated by the radiation in the ionization chamber. This parameter is determined for current type measuring instruments.

Calibration Factor: The calibration factor is defined as a dimensionless ratio of air kerma (or exposure) and the electrometer reading with a given ionization chamber or detector. This parameter is determined for cable-connected-type instruments consisting of an electrometer and probe combination.

Pressure and Temperature Correction: The average charge used to compute the calibration coefficient is based on measurements with the wall of the ionization chamber at the stated polarity and potential. With the assumption that the chamber is open to the atmosphere, the measurements are normalized to a pressure of one standard atmosphere (101.325 kPa) and a temperature of 295.15 K (22 ^{o}C). Use of the chamber at other pressures and temperatures requires normalization of the ion currents to these reference conditions using the normalizing factor F. The normalizing factor F is computed from the following expression:

$$F = (273.15 + T)/(295.15H)$$

where T is the temperature in degrees Celsius, and H is the pressure expressed as a fraction of a standard atmosphere. (1 standard atmosphere = 101.325 kilopascals = 1013.25 millibars = 760 millimeters of mercury).

Equipment

Gamma-Ray Sources

All NIST calibration sources are collimated. The orientation of each of these sources is listed in the table below.

Radionuclide	Nominal Rates as of 2021-01-01 (Gy/s)	Orientation
^{60}Co	1.5×10^{-2}	Vertical
^{60}Co	5.0×10^{-4}	Vertical
^{60}Co	4.5×10^{-8}	Horizontal
^{60}Co	5.0×10^{-9}	Horizontal
^{137}Cs	4.0×10^{-4}	Vertical
^{137}Cs	8.2×10^{-6}	Horizontal
^{137}Cs	8.5×10^{-7}	Horizontal

Console

In each of the radiation facilities there is a separate control unit for each source. The control unit operates the shutter in front of the radioactive source to either expose or shield the radiation source contained in the irradiator unit. These control units are interfaced to a computer containing the data-acquisition software.

Data-Acquisition System

There are two data acquisition systems (DASs) used in these services. One is a mobile measurement console referred to as the portable system. The home location of the portable system is in the horizontal beam range; however, it can be transported to other locations and used in all the gamma-ray facilities to perform calibration of instruments.

The portable system consists of all instrumentation required for measurement and standardization of ionization currents. This data acquisition system is a Visual Basic interfacing system, which can automatically acquire all or some of the calibration data for cable-connected instruments and passive or other types of cable-connected instruments, such as those with their own readout. The mobile console contains a Keithley Model 616 electrometer, a Setra Model 350A digital barometer and a Digitec Model 5810 digital thermometer. Each cable connected instrument has an analog output signal. The feedback elements for the electrometer selector switch in the "Volts" position are capacitors mounted in a capacitor-selector chassis. The equations for computing temperature are dependent on the thermistor used and, for measurements in control room, the signals are taken from YSI readouts mounted in the source-control consoles. The equation used for computing atmospheric pressure from the Setra device, and the data for converting the analog signals from the thermistor probes to air temperatures and from the pressure transducer to atmospheric pressure are stored in the computer program for each calibration range.

A second data-acquisition system, permanently located in the vertical beam facilities, is used to perform calibration of instruments in this facility. This system consists of a computer containing the appropriate boards that interface a Hart Scientific temperature readout, a Setra pressure transducer and two Keithley 617 electrometers used to collect the charge. The software is developed in LabVIEW and is used to perform calibrations of ion chambers in terms of air-kerma rate and absorbed-dose-to-water.

Temperature probes

In each of the calibration facilities, a temperature probe is located near the chamber. All of the temperature probes are interfaced to the DAS computer that records the value of the temperature during the data acquisition.

Pressure Transducer

A pressure transducer, located in the control room at approximately the same height above sea level as the height of the ionization chambers positioned for calibration, is interfaced to the DAS-computer and is used to measure the atmospheric pressure during irradiation time.

The temperature probes, pressure transducers and electrometers are auxiliary equipment used for the calibration service. The temperature probes are calibrated against a reference standard thermometer. The pressure transducers are calibrated against a reference standard barometer. The electrometers are calibrated against reference class air capacitors. The calibrations of the reference standards are provided by the NIST Measurement Services Division. A NIST check chamber is used to decide if the calibration of the equipment used for calibration needs to be checked against reference standards calibrated by the Process Measurements Division. Further discussions on the use of the NIST check chamber are provided in the sections ahead.

Reference Scale

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

Other

Other equipment used during a typical calibration include a telemicroscope, a movable cart and a chamber stand for positioning the chamber at a fixed distance from the source. Also, a laser is used for positioning the detectors along the beam-centerline.

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 calibration. 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, any accessories that the customer may need to include in the shipment depending on the type of instrument being calibrated, etc… 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 the NIST calibration service webpage. 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 purchase order has been submitted 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.

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 numbers 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, a copy 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 instrument received. This identifier is used by several members of the Dosimetry Group and it 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 the instruments, instruments arriving for calibration are unpacked and inspected for damage. Special attention is given to the condition and type of connector. If an adapter is sent with the chamber, this should be noted on the inventory list along with the description of the chamber. 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, or if the repair is minor, have NIST personnel perform the repair.

Only ionization chambers known to be stable and reproducible are accepted for calibration in this program. Institutions submitting ionization chambers for calibration are strongly urged to perform stability checks involving redundant measurements in highly reproducible radiation fields before sending their instruments to NIST, and to repeat those checks after NIST calibration, and again at suitable intervals. Instruments submitted for calibration, and material submitted for irradiation, must be shipped in reusable containers.

Detector Setup and calibration

The instruments to be calibrated using gamma-ray beams are calibrated by using a previously determined value of the air-kerma rate obtained by the decay of the initial value to the date and time of the calibration being made. The value of the air-kerma rate for a given distance from the source at a given date and time is displayed by the data-acquisition program.

For all customer calibrations, a NIST reference-class transfer ionization chamber is calibrated for quality assurance. Generally, the NIST chamber selected is similar in design or collection volume to the customer chamber being calibrated and has a previous calibration history in the reference radiation qualities which were selected by the customer.

The following environmental conditions should exist when performing calibrations. The temperature of the room should be stable during one single measurement, ideally around 22 ºC. If the temperature is not stable during a single measurement, calibrations should be postponed. Also, the temperature should not exceed 25 ºC and should not be lower than 19 ºC. If the temperature falls out of this range, the calibration should be postponed until the temperature is back within the working range. Preferred humidity conditions are between 20 % and 50 %, but calibrations can still be performed if humidity levels fall out of this range. It is preferable to calibrate instruments on days that the pressure is around 101.3 kPa (760 mm Hg), but calibrations can still be performed if the atmospheric pressure deviates from this value. Calibrations should be postponed, however, if the pressure is not stable during a single measurement.

The procedure followed in all the gamma ranges for positioning the ion chambers and detectors is basically the same in all rooms. There are some minor differences regarding the positioning of detectors in the vertical orientation that mainly have to do with the order of the steps followed (steps 1 through 5). The procedure described below assumes a setup being made in any of the four horizontal calibration ranges.

1. Previous to setting up an instrument for calibration, a choice must be made for the appropriate source-to-detector distance taking into account the appropriate exposure rate and beam size for that particular detector. The beam size is compared to the largest dimension of the active volume. The general practice is to use a beam size that is only a few centimeters larger than the active volume size so as to minimize irradiation of inappropriate volumes in the probe stem. The beam size at a given distance from the source is shown by the data acquisition software for any distance from the source.

2. In all the gamma-ray facilities, a metallic scale 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.

3. Set the detector in the holder and connect all cables.

4. The probe to be calibrated is adjusted to the beam center-line using the laser beam associated with each source.

5. The probe is then centered in the telemicroscope scale-reticle. An exception to this technique is when the probe is larger than 10 cm. The technique for set-up then involves measuring the probe in the direction of the beam using metric calipers and determining the radius. The probe is then placed in the beam, aligned as above, and adjusted so that the front or back of it is tangent to the telemicroscope cross hairs.

6. In the case of ionization-type detectors, apply the appropriate collection potential requested by the customer. The collecting voltage is verified at the chamber. This ensures that the voltage connection has been made. It is also important to minimize the exposure of all connections to the radiation beam.

7. The chamber is now ready to be calibrated. Follow the source setup procedure and then exit the room.

<u>Source Setup for horizontal ranges</u>

1. Sign in using the logbook for operating the source. This logbook is located in the control room for operating the relevant 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 source's mechanical safe-lock and unlock the source. **ATTENTION**: It is extremely important to unlock before operating the source. Failure to do so can damage the source.

3. Turn on main power to console.

4. Once the chamber has been aligned for calibration following the procedure described in the subsection entitled "Detector Setup," enter the room to make sure it is vacant of people. 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 and later opening the door to the room containing the sources. The source must close immediately upon opening the door. This is verified only once at the start of the day.

6. The source is opened by first pressing the "Reset" Interlock button, then initializing the timer by pressing the "Initialize" button, and finally pressing the "Open" button. In the open position, radiation is present in the room. By pressing the "Close" button, the source 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 the buzzer sounds, indicating the detection of radiation in the room.

8. After all safety checks outlined above have been performed, close the door to the room once more and reset the interlocks as explained above. At this point it is possible to start performing calibrations.

9. Upon completion of the work, shut down the power to the console. Remove the key from the source and place it in the drawer in the control room.
10. Sign out in the logbook. Turn all lasers off. Turn off all voltages applied to ionization chambers.

<u>Calibration of Instruments/Data Collection</u>

1. Start the data-acquisition program. The name of the program is "Calibrator."

2. On the first page, complete all information regarding the ion chamber to be calibrated. The steps described here apply to both the NIST chamber used for check purposes and to the customer ion chamber and/or radiation detector. Information entered includes items such as: customer name, calibration date, chamber make, model and serial number, voltage applied to chamber, calibration distance, reference used for alignment, number of scans, scan time, etc.

3. Once the information is entered, data collection can start. The system is automated for current-type instruments. Typically, the scan times vary between 1 minute and 2 minutes, depending on the

instrument being calibrated. The number of scans taken once the system has reached a stable regime must be no fewer than 5. Typically, between 5 and 10 scans are taken after a stable regime is reached; detectors typically take anywhere between 30 minutes to 3 hours to stabilize from the time the voltage is applied. Some ion chambers require a period of pre-irradiation (typically between 30 minutes and 60 minutes).

4. Background measurements are taken prior to calibration of the instrument and after irradiation. If the background is a significant fraction of the expected exposure reading, this may be a sign of dirty insulators that, in most cases, can be fixed by cleaning the connector using canned dry gas. Since the gas is cold (due to expansion), some time must be allowed for the chamber to equilibrate with room temperature. If the cleaning procedure is not successful and the calibration system has been verified to be working correctly, then the chamber is not calibrated, and the customer is informed.

5. After data collection, a data sheet with the results is printed out. The data sheet contains the calibration coefficient or calibration factor obtained for that instrument.

6. The current calibration results are compared with previous results to verify the quality of the calibration.

Quality Control

A minimum of 5 total measurements should be made for each calibration point. The standard deviation within these 5 or more measurements is expected to be no greater than 0.1 % to 0.2 % for reference-class chambers. If it is greater, the cause of the value being larger needs to be understood. For example, in some cases this could be caused by the chamber needing more time to equilibrate thermally. In other cases, it could be that an additional pre-irradiation time is required.

Two methods are used to verify a calibration. The first is to calibrate a NIST chamber that has a calibration history and is similar to the customer's chamber described previously. The second check is an examination of previous calibrations of the customer's instrument at the same beam quality. If the discrepancy is significant, greater than 2.0 %, but dependent on the chamber type, an investigation is warranted. When there are several previous calibrations of the customer's instrument at any one beam quality, one can estimate the reproducibility and decide whether the current value is acceptable.

For all NIST reference-class chambers, a record is maintained of all calibrations, and the previous calibrations are compared with the current calibration to detect any trend or measurement discrepancy. The calibration history for many NIST reference chambers is accessible electronically from the computer located in the horizontal beam facility. ***Any discrepancy arising with a NIST check chamber greater than 0.5 % gives rise to a thorough investigation of the calibration procedure***. Alignment, temperature indications, distance, etc., are to be checked again. If the discrepancy cannot be resolved, the complete calibration process is repeated.

Assessment of Uncertainties

The method of uncertainty assessment follows the NIST policy of expressing uncertainty, as outlined in the NIST Technical Note 1297. Conventional statistical estimates are given as standard deviations of the mean, and are designated as “Type A”, which can be considered to be objective estimates. All other uncertainty estimates, which are designated “Type B”, are subjective estimates, based on extensive experience. The “Type B” uncertainties are estimated so as to correspond to approximately one standard deviation. The Type A and Type B estimates are combined according to the usual rule for combining standard deviations, by taking the square root of the sum of the squares (the quadratic sum). The quadratic sum of the two types of uncertainty is then considered to be the combined standard uncertainty, which is in turn multiplied by the coverage factor of two (k=2) to give an expanded uncertainty. The uncertainty is considered to have the approximate significance of a 95 % confidence limit. The appendix lists the details of the assessment of uncertainty in the air-kerma rates determined for the different gamma-ray beams. Also listed in the appendix are the details of the assessment of uncertainty in the calibration of a typical ionization chamber.

Documentation/Calibration Reports/Storage

After the instrument has been calibrated the calibration report is electronically generated. Currently, the reports are generated in the most recent version of Microsoft Word. Templates are available to simplify this procedure and to ensure consistency in the reporting format. A sample report can be found in the Appendix of this report.

The calibration report is reviewed and initialed by the preparer and then sent electronically for review to a Dosimetry Group calibration staff member. This first reviewer may or may not find any issues with the report. In the case any issues are found, they are discussed with the person conducting the calibration to clarify and resolve the issue prior to the reviewer’s approval. Once any potential issues are resolved the reviewer approves the final report and it is sent electronically to the remaining reviewers which are the Group Leader and Division Chief. 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 requested calibration 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 calibration are stored in My Documents folder under a folder called calibrations and can be accessed from the computer in the calibration facility. The calibration is identified by the NIST order number and each instrument sent for calibration is identified by the DG number described previously.

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. Another safety consideration is exposure to high voltage, such as exists on ionization chambers and standard chambers during calibration. All radiation areas in the building are marked with striped tape and dosimeters must be worn by all personnel in these areas. Radiation safety training and assessment services are provided by the NIST Gaithersburg Radiation Safety Division.

Radiation Safety

All doors permitting access to the gamma-ray calibration ranges have interlocks as required by the Nuclear Regulatory Commission. The vertical-beam rooms have a time-delay device inside the room that must be actuated before leaving the radiation area. Automatic shielding doors protect occupants in the control area from the sources. In addition to the above safety features, a radiation detector with indicator lights and an audible signal is in each gamma calibration range. A second radiation detector located in the vertical-beam area, between the shielding door of the vertical beams and the outer door, alarms whenever the interlock is broken during an irradiation. At each entrance to a gamma-ray calibration range, a set of two red lights indicates a "beam on" condition.

High-Voltage Safety

The only danger that exists from high voltage comes from voltage that must be applied to the ionization chambers. To prevent dangerous electric shock, almost all power supplies contain current-limiting resistors in the high-voltage circuit. Common sense is dictated when working around ionization chambers that have exposed high-voltage electrodes. Appropriate warning signs are posted.

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.

References

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5. NIST Technical Note 1297 Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurements.

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Appendices

A. Example Uncertainty Analysis

B. Sample Calibration Reports

C. Proficiency Test: Service 46050S

Appendix A: Example Uncertainty Analysis

Uncertainty analysis for the primary-standard measurement of air kerma rate, $\overline{\dot{K}}$, in the vertical beam facility (^{60}Co beams). $\dot{K}_1$ and $\dot{K}_{10}$ represent the air kerma rate measured with each one of the primary standard chambers with nominal volumes of 1 cm^3 and 10 cm^3, respectively. Values shown are for the relative standard uncertainties in %.

Uncertainty component	$\dot{K}_1$		$\dot{K}_{10}$	
	Type A	Type B	Type A	Type B
charge	0.10	0.10	0.06	0.10
time		0.05		0.05
volume	0.10	0.10	0.16	0.10
air density correction (temperature and pressure)		0.03		0.03
distance (axial)		0.02		0.02
, loss of ionization due to recombination	0.01	0.05	0.05	0.10
stem scatter		0.05		0.05
axial nonuniformity		0.02		0.05
radial nonuniformity		0.01		0.01
density of dry air at T = 0 ºC and P =101.325 kPa		0.02		0.02
humidity correction		0.06		0.06
k_{wall}, wall correction		0.17		0.17
ratio of mean photon mass energy-absorption coefficients, air/graphite		0.04		0.04
product of W_{air}/e and ratio of mean electron mass electronic stopping powers, graphite/air		0.11		0.11
$(1-\overline{g})$, radiative-loss correction		0.03		0.03
quadratic sums	0.14	0.28	0.18	0.29
relative combined standard uncertainties of $\dot{K}_1$ and $\dot{K}_{10}$	0.31		0.34	
relative combined standard uncertainty of $\overline{\dot{K}}$	0.31			
relative expanded ($k=2$) uncertainty of $\overline{\dot{K}}$	0.62			

Uncertainty analysis for the calibration of a reference-class ionization chamber in terms of air kerma. Values are for the relative standard uncertainties in %.

Uncertainty component	Type A	Type B
charge	0.10	0.10
time		0.05
air density correction (temperature and pressure)		0.03
distance		0.02
k'_{sat}, loss of ionization due to recombination	0.01	0.05
probe orientation		0.01
humidity		0.06
^{60}Co decay[1]		0.01
quadratic sum	0.10	0.14
relative combined standard uncertainty of the chamber current I	0.17	
relative combined standard uncertainty of $\overline{\dot{K}}$	0.31	
relative combined standard uncertainty of the calibration coefficient N_K	0.36	
relative expanded ($k = 2$) uncertainty of the calibration coefficient, N_K	0.71 (→ 0.8)	

[1] The air-kerma rate, determined by the primary-standard instruments, of the ^{60}Co source is decay corrected to the time of the calibration measurement. For this correction, NIST uses a half life of 1925.3 days.

Appendix B: Sample Calibration Report

National Institute of Standards and Technology

REPORT OF AIR KERMA CALIBRATION

FOR

Detector Technologies Inc
100 Technology Road
Gaithersburg, MD 20899

Radiation Detection Chamber: Exradin Model A6, SN 1001

Calibrations performed by Ronaldo Minniti

Report reviewed by [name of Fellow Scientist]

Report approved by Michael G. Mitch, Leader
Dosimetry Group

For the Director
National Institute of Standards and Technology
by

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CALIBRATION SERVICE 46010C. ORDER NUMBER: 682.02/O-0000000000
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REPORT OF AIR KERMA CALIBRATION

FOR

Detector Technologies Inc
100 Technology Road
Gaithersburg, MD 20899

Radiation Detection Chamber: Exradin Model A6, SN 1001

Chamber orientation: The cavity was positioned in the center of the beam with the stem of the chamber perpendicular to the beam direction.
Chamber collection potential: A potential difference of 1000 volts was applied to the chamber (negative charge collected).
Chamber rotation: The white mark on the chamber stem faced the source of radiation.
Half Value Layer in millimeters of Copper: 10.8 mm and 14.9 mm for the ^{137}Cs and ^{60}Co beams, respectively.
Environmental conditions: The chamber is assumed to be open to the atmosphere. The measurements are normalized to a pressure of one standard atmosphere (101.325 kPa) and a temperature of 295.15 K (22 °C) as described in the *Explanation of Terms* section of this report. The average measured values of temperature and pressure were 295.6 K and 100.1 kPa for the ^{137}Cs calibration and 297.2 K and 99.9 kPa for the ^{60}Co calibration
Average background current: 0.03 % and 0.09 % of the collector currents for the ^{137}Cs and ^{60}Co beams, respectively.
Beam radius: 56 cm and 32 cm for the ^{137}Cs and ^{60}Co beams, respectively.
Calibration dates: May 1, 2021
Current ratio at full to half collection potential: 1.001 for air kerma rates of 8.82 x 10^{-7} Gy/s. A detailed study of the ion recombination was not performed and no correction was applied to the calibration coefficient(s). If the chamber is used to measure an air kerma rate significantly different from that used for the calibration, it may be necessary to correct for recombination loss.

Beam Code	Build Up Shells (or Cap) Added	Calibration Coefficient (Gy/C) 295.15 K (22 °C) and 101.325 kPa (1 Atm)	Expanded Uncertainty of the Calibration (%)	Air Kerma Rate (Gy/s)	Calibration Distance (cm)
^{137}Cs	YES	3.900 x 10^{4}	0.8	8.82 x 10^{-7}	300
^{60}Co	YES	3.842 x 10^{4}	0.8	1.50 x 10^{-7}	150

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Explanation of Terms Used in the Calibration Procedures and Tables

The Air Kerma Standard: 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

$\prod k_i$ 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:

$$X = \frac{K}{2.58E-4} \frac{1 - g_{\text{air}}}{W_{\text{air}}/e}$$

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.

Selecting a Beam Quality: The beam quality (a.k.a. beam code) identifies important beam parameters and describes the quality of the radiation field. For x-rays, NIST offers four types of reference beam qualities developed at NIST, as well as the ISO reference radiation qualities. NIST x-ray beam qualities are referred to as L, M, H, and S beams, which stand for light, moderate, heavy, and special filtration, respectively. For gamma radiation, the beam quality identifies the radionuclide. The effective energy for gamma radiation is the mean photon energy emitted by the radionuclide. The effective energies for ^{137}Cs and ^{60}Co gamma beams are 662 keV and 1250 keV, respectively. The beam quality selected for calibrating at NIST radiation measurement equipment should be one that has an energy spectrum that closely matches the energy spectrum of the beams with which the customer's instruments will be used.

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Half-Value Layer: The half-value layers (HVL) were calculated for the copper HVLs of ^{60}Co and ^{137}Cs.

Calibration Distance: The calibration distance is that between the radiation source and the detector center or the reference line. For thin-window chambers with no reference line, the window surface is the plane of reference. The beam size at the stated distance is appropriate for the chamber dimensions.

Calibration Coefficient: The calibration coefficients given in this report are quotients of the air kerma and the charge generated by the radiation in the ionization chamber. The average charge used to compute the calibration coefficient is based on measurements with the wall of the ionization chamber at the stated polarity and potential. For chambers that are assumed to be open to the atmosphere, the measurements are normalized to a pressure of one standard atmosphere (101.325 kPa) and a temperature of 295.15 K (22 °C) using the normalizing factor F described in the section below (this does not apply to chambers that are sealed to the atmosphere). The air kerma calibration coefficient provided in this report can be used to determine air kerma rate and air kerma values at the customer's facility by multiplying it with the ionization charge generated in the cavity volume when exposed to radiation.

Normalizing Factor, F: The normalizing factor, F, is computed from the following expression: $F = (273.15 + T)/(295.15H)$, where T is the temperature in degrees Celsius and H is the pressure expressed as a fraction of a standard atmosphere (1 standard atmosphere = 101.325 kilopascals = 1013.25 millibars = 760 millimeters of mercury).

Equilibrium Shell: Material added to the nominal wall thickness of the chamber to ensure electronic equilibrium.

Humidity: No correction is made for the effect of water vapor on the instrument being calibrated. It is assumed that both the calibration and the use of that instrument take place in air with a relative humidity between 10 % and 70 %, where the humidity correction is nearly constant.

Uncertainty: The expanded, combined uncertainty of the air kerma rates for the NIST reference ^{137}Cs and ^{60}Co beams are 0.7 % and 0.6 %, respectively. 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 references below.

[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.

<u>APPENDIX C</u>: Service 46050S, Proficiency Test for air kerma from gamma-ray beams

General

The proficiency test for this measurement service complies with the NIST QMS ISO/IEC 17025:2017 Appendix F for proficiency testing. This sub-level quality document provides the details of the additional requirements of ISO 17043:2010 for this measurement service proficiency test program.

Design of proficiency testing schemes

The protocol for each proficiency test will include the following details, taken from QMI, Appendix F, but repeated here for thoroughness. Each participant will receive a personalized proficiency test protocol. A sample protocol is provided in this procedure with the required elements listed below

a) the name and location of the NIST ***measurement service***;
b) identification of the ***proficiency testing*** program manager and other personnel involved in the design and operation of the ***proficiency testing*** scheme;
c) the activities to be conducted by NIST ***collaborators*** and the names and addresses of NIST ***collaborators*** involved in the operation of the ***proficiency testing*** scheme; collaborations do not exist for this proficiency test.
d) criteria to be met for participation if applicable;
e) the number and type of expected ***participants*** in the ***proficiency testing*** scheme;
f) selection of the measurand(s) or characteristic(s) of interest, including information on what the participants are to identify, measure, or test for in the specific ***proficiency testing round***;
g) a description of the range of values or characteristics, or both, to be expected for the ***proficiency test items***;
h) the potential major sources of errors involved in the area of ***proficiency testing*** offered;
i) requirements for the production, quality control, storage and distribution of ***proficiency test items***;
j) reasonable precautions to prevent collusion between ***participants*** or falsification of results, and procedures to be employed if collusion or falsification of results is suspected;
k) a description of the information which is to be supplied to ***participants*** and the time schedule for the various phases of the ***proficiency testing*** scheme;
l) for continuous ***proficiency testing*** schemes, the frequency or dates upon which proficiency test items are to be distributed to ***participants***, the deadlines for the return of results by ***participants*** and, where appropriate, the dates on which testing or measurement is to be carried out by ***participants***;
m) any information on methods or procedures which ***participants*** need to use to prepare the test material and perform the tests or measurements;
n) procedures for the test or measurement methods to be used for the homogeneity and stability testing of proficiency test items and, where applicable, to determine their biological viability;
o) preparation of any standardized reporting formats to be used by ***participants***;
p) a detailed description of the statistical analysis to be used;
q) the origin, ***metrological traceability*** and ***measurement uncertainty*** of any ***assigned values***;
r) criteria for the evaluation of performance of ***participants***;
s) a description of the data, interim reports or information to be returned to ***participants***;
t) a description of the extent to which ***participant*** results, and the conclusions that will be based on the outcome of the ***proficiency testing*** scheme, are to be made public; and

u) actions to be taken in the case of lost or damaged ***proficiency test items***.

Preparation of proficiency test items

The NIST proficiency test chamber must meet the stated stability specifications of the manufacturer. The NIST reference class transfer ionization chambers have been determined appropriate for use through published comparison studies and history of use. The NIST ***proficiency testing*** program calibrates each using the calibration procedure associated with this service. The NIST ***proficiency testing*** program uses the same acquisition and storage procedures as the calibration service. The chambers procured for the proficiency testing quality assurance are dedicated to that purpose. The NIST ***proficiency testing*** program uses the same type chambers as are used for the calibration service. NIST will ship the chamber in a reusable shipping container which should be used for the return of the chamber to NIST.

Homogeneity and stability

The performance of the NIST testing chamber is evaluated at NIST according to the calibration procedure. The collected charge from the testing chamber is statistically analyzed in the same manner as stated in the calibration procedure. If the chamber completes the procedure at NIST with acceptable stability and is found to become unstable at the participant’s facility, NIST should be notified and the chamber should be excluded from the measurement comparison and a replacement chamber will be provided. NIST calibrates the ionization chamber once it is returned. If the proficiency test involves multiple participants, the testing is a star shaped design which means NIST recalibrates the chamber after it is used at each facility. This allows NIST to monitor the stability of the chamber throughout the comparison.

Statistical design

The same statistical design is used for the proficiency test data as is used for the calibration service. Each chamber is measured at least three times and the average is used. The NIST value will be the average of the results before and after the chamber was sent to the customer. The standard deviation on the charge measurement is used in the uncertainty analysis. The proficiency test is a direct comparison of the measured calibration coefficients determined at NIST and the participating facility. The criteria for the comparison are established by the accreditation program, not by NIST. NIST does not provide the normalized error nor the Z-score.

Assigned values

The calibration coefficient determined through the proficiency test process is clearly explained in the calibration service and the proficiency test report and repeated here for convenience: 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.

Choice of method or procedure

The participant must have a linking traceable measurement of air-kerma in order to participate in a proficiency test. The participant agrees to use the NIST chamber. Using the participant's established measurement methods and procedures, the participant should provide NIST with the calibration coefficient(s) for the chamber found at their facility for each beam in units of Gy/C.

Operation of proficiency testing schemes - Instructions for participants

The proficiency test is requested by the participant or group of participants and the coordination of the test date is established on a mutually agreed upon schedule. The instructions for the test are provided in the test protocol.

Proficiency test items handling and storage

The NIST test chamber is stored in the laboratory where the test is conducted at NIST which is conducive to the manufacturer's recommendations of the conditions for use.

Packaging, labelling and distribution of proficiency test items

The chambers are securely packed with foam in reusable boxes. All chambers have unique serial numbers which are documented in the NIST reports.

Data analysis and evaluation of proficiency testing scheme results

The data analysis and records are handled according to the calibration service. Evaluation of performance is conducted by NIST staff. The evaluation is limited to a direct comparison as a percent difference. Generally, NIST commentary is not provided, since that is left to the accrediting body which would analyze the results applying the established criteria. NIST would include in the proficiency test report, commentary, where applicable, on an educational basis if the participant encounters complications.

Reports

The NIST **proficiency testing** report for each proficiency test will include the following details, taken from QMI, Appendix F, but repeated here for thoroughness. A sample NIST report is provided in this procedure. NIST **proficiency testing** reports include the following, unless it is not applicable or the NIST *proficiency testing* program has valid reasons for not doing so:

a) the name and contact details for the NIST ***proficiency testing*** program;
b) the name and contact details for the coordinator;
c) the name(s), function(s), and signature(s) or equivalent identification of person(s) authorizing the report;
d) an indication of which activities are performed by the ***participant(s)***;
e) the date of issue and status (e.g. preliminary, interim, or final) of the report;
f) page numbers and a clear indication of the end of the report;

g) a statement of the extent to which results are confidential;
h) the report number and clear identification of the proficiency testing scheme;
i) a clear description of the ***proficiency test items*** used, including necessary details of the ***proficiency test item's*** preparation and homogeneity and stability assessment;
j) the ***participants'*** results;
k) statistical data and summaries, including ***assigned values*** and range of acceptable results and graphical displays;
l) procedures used to establish any assigned value;
m) details of the ***metrological traceability*** and ***measurement uncertainty*** of any assigned value;
n) procedures used to establish the standard deviation for proficiency assessment, or other criteria for evaluation;
o) ***assigned values*** and summary statistics for test methods/procedures used by each group of ***participants*** (if different methods are used by different groups of ***participants***);
p) comments on ***participants'*** performance by the NIST ***proficiency testing*** program and technical advisers;
q) information about the design and implementation of the ***proficiency testing scheme***;
r) procedures used to statistically analyze the data;
s) advice on the interpretation of the statistical analysis, only when applicable; and
t) comments or recommendations, based on the outcomes of the ***proficiency testing round,*** only when applicable.

When it is necessary to issue a new or amended report for a ***proficiency testing scheme***, the report includes the following:

a) a unique identification;
b) a reference to the original report that it replaces or amends; and
c) a statement concerning the reason for the amendment or re-issue.

Communication with participants

The NIST calibration ordering system includes the option to request proficiency testing and provides the following details.

a) documented eligibility criteria for participation;
b) confidentiality arrangements; and
c) details of how to apply.

If changes to the ***proficiency test scheme*** design or operation are required, the participant will be notified by email. If the results conclude in a performance that the participant needs to appeal, a retest will be offered at the expense of the participant, after an investigation by NIST and the participant. The participant must communicate the error of the previous test and the reason for the request to retest. If an error was made by NIST, the proficiency test will be repeated at no expense to the participant. If no reason is determined for poor performance, the test can be repeated at the expense of the participant.

Sample Report

See below for a sample proficiency test report

National Institute of Standards and Technology

REPORT OF PROFICIENCY TEST OF AIR KERMA CALIBRATIONS

FOR
Detector Technologies Inc
100 Technology Road
Gaithersburg, MD 20899

Radiation Detection Chamber: Exradin Model A6, SN 2021

Calibrations performed by Ronaldo Minniti

Report reviewed by [name of Fellow Scientist]

Report approved by Michael G. Mitch, Leader
Dosimetry Group

For the Director
National Institute of Standards and Technology
by

James M. Adams, Chief
Radiation Physics Division
Physical Measurement Laboratory

Information on technical aspects of this report may be obtained from 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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REPORT OF PROFICIENCY TEST OF AIR KERMA CALIBRATIONS

FOR

Detector Technologies Inc
100 Technology Road
Gaithersburg, MD 20899

Radiation Detection Chamber: Exradin Model A6, SN 2021

Proficiency test protocol

The protocol for proficiency testing involves the calibration of a NIST reference class, transfer ionization chamber, by the participating facility. After the participating facility calibrates the NIST ionization chamber, using their appropriate NIST equivalent beam quality(s), the chamber is returned to NIST. The participant provides NIST with the calibration coefficient(s), for the NIST chamber, found at their facility in units of Gy/C in terms of the half-value layer of the NIST beam quality(s). The chamber is re-calibrated upon arrival at NIST, to detect damage or any changes which may have occurred while in transit. The participant calibration coefficient is compared to the average of the NIST calibration coefficients. The comparative results are given in the following tables. The results reveal the degree to which the participating calibration facility can demonstrate proficiency in transferring a NIST air kerma calibration under the conditions of the said facility at the time of the proficiency test. It is the responsibility of the participant to inform the accrediting body of the results of this proficiency test.

Stability Assessment

The NIST QA procedure requires stability for the transfer chamber and primary chamber measurements. Any change in the reproducibility of the charge above 0.2 % will be investigated.

Confidentiality of Results

The identification of the test results will remain confidential and secured and with limited access to authorized NIST calibration staff. Summary reports may be published but the identification of the participant will be withheld. It is the decision and the responsibility of the owner of the transfer chamber to provide proficiency test results to the accreditation organization.

Statistical Design

The chamber is measured a minimum of three times for each beam by NIST and the average is used. The standard deviation on the charge measurement is used in the uncertainty analysis as the type A uncertainty component. The proficiency test is a direct comparison of the measured calibration coefficients determined at NIST and the participating facility. The criteria for the comparison are established by the accreditation program, not by NIST. NIST will not provide the normalized error or the Z-score.

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REPORT OF PROFICIENCY TEST OF AIR KERMA CALIBRATIONS

FOR
Detector Technologies Inc
100 Technology Road
Gaithersburg, MD 20899

Radiation Detection Chamber: Exradin Model A6, SN 2021

Conditions for the Chamber in the NIST Facility

Calibration distance: 300 cm
Chamber orientation: The cavity was positioned in the center of the beam with the stem of the chamber perpendicular to the beam direction.
Chamber collection potential: 1000 volts (negative charge was collected).
Chamber rotation: The white mark on the chamber stem faced the source of radiation.
Environmental conditions: The chamber is assumed to be open to the atmosphere. The measurements are normalized to a temperature of 295.15 K (22 °C) and a pressure of one standard atmosphere (101.325 kPa) as described in the *Explanation of Terms* section of this report. The average measured values of temperature and pressure during calibration were 295.5 K and 99.9 kPa.
Buildup cap added: Yes
Beam radius: 56 cm
Average background current: 0.01 % of signal
A detailed study of ionization recombination was not performed, and no correction was applied to the calibration coefficient(s). If the chamber is used to measure an air kerma rate significantly different from that used for the calibration, it may be necessary to correct for recombination loss.

Calibration Results from the NIST Facility

Beam Code	Half Value Layer (mm Cu)	Calibration Coefficient (Gy/C) 295.15 K (22 °C) and 101.325 kPa (1 Atm)	Air Kerma Rate (Gy/s)
^{137}Cs	10.8	4.000×10^{4}	8.82×10^{-7}

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REPORT OF PROFICIENCY TEST OF AIR KERMA CALIBRATIONS

FOR
Detector Technologies Inc
100 Technology Road
Gaithersburg, MD 20899

Radiation Detection Chamber: Exradin Model A6, SN 2021

Participant's Calibration Conditions as reported by Participant

Chamber type: spherical cavity ionization chamber
Atmospheric communication: open
Source chamber distance: 200
Field size: 20 cm x 20 cm at 100 cm source chamber distance
Chamber orientation: white line towards source
Chamber reference point: center of chamber volume
Collecting electrode bias: +1000 V
Charge collected: negative
Leakage: -10 x 10^{-15} A
Calibration uncertainty: 1.6 %
Air kerma rate: 6.38 mGy/s
Ion Collection Efficiency (Aion): 1.000

Comparative Results for the NIST Transfer Standard

NIST Beam Code	NIST Calibration Coefficient (Gy/C) 295.15 K (22 °C) and 101.325 kPa (1 Atm)	Participant Calibration Coefficient (Gy/C) 295.15 K (22 °C) and 101.325 kPa (1 Atm)	Difference in Percent (%)
^{137}Cs	4.000 x 10^4	4.082 x 10^4	2.0

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Explanation of Terms Used in the Calibration Procedures and Tables

<u>The Air Kerma Standard</u>: The air kerma rate at NIST is realized at the calibration position by graphite cavity ionization chambers for ^{60}Co 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 rate is corrected to the date of calibration (from the previously measured value) by a decay correction based on a half-life of 5.27 years for ^{60}Co. For a cavity 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 value used at NIST is 0.0032 for ^{60}Co.

$\Pi\ k_i$ 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:

$$X = \frac{K}{2.58E-4} \frac{1-g_{\text{air}}}{W_{\text{air}}/e}$$

To obtain exposure in roentgens, divide air kerma in grays by 8.79E-3 for ^{60}Co gamma rays.

<u>Air Kerma Calibration Coefficient, N_k</u>: The air kerma calibration coefficients, N_k, given in this report are quotients of the air kerma and the charge generated by the radiation in the ionization chamber. The average charge used to compute the calibration coefficient is based on measurements with the wall of the ionization chamber at the stated polarity and potential. With the assumption that the chamber is open to the atmosphere, the measurements are normalized to a pressure of one standard atmosphere (101.325 kPa) and a temperature of 295.15 K (22 °C). Use of the chamber at other pressures and temperatures requires normalization of the ion currents to these reference conditions using the normalizing factor F (see below). The air kerma calibration coefficient provided in this report can be used to determine air kerma rate and air kerma values at the customer's facility by multiplying it with the ionization charge generated in the cavity volume when exposed to radiation.

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Normalizing Factor F: The normalizing factor F is computed from the following expression: $F = (273.15 + T)/(295.15H)$ where T is the temperature in degrees Celsius, and H is the pressure expressed as a fraction of a standard atmosphere (1 standard atmosphere = 101.325 kilopascals = 1013.25 millibars = 760 millimeters of mercury).

Beam Code: The beam code identifies important beam parameters and describes the quality of the radiation field. For gamma radiation, the beam code identifies the radionuclide.

Calibration Distance: The calibration distance is that between the radiation source and the detector center or the reference line. For thin-window chambers with no reference line, the window surface is the plane of reference. The beam size at the stated distance is appropriate for the chamber dimensions.

Beam Size: The beam size is the perpendicular distance from the centerline of the calibration beam to the fifty-percent intensity line.

Equilibrium Shell: Material added to the nominal wall thickness of the chamber to ensure electronic equilibrium.

Half-Value Layer: The value of the ^{137}Cs and ^{60}Co half-value layers (HVL) are 10.8 mm and 14.9 mm of copper, respectively, which have been determined from calculations.

Humidity: No correction is made for the effect of water vapor on the instrument being calibrated. It is assumed that both the calibration and the use of that instrument take place in air with a relative humidity between 10 % and 70 %, where the humidity correction is nearly constant.

Uncertainty: The expanded, combined uncertainty of the chamber calibration is 0.8 %, of which 0.7 % is assigned to the expanded, combined uncertainty of the NIST reference air kerma rate. 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 references below.

[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.