Calibration Service 46010C

Calibration of radiation detectors in terms of air-kerma using gamma-ray beams

Purpose

The purpose of this procedure 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 sources. The primary standard instrument for determining air-kerma for gamma-ray beams is a suite of graphite-wall, air-ionization, Bragg-Gray cavity chambers developed at NIST.

Scope

This report describes the gamma-ray portion of the calibration service. 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 the current calibration reports used for the different type of instruments submitted for calibration.

Definitions and Background

Description of Service

The NIST, Ionizing Radiation Division, Radiation Interactions and Dosimetry Group receives a variety of instruments for calibration in gamma-ray beams. These services are assigned test numbers 46010C and 46011C. 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 Quantity Air-Kerma and Exposure

The quantity air 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 an 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 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:

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

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 currently accepted value 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>

As of October 2003 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 rate 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 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 form the source for any given date and time of the year.

Charts are listed in each of the control rooms where the sources are located displaying the exposure rates for a given day and time of the year. This information is also displayed by 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 coefficients is defined as the quotients 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 location of each of these sources is listed in the table below along with the nominal activities as of January 1, 1999.

Radionuclide	Activity (Bq)	Location (Room #)	Orientation
^{60}Co	2.7x10^{13}	B034	Vertical
^{60}Co	1.5x10^{14}	B036	Vertical
^{60}Co	1.3x10^{11}	B021B	Horizontal
^{60}Co	9.6x10^{09}	B015B	Horizontal
^{137}Cs	3.1x10^{13}	B036	Vertical
^{137}Cs	5.8x10^{12}	B021A	Horizontal
^{137}Cs	6.3x10^{11}	B015A	Horizontal

Console
In each of the radiation facilities there is a separate control unit for each source. The control unit is an in-house electronic box that allows the operation of the sources. It mainly opens and closes a shutter in the cases of the sources used in rooms B036 and B034. In the other cases it raises and lowers a cylinder containing the source. These control units are interfaced to a computer containing 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 room B019; however it can be transported to other locations and used in all the gamma-ray facilities to perform calibration of instruments. From its location in room B019 the portable system is used to calibrate instruments using the gamma-ray sources located in rooms B021 and B015. Occasionally the portable system is moved to room B035 to calibrate instruments using the ^{137}Cs source located in room B036. However it can also be used to perform calibrations using the ^{60}Co sources located in rooms B034 and B036 as well.

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 as 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 B019, 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 room B035, is used to perform calibration of instruments using the ^{60}Co sources located in rooms B034 and B036. This system consists of a computer containing the appropriate boards that interface alternatively a Hart Scientific or a Keithley temperature readout, a Setra pressure transducer and two Keithley 617 electrometers used to collect the charge. The software is developed in Lab View and is used to perform calibration of ion chambers in terms of air-kerma rate and absorbed- dose-to-water using the ^{60}Co sources.

Temperature probes

In each of the calibration facilities, a temperature probe is located near the location of 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 used constitute essential equipment used for the calibration service. The temperature probes are calibrated against a reference standard Taylor liquid-in-glass thermometer. The pressure transducers are calibrated against a reference standard W&T barometer. The electrometers are calibrated against reference class air capacitors. The calibration of the reference standards are provided by the NIST process measurements division. A NIST check chamber is used to decide when the calibration of the equipment used for calibration needs to be checked against reference standards calibrated by the process and measurements division. Further discussions the use of the NIST check chamber are provided in the sections ahead.

Reference Scale: In each room there 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 telescope, a movable cart and a chamber stand for positioning chamber at a fixed distance from the source. Also a laser is used for positioning the detectors along the beam-center-line.

Procedure

Communication with the Customer.

The recommended procedure for requesting a NIST calibration service is outlined in NIST Calibration Services Users Guide. In practice, however, customers request calibration service in a variety of ways. Typically a new, or first-time customer will establish contact with the Radiation Interactions and Dosimetry Group by telephone, letter, e-mail or fax 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 qualities of radiation for the type of service being requested and methods of shipment to reduce the risk of damage. The customer is informed that a purchase order must be received at NIST before an official calibration is performed. The purchase order can be sent with the instrument to be calibrated or can be sent separately by fax, mail or e-mail. In addition to an authorization for payment, the purchase order should include a detailed description of the calibration request, including beam quality codes, instrument model and serial numbers, 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

If the purchase order and the instruments are sent to NIST on the date agreed between the customer and the NIST contact, every effort is made to start the calibration process as soon as possible. This process consists of two stages: One involves the handling of the paperwork and the other the handling of the instruments and their calibration.

Regarding the paperwork, after a purchase order is received, a customer test folder is generated. A copy of the purchase order, the final copy of the calibration report, the calibration raw data and summary sheets and any documents of correspondence between the customer or the Office of Measurement Services (O.S.), Calibration Program Office are maintained in the customer's calibration report folder filed by the unique dosimetry group (DG) number. After copying the purchase order for the customer folder, the original purchase order, along with a request for a test folder, is sent to the O.S.. A test folder will be sent by O.S. and will contain the original purchase order and appropriate forms. The test folder's unique number is used as one of the identifiers on 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

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 be followed when performing calibrations: The temperature of the room should be stable within one single measurement and ideally around 22 C. If the temperature is not stable during a single measurement calibrations should be postponed. Also the temperature shouldn't exceed 25 C and shouldn't be lower than 19 C. 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 still can be performed if humidity levels fall out of this range. It's preferred to calibrate instruments on days that the pressure is around 760 Torr 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 rooms B036 and B034 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 calibration ranges located in rooms B021 and B015.

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 give 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 insures 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 rooms B021 and B015</u>

1. Sign in the logbook for operating the source. This logbook is located in room B019 for operating the sources located in rooms B021 and B015. Login the information requested in the logbook: date, operator name, time, shutter elapsed time, room, use, etc…

2. After signing 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 the first time also verify that the buzzer sounds indicating the detection of radiation in the room.

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

9. Upon completion of the work, shutdown the power to the console. Remove the key from the source and place it in the drawer in room B019. Also 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 or 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 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 less than 5. Typically a number between 5 and 10 scans is taken after a stable regime is reached. Typically detectors 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. Basically, the data sheet contains the calibration coefficient or calibration factor obtained for that particular instrument.

6. The final data is recorded on index card forms that have been maintained for many years for all previously calibrated chambers. 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 should not be greater than 0.10% for reference-class chambers. If it is greater, additional time or pre-irradiation may be required to help the chamber settle.

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 1.0% 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 maintained in binders located in room B017. ***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.

Documentation/Calibration Reports/Storage

After the instrument has been calibrated the calibration report is generated. Currently the reports are generated in 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 final copy of the calibration report is reviewed and initialed by the preparer and an additional reviewer and then given to the Group Leader for review. After the Group Leader approves and initials the report, it is sent to the Division Office for signature. Upon return, two copies are made. The original is mailed to the customer, one copy is filed in *the customer DG folder*, and one copy is added to the *test folder*.

After all requested calibration work is completed, the fees are computed and NIST form 64 is generated using the ISSC database. Copies are filed in the *test folder* and the *customer DG folder,* and the original is sent to the Administrative Officer for the Radiation Interactions and Dosimetry Group. The *test folder* is then signed and returned to the calibration program. The *customer DG folder* is filed in room B033.

Index cards are also filed in room B033. The index cards contain a summary of the results contained in the calibration report and any relevant information that could be useful for future calibrations of the same instrument (such as e.g., the voltage applied to the probe, the diameter, volume, etc., of a given ionization chamber). The index card provides a quick way of finding out if the instrument under test has been calibrated at NIST. In addition, it facilitates retrieving information quickly for comparison purposes without having to pull out from the storage area the files containing the complete set of past data and past calibration reports.

Shipping request forms are prepared after the Division Chief signs off on a calibration report and returns it to the Group office. The instrument is packed either in its original container or in a more suitable one if necessary.

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 approximately to 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 uncertainty, which is in turn multiplied by the coverage factor of two 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.

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

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 of room B035 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.

References

1. Seltzer S. M. , Bergstrom P., “Changes in the US Primary Standards for the Air-Kerma from Gamma-Ray Beams”, in press.

2. Lamperti P.J., O’Brien M, “Calibration of X-ray and Gamma-ray Measuring Instruments”, NIST Special Publication 250-58, (2001).

3. Lamperti P. J., Loftus T. P., Loevinger R., “Calibration of X-ray and Gamma-ray Measuring Instruments”, NBS Special Publication 250-16 (1988)

4. Loftus, T. P. and Weaver, J. T., Standardization of 60Co and 137Cs gamma-ray beams in terms of exposure, J. Res. Nat. Bur. Stand. (U.S.), 78A, 465-476 (1974).

5. NIST Calibration Services Users Guide 1998.

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

Appendices

A. Uncertainty Analysis

B. Calibration Reports

Appendix A: Uncertainty Analysis

Air-Kerma Rate Uncertainty Analysis for Gamma-Rays Shown in %		
	Type A	Type B
Uncertainty components specific to a chamber		
Charge	0.03	0.1
Timing	0.04	0.1
Volume	0.06	0.05
ksat, loss of ionization due to recombination	0.01	0.05
axial nonuniformity		0.07
radial nonuniformity		0.01
stem scatter		0.05
Uncertainty components common to all chambers		
Temperature		0.03
Pressure		0.01
distance (axial)		0.02
air density		0.02
calculated humidity correction		0.06
kwall, zero wall thickness		0.17
energy-absorption coefficient ratio		0.06
stopping-power ratio		0.57
W/e, ion pair energy		0.15
(1-g), radiative loss correction.		0.02
quadratic sum	0.08	0.65
combined standard uncertainty	0.65	
Expanded uncertainty (k=2)	1.30	

Uncertainty Analysis for the Reading of a Secondary Chamber

Uncertainty components	**Type A**	**Type B**
Current	0.10	0.10
Timing		0.10
Distance	0.01	
air density		0.08
Humidity		0.06
radiation background		negligible
radial nonuniformity		0.01
quadratic sum	0.10	0.17
combined uncertainty	**0.20**	
expanded uncertainty	**0.40**	

Uncertainty Analysis of a Calibrated Instrument

comb. Uncertainty for air-kerma rate	0.65
comb. Uncertainty for instr. Reading	0.20
combined uncertainty	**0.68**
expanded uncertainty	**1.4**

Appendix B: Calibration Report

National Institute of Standards and Technology

REPORT OF AIR KERMA CALIBRATION

FOR

Customer Address
Customer Address
Customer Address

Radiation Detection Chamber: Manufacturer name, Model xxxxxx, SN xxxxxx

Calibrations performed by Ronaldo Minniti

Report reviewed by Michelle O'Brien

Report approved by Stephen M. Seltzer

For the Director
National Institute of Standards and Technology
by

Lisa R. Karam, Acting Chief
Ionizing Radiation Division
Physics 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. The results provided herein were obtained under the authority granted by Title 15 United States Code Section 3710a. As such, they are considered confidential and privileged information, and to the extent permitted by law, NIST will protect them from disclosure for a period of five years, pursuant to Title 15 USC 3710a(c)(7)(A) and (7)(B).
Report format revised 8/03

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

DG: xxxxx/02
TFN
date
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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: +/- volts with respect to the inner electrode.
Chamber rotation: The window faced the source of radiation.
Environmental conditions: The chamber is assumed to be open to the atmosphere.
Average leakage: 0.0XXX % of collector current.
Current ratio at full to half collection potential: 0.000 for an air-kerma rate of 0.00 E 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	**Half –Value Layer**		**Equilibrium Shell Added**	**Calibration Coefficient (Gy/C) 295.15 K (22 ^{o}C) and 101.325 kPa (1 Atm)**	**Air- Kerma Rate (Gy/s)**	**Calibration Distance (cm)**
	mm Al	**mm Cu**				
^{137}Cs		10.8	YES/NO	X.XXX E0	X.XX E0	000
^{60}Co		14.9	YES/NO	X.XXX E0	X.XX E0	000
Beam			YES/NO	X.XXX E0	X.XX E0	000
Beam			YES/NO	X.XXX E0	X.XX E0	000
Beam			YES/NO	X.XXX E0	X.XX E0	000
Beam			YES/NO	X.XXX E0	X.XX E0	000
Beam			YES/NO	X.XXX E0	X.XX E0	000
Beam			YES/NO	X.XXX E0	X.XX E0	000
Beam			YES/NO	X.XXX E0	X.XX E0	000
Beam			YES/NO	X.XXX E0	X.XX E0	000
Beam			YES/NO	X.XXX E0	X.XX E0	000
Beam			YES/NO	X.XXX E0	X.XX E0	000
Beam			YES/NO	X.XXX E0	X.XX E0	000

NIST Calibration Conditions for X- and Gamma-Ray Measuring Instruments

Beam code	Additional Filtration [a]				Half-value layer[b] (HVL)		Homogeneity coefficient (HC)		Effective energy
	Al (mm)	Cu (mm)	Sn (mm)	Pb (mm)	Al (mm)	Cu (mm)	Al	Cu	(keV)
X-Ray Beam Qualities									
L10					0.037		86		
L15					0.059		70		
L20					0.070		72		
L30	0.30				0.23		60		
L40	0.53				0.52		61		
L50	0.71				0.79		63		
L80	1.45				1.81		56		
L100	1.98				2.80		58		
M20	0.27				0.15		72		
M30	0.5				0.36		65		
M40	0.89				0.74		67		
M50	1.07				1.04		68		
M60	1.81				1.64	0.052	63	60	
M80	2.86				2.98	0.10	68	61	
M100	5.25				5.00	0.20	74	55	
M120	7.12				6.72	0.31	77	53	
M150	5.25	0.25			10.1	0.66	88	63	
M200	4.35	1.12			14.7	1.64	94	68	
M250	5.25	3.2			18.3	3.2	98	85	
M300	4.25		6.5		21.7	5.3	100	97	
H10	0.105				0.051		77		
H15	0.5				0.16		87		
H20	1.01				0.36		89		
H30	4.50				1.20		86		
H40	4.53	0.26			2.93		94		
H50	4.0			0.1	4.2	0.14	93	93	38
H60	4.0	0.61			6.0	0.25	94	94	46
H100	4.0	5.2			13.4	1.15	97	92	80
H150	4.0	4.0	1.51		16.9	2.43	100	96	120
H200	4.0	0.6	4.16	0.77	19.7	4.10	99	99	166
H250	4.0	0.6	1.04	2.72	22	5.19	99	98	211
H300	4.1		3.0	5.0	23	6.19	99	98	252
S60	4.35				2.79	0.09	76	66	
S75	1.50				1.81		58		
Gamma-Ray Beam Qualities									
^{137}Cs						10.8			662
^{60}Co						14.9			1250

Beam code	Additional Filtration [a]	Half-value layer[b] (HVL)	Homogeneity coefficient (HC)	Effective energy

[a]The additional filtration value does not include the inherent filtration. The inherent filtration is approximately 1.0 mm Be for beam codes L10-L100, M20-M50, H10-H40 and S75; and 3.0 mm Be for beam codes M60-M300, H50-H300 and S60.[b]The HVL values were measured directly using the two new x-ray tubes installed in November of 2001 and May of 2002.

ISO X-Ray Beam Quality Parameters Offered at NIST

Beam	Additional Filtration (mm)[a]				First HVL		Second HVL	
Code	Al	Cu	Sn	Pb	mmAl	mmCu	mmAl	mmCu
HK10					0.04		0.05	
HK20	0.15				0.13		0.16	
HK30	0.52				0.39		0.59	
HK60	3.19					0.08		0.11
HK100	3.90	0.15				0.31		0.46
HK200		1.15				1.72		2.43
HK250		1.60				2.52		3.37
HK280		3.06				3.45		4.07
HK300		2.51				3.46		4.21
WS60		0.3				0.177		0.23
WS80		0.529				0.337		0.44
WS110		2.029				0.97		1.13
WS150			1.03			1.88		2.13
WS200			2.01			3.09		3.35
WS250			4.01			4.30		4.50
WS300			6.54			5.23		5.38
NS10	0.095				0.051		0.060	
NS15	0.49				0.15		0.18	
NS20	0.90				0.32		0.33	
NS25	2.04				0.69		0.76	
NS30	4.02				1.16		1.35	
NS40		0.21				0.085		0.092
NS60		0.6				0.25		0.26
NS80		2.0				0.59		0.66
NS100		5.0				1.13		1.19
NS120		4.99	1.04			1.70		1.85
NS150			2.50			2.40		2.52
NS200		2.04	2.98			4.09		4.20
NS250			2.01	2.97		5.26		5.32
NS300			2.99	4.99		6.17		6.30
LK10	0.30				0.062			
LK20	2.04				0.43		0.43	
LK30	3.98	0.18			1.48			
LK35		0.25			2.16		2.16	
LK55		1.19				0.26		
LK70		2.64				0.51		

LK100		0.52	2.0			1.27		
LK125		1.0	4.0			1.94		
LK170		1.0	3.0	1.5		3.59		
LK210		0.5	2.0	3.5		4.68		
LK240		0.5	2.0	5.5		5.49		

a The additional filtration does not include the inherent filtration. The inherent filtration is a combination of the filtration due to the monitor chamber plus 1 mm Be for beam codes LK10-LK30, NS10-NS30, HK10-HK30 and for all other techniques the inherent filtration is adjusted to 4 mm Al.

Explanation of Terms Used in the Calibration Procedures and Tables

Air Kerma: The air–kerma rate at the calibration position is measured 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). 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 30.0 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:

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

To obtain exposure in roentgens, divide air kerma in grays by 8.79E-3 for ^{60}Co gamma rays, 8.78E-3 for ^{137}Cs gamma rays, and 8.76E-03 for x rays with energies less than 300 keV.

Beam Code: The beam code identifies important beam parameters and describes the quality of the radiation field. NIST offers four types of reference beam qualities, as well as the ISO reference radiation qualities. NIST beam codes are referred to as L, M, H, and S beams, which stand for light, moderate, heavy, and special filtration, respectively. The number following the letter is the constant potential across the x-ray tube. 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.

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. 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 $^{\circ}$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).

Effective Energy: The effective energy is shown for those beams where it is considered a meaningful characterization of the beam quality. The effective energy for gamma radiation is the mean photon energy emitted by the radionuclide, and for x radiation it is computed from good-geometry copper attenuation data. The initial slope of the attenuation curve is used to determine the attenuation coefficient, and the photon energy associated with this coefficient is given as the "effective energy." The energy vs attenuation-coefficient data used for this purpose were taken from J. H. Hubbell, Int. J. Appl. Radiat. Isot. 33, 1269 (1982). For beam codes H50-H300, the effective energy is well represented by the equation: effective energy = $0.861V$ - 6.1 keV where V is the constant potential in kilovolts.

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

Half-Value Layer: The half-value layers (HVL) in aluminum and in copper have been determined by measurements with a free-air chamber for x radiation, and have been calculated for the copper HVLs of ^{60}Co and ^{137}Cs.

Homogeneity Coefficient: The homogeneity coefficient is the quotient of the first HVL and the second HVL, generally expressed as a percent.

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.

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).

Uncertainty: The expanded, combined uncertainty of the calibration described in this report is 1.4%. 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. Details of the uncertainty analysis are given in: P. J. Lamperti and M. O'Brien, "Calibration of X-Ray and Gamma-Ray Measuring Instruments", NIST Special Publication 250-58 (2001).

Change in Terminology:

The Radiation Interactions and Dosimetry Group of the NIST Ionizing Radiation Division has made a change in its terminology in calibration and special test reports pertaining to photon and electron dosimetry. This change in terminology is in effect as of 1 May 2002. The proposed changes are based on recommendations in ISO 31-0 (1992) that have been followed for some years now by a number of other international organizations: a quantity with dimensions should be termed a "coefficient," and a quantity that is dimensionless should be termed a "factor."

In this revised terminology, the calibration quantity is defined as the conventional true value of the quantity the instrument is intended to measure, divided by the instrument's reading; this calibration ratio is termed a *coefficient* if it has dimensions or a *factor* if it is dimensionless.

Thus: (a) For our x-ray and gamma-ray calibrations of ionization chambers, for which the calibration ratio has dimensions of gray (or roentgen) per coulomb, the reported quantity is a *calibration coefficient*, rather than the old calibration factor.

(b) For calibrations of instruments that read directly in absorbed dose, kerma or exposure, or their rates, for which the calibration ratio is dimensionless, the reported quantity is a *calibration factor*, rather than the old correction factor.

(c) Other similar calibrations, such as for well-chambers used in brachytherapy dosimetry, will also incorporate these changes.

This change should provide improved clarity in our calibration reports, removing any possible confusion between a reported calibration correction factor (using the old terminology) and those correction factors (*e.g.*, for pressure, temperature, saturation) used in the calibration procedures.

The change in terminology is intended to be benign. *The meaning of the reported calibration quantity has not changed*. The correspondence with the older terminology is outlined above to establish the equivalence of the new terms for those concerned with satisfying, to the letter, documentary standards and protocols.

Stephen M. Seltzer
Leader, Radiation Interactions and Dosimetry Group

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 ^{60}Co and ^{137}Cs gamma-ray beams. ***The new standards are effective 1 July 2003***. The changes are mainly due to the implementation of new wall corrections for the graphite-wall air-ionization chambers that serve as our primary standards for gamma-ray air kerma. A complete description of these changes can be found in reference [1]. In addition, the air-kerma rates in our two therapy-level ^{60}Co gamma-ray beam facilities have been re-characterized through recent measurements using NIST primary-standard instruments. The result of these changes in standards is that the air-kerma rates delivered by our various ^{60}Co and ^{137}Cs sources now have values roughly **1%** higher than before.

Calibration coefficients and calibration factors reported prior to 1 July 2003 for instruments sent to NIST for calibration in these beams should be modified or re-determined to account for these changes as described below.

Therapy-Level ^{60}Co Beams: Instruments that are regularly calibrated in our therapy-level ^{60}Co beams will receive a calibration incorporating the change in the standard when next sent back to NIST for calibration. No precise adjustment can be applied to the calibration coefficients reported previously because the irradiation conditions have been modified. Calibrations of instruments are now performed at distance of 1.0 m from the source with a collimator setting for a field of 10.0 x 10.0 cm^2, as recommended in most protocols.

Radiation-Protection-Level ^{60}Co Beams: If an instrument was calibrated at NIST prior to 1 July 2003 in one of our radiation-protection-level ^{60}Co-beam facilities, that calibration coefficient or calibration factor should be multiplied by **1.0105** to account for the change in the standard. Customers can contact Dr. Ronaldo Minniti at NIST (phone: 301-975-5586, e-mail: ronnie.minniti@nist.gov) to verify that their instruments were calibrated in the radiation-protection-level ^{60}Co facility prior to applying this adjustment.

^{137}Cs Beams: If an instrument was calibrated at NIST prior to 1 July 2003 in one of our ^{137}Cs-beam facilities, that calibration coefficient or calibration factor should be multiplied by **1.009** to account for the change in the standard.

If there are any questions regarding the changes in NIST gamma-ray air-kerma standards or how they apply to your calibrations, please contact us at NIST.

References:

[1] S.M. Seltzer and P.M. Bergstrom, Jr., “Change in the US Primary Standards for the Air Kerma from Gamma-Ray Beams,” NIST J. Res. (in press).