Purpose

The purpose of this procedure is to describe all steps involved in the measurement of air kerma using the three, primary x-ray standard free-air ionization chambers required for the calibration service listed as 46011C [1]. The details of the proficiency test service (46050S) are included in Appendix C.

Scope

The calibration and irradiation of instruments that measure x rays are performed in terms of the physical quantity air kerma. The process for establishing calibration coefficients (or factors) for radiation detectors is explained in this procedure. Calibrations are performed by comparing the instrument to a NIST primary standard, which includes three free-air chambers for x rays.

Referenced documents

International Organization for Standardization

ISO/IS 4037-1:1996 X and gamma reference radiations for calibrating dosimeters and dose rate meters and for determining their responses as a function of photon energy--Part 1.: Radiation characteristics and production methods

Consultative Committee for Ionizing Radiation (CCRI)

BIPM, Qualités de rayonnement, Consultative Committee for Ionizing Radiation (CCEMRI) (Section I), 1972, 2, R15.

National Institute of Standards and Technology

NBS Special Publication 250-16 Calibration of X-ray and Gamma-ray Measuring Instruments
NIST Special Publication 250-58 Calibration of X-ray and Gamma-ray Measuring Instruments
NIST Calibration Services Users Guide 1998
NBS Handbook 64 Design of Free-Air Ionization Chambers
NBS Handbook 78 Report of the International Commission on Radiological Units and Measurements
NIST Special Publication 811 Guide for the Use of the International System of Units (SI)
NIST Technical Note 1297 Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurements

Records

Laboratory data books
Binders
Electronic files

Definitions

air kerma - 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. The SI unit of air kerma is the gray (Gy).

beam quality - used to refer to a specific x-ray beam with a characteristic half-value layer and produced by a constant potential kilovoltage.

calibration - the process whereby the response of a dosimeter or measuring instrument is characterized through comparison with an appropriate national standard.

calibration coefficient - the quotient of the air kerma in the absence of the chamber and the charge generated by that radiation in the ionization chamber, expressed in units of Gy/C.

calibration factor - the quotient (dimensionless) of the air kerma or exposure in the absence of the chamber and the electrometer reading with the ionization chamber.

effective energy - the energy of a monoenergetic x-ray beam that has the same half-value layer as the spectrum in question.

exposure - exposure (X) is the quotient of dQ by dm, where dQ is the sum of the electrical charges on all the ions of one sign produced in air when all the electrons are completely stopped in air of mass dm. The SI unit of exposure is the coulomb per kilogram (C/kg); the special unit of exposure, the roentgen (R), is equal to exactly 2.58E-4 C/kg.

half-value layer - (HVL) the thickness of the specified material added as a beam attenuator that reduces the air-kerma rate by one half of the unattenuated-beam air-kerma-rate value.

homogeneity coefficient - (HC) the ratio of the first to the second half-value layer.

monitor instrument - an instrument used to monitor the stability of the air-kerma rate during an irradiation.

QMS – quality management system

quarter-value layer - (QVL) the thickness of the specified material added as a beam attenuator that reduces the air-kerma rate to one quarter of the unattenuated-beam air-kerma-rate value.

second half-value layer - the difference between the quarter-value layer and the half-value layer.

x-ray unit - system comprised of a high-voltage generator, an x-ray tube and an x-ray controller.

Key words

air kerma; calibration; exposure; free-air chamber; half-value layer; ionization chambers; mammography chamber calibrations; primary standard; standard; uncertainty estimate; x rays.

Background information

The quantity *kerma* characterizes a beam of photons or neutrons in terms of the energy transferred to any material. For the calibration procedures described in this document, consideration is limited to photon beams in air. A complete description of the determination of air kerma and the traceability of the standards is found in sections 4.1, 6.2 and 6.8 of the NIST Special Publication 250-58.

Requirements of instruments to be calibrated

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.

Explanation of calibration service offered

An x-ray tube produces bremsstrahlung spectra, inhomogeneous beams with photon energies from very low values to a high-energy cutoff given by the maximum potential applied to the x-ray tube. These beams are customarily filtered with a high purity metal to reduce the unwanted low-energy x-rays. Four x-ray calibration systems are used for the calibration services. Two of the systems contain x-ray tubes with tungsten anodes. The x-ray beams from these anodes are filtered with aluminum, copper, tin and/or lead. Two anode types are offered for the mammography calibration service, molybdenum (Mo) and rhodium (Rh). The Mo-generated x-ray beams are filtered with Mo, Al, or Rh foils, while the Rh beams are filtered with Rh and Al foils. It is conventional to characterize the "quality" of the filtered x-ray beam in terms of the thickness of aluminum or copper required to reduce the air kerma rate to 50 % and to 25 % of its original value. These thicknesses are called the half-value layer (HVL) and the quarter-value layer (QVL). The HVL and QVL measurements must be made using good-geometry attenuation in order to obtain accurate and reproducible numbers. The second HVL is the difference between the QVL and HVL. The homogeneity coefficient (HC) is the ratio of the first to the second HVL, often expressed as a percent. A HC value near 1 (or 100 %) indicates that the filtration has produced an approximately homogeneous beam that is approaching monoenergetic conditions.

The NIST tungsten x-ray beam qualities are divided into three groups according to filtration, i.e., light (L), moderate (M), and heavy (H) filtration. The beam codes consist of a letter L, M, or H, followed by the generating constant potential in kilovolts. For example, M100 indicates moderate filtration and 100 kV constant potential. The special (S) series beam codes, S60 and S75, have characteristics that are not consistent with those of the L, M, and H groups. The qualities for each group were chosen so that relatively smooth curves result for the graph of tube potential versus HVL. Table 1 gives a complete listing of the available NIST beam codes. Depending on the energy response and design of the ionization chamber, the calibration coefficients for a specific ionization chamber often fall on smooth curves when plotted against HVL. In this case, all calibration points have been chosen from a single group, L, M, or H. If calibration points are chosen from more than one group, discontinuities will occur, hence no attempt should be made to interpolate between such calibration factors.

The mammography beam qualities offered at NIST were chosen to cover the range of HVLs of x-ray beams found in clinical settings. The beam codes that name the beam qualities are a combination of the chemical symbol of the anode and the filter respectively, followed by the constant potential in kilovolts. The letter "x" ends the beam codes that name the exit beam qualities. The exit beam qualities, which represent the transmission of the x-rays through the breast, are generated by an additional filtration of 2.0 mm of Al. The mammography beam qualities offered are listed in Table 2.

NIST maintains reference beam qualities from two international organizations, the ISO and the CCEMRI (now known as the CCRI). These beams are generally used for international traceability and measurement comparisons. A list of all ISO beams offered at NIST is found in Table 3a, using the ISO 4037 1996 version; the changes to the reference beams from the updated ISO4037 have not been implemented at NIST. The NIST H group of qualities agrees with the ISO narrow spectrum (NS) qualities recommended by the ISO document 4037. The NIST M group of qualities is in agreement with the recommendation for radiation therapy calibration in IEC Publication 731. NIST supports the reference CCRI beam qualities, 25 kV and above, described in the CCEMRI/CCRI (1972) document for traceability with the BIPM. The NIST techniques based on these beams are listed in Table 3b.

The selection of beam qualities for instrument calibration depends on the situation of interest. The H qualities are usually used for calibration of radiation-protection instrumentation, as these beams have the narrowest spectrum at each generating potential, and probably most nearly approximate radiation that has penetrated a protective barrier. The M qualities are usually used for calibration of radiation-therapy instruments. The L qualities are predominately for calibration of instruments used for measurement of unfiltered or lightly filtered beams that give high exposure rates, as is often the case in radiation biology and Grenz-ray therapy. The Mo and Rh beam qualities are offered to simulate the clinical mammography beams.

Design philosophy and theory

X-ray calibrations are performed by using the substitution method. Using this method, the air kerma or air-kerma rate is determined at some point in space by a free-air chamber. The instrument to be calibrated is then placed at the same point in space as the standard and the response of the instrument is determined. The calibration coefficient is the quotient of the air kerma, K_{air} in the absence of the chamber, and the charge, Q, generated by that radiation in the ionization chamber:

$$Calibration\ Coefficient = \frac{K_{air}}{Q}$$

The calibration factor is the quotient of the air kerma or exposure, in the absence of the chamber, and the electrometer reading with the ionization chamber:

$$Calibration\ Factor = \frac{K_{air}}{electrometer\ reading}$$

$$Calibration\ Factor = \frac{X}{electrometer\ reading}$$

X-ray facility features

Four x-ray calibration systems are available for instrument calibrations; the x-ray calibrators and the primary standards are shown in Figure 1, which shows H127-3, the NIST X-Ray Calibration Range and the linear positioning system. One system is used for tungsten x rays generated at constant potentials of 10 kV to 100 kV, another is used for tungsten x rays generated at potentials of 50 kV to 300 kV. The mammography x rays are generated at constant potentials of 23 kV to 40 kV either using the Mo or the Rh system. Standardization of x-ray beams for the quantity air kerma or exposure is carried out at NIST by means of three free-air ionization chamber standards. These standards are discussed in Refs. [3, 4, 5 and 6]. Features critical to the proper use of the standards are listed in Table 4. All the standards are shown in Figure 2 and Figure 3, except for the Lamperti chamber. The Lamperti primary free-air chamber has been established as a primary standard for low energy x-rays so it is included, as an available standard and offers redundancy. Currently it is dedicated for use in the Electronic Brachytherapy facility.

Figure 1 The NIST X-Ray Calibration Facility showing primary standards and the linear positioning system.

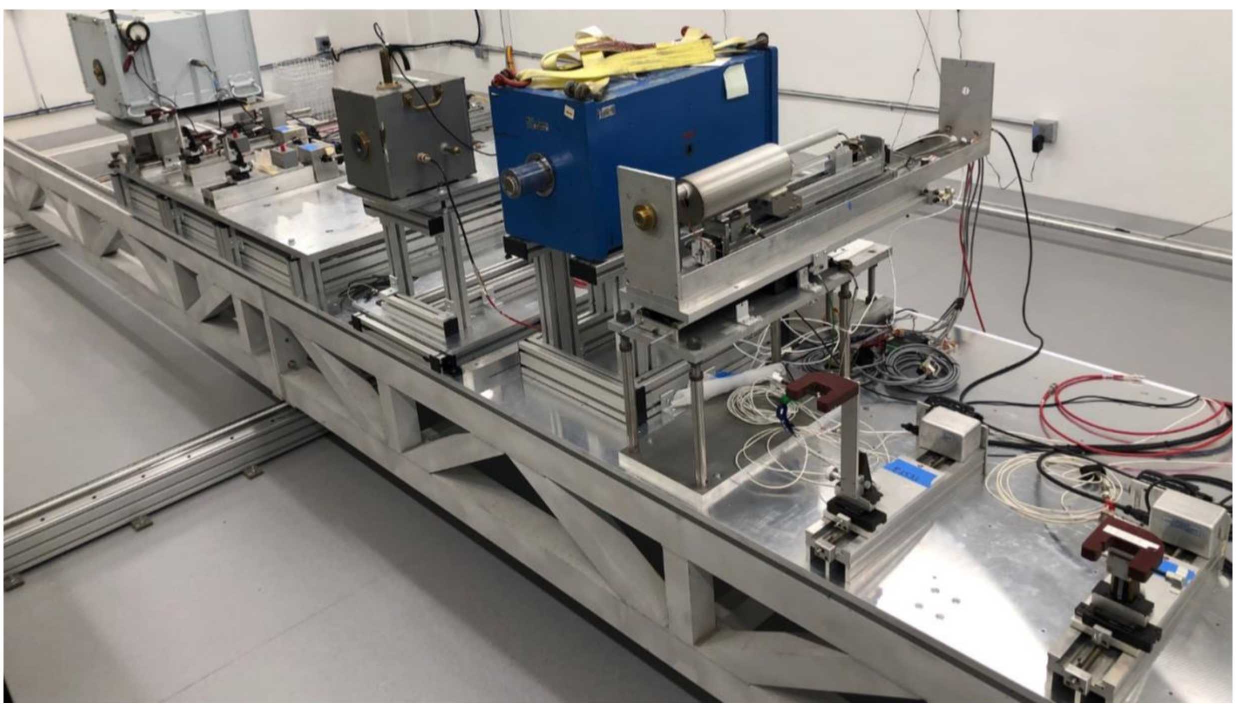


Figure 2a Position of the device under test (DUT) from left to right: 300 kV FAC, T1, T2, 100 kV FAC, Mammo FAC, T3 and T4 .

Figure 2b Position of the device under test (DUT) from right to left: 300 kV FAC, T1, T2, 100 kV FAC, Mammo FAC, T3 and T4 .

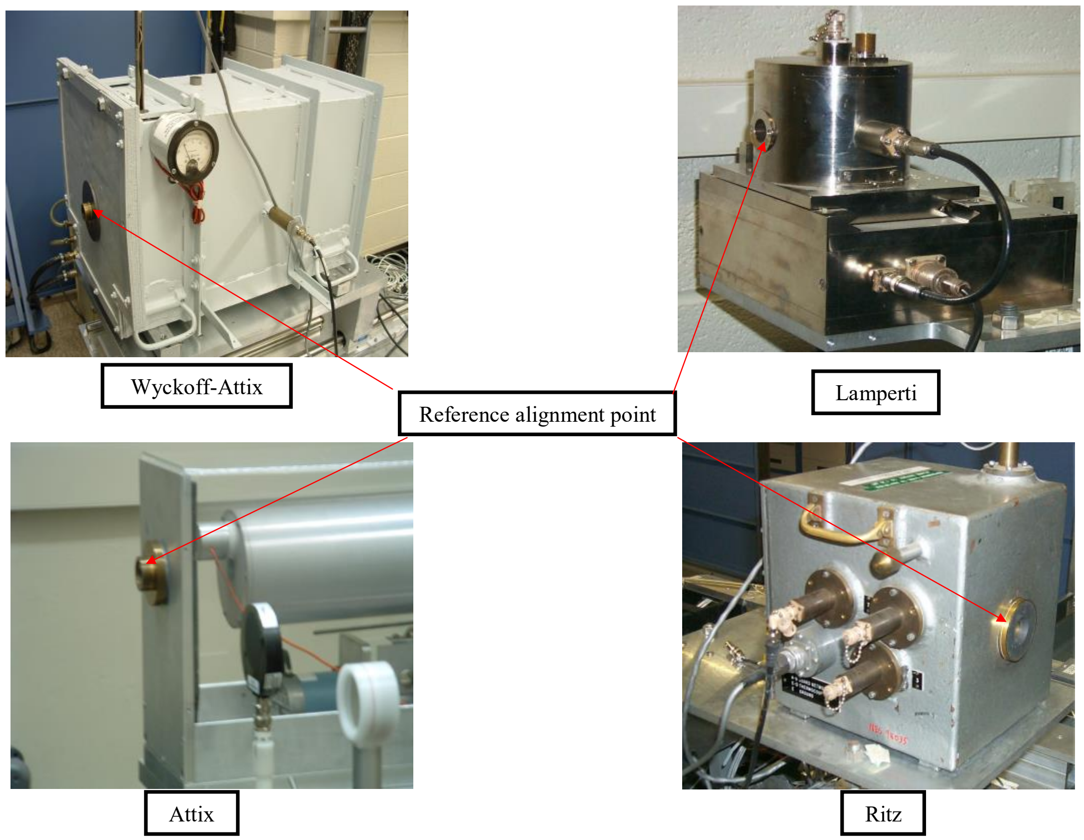


Figure 3 The primary x-ray standards, showing the alignment points.

Features of the x-ray systems are listed in Table 5. The equipment room, H127-2, is shown in Figure 4 and contains the x-ray generators, heat exchangers, voltage dividers, power disconnects, safety interlock controls, and junction control box. H127-2 is connected to the x-ray range and control area by custom shielding ports for the HV cable, oil and water-cooling lines. The Figure 4 inset pictures show the junction control interface and a generator control interface. Figure 4a shows the past customer calibration records which are stored in file cabinets at the end of the equipment room. Figure 4b shows the GE voltage dividers which are used for the 300 kV unit and a Pantak divider used for the 100 kV unit. The equipment room is shielded from ionizing radiation and accessible during the production of x-rays. The Kimtron operating procedure, located in Appendix A, describes the use of the equipment.

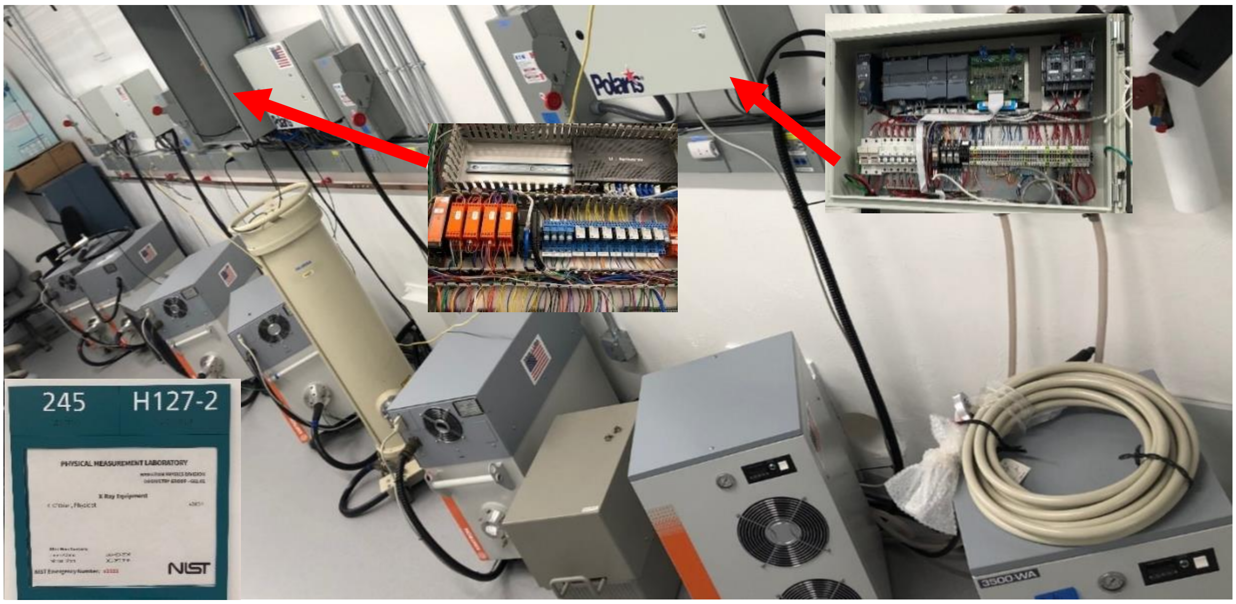


Figure 4 The Equipment Room, showing location of junction control interface and interlocks.

Figure 4a Customer records

Figure 4b Voltage dividers, GE on left and Pantak on right.

The facility is equipped with a storage room for equipment, equipment manuals, quality equipment calibration records, shipping crates, and security for the vast array of secondary standards and high purity metals. This room has dedicated space for the inspection, storing and packing of the customer's chambers. Figure 5, on the left, shows the NIST collection of secondary, reference class chambers and high purity metals. The bookcase seen at the end of the storage room has all quality management system (QMS) manuals and calibration support equipment records. Figure 5, on the right, shows NIST redundancy equipment storage as well as the shipping preparation area.

Figure 5 The storage room, showing NIST secondary standards on the left and calibration redundancy equipment on the right with customer shipping station.

The control area of the NIST x-ray calibration facility shows access to the three connecting rooms in Figure 6. The operator control center, laboratory benches, and workspace to facilitate measurement exchanges are contained in the large open area which was designed to allow movement of large equipment used during some measurement tests. The cable management network is shown in this picture connecting all rooms. The open control area allows for viewing of the calibration range through a lead glass window.

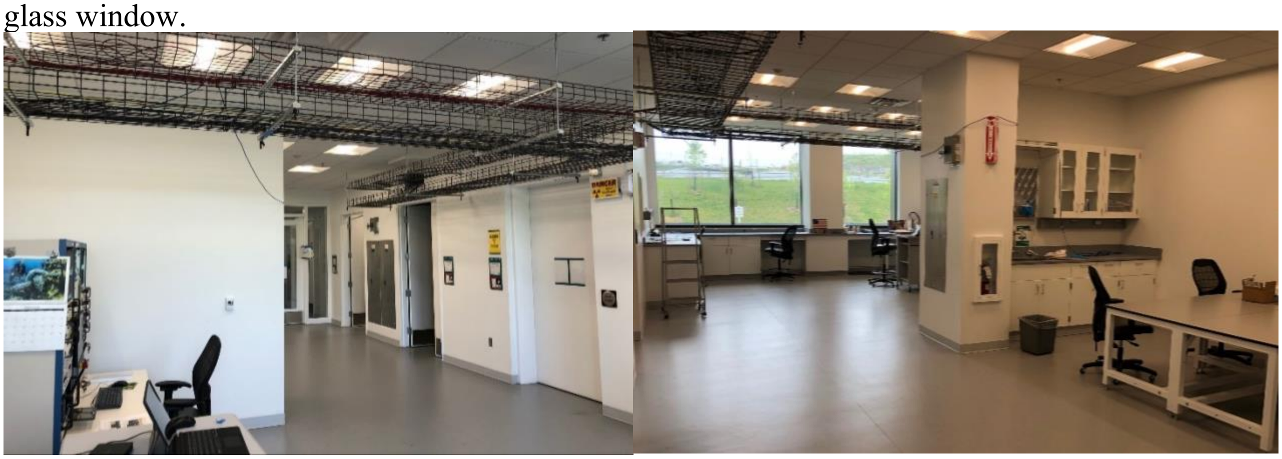


Figure 6 X-ray facility control area

X-ray calibration data

Data are acquired for x-ray standardization by measurement of all conditions relevant to establishing the x-ray air-kerma rate at a particular distance from the x-ray-tube target. The data acquired consists of data for the computation of ionization currents, parameter data, and measurement-system test and information data. Data used to determine the ionization currents includes the electrometer charge measurements, the atmospheric pressure and pertinent air temperatures, and the shutter-open time interval. The parameter data includes the x-ray tube current and potential, the x-ray tube target-to-reference-point distance, and the beam-defining filter thickness and the diaphragm diameters. Test data includes the measurements of the collection potentials on the standard free-air chamber, the monitor chamber, and the chamber being calibrated, if appropriate.

Ionization-chamber current-measurement techniques

Ionization currents in air-kerma-standardization measurements are produced by the irradiation of a gas in an ionization chamber. The ionization chamber may be a free-air chamber, such as one of the national standard chambers, or a cavity chamber, where the gas is surrounded by some wall material. Ionization chambers, regardless of type, consist of electrodes that are insulated from one another and are polarized in order to collect charge produced in the gas. The ions produced in the air by the beam are swept from the chamber volume by the electric field between the electrodes. Included in the measurement of these currents are currents not produced by the radiation of interest, but by background radiation and insulator leakage, which is referred to as background current. The magnitude and sign of these extraneous currents must be determined and the measured current corrected for their effects in order to determine the true ionization current. The importance of the correction for background and leakage is, of course, relative to the magnitude of the ionization current, but good measurement technique requires, prior to attempting radiation measurements, that the background currents be determined. As a rule of thumb, and without taking special precautions, the background current for a good-quality ionization chamber should be less than 5 fA. The measurement of background currents will also include currents due to background radiation, so the environment and special circumstances must be considered in evaluating data. For example, if tests are made on a large-volume ionization chamber in a background environment found suitable for small-volume chambers, the extra sensitivity of the large chamber requires separate evaluation of the background environment. Keithley 617, 6512 and 6514 electrometers are used to measure the charge collected in the ionization chambers.

Special operating features for the Attix Chamber

The Attix chamber, a variable-length, cylindrical free-air chamber, differs in design from the other three NIST conventional parallel-plate free-air ionization chambers. The differences contribute to its appropriateness as a standard for the measurement of exposure in the mammography energy region. This measurement procedure is based on a subtraction method [7], which involves finding the difference in collected charge for different electrode lengths. The chamber is composed of an aluminum cylinder with a fixed front plate, a variable-position back plate, and an off-center electrode. The cylinder and back plate are positioned with precision stepping-motor controlled slides. For a detailed description of the chamber see Refs. [8 and 9].

The air-kerma determination with the Attix chamber involves the collection of charge with various plate configurations. By changing the volume of the Attix chamber and knowing the corresponding change in length of the collecting electrode, the air kerma can be determined with a minimum of two different plate configurations. Although the minimum number of plate configurations needed to determine the air kerma is two, four measurements are conducted, with the fourth being a repeat of the first position. The electrode length is typically changed by 5 cm with each plate configuration. The average of the three resulting ratios of the change in charge to change in electrode length is calculated and used in the air-kerma calculation as a component of the mass ionization current. For routine measurements, the defining point of the Attix chamber is positioned at one meter from the focal spot of the x-ray source. Figure 7 shows the Attix chamber configuration used for the measurement procedure.

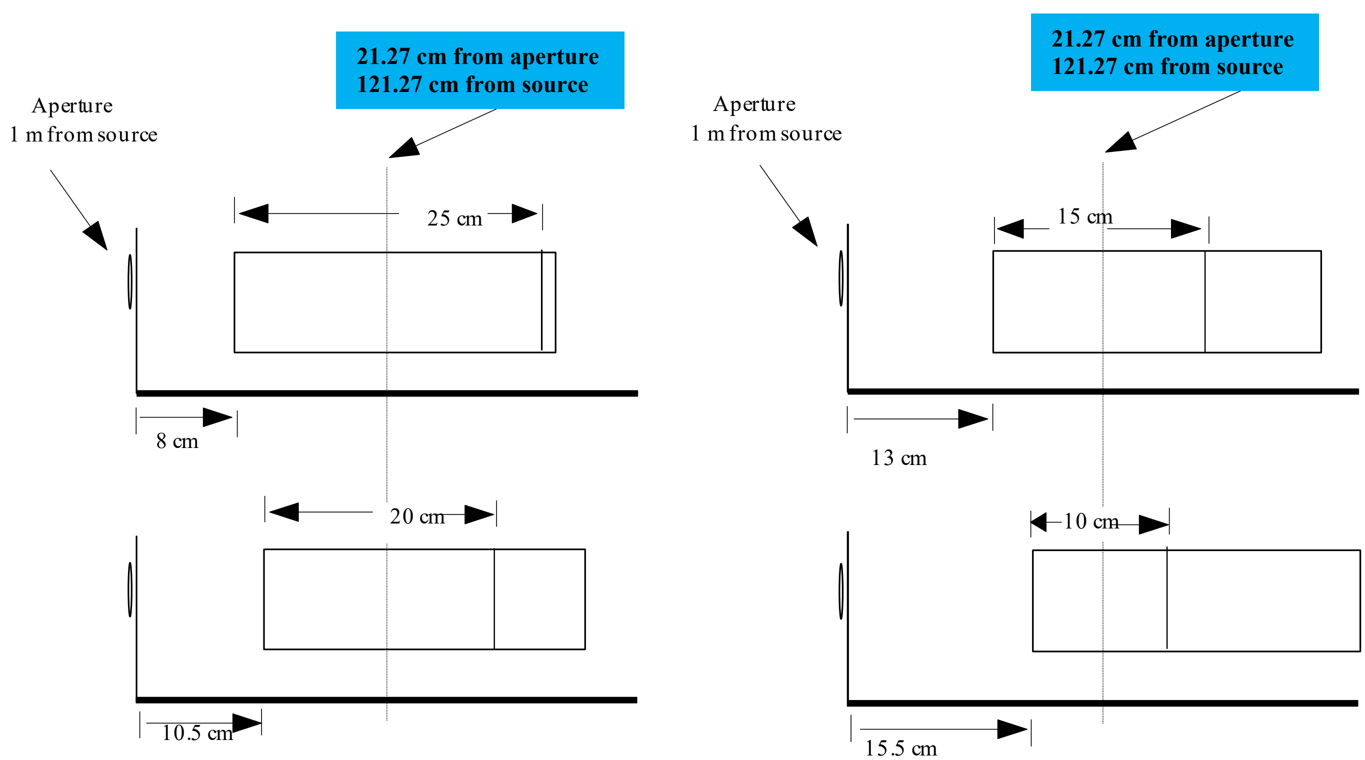


Figure 7 Attix primary standard measurement positions.

Equipment

The required equipment is listed in Table 6.
All data are acquired through National Instrument's LabVIEW interfacing using the Hopewell Designs Inc. (HDI) controller, which is contained in the control console, seen in Figure 8 and shown enlarged in Figure 8a. The interaction with the HDI controller is explained in various procedures. The open and close buttons are used to control the shutters for non-automated shutter control. The x-ray tube keys are part of the interlock system and required for production of x-rays and the emergency off switch is connected to all motion associated with the LPS and the shutters and is explained in the safety feature section.

Figure 8 X-ray control console

Figure 8a HDI controller and x-ray tube key interlock

HDI calibrators

The information on the HDI calibrators is from the HDI documentation. HDI designed the calibrators specific for the geometry used at NIST. The HDI calibrator consists of a shielded enclosure of the tube head, head mount, cables, and high-speed shutter. The enclosure is made of steel, lead, and steel laminate with a nominal thickness of 15 mm between two layers of sheet metal. Exposure rates are limited to less than 5 mR/h at the surface of the enclosure when the tube is operating at any setting. When the side doors of the cabinet are opened, an interlock disables power to the tube head. Baffled penetrations allow the cables to exit without increasing radiation exposure rates. The axis of the radiation beam is horizontal and is 51 inches above floor height. Figure 9 shows the three calibrators, left to right in this order: mammography, 100 kV system and 300 kV system. The 300 kV tube is contained in the calibrator closest to the north wall. The right picture of Figure 9 shows the 300 kV tube with one of the side doors opened. The 100 kV tube is in the middle calibrator and the mammography calibrator closest to the shielding door contains the Mo and Rh tubes.

Figure 9 The three x-ray calibrators, showing the interior of the 300 kV calibrator with x-ray tube.

The HDI mammography calibrator is of a different design than the other HDI calibrators, modified to incorporate the previous tube translator. The Mo and Rh x-ray tubes, shielded to 60 kV, are fully enclosed in ¾ inch thick steel, which contains the previously used, lead-lined translating tube positioning mechanism. The unit consists of the translation tube support, shown in Figure 10, a collimated opening, the tungsten shutter and a pneumatic solenoid. Figure 10a shows the side view of the tube support with positioning interlock switches and Figure 10b is a closeup of the shutter collimator.

Figure 10 The mammography translation tube support.

Figure 10a Positioning switches

Figure 10b Tube collimator

The HDI calibrator consists of a collimated opening, the tungsten shutter, a pivot mechanism, and the pneumatic solenoid. A lead collimator is installed in the beam port to establish a beam with an approximate 15-degree to 17-degree solid angle. The high-speed shutter consists of a tungsten disk that is 50 mm diameter x 25 mm thick (2 in. dia. x 1.125 in. thick) and completely covers the beam port to block radiation when closed. An electric solenoid operates an air cylinder to open and close the shutter in less than 150 milliseconds. Flow control valves allow the shutter speed to be controlled and shock absorbers slow movement at the end of travel. Electric switches indicate when the shutter is fully open or closed. When power is turned off to the solenoid, air pressure and a spring pulls the shutter closed in the same amount of time. A Panasonic FP0H PLC is used for the timing of each shutter which is triggered by a pair of solid-state switches mounted directly to the actuating air cylinder. The timer initiates once the shutter shielded switch is deactivated as the shutter uncovers the beamline. At the end of the preset exposure time, the shutter is signaled to close, which activates the exposed sensor and the duration time is achieved. The opening and closing transition should deliver approximately half the dose rate, so by counting during one transition, the average results in the elapsed time. The shutter motion open and close times are independently tracked and monitored. During the installation of the shutters a quartz-crystal digital timer, accuracy of 0.001 %, was used to establish traceability for the PLC times. The shutter open and close transition times are initially adjusted by the switch placement and air pressure regulators, resulting in balanced shutter motion. Figure 11 shows the interior of the 100 kV x-ray tube and the closeup shutter details on the left and center and the 300 kV tube and shutter on the right.

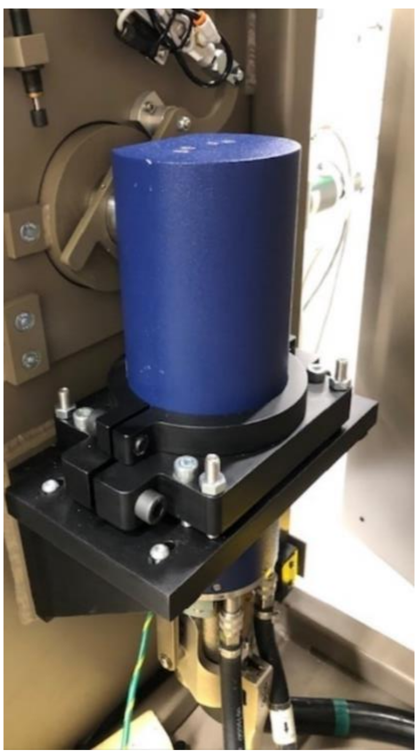


Figure 11 The 100 kV tube and closeup of the shutter assembly on left and center picture and the 300 kV tube shown in the right picture.

A pressure sensor for the compressed air shutter operation is contained in each calibrator and is connected to the pressure gauge in the interlock junction box in H127-2. Figure 12 shows the access to the pressure sensor at the bottom of the calibrator. The pictures on the right of Figure 12 show the interior of the calibrator bottom with the interlock system and the adjustable pressure sensor with a closeup of the pressor dial that displays the setpoint by the green pin, the lower limit by the green needle and the actual pressure by the black needle.

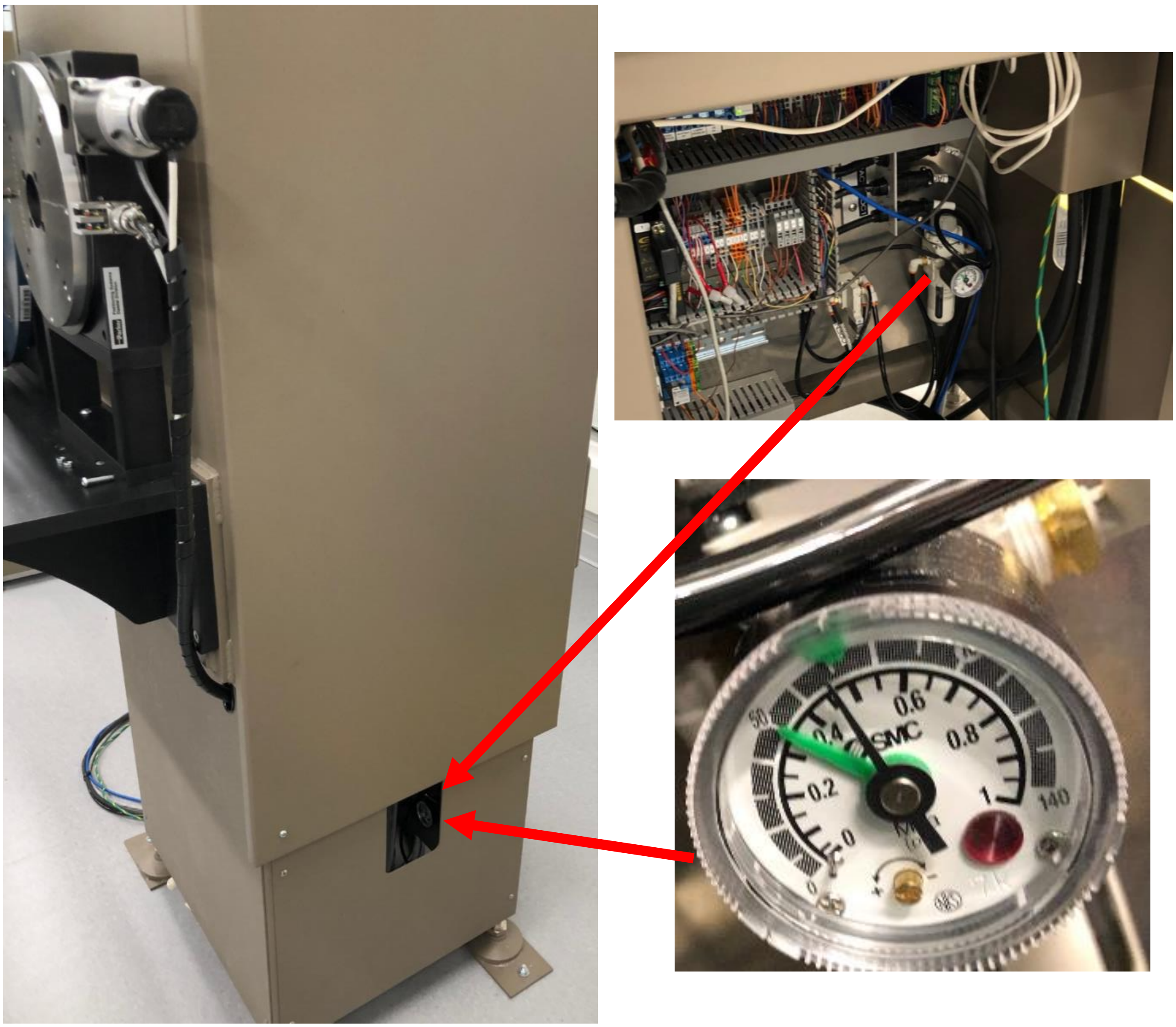


Figure 12 Calibrator pressure sensor and indicator controls.

Linear positioning system

The NIST x-ray calibration facility features a precision motion controlled 2 axis, X-travel: 3 m x Y-travel: 4 m, linear positioning system (LPS) that translates across the x-ray beam lines of three x-ray

calibrators allowing the direct comparison of the three primary x-ray standards and radiation detection instrumentation at source to detector distances from 60 cm to 370 cm, repositioning in both directions to within 0.05 mm. The platform of the LPS was designed to incorporate the unique positioning requirements of the three NIST primary x-ray standards and a HPGe detector and 3000 lbs to the same beam height of 51 inches, shown in Figure 2. The LPS features a linear encoder that has a resolution of 2 microns. The HDI Operations and Maintenance Manual for the Sliding Stage Positioning System, shown in Figure 13 is located near the HDI console and explains the use of the LPS to the qualified trained operator. The manual includes the procedure for using the LPS with the HMI touchscreen located on the telescope stand, shown in Figure 14. The description for use of the LPS control PC software, interface shown in Figure 15, is also described in the manual. The configuration files for the LPS software are located on the HDI control computer: C:\ProgramData\HDI\NIST\X-Ray Lab\LPS\LabVIEW\X-Ray LPS\ParkerIPADrive Config XAxis.ini
C:\ProgramData\HDI\NIST\X-Ray Lab\LPS\LabVIEW\X-Ray LPS\ParkerIPADrive Config YAxis.ini
C:\ProgramData\HDI\NIST\X-Ray Lab\LPS\LabVIEW\X-Ray LPS\YAxis Presets.ini
The Y-Axis position presets are seen on the LPS vi. If a new preset is necessary, the change is made from the user interface and saved to the configuration file for future use as a pre-set.

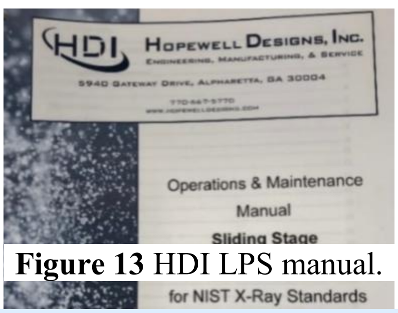


Figure 13 HDI LPS manual.

Figure 14 LPS touchscreen control

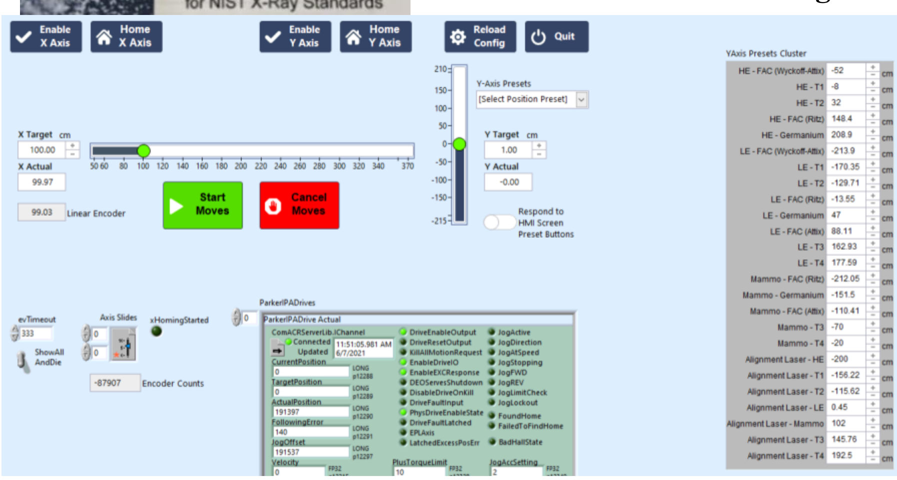


Figure 15 LPS software interface

Alignment Lasers and instrument positioning controls

The use of the alignment lasers and instrument positioning controls is explained in the section, *Set-up procedure using the alignment lasers*. Two alignment lasers are essential for the calibration chamber alignment process. One laser is referred to as the *telescope alignment laser* and verifies the plane of the alignment of all instruments. It is attached to the telescope stand, below the telescope. The other is mounted on the east wall, located between the EMO switch and the 100 kV tube laser. It is referred to as the *beam height alignment laser*; both are shown in Figure 16. The four hand controls for the test chambers are also shown and labeled right to left at T1, T2, T3 and T4. These correspond to the test chamber positions.

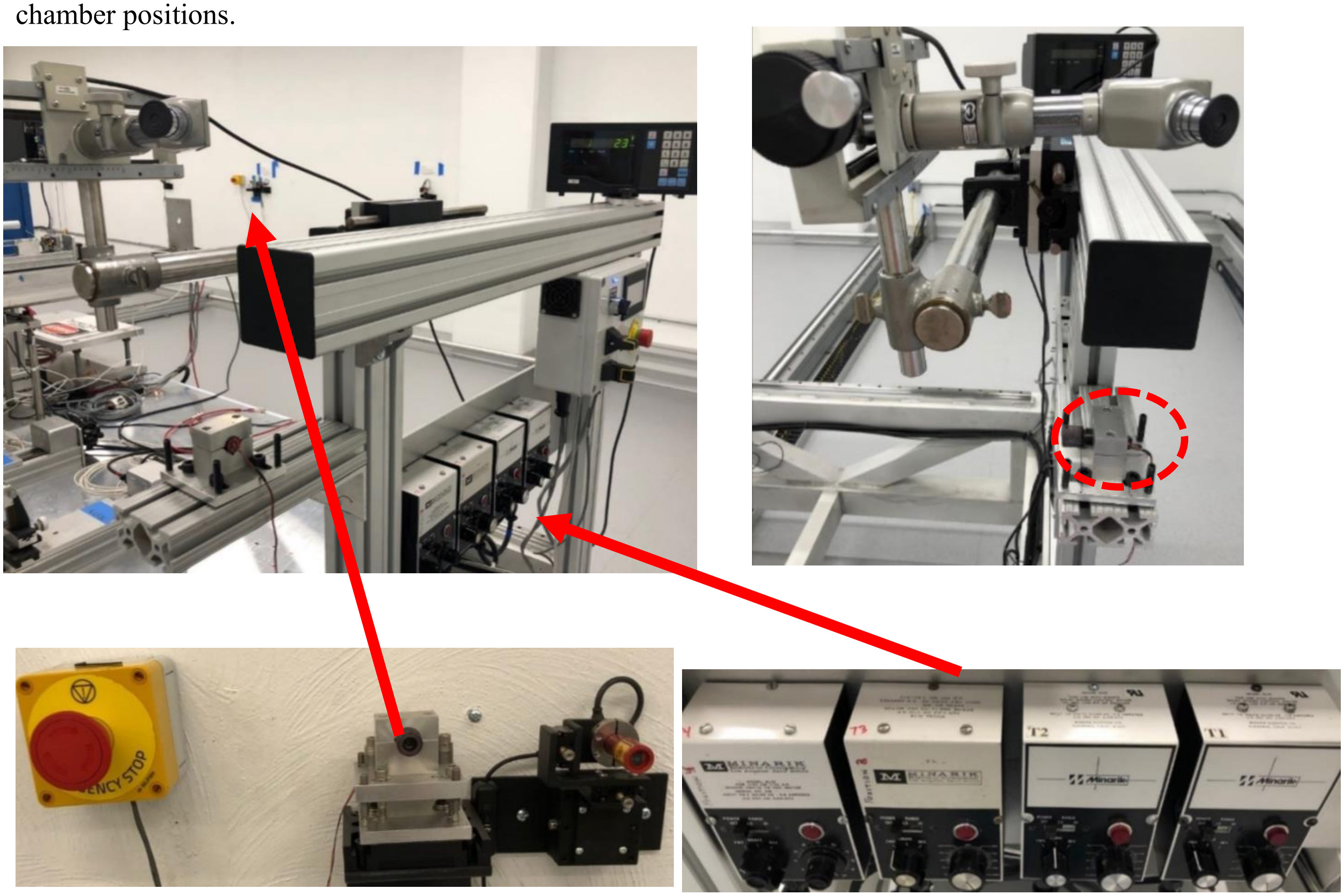


Figure 16 Alignment lasers and test chamber positioning controls.

Electrometers

The charge measurements are acquired through the use of Keithley 617, 617-HiQ, 6514 and 6512 electrometers. The charge ranges of the electrometers are calibrated upon introduction into the system and any time the charge collection is suspect. Any necessary correction would be applied as part of the air-kerma calculation in the LabVIEW software, however no such calibration correction is required. The Keithley 6512 and 617 electrometers are interchangeable in the HDI data acquisition system. The HiQ is dedicated for use if a monitor chamber is required. The 20 nC capacitance range electrometer is used for the customer chamber. The 6514 electrometer is available as a backup or redundancy for the standard electrometer. LabVIEW control software is available for a seamless transition for the use of the 6514, and eventually for other electrometers as funds exist.

Temperature indicators

The temperature sensors are various models of platinum resistance probes and thermistors, and Hart/Fluke digital thermometers that are used to measure room, free-air chamber, and monitor-air temperatures. The thermometer calibration correction is applied internally to the digital meters. A Fluke/Hart meter 1504 (sn A95694) with probe model 5610-5 SNA932006 serves as the “in-house” temperature reference standard for x- and gamma-ray calibrations. The meter/probe will continue to be calibrated periodically as necessary to the NIST primary standard. Various probe and meter combinations are periodically directly calibrated by the NIST temperature experts. One liquid-in-glass thermometer that was a previous lab reference is maintained, but will no longer be calibrated, for resolving possible measurement discrepancies.

Pressure indicators

The atmospheric pressure for the x-ray range is measured by the Setra 370 digital barometer. No calibration correction is necessary, but if one was necessary, the correction would be documented and applied in the LabVIEW software. An aneroid barometer, Wallace and Tierman, Model FA 139, Serial Number XX11242 is the “in-house”, lab standard and has direct NIST traceability. Some of the Setra 370 barometers have direct NIST traceability, serving as a backup or secondary standard. All barometers are compared to the in-house lab standard routinely. Calibrations of the lab barometers used at the various facilities are made by placing the “in- house” standard barometer alongside the instrument to be tested. If a correction factor is required, it would be clearly identified on the meter. This calibration procedure is conducted periodically.

Voltage dividers

Two customized voltage dividers were manufactured for the purpose of voltage calibration of the x-ray generators used in the calibration range. Both dividers were initially calibrated by the NIST Electricity group. These dividers are periodically used for routine calibrations and for measurement comparisons. A check of the voltage calibration is required after any of the x-ray generators are changed due to maintenance or replacement. The dividers must be directly placed in series with the generator cables into the x-ray tube and require a knowledgeable, experienced person for installation. A high precision voltage meter must be used to read each divider. This equipment is listed in Table 6. Two commercially available GE voltage dividers are dedicated for use on the 300 kV system. Obtaining direct voltage calibrations for this specialized equipment is difficult and is not a service routinely offered at NIST.

Support equipment calibration and validation

The temperature probes, pressure transducers and electrometers are considered essential support equipment to allow routine calibrations of ionization chambers. The details of maintenance and calibration of this support equipment follows. The quality of the ionization chamber calibration is not monitored by the calibration of the support equipment but rather by the NIST artifact quality procedure. The quality check of the calibration of all customer ionization chambers is determined by the reproducibility of the calibration coefficients of the NIST test chamber. Therefore, if a calibration coefficient does not reproduce, the performance and calibration of the support equipment would be investigated. There are no specified calibration intervals for the critical support equipment because the equipment is calibrated using the in-house reference standards, described below, if there is a question of reproducibility of the NIST transfer ionization chamber. Since the QA procedure for all x-ray calibrations requires the calibration of a NIST ionization chamber, any change in the reproducibility above 0.5 % to 1 % of a typical chamber response depending on the chamber type and history, may require an investigation into the support equipment used for the calibration. If any of the critical support equipment is found to be out of calibration or damaged, it would be disconnected, and its condition clearly marked on the instrument. A calibrated, identical model replacement instrument would be used for calibrations to continue and the instrument would be clearly identified on the Access equipment log in the data acquisition software, which serves as the instrument log for calibrations. All new equipment is calibrated against the “in house” reference standard and history is created and maintained. The new equipment is checked to verify it meets the specifications of the stated procurement, using the “in house” standards. The validation records are kept in *L:\internal\846.02\x-ray\QMSvalidateH127.xlsx* located on the group server for calibration data, in the x-ray folder. The tracking of all equipment used for calibrations is performed by the LabVIEW data acquisition system and stored in Access log sheets. All NIST issued calibration reports for the critical support equipment are located in H127-1. In-house calibration records for the barometers and thermometers are maintained in electronic files in the folder named *supportequipqa* located on the group server for calibration data, in the x-ray folder.

Procedures

Administrative procedures

Customers request calibration services in a variety of ways. Typically, a new or first-time customer will establish contact with the Dosimetry Group by email, requesting information regarding techniques offered, charges, turnaround time, and shipping information. At this stage, there is generally an opportunity to discuss with the prospective customer the type of service being requested and methods of shipment to reduce the risk of damage. The customer is informed of the administrative procedures for acceptance of the requested work as outlined in the NIST QMI and in the RPD QMII, in accordance with the NIST calibration policy. In addition to completing the NIST payment authorization requirements, the customer must include a detailed description of the calibration request, instrument model and serial numbers, name and telephone number of a technical contact, the official address which will appear on the calibration report, the return shipping instructions including the address, any special handling requirements, the specified mail carrier with account number for payment, the value of the equipment, and instructions for the insurance amount, if any. The customer is directed to the complete instructions and policies for calibrations on the NIST calibration ordering webpage. The Calibration Information request form, see Table 8, can be completed by the NIST technical contact, as a method to organize the dates and information about the calibration request. The NIST order number is generated by the NIST online ordering system upon completion of the NIST policy for payment documentation. At the completion of the calibration, a copy of the purchase order if available, the final copy of the calibration report, summary sheets, and any significant documents of correspondence concerning the calibration are maintained in the customer's calibration report folder filed by the unique dosimetry group (DG) number.

When instruments arrive for calibration, they are unpacked and inspected for damage. The customer chamber is stored in the H127-1 storage room on the customer shelf until the scheduled calibration. Special attention is given to the condition and type of connector on the customer chamber. If an adaptor is sent with the chamber, it should be noted on the inventory list along with the description of the chamber. Shipping damage is reported to the NIST shipping department. If an instrument arrives in a state of disrepair that is obvious by visual inspection, the customer would be notified, and the instrument returned without calibration. The instrument would be rejected if the window is obviously dented or punctured or if the chamber cable is damaged. If the shipping box is visually damaged, this should be noted, and the customer consulted.

After the instrument is calibrated, the calibration report is generated. Templates generated in Microsoft Word and Excel are available to simplify this procedure and to ensure consistency in the reporting format. The electronic reports are finalized with an official NIST logo. A sample report is found in Appendix B. A sample NIST report is provided in this procedure with the required elements identified by the corresponding letter in red font. Upon completion of the requested calibration, the final calibration report is reviewed and initialed by the preparer, the technical reviewer, the Group Leader and the Division Chief, electronic signatures are acceptable. A copy of the signed report is maintained in the customer's DG folder located in room H127 of building 245 and in the customer's electronic file. The original or an electronic equivalent is sent to the customer within the container of the returned equipment, by email or by mail, if requested by the customer. An electronic version of the final report is uploaded to the E-commerce ordering system. The instrument(s) is(are) then repackaged in the original container, or a more suitable one, for return shipping. The shipping page of the NIST online ordering system is printed and attached to the box. The NIST shipping department collects the box from outside of H127 or the designated collection point.

General overview of the X-ray calibration process

X-ray calibrations are performed using the substitution method: the standard is used to measure the air-kerma rate at a given point; the instrument to be calibrated is placed at that point and exposed to the same calibrated x-ray source under the same conditions. The probe's response is normalized to 101.325 kPa (760 mmHg) pressure and 295.15 K (22 °C) when the instrument is open to the atmosphere.

After mounting and aligning the chamber in the holder and applying the appropriate chamber voltage, which is often requested by the customer, the applied chamber bias is checked at the chamber voltage connection box located near the chamber mounts, shown in Figure 17. This verifies the voltage connection has been made. Certain triax-to-BNC adapters can accidentally ground, and a short circuit occurs if the triaxial portion of the adapter, which is held at high voltage, is not insulated; see Figure 18. To prevent electrical shock, the adapter is insulated with heat shrink insulator and secured in place so that movement of the instrument does not remove the insulator; see orange and white insulators in Figure 17. Effort is made to keep all signal connections out of the radiation beam when possible.

Figure 17 Test chamber voltage connection boxes.

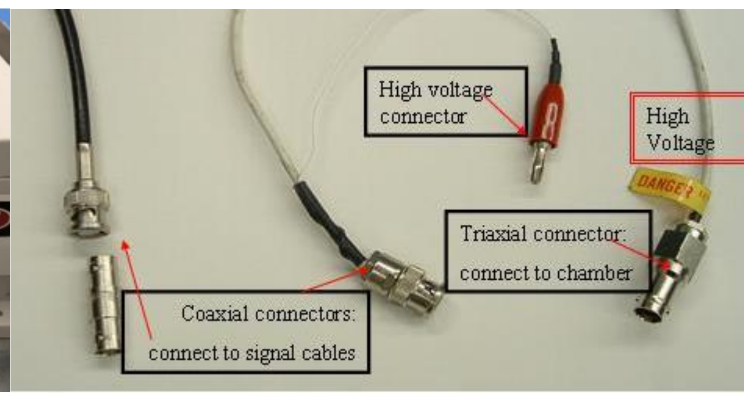


Figure 18 Chamber triax to BNC adapters

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

After a pre-irradiation of around 1000 seconds, background current measurements are taken prior to calibration. If the background current is elevated compared to the exposure reading, either the connector of the chamber is inspected and resecured, or the chamber is not calibrated. This is rarely the case, since customers are asked to verify the function of the chamber prior to shipment to NIST. A typical signal to noise ratio is 0.01 %. In addition, background current measurements are made at the time of calibration.

Environmental parameters

During all calibrations, the laboratory temperature must be maintained between 22 °C +/- 2 °C and stable to +/- 0.1 °C for typical measurement sets of 10 minutes. If the temperature is not stable during a typical measurement set, calibrations should be postponed. The laboratory humidity should be maintained between 20 % and 50 % relative humidity. Since the pressure is monitored and the charge data is normalized to pressure, it is good laboratory practice to postpone data collection and calibration work during sudden changes in pressure due to storms or weather fronts. If the pressure reading is stable during the calibration collection time, the measurements can continue. The pressure should be monitored and the influence on the normalization factor should be considered.

Set-up procedure using the alignment lasers

Prior to calibration, the position of the free-air ionization chamber (FAC) must be established and used to position the NIST QA chamber and the customer test chamber to the x-ray beam in use. The beam height alignment laser on the east wall is the position on the LPS that each chamber must be placed to verify the correct height. The laser on the LPS telescope stand is used to set the distance from the source. The defining point on the FAC aperture should be verified by the laser spot of the telescope stand laser. The center dot of the laser should shine on the alignment point of the FAC. Figure 19 shows all the alignment points on the standards with the laser dots. The telescope is used as a redundancy for positioning, see Figure 16. The cross-hair reticle of the telemicroscope is set to the defining plane of the appropriate free-air chamber prior to alignment of the test chambers. For the Wyckoff-Attix (50 kV to 300 kV) chamber, the defining plane is the white line on the aperture holder. For the Ritz (20 kV to 100 kV) chamber, the defining plane is exactly 15.00 mm beyond the white line on the aperture holder in the downstream direction from the x-ray source. For the Lamperti (10 kV to 20 kV) chamber, which has been dedicated to electronic brachytherapy calibrations, located in H116 but could still be used in the x-ray facility if needed, the defining plane is exactly 20.00 mm downstream from the source from the scribed line on the plastic insert that fits into the removable shield and touches the front face of the aperture. For the Attix (10 kV to 50 kV) chamber, the defining plane is the scribed line in the brass aperture holder.

Figure 19 Alignment points of standards, showing laser crosshair.

Once it is verified that the telescope alignment laser hits the defining point on the aperture and the cross-hair of the telescope is established, if required, the NIST QA chamber position T1 or T3 is translated to the beam height alignment laser. The NIST QA chamber is placed in a holder and the height laser beam is used to determine vertical and horizontal alignment. Adjustment of the NIST QA chamber position to the defining plane, distance from the source, is accomplished by use of the telescope alignment laser and also sighting through the telemicroscope that was previously aligned on the defining plane of the free-air chamber. Motorized slides are then used to adjust the NIST QA chamber reference point to the standard defining plane. Control of the motorized slides is accomplished using the corresponding hand operated control box located on the telemicroscope stand, see Figure 16. In general, all chambers should be aligned to the center of the test-chamber volume, but this should be verified with the customer. Most chambers are mounted perpendicular to the beam axis. If the chamber has a window, then it should be mounted such that the window faces the x-ray source. If a chamber has a reference line, then it should be used for alignment purposes. An identification mark or serial number should be used to reference the rotation with respect to the x-ray source. The alignment conditions, orientation and rotation of the chamber should be recorded in the calibration report. This process is then repeated for the customer chamber which will be placed in position T2 or T4 by translation of the LPS.

For large diameter chambers, larger than the field of view of the telescope, the use of the telescope to verify the position is more difficult. After centering the chamber on the alignment laser dots, the scale reading of the electronic telemicroscope and the diameter of the chamber can be used to verify the position. A further consideration in the setup for x-ray calibrations is the choice of an appropriate beam size. For this purpose, a parameter called the "beam size" is compared to the largest dimension of the active volume of the chamber. 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. For x rays, as opposed to high-energy gamma rays, this is of secondary importance because the chamber stem attenuates the radiation considerably. The beam size of the x-ray beams, for all beam-defining apertures for the vertical and horizontal beam positions, is determined using an Exradin A1 ion chamber, using the method described in the ISO4037. The ratio of the intensity as measured with the ion chamber of the center to the outer point of the useful beam should also change by less than 0.5 percent. Table 9 lists the possible beam sizes for each calibration range. The aperture defining beam size is set in the HDI software with the selection of the aperture in use. The operator must select a beam size that fully irradiates the chamber. Once selected, the same beam defining aperture is used for the FAC, the NIST QA chamber and the customer chamber.

Procedures for the calibration of chambers and collection of data

The following procedures are listed in numerical order. The actual order in which the steps are completed is required only where noted.

100 kV or 300 kV x-ray calibration range

1. Turn on the HDI controller using the key on the front panel. This energizes the communication junction box that controls all systems.

2. Turn on water supply and return for the 300 kV system. Failure to turn on water will result in an interlock error. The heat exchanger for the 100 kV system is a closed loop and energizes automatically during the Kimtron warmup procedure.

3. Follow the Procedure for the Use of the Kimtron; Appendix A.

4. Data entry in Access
   a. start Access and use C:\100-300 XRay Sys\100300 NIST Track Rev*current#*
   b. select the form tab
   c. select the switchboard option
   d. enter appropriate data under the customer, instrument and work order options

5. Start the HDI LabVIEW software using the provided shortcut for Rev*current#*.vi
   a. login by entering operator's initials (CMO) and the configuration code (456)
   b. select the range to use. The default is the 300 kV range; for the 100 kV range, click on the pink "300 x-ray system" selector key in the upper right of the front panel HDI software to toggle to the blue 100 kV system

6. Run the LPS vi, homing the x and y axes and secure LPS in the desired position and distance.

7. Mount chambers as described previously using the lasers and telescope for redundancy. Connect signal and high-voltage cables.

8. Verify that the correct filter wheel is mounted; if not, then repeat the homing procedure of the filter wheel and verify that the filter corresponds to the selection. If an M-series beam is being used on the 300 kV range, verify that the additional M-filtration was put in place.

9. Verify that all support equipment is energized.

10. Verify that the signal lead of the FAC in use is connected to the FAC electrometer.

11. Once the chambers are positioned and secured, apply high voltage to the test chamber and the NIST QA chamber. Enter the desired high voltage on the front panel display of the HDI software and flip the Bertan HV switch on. The voltage is maintained on the primary standards, but make a visual check that voltage is set on the Bertans and also that the 300 kV and the 100 kV FAC DC microampere meters

show applied voltage. See Figure 20 for the location and expected reading for the FACs. The mammography FAC does not have an independent meter and the application of voltage is assessed by performance. As the chamber bias of the FACs is well above the safe range for a hand-held voltmeter, never test the FAC bias at the required operating voltage. Select a lower voltage of nominally 100 volts to 300 volts.

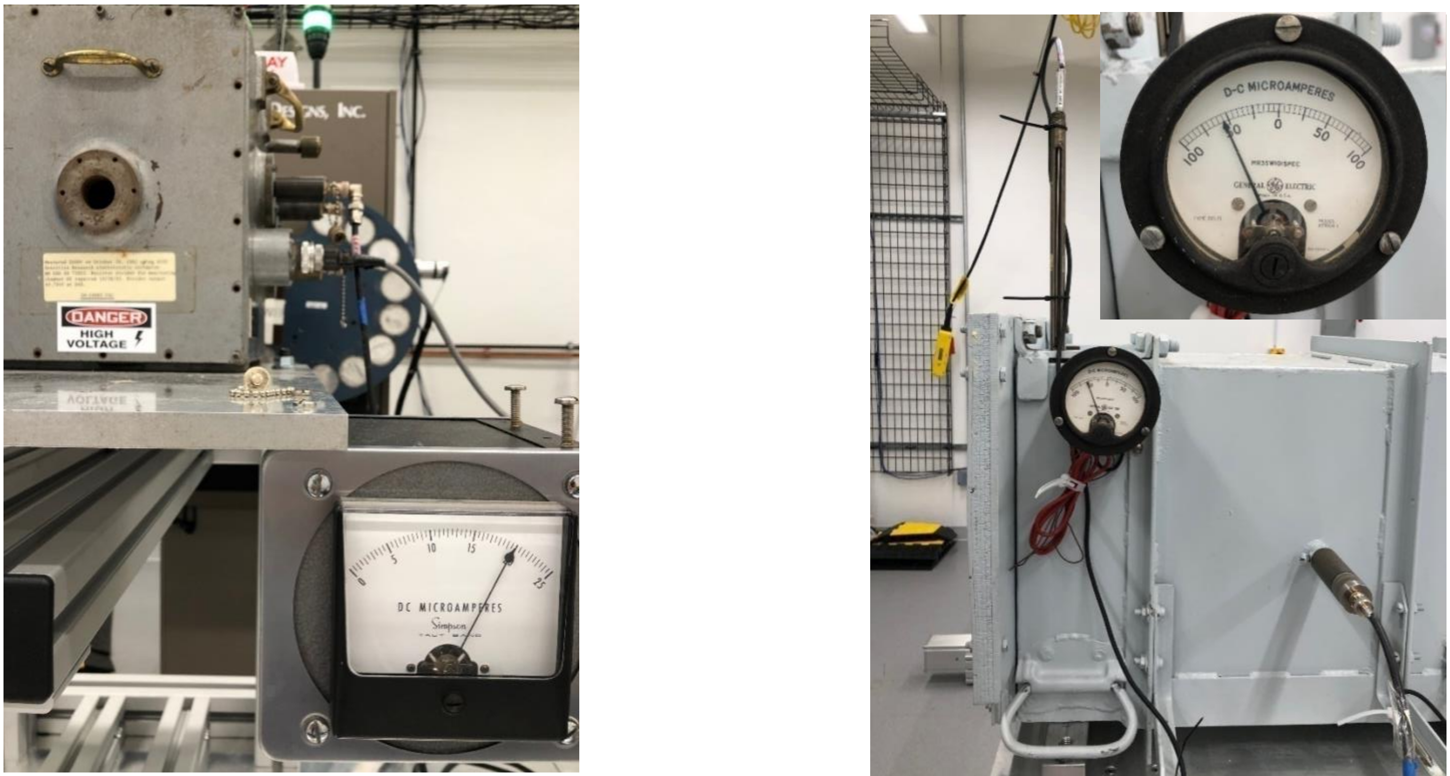


Figure 20 The Ritz (left) and Wyckoff-Attix (right) chamber meters showing voltage application.

12. Close the shielding door and set the LMO switch to allow the use of the x-ray beam.

13. Verify that the HDI software is communicating with the Kimtron generator

14. Verify the collection time so as to not overload the electrometers. This depends on the air-kerma rate for the beam quality. Put each chamber in the beam using the conditions for the calibration and establish the collection time. Press the "exposure enable" at the bottom of the screen so it is not red. Secure the interlocks for entrance to the rooms. Press the red "open" button on the HDI control panel to open the shutter. The time of the exposure will accumulate on the front panel of the HDI software.

15. Press "build sequence" to prepare an automated test sequence.

16. Enter the work order number of the previously entered data in Access. When the “get work order” button is selected, the background information for the customer chamber automatically is entered. The toggle switch for the customer chamber position should correspond to the position used.

17. Create a unique cal run ID.

18. Enter the pressure, temperature and humidity from the front-panel displays.

19. Enter the beam aperture selected, the diameter of the beam, and the distance of the calibration.

20. Enter the identification information of the NIST reference-class chamber to be calibrated.

21. Enter the desired collection times and the number of measurements to be collected.

22. Finally, select the beam codes, enter the currents and select the ISO Al filter if appropriate.

23. Upon completion, press “build sequence”.

24. At the front panel press “start auto sequence” to begin the calibration.

25. Upon completion of the calibration, review the data from the printed reports. If some data needs to be eliminated go to Access.

    a. open the “exphist” table and find the data points to delete. Place a check in the appropriate column to delete the data point.
    b. on the front panel of the HDI software select “Redo Report”. Enter the work order number and the unique cal run ID. Press “get records”. Select the appropriate beam code. Repeat until all data is recalculated.

26. A summary of the final data for both chambers is stored to an Access file named InstCalReport. Select the records desired and copy to an Excel spreadsheet to complete the summary calculations. The spreadsheet should be named by the DG number and stored in the locations as described below.

27. Repeat until a sufficient number of calibrations have been completed for each beam quality, typically three to five.

28. The expected standard deviation on the calibration results depends on the chamber type but, generally, a standard deviation near 0.1 % is acceptable.

29. The averages of multiple calibrations are maintained in the Excel spreadsheets. These Excel files are named by the DG number and saved as described in the electronic-data section of this manual.

30. The data is also 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. This verifies the quality of the calibration. The previous data is also in electronic form for comparison.

31. The summary data is then pasted into the Word or Excel templates for the calibration report. A sample report follows in Appendix B.

Mammo FAC steps

1. Turn on the HDI controller using the key on the front panel. This energizes the communication junction box that controls all systems.

2. The heat exchanger for the mammography system is a closed loop and energizes automatically during the Kimtron warmup procedure.

3. Follow the Procedure for the Use of the Kimtron; Appendix A., selecting the Mo or Rh tube.

4. Run the LPS vi, homing the x and y axes and secure LPS in the desired position and distance.

5. Mount chambers as described previously using the lasers and telescope for redundancy. Connect signal and high-voltage cables.

6. Verify that the Attix chamber's moveable alignment slide is in the position furthest from the source.

7. Verify that the Attix chamber is locked in the air-kerma position.

8. Verify power is on all instruments visible from the control area. These include four Keithley electrometers, four Bertan high-voltage supplies, three Hart thermometers and a Setra barometer.

9. Start the HDI LabVIEW software using the provided shortcut for Rev*current#*.vi

10. Once the chambers are positioned and secured, apply high voltage. Enter the desired high voltage on the front panel display of the HDI software and flip the Bertan HV switch on. The voltage is maintained on the primary standards, but make a visual check that voltage is set.

11. Close door to range so that the safety interlocks will allow the opening of the x-ray shutter.

12. Data entry in Access
    a. start Access and use C:\100-300 XRay Sys\100300 NIST Track Rev*current#*
    b. select forms
    c. select switchboard
    d. enter appropriate data under the customer, instrument and work order forms

13. Verify the collection time, so as to not overload the electrometers. This depends on the air-kerma rate for the beam quality. Put each chamber in the beam using the conditions for the calibration and establish the collection time. Press the "exposure enable" at the bottom of the screen so it is not red. Secure the interlocks for entrance to the rooms. Press the red "open" button on the HDI control panel to open the shutter. The time of the exposure will accumulate on the front panel of the HDI software.

14. Press "build sequence" to prepare an automated test sequence.

15. Enter the work order number of the previously entered data in Access. When the "get work order" button is selected, the background information for the customer chamber automatically is entered. The toggle switch for the customer chamber position (T3 or T4) must correspond to the correct position.

16. Create a unique cal run ID.

17. Enter the pressure, temperature and humidity from the front-panel displays.

18. Enter the beam aperture selected, the diameter of the beam, and the distance of the calibration.

19. Enter the identification information of the NIST reference-class chamber to be calibrated.

20. Enter the desired collection times and the number of measurements to be collected.

21. Finally, select the beam codes.

22. Upon completion, press "build sequence".

23. At the front panel press "start auto sequence" to begin the calibration.

24. Upon completion of the calibration, review the data from the printed reports. If some data needs to be eliminated, go to Access.
   a. open the "exphist" table and find the data points to delete. Place a check in the appropriate column to delete the data point.
   b. on the front panel of the HDI software select "Redo Report". Enter the work order number and the unique cal run ID. Press "get records". Select the appropriate beam code. Repeat until all data is recalculated.

25. A summary of the final data for both chambers is stored to an Access file named InstCalReport. Select the records desired and copy to an Excel spreadsheet to complete summary calculations. The spreadsheet should be named by the DG number and stored as described in the electronic-data section of this manual.

26. Repeat until a sufficient number of calibrations have been completed for each beam quality, typically three to five.

27. The expected standard deviation on the calibration results depends on the chamber type but generally a standard deviation less than 0.5 % is acceptable.

28. The averages of multiple calibrations are maintained in the Excel spreadsheets. These Excel files are named by the DG number and saved as described in the electronic-data section of this manual.

29. The data is also 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. This verifies the quality of the calibration.

30. The summary data is then pasted into the Word or Excel templates for the calibration report. A sample report follows in Appendix B.

Electronic data

All data collected with the NIST reference-class chambers is saved in the appropriate files located in the group server in the *x-ray\chamberhistory* folder. The folder to be used is either *NISTREFSTD* or *NISTREFSTDMAMMO*, depending on which type of chamber is used. The files are organized and named by model and serial number. The group server is backed up routinely.
Similarly, the data collected using the customer chamber and the associated files and the final calibration report is saved in the group server: *L:\internal\846.02\x-ray\calibrationreports\allcustomerdata*. Paper copies of the reports are kept in H127, as described in the administrative procedure section. All collected raw data is stored in the Access database mentioned in the above procedure, C:\100-300 XRay Sys\100300 NIST Track Revcurrent# on the Labview data acquisition system.

In-house calibration checks and traceability

The long-term reliability of NIST dosimetry calibrations depends on the stability of the NIST air-kerma standards. For x rays, the NIST air-kerma standard is the response of the appropriate free-air chamber. The four free-air chambers are also periodically compared. The in-house calibration checks are intended to check both the stability of the NIST standards and the reliability of the calibration procedures. Comparison results are listed in Ref. 6 and in published reports. References 10-20 are the most recent published comparisons which establish and demonstrate traceability of air-kerma.

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 as 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 0.5 % but dependent on the chamber type, an investigation is warranted. If 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. Any discrepancy found for a NIST check chamber of the order of magnitude mentioned above 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.

Uncertainty Analysis

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 (i.e., 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 a coverage factor of two (k=2) to give the expanded uncertainty. This expanded uncertainty is considered to have the approximate significance of a 95 % confidence limit. Table 10 lists the details of the assessment of uncertainty for the air-kerma rates determined for the tungsten x-ray beams by the free-air ionization chambers. Table 11 lists the details of the assessment of uncertainty in the calibration of a typical ionization chamber. Table 12 lists the details of the assessment of uncertainty in air-kerma rates determined for the mammography x-ray beams by the Attix chamber. Table 13 lists the uncertainty components for the calibration of instruments used for mammography. As the estimate of uncertainty varies slightly with beam qualities, methods of measurement, and rate, in each case the largest value is used for the estimate. In an official calibration, measurements could be repeated to maintain optimal conditions.

Safety

As described below, every effort is made to avoid any possibility of radiation exposure to lab occupants, 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. There is no danger of high voltage related to the x-ray generators because the equipment has no exposed high voltage in a normal operating mode. The potential risk from the motion control associated with the LPS is addressed through various indicators, fully explained in the safety protocol, and shown below in the visual explanation of safety features. Risks due to trip hazards are reduced by secure floor cable ramp protectors and the reduction of occupancy to properly trained personnel.

High-voltage safety

The only danger that exists from high voltage comes from the free-air ionization chambers, the customer chamber, and the x-ray-calibration-range monitor 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. The risk of high voltage from the Attix chamber is minimized by surrounding the chamber with its protective cover.

Radiation safety

The radiation area is marked with the proper signs and a dosimeter must be worn by all personnel. Radiation safety training and assessment services are provided by the NIST Gaithersburg Radiation Safety Division. The x-ray range, H127-3 was designed to eliminate any possible exposure to x radiation. Details are listed in the safety protocols for each x-ray system. The entrance, shielding door features a pair of ISO13849-1 "PL-e" rated safety switches, with independent feedback to an equally rated multifunction safety relay. This is the highest degree of machine safety rating, intended for systems which could cause instant death or dismemberment in the event of a failure, thus exceeding the facility safety requirements. Additionally, a LMO "Last Man Out " wall switch is present for the search and evict sequence to be performed prior to closing the door relay. Scram buttons are on the control panel and in the experiment room, any of which, in an unsafe state, will break the electrical circuit which allows the shutter air solenoid to energize forming a hardware interlock system independent of software control. Additionally, the high voltage from the generator will be deenergized. Hardware interlocks include an enable key for the shutter system and for high voltage production from each generator. The shared interlock monitoring PLC for the room also monitors these key signals to ensure that shutters close. For a further understanding of the safety features, a visual explanation is provided for the radiation safety lights and the motion control in the x-ray calibration range.

Visual Explanation of Various Safety Lights in H127-3

Shutter indicator light

Power on x-ray system indicator light

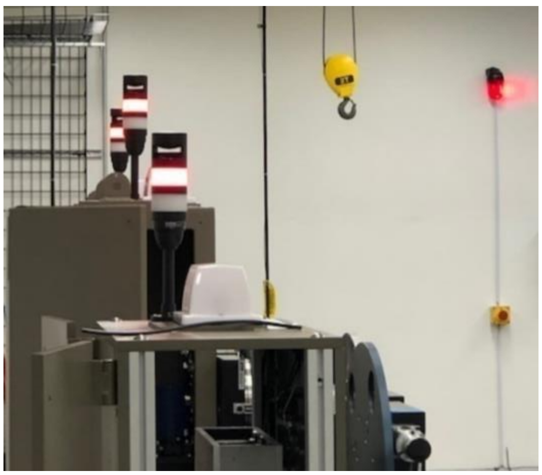
The H127-3 door "x-ray on" light illuminates when power is on the x-ray tube. The H127-3 door "Danger High Radiation Area" light illuminates when the shutter is open.

Location of lights next to the shielding door for H127-3

When HDI controllers are energized, the calibrator status lights are green when the shutters are closed.

Calibrator status lights, showing green when shutters are closed

Calibrator status lights visible through the lead glass window



Calibrator status lights showing red

Calibrator status lights glow red when shutter is open. This picture was taken during installation so the condition of being inside H127-3 with the red status lights is not achievable in normal operation.

Calibrator "x-ray on" light illuminates when the generator is energized

EMO red status light on NORTH wall glows red when shutter is open.

Visual Explanation of Motion Control Safety Features in H127-*3*

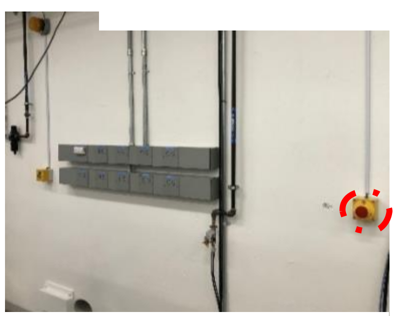
Hand control LPS motion controller with EMO button on telescope stand

Telescope stand with motion control and EMO

North wall EMO and shutter open indicator light

EMO ready position

East wall EMO



West wall EMO

South wall EMO

Filing and Retention

The administrative procedures section describes the handling of the calibration reports. The electronic data section describes the organization of the electronic data files.
The RPD Quality Manager shall maintain the original and all past versions of this RPD Procedure. Copies of the current revision of this Procedure shall be placed in controlled Quality Manuals. Electronic copies of this Procedure are uncontrolled versions.

Table 1. NIST Calibration Conditions for X-Ray Measuring Instruments

NIST Calibration Conditions for X-Ray Measuring Instruments

Beam code	Additional filtration [a]				Half-value layer[b] (HVL)		Homogeneity coefficient (HC)		Effective energy (keV)
	Al (mm)	Cu (mm)	Sn (mm)	Pb (mm)	Al (mm)	Cu (mm)	Al	Cu	
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				1.68	0.052	63	60	
M80	2.86				3.08	0.1	67	61	
M100	5.25				5.10	0.2	74	55	
M120	7.12				6.77	0.31	76	53	
M150	5.25	0.25			10.30	0.66	86	63	
M200	4.35	1.12			14.73	1.64	94	68	
M250	5.25	3.2			18.49	3.2	98	85	
M300	4.25		6.5		21.77	5.3	99	97	
H10	0.105				0.051		77		
H15	0.5				0.16		87		
H20	1.01				0.36		89		
H30	4.50				1.2		86		
H40	4.53	0.26			2.93		94		
H50	4.0			0.1	4.16	0.14	92	93	38
H60	4.0	0.61			6.06	0.25	92	94	46
H100	4.0	5.2			13.51	1.15	98	92	80
H150	4.0	4.0	1.51		16.93	2.43	99	96	120
H200	4.0	0.6	4.16	0.77	19.72	4.1	99	99	166
H250	4.0	0.6	1.04	2.72	21.59	5.19	99	98	211
H300	4.1		3.0	5.0	23.55	6.19	98	98	252
S60	4.35				2.81	0.09	74	66	
S75	1.50				1.81		58		

[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 x-ray tubes were installed in 2008 and 2015.

Table 2. Mammography X-Ray Beam Quality[a] Parameters

Beam code	Tube voltage (kV)	Additional filtration[b] (mm)	Half-value layer (mm Al)
Mo Anode[c]			
Mo/Mo23	23	0.032 Mo	0.288
Mo/Mo25	25	0.032 Mo	0.313
Mo/Mo28	28	0.032 Mo	0.346
Mo/Mo30	30	0.032 Mo	0.370
Mo/Mo35	35	0.032 Mo	0.404
Mo/Rh28	28	0.029 Rh	0.420
Mo/Rh32	32	0.029 Rh	0.453
Mo/Mo25x	25	0.030 Mo + 2.0 Al	0.551
Mo/Mo28x	28	0.030 Mo + 2.0 Al	0.589
Mo/Mo30x	30	0.030 Mo + 2.0 Al	0.633
Mo/Mo35x	35	0.030 Mo + 2.0 Al	0.715
Rh Anode			
Rh/Rh25	25	0.029 Rh	0.351
Rh/Rh30	30	0.029 Rh	0.438
Rh/Rh35	35	0.029 Rh	0.512
Rh/Rh40	40	0.029 Rh	0.559
Rh/Rh30x	30	0.029 Rh + 2.0 Al	0.814
Rh/Rh35x	35	0.029 Rh + 2.0 Al	0.898

[a] Kessler, C., Burns, D.T. and O'Brien, M., "Key comparison BIPM.RI(I)-K7 of the air-kerma standards of the NIST, USA and the BIPM in mammography x-rays," Metrologia **48** 06014 (2011).
[b]The additional filtration value does not include the inherent filtration, which is comprised of 1.0 mm Be from the x-ray tube window and 0.075 mm polyamide from the transmission monitor.
[c]The HVL values were measured directly using the Mo anode installed in Dec 2008.

Table 3a. ISO X-Ray Beam Quality Parameters Offered at NIST

Beam code	Additional filtration (mm)[a]				First HVL[b]		Second HVL	
	Al	Cu	Sn	Pb	mm Al	mm Cu	mm Al	mm Cu
HK10					0.042		0.045	
HK20	0.15				0.128		0.170	
HK30	0.52				0.408		0.596	
HK60	3.19					0.079		0.113
HK100	3.90	0.15				0.298		0.463
HK200		1.15				1.669		2.447
HK250		1.60				2.463		3.37
HK280		3.06				3.493		4.089
HK300		2.51				3.474		4.205
WS60		0.3				0.179		0.206
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				0.049		0.061	
NS15	0.49				0.153		0.167	
NS20	0.90				0.324		0.351	
NS25	2.04				0.691		0.762	
NS30	4.02				1.154		1.374	
NS40		0.21				0.082		0.094
NS60		0.6				0.241		0.271
NS80		2.0				0.59		0.62
NS100		5.0				1.14		1.19
NS120		4.99	1.04			1.76		1.84
NS150			2.50			2.41		2.57
NS200		2.04	2.98	1.003		4.09		4.20
NS250			2.01	2.97		5.34		5.40
NS300			2.99	4.99		6.17		6.30
LK10	0.30				0.061			
LK20	2.04				0.441			
LK30	3.98	0.18			1.492			
LK35		0.25			2.21			
LK55		1.19				0.260		
LK70		2.64				0.509		
LK100		0.52	2.0			1.27		
LK125		1.0	4.0			2.107		2.094
LK170		1.0	3.0	1.5		3.565		3.592
LK210		0.5	2.0	3.5		4.726		4.733
LK240		0.5	2.0	5.5		5.515		5.542

[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; for all other techniques the inherent filtration is adjusted to 4 mm Al. Details of these reference radiation qualities can be found in the following: ISO/IS 4037-1:1996(E) X and Gamma Reference Radiations for Calibrating Dosimeters and Dose Rate Meters and for Determining Their Response as a Function of Photon Energy - Part 1; Radiation Characteristics and Production Methods. [b]The x-ray tubes were installed in 2015 and 2008.

Table 3b. CCRI[a] X-Ray Beam Quality Parameters Offered at NIST

Beam code	Tube voltage (kV)	Added filtration[b] (mm Al)	(mm Cu)	Half-value layer[c] (mm Al or mm Cu)
BIPM25	25	0.373		0.24 mm Al
BIPM30	30	0.208		0.167 mm Al
BIPM40	40	3.989	0.212	2.649 mm Al
BIPM50a	50	3.989		2.291 mm Al
BIPM50b	50	1.007		1.038 mm Al
BIPM100	100	3.248		0.149 mm Cu
BIPM135	135	1.060	0.265	0.496 mm Cu
BIPM180	180	3.842	0.482	1.003 mm Cu
BIPM250	250	3.842	1.618	2.502 mm Cu

[a]BIPM, Qualités de rayonnements, Consultative Committee for Ionizing Radiation (CCEMRI) (Section I), 1972, 2, R15. Details of these reference radiation qualities can be found in: Burns, D.T. and O'Brien, M., "Comparison of the NIST and BIPM Standards for Air Kerma in Medium-Energy X-Rays," J. Res. Natl. Inst. Stand. Technol. 111, 385-391(2006) and Burns, D.T., Kessler, C. and O'Brien, M., "Key comparison BIPM.RI(I)-K2 of the air-kerma standards of the NIST, USA and the BIPM in low-energy x-rays," *Metrologia* **49** 06006 (2012).
[b]The additional filtration does not include the inherent filtration of the x-ray tubes which is approximately 3 mm Be and 1 mm Be.
[c]The HVL values were determined for the tubes installed in 2015 and 2008.

Table 4. Important dimensions and parameters for the use of the NIST standard free-air ionization chambers.

Chamber (alternative name)	X-ray tube potential (kV)	Alignment offset[a]	Operating potential (v)	Diaphragm diameter/ID (mm)	Air absorption length (mm)
Lamperti[b]	10 to 60	20 mm	1500	4.994/5s	39.18
Attix (Mammo)	10 to 50	None	2500	10.00/10u	212.7[c]
Ritz (LE or 100 kV)	20 to 100	15 mm	5000	10.00/10A	127.39
Wyckoff-Attix (HE or 300 kV)	50 to 300	None	5000	10.00/10B	308

[a] The distance down-stream from the chamber aperture to move the alignment telescope to properly align the chamber.
[b] The Lamperti Chamber is dedicated for use in Electronic Brachytherapy calibrations but has been established for use in low energy x-rays.
[c]This is variable; the value shown is used for routine use.

Table 5. Features of x-ray systems.

Features	Unipolar[a]	Bipolar[b]	Mammography[c]	Mammography[d]
Generator manufacturer	Kimtron	Kimtron	*Kimtron*	*Kimtron*
Calibrator	HDI Model X80-100A-SP	HDI Model X80-320kVA-SP	HDI Model X82-100-Mo-Rh-A-Sp	HDI Model X82-100-Mo-Rh-A-Sp
Output voltage (kV)	7.5-180 kV	20-360 kV	7.5-180 kV	7.5-180 kV
Output current (mA)	0 to 45 mA	0 to 30 mA	0 to 45 mA	0 to 45 mA
Output power (kW)	4,5	4,5	4,5	4,5
kV adjustment (kV)	0.1	0.1	0.1	0.1
mA adjustment (mA)	0.1	0.1	0.1	0.1
Tube manufacturer	Thales	Comet	Lohmann	RTW
Fixed anode material	W	W	Rh	Mo
Tube window (mm Be)	1	3	1	1
Focal spot size (mm)	5.5 x 5.5	5.5 x 5.5	5 x 5	3 x 3

[a] Tube installed in November 2008.
[b] Tube installed in May 2015.
[c] Rh tube installed in 1994.
[d] Mo tube in 2008

Table 6. Essential equipment to conduct calibrations in the x-ray range located in H127.

Description	Model	Serial number	Use
300 kV Free-air chamber	Wyckoff- Attix	none	FAC
100 kV Free-air chamber	Ritz	none	FAC
Mammography Free-air chamber	Attix	none	FAC
Transmission monitor chamber	PTW 34014	0024	300kV
Transmission monitor chamber	PTW 34014	0023	100kV
Transmission monitor chamber	PTW 34014	072	Mammo
Oenoke voltage divider	PN OE-908-160-V		100 kV
Oenoke voltage divider	PN OE-908-160-V		Mo kV
HP high-precision digital voltmeter	3456A	2201A11673	meter test
HP high-precision digital voltmeter	HP34401A	US36043465	divider
HP high-precision digital voltmeter	HP34401A	US36043467	divider
HP high-precision digital voltmeter	HP34401A	US36037412	divider
HP high-precision digital voltmeter	HP34401A	US36037414	divider
High-voltage power supply EDC	09417	FC51033	divider
Agilent	34411A	48000105	backup
Setra barometer	370	498554	DAS
Setra barometer	370	3318085	backup
Wallace-Tiernan barometer	FA139	MM14869	QA check
Wallace-Tiernan barometer	FA139	XX11242	Lab reference
Bertan high-voltage power supply	Series 23005R	9188	Wyckoff-Attix
Bertan high-voltage power supply	Series 22501R	7192	Test 2
Bertan high-voltage power supply	Series 22505R	70982	Test 1
Bertan high-voltage power supply	Series 22505R	4183	Ritz
Bertan high-voltage power supply	Series22501R	7191	PTW
Bertan high-voltage power supply	Series 22503R	6252	Test 4
Bertan high-voltage power supply	Series 22503R	04024	Test 3
Bertan high-voltage power supply	Series 22505R	4172	Attix
Keithley electrometer	617-HIQ	06463833	PTW
Keithley electrometer	6512	0664956	FAC
Keithley electrometer	6512	0762177	test 1

Keithley electrometer	6512	0664959	test 2
Keithley electrometer	617	0566314	test 3
Keithley electrometer	617	388587	test 4
Keithley electrometer	6514	1466987	All FAC backup
Hart thermometer Chub-E4 and 4 probes	1529/ PT1000	A1B165/ #1N31P300606 #2N31P300603 #3N31P300604 #4N31P300605	#1Wyckoff-Attix FAC #2Ritz FAC #3 test1/2 #4 test3/4
Hart thermometer and probe	1502/ PT1000	62495/ N31P300608	PTW
Hart thermometer and thermistor	1504/5611	C11444/ RC-201031284	backup
Fluke thermometer and probe	1502A/5613 PT1000	A63236/763272 N31P300609	Attix backup
Fluke thermometer and probe	1504/5610-6	A95694/A932006	Lab reference
300 kV generator	Polaris III 360kV	C360-100080	Cathode -
300 kV generator	Polaris III 360kV	A360-100080	Anode +
100 kV generator	Polaris III 180kV	C180-100079	100 kV
Rh generator	Polaris III 180kV	C180-100085	Rh tube
Mo generator	Polaris III 180kV	C180-100086	Mo tube
Thales x-ray tube	THX160/1055	581082	100 kV
Comet x-ray tube	MXR-320/26	415574	300 kV
Rhodium x-ray tube	Lohmann 84005	047	Rh kV
Molybdenum x-ray tube	RTW MCD-100H-3MO	6464	Mo kV
Kimtron Polaris water cooler	3500-WA	11798-01-20WA	Mo/Rh
Kimtron Polaris water cooler	3500-WA	11796-12-19WA	100 kV
GE water cooler	OW4002	115001	300 kV
Hopewell Designs, Inc. controller		NIST#585204 & NIST#583270	

Electronic rack		NIST#585799	
HDI Calibrator 320 kV	HDI X80-320-A-SP	0521-5406	300 kV
HDI Calibrator 100 kV	HDI X80-100-A-SP	0521-5405	100 kV
HDI Calibrator Mammo	HDI X80-100-A-SP	0521-5407	Mo/Rh
Linear Positioning System (LPS)	HDI T20-2-X3-Y4	0521-5408	

Table 7. Example of the optional checklist for calibration order details

Calibration Information Request Form			
Required Dates		**Optional Dates**	
PO received		Estimated job start	
Estimated completion		Equipment arrival	
Report mailed		Inspection complete	
Equipment returned			

Contact Information
NIST Technical Contact: **Csilla Szabo-Foster x4334**
Company:
Technical Contact:
DG Number:

Instrument Description		
Manufacturer	Model	Serial Number

Calibration Request and Cost				
SP 250 Cal ID/SKU **46011C**	Item Description **X-Ray Calibration**	Qty	Cost for this Cal ID **$**	**TOTAL**

Table 9. Nominal calculated beam sizes

Distance from source (cm)	Beam defining aperture (cm)	Diameter at measurement point (cm)
300 kV X-Ray Calibrator		
100	1.27	4
	1.90	7
	2.54	10
	5.08	22
200	1.27	7
	1.90	14
	2.54	20
	5.08	44
100 kV X-Ray Calibrator		
100	1.27	4
	1.90	7
	2.54	10
Mammography X-Ray Calibrator		
100	1.27	4
	2.54	10

Table 10. Typical uncertainty analysis for tungsten x-ray air-kerma rates, relative uncertainties shown in %.

Uncertainty components	Type A	Type B
air density	0.01	0.07
charge	0.1	0.06
humidity		0.03
volume	0.04	0.01
g		0.02
W/e		0.35
air attenuation, k_a	0.05	0.02
electric field distortion, k_d		0.2
initial ion·mean energy per ion pair, $k_{ii}k_w$		0.05
electron loss, k_e		0.1
penetration of aperture, k_l		0.04
penetration of chamber face, k_p		0.01
polarity difference	0.05	
recombination loss, k_s	0.1	
fluorescence, k_{fl}		0.03
scattered photons, k_{sc}		0.07
quadratic sum	0.163	0. 439
combined standard uncertainty	0.469	
expanded uncertainty	0.937	

Table 11. Uncertainty analysis for x-ray calibrations, shown in %

Uncertainty components	Type A	Type B
air-kerma rate	0.163	0.439
air density	0.01	0.07
charge	0.1	0.06
distance	0.01	
humidity		0.03
radiation background		
quadratic sum	0.192	0.450
combined standard uncertainty	0. 489	
expanded uncertainty	0.978	

Table 12. Uncertainty analysis for air-kerma rates with the Attix chamber, shown in %

Uncertainty components	Type A	Type B
air density	0.010	0.070
charge	0.120	0.060
humidity		0.030
g		0.020
W/e		0.35
air attenuation, k_a	0.050	0.010
ion pair mean energy $k_{ii}k_w$		0.11
aperture area	0.010	0.010
plate separation	0.010	0.070
electron loss		0.05
recombination loss, k_s	0.060	
scattered photons, k_p		0.07
polarity	0.1	
quadratic sum	0.162	0.396
combined standard uncertainty	0.428	
expanded uncertainty	0.856	

Table 13. Uncertainty analysis for mammography calibrations, shown in %

Uncertainty Components	Type A	Type B
air density	0.01	0.07
air kerma	0.162	0.396
charge	0.1	0.06
humidity		0.03
distance		0.02
quadratic sum	0.191	0.408
combined standard uncertainty	0.451	
expanded uncertainty	0.902	

REFERENCES

1. Marshal, J.L.,ed. NIST Calibration Services Users Gide, NIST (U.S.) Spec. Publ. 250; 1998 January.

2. Boutillon, M. and Perroche-Roux, A.M., Re-evaluation of the W value for electrons in dry air, Phys. Med. Biol., 32, 213-219 (1987).

3. Wyckoff, H. O. and Attix, F. H., Design of free-air ionization chambers, National Bureau of Standards Handbook 64, 1957.

4. Ritz, V. H., Standard free-air chamber for the measurement of low energy x rays (20-100 kilovolts-constant-potential), J. Res. Nat. Bur. Stand. (U.S.), 64C, 49-53 (1960).

5. Lamperti, P. J. and Wyckoff, H. O., NBS free-air chamber for measurement of 10 to 60 kV x rays, J. Res. Nat. Bur. Stand. (U.S.), 69C, 39-47 (1965).

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

7. Attix, F. H.,"Electronic equilibrium in free-air chambers and a proposed new chamber design," Naval Research Laboratory Report No. 5646, 1961.

8. Coletti, J.G., Pearson, D. W. and DeWerd, L.A., "Mammography exposure standards: Design and characterization of free-air ionization chamber," Rev. Sci Instrum. 66, 2574-2577 (1995).

9. Coletti, J. G., Pearson, D. W., DeWerd, L.A., O'Brien, C. M. and Lamperti, P.J. "Comparison of exposure standards in the mammography x-ray region," Med. Phys. 24(8), 1263-1267 (1997).

10. Burns, D.T., Lamperti, P. and O'Brien, M., "Comparison of the NIST and BIPM Air-Kerma Standards for Measurements in the Low-Energy X-Ray Range," J.Res. Natl. Inst. Stand. Technol. 104, 135 (1999).

11. Burns, D.T.,and O'Brien, M,.et.al "Comparison of the NIST and BIPM Medium-Energy X-Ray Air-Kerma Measurements," J.Res. Natl. Inst. Stand. Technol. 108, 383-389 (2003).

12. Burns, D.T.,and O'Brien, M,. "Comparison of the NIST and BIPM Standards for Air Kerma in Medium-Energy X-Rays," J.Res. Natl. Inst. Stand. Technol. 111, 385-391 (2006).

13. Büermann, L., O'Brien, M., Butler, D., Csete, I., Gabris, F., Hakanen, A., Lee, J-H., Palmer, M., Saito, N. and de Vries, W. , "Comparison of National Air Kerma Standards for ISO 4037 Narrow Spectrum Series in the Range 30 kV to 300 kV," Metrologia **45** 06013 (2008).

14. O'Brien, M. and Büermann, L.,"Comparison of the NIST and PTB Air-Kerma Standards for Low-Energy X-Rays," J. Res. Natl. Inst. Stand. Technol. **114**, 321-331 (2009).

15. O'Brien, M., Minniti, R. and Masinza, M., "Comparison Between the NIST and the KEBS for the Determination of Air Kerma Calibration Coefficients for Narrow X-Ray Spectra and ^{137}Cs Gamma-Ray Beams," J. Res. Natl. Inst. Stand. Technol. **115**, 7-13 (2010).

16. Burns, D.T., Kessler, C. and O'Brien, M., "Key comparison BIPM.RI(I)-K2 of the air-kerma standards of the NIST, USA and the BIPM in low-energy x-rays," Metrologia **49** 06006 (2012).

17. Kessler, C., Burns, D.T. and O'Brien, M., "Key comparison BIPM.RI(I)-K7 of the air-kerma standards of the NIST, USA and the BIPM in mammography x-rays," Metrologia **48** 06014 (2011).

18. Seltzer, S.M., O'Brien, M. and Mitch, M.G., "*New National Air-Kerma Standard for Low-Energy Electronic Brachytherapy Sources*," J. Res. Natl. Inst. Stand. Technol. Volume **119** (2014).

19. M O'Brien, J McCaffrey, H Shen, M Saraví, A Stefanic, G Montaño Ortiz, M Carlos, C da Silva, J Álvarez and V Tovar, "SIM.RI(I)-K3 comparison of calibration coefficients at radiotherapy level for orthovoltage x-ray beams," Metrologia 52 06015, Tech. Suppl., (2015).

20. D. T. Burns et al, "Key comparison BIPM.RI(I)-K3 of the air-kerma standards of the NIST, USA and the BIPM in medium-energy x-rays," Metrologia **54** 06006 (2017).

Appendix A: Procedure for the Use of the Kimtron X-ray Generators Outside the HDI Automated Control Interface

System Initialization

1) Power on the HDI control computer, located in the instrument control console of H127. Use the screensaver password to unlock. This computer is not connected to the internet.

2) Verify all four x-ray tube position keys are in position **OFF**.
3) Turn on the POWER key in the bottom right corner of the HDI controller, as shown in picture. The HDI power switch enables the system and starts the controller.

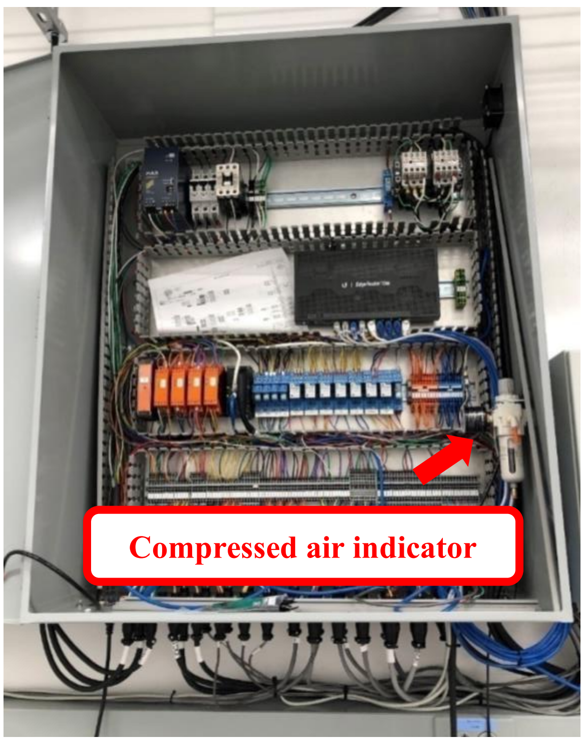
4) In the x-ray range room, H127-3, verify that the status lights on the HDI x-ray tube cabinets/calibrators are green to indicate system status as ready and safe. This indicates safe entrance and that the tube shutters are all closed.

Energize the X-ray System

5) In the equipment room, H127-2, turn on the power breaker of the generator in use, these are labeled as follows: HE (300 kV), LE (100 kV), Mo and Rh.

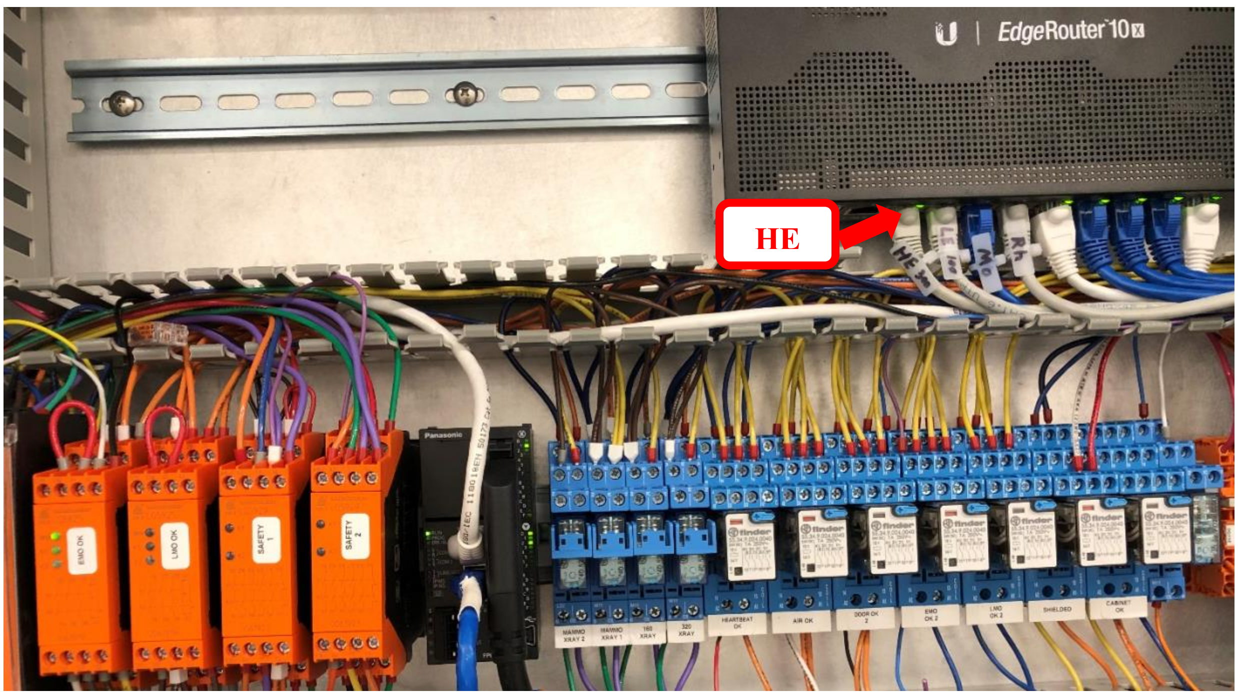
6) In H127-2, verify that the Interlock Control junction box is energized. The interlock junction box is towards the center of the room.

7) Inside the Interlock box, verify that the compressed air indicator light is NOT RED. A red light indicates no air pressure. The air pressure should be in the safe green range of approximately 80 psi.



8) On the HDI key control, turn the key to STANDBY of the x-ray system in use. The generator and heat exchanger will energize automatically as the key is switched to STANDBY.

9) Once the tube position key is in standby mode, the corresponding green light on the Edge Router in the interlock junction box illuminates. In this picture the HE tube is selected.

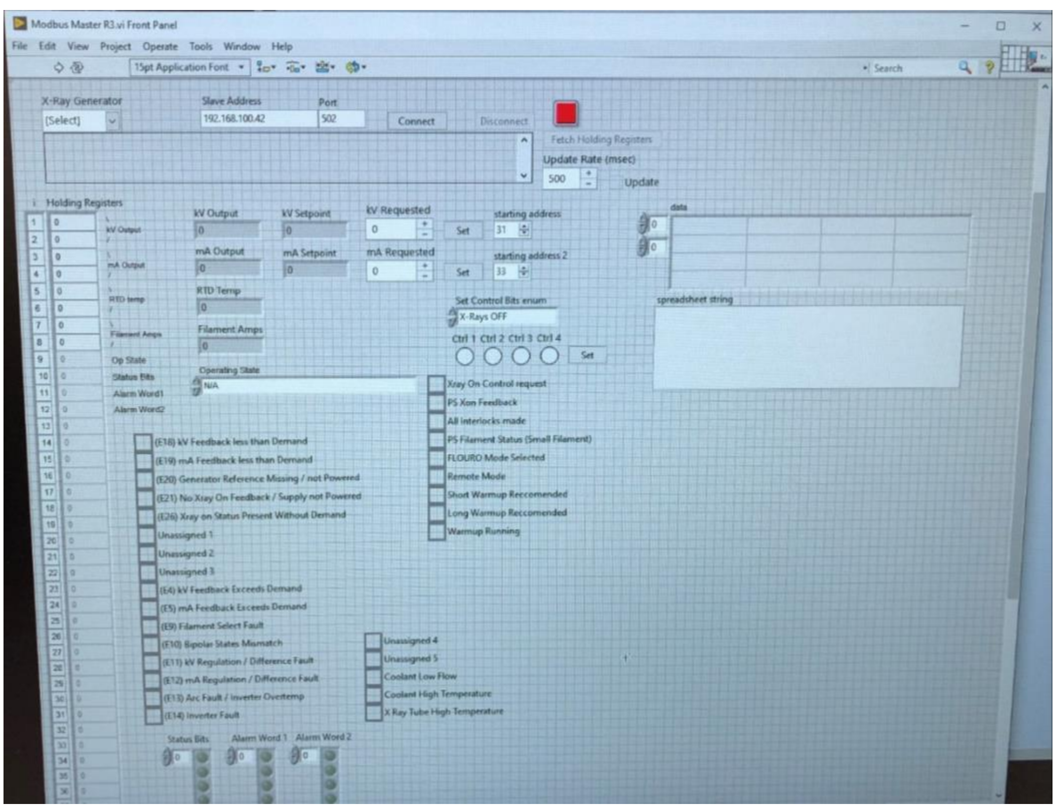


10) In the x-ray range, H127-3, after verifying the room is empty of all persons, the Last Man Out (LMO) button must be pressed, prior to closing the door. Press the LMO, which will have an audible alarm and flashing yellow light. Then the door must be closed within 40 seconds.

11) Open the Kimtron vi found on the desk top screen of the HDI computer. Once opened, the name is Modbus Master R3.vi Front Panel.
12) In the Slave Address entry, change the suffix place, shown here as ##, 192.168.100.##, to the corresponding system in use: **HE** 192.168.100.**41**, **LE** 192.168.100.**42**, **Mo** 192.168.100.**43** and **Rh** 192.168.100.**44.** ***Initializing*** appears in comment box.
13) Select ***connect***. ***Connected*** appears in text box.
14) Select ***update***.
15) In the Set Control Bits Enum selector, chose ***long warmup***.
16) Turn tube selector key to the on (**HV ENABLE)** state.

17) In the Operating State box confirm ***ready***.
18) In the Set Control Bits Enum selector, chose ***x-ray on***.
19) X-ray door lights illuminate when power is on x-ray tube during warmup.

20) Turn the key to **STANDBY** mode after warmup.
21) The door ***x-ray on*** light goes off when key is in **STANDBY**.
22) When prepared for x-ray use, turn the key to **HV ENABLE**.
23) In the Set Control Bits Enum selector, chose ***x-ray off*** then ***x-ray on***.
24) Enter desired x-ray kV and mA in the ***request*** entry boxes and select ***set***.
25) At completion of use, select ***x-ray off*** and turn key to **STANDBY**.
26) Deselect ***update***. Select ***disconnect***, then wait at least 5 minutes or go touch the cooling lines of heat exchanger to see if cool for HE heat exchanger or see if the other heat exchanger's temperature is near set point temperature.
27) Press the red STOP VI square button next to disconnect.



Appendix B: *Sample Calibration Report*

REPORT OF AIR-KERMA CALIBRATION(a)

OF

Name and complete postal address **(f)**

Radiation Detection Chamber: chamber/model (h, m)
(p)

Calibrations performed by Csilla Szabo-Foster

Report reviewed by Ronaldo Minniti

Report approved by Michael G. Mitch, Dosimetry Group Leader

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

Information on technical aspects of this report may be obtained from Csilla Szabo-Foster, National Institute of Standards and Technology, 100 Bureau Drive Stop 8460, Gaithersburg, MD 20899, csilla.szabo-foster@nist.gov, or (301) 975-4334.

Report format revised 6/22
(b,c) Official NIST letterhead is used.

NIST NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY U.S. DEPARTMENT OF COMMERCE

Dosimetry Group Number DG: #####-20
NIST ID 46011C Order Number: 682.02/O-0000000###-20 **(d)**
Report Date: 00/00/2020 **(l)**
Page 1 of 8 **(e)**

REPORT OF AIR-KERMA CALIBRATION

OF

Name and complete postal address

Radiation Detection Chamber: chamber/model

(h to k)

Chamber orientation: The cavity was positioned XXX

Chamber collection potential: A positive or negative XXX volts, with respect to the outer electrode was applied to the chamber and positive or negative charge was collected by the electrometer.

Chamber rotation: The window faced the source of radiation.

Environmental conditions: The chamber is assumed to be open to the atmosphere.

Average background current: The background current is 0.00 % of exposure current.

Temperature range: example 293.6 K (20.5 °C) to 294.1 K (21.0 °C)

Pressure range: example 100.7 kPa to 101.8 kPa

Calibration date: date range

Current ratio: The current ratio at the full to half collection potential is X.XXX for beamXXX. The results relate only to the instrument calibrated in this report. **(m)**

Results

Beam Code	Half-Value Layer (mm Al/mm Cu)	Calibration Coefficient (Gy/C) 295.15 K (22 °C) and 101.325 kpa (1 Atm)	Air- Kerma Rate (Gy/s)	Beam Diameter (cm)	Calibration Distance (cm)

Expanded, Combined Uncertainty, in Percent Beam Code	Air-Kerma Rate (Gy/s)	NIST Calibration Coefficient (Gy/C)

Dosimetry Group Number DG: #####-20
NIST ID 46011C Order Number: 682.02/O-0000000###-20
Report Date: 00/00/2020
Page 2 of 8

NIST Calibration Conditions for X-Ray Measuring Instruments

Beam code	Additional filtration [a]				Half-value layer[b] (HVL)		Homogeneity coefficient (HC)		Effective energy (keV)
	Al (mm)	Cu (mm)	Sn (mm)	Pb (mm)	Al (mm)	Cu (mm)	Al	Cu	
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				1.68	0.052	63	60	
M80	2.86				3.08	0.1	67	61	
M100	5.25				5.10	0.2	74	55	
M120	7.12				6.77	0.31	76	53	
M150	5.25	0.25			10.30	0.66	86	63	
M200	4.35	1.12			14.73	1.64	94	68	
M250	5.25	3.2			18.49	3.2	98	85	
M300	4.25		6.5		21.77	5.3	99	97	
H10	0.105				0.051		77		
H15	0.5				0.16		87		
H20	1.01				0.36		89		
H30	4.50				1.2		86		
H40	4.53	0.26			2.93		94		
H50	4.0			0.1	4.16	0.14	92	93	38
H60	4.0	0.61			6.06	0.25	92	94	46
H100	4.0	5.2			13.51	1.15	98	92	80
H150	4.0	4.0	1.51		16.93	2.43	99	96	120
H200	4.0	0.6	4.16	0.77	19.72	4.1	99	99	166
H250	4.0	0.6	1.04	2.72	21.59	5.19	99	98	211
H300	4.1		3.0	5.0	23.55	6.19	98	98	252
S60	4.35				2.81	0.09	74	66	
S75	1.50				1.81		58		

[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 x-ray tubes were installed in 2008 and 2015.

Dosimetry Group Number DG: #####-20
NIST ID 46011C Order Number: 682.02/O-0000000###-20
Report Date: 00/00/2020Page 3 of 8

ISO X-Ray Beam Quality Parameters Offered at NIST

Beam Code	Additional filtration[a]				First HVL[b]		Second HVL	
	Al (mm)	Cu (mm)	Sn (mm)	Pb (mm)	Al (mm)	Cu (mm)	Al (mm)	Cu (mm)
HK10					0.042		0.045	
HK20	0.15				0.128		0.170	
HK30	0.52				0.408		0.596	
HK60	3.19					0.079		0.113
HK100	3.90	0.15				0.298		0.463
HK200		1.15				1.669		2.447
HK250		1.60				2.463		3.37
HK280		3.06				3.493		4.089
HK300		2.51				3.474		4.205
WS60		0.3				0.179		0.206
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				0.049		0.061	
NS15	0.49				0.153		0.167	
NS20	0.90				0.324		0.351	
NS25	2.04				0.691		0.762	
NS30	4.02				1.154		1.374	
NS40		0.21				0.082		0.094
NS60		0.6				0.241		0.271
NS80		2.0				0.59		0.62
NS100		5.0				1.14		1.19
NS120		4.99	1.04			1.76		1.84
NS150			2.50			2.41		2.57
NS200		2.04	2.98	1.003		4.09		4.20
NS250			2.01	2.97		5.34		5.40
NS300			2.99	4.99		6.17		6.30
LK10	0.30				0.061			
LK20	2.04				0.441			
LK30	3.98	0.18			1.492			
LK35		0.25			2.21			
LK55		1.19				0.260		
LK70		2.64				0.509		
LK100		0.52	2.0			1.27		
LK125		1.0	4.0			2.107		2.094
LK170		1.0	3.0	1.5		3.565		3.592
LK210		0.5	2.0	3.5		4.726		4.733
LK240		0.5	2.0	5.5		5.515		5.542

[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; for all other techniques the inherent filtration is adjusted to 4 mm Al. Details of these reference radiation qualities can be found in the following: ISO/IS 4037-1:1996(E) X and Gamma Reference Radiations for Calibrating Dosimeters and Dose Rate Meters and for Determining Their Response as a Function of Photon Energy - Part 1; Radiation Characteristics and Production Methods. [b]The x-ray tubes were installed in 2008 and 2015.

Dosimetry Group Number DG: #####-20
NIST ID 46011C Order Number: 682.02/O-0000000###-20
Report Date: 00/00/2020
Page 4 of 8

Mammography X-Ray Beam Quality Parameters

Beam code	Tube voltage (kVp)	Additional filtration[a] (mm)	Half-value layer Al (mm)
Mo Anode[b]			
Mo/Mo23	23	0.032 Mo	0.288
Mo/Mo25	25	0.032 Mo	0.313
Mo/Mo28	28	0.032 Mo	0.346
Mo/Mo30	30	0.032 Mo	0.370
Mo/Mo35	35	0.032 Mo	0.404
Mo/Rh28	28	0.029 Rh	0.420
Mo/Rh32	32	0.029 Rh	0.453
Mo/Mo25x	25	0.030 Mo + 2.0 Al	0.551
Mo/Mo28x	28	0.030 Mo + 2.0 Al	0.589
Mo/Mo30x	30	0.030 Mo + 2.0 Al	0.633
Mo/Mo35x	35	0.030 Mo + 2.0 Al	0.715
Rh Anode			
Rh/Rh25	25	0.029 Rh	0.351
Rh/Rh30	30	0.029 Rh	0.438
Rh/Rh35	35	0.029 Rh	0.512
Rh/Rh40	40	0.029 Rh	0.559
Rh/Rh30x	30	0.029 Rh + 2.0 Al	0.814
Rh/Rh35x	35	0.029 Rh + 2.0 Al	0.898

[a]The inherent filtration is approximately 1.0 mm Be from the x-ray tube window and 0.075 mm polyimide, graphite coated, from the transmission monitor. [b]The HVL values were measured directly using the Mo anode installed in Dec 2008. The linking comparison for mammography beams: Kessle C., Burns, D.T. and O'Brien, M., "Key comparison BIPM.RI(I)-K7 of the air-kerma standards of the NIST, USA and the BIPM in mammography x-rays," Metrologia 48 06014 (2011).

Dosimetry Group Number DG: #####-20
NIST ID 46011C Order Number: 682.02/O-0000000###-20
Report Date: 00/00/2020
Page 5 of 8

CCRI[a] X-Ray Beam Quality Parameters Offered at NIST

Beam code	Tube voltage (kV)	Added filtration[b]		Half-value layer[c]
		(mm Al)	(mm Cu)	
BIPM25	25	0.373		0.240 mm Al
BIPM30	30	0.208		0.167 mm Al
BIPM40	40	3.989	0.212	2.649 mm Al
BIPM50a	50	3.989		2.291 mm Al
BIPM50b	50	1.007		1.038 mm Al
BIPM100	100	3.248		0.149 mm Cu
BIPM135	135	1.060	0.265	0.496 mm Cu
BIPM180	180	3.842	0.482	1.003 mm Cu
BIPM250	250	3.842	1.618	2.502 mm Cu

[a]BIPM, Qualités de rayonnement, Consultative Committee for Ionizing Radiation (CCEMRI) (Section I), 1972, 2, R15. Details of these reference radiation qualities can be found in the following: D. T. Burns et al, "Key comparison BIPM.RI(I)-K3 of the air-kerma standards of the NIST, USA and the BIPM in medium-energy x-rays," Metrologia **54** 06006 (2017) and Burns, D.T., Kessler, C. and O'Brien, M., "Key comparison BIPM.RI(I)-K2 of the air-kerma standards of the NIST, USA and the BIPM in low-energy x-rays," Metrologia **49** 06006 (2012).
[b]The additional filtration does not include the inherent filtration of the x-ray tubes which is approximately 3 mm Be and 1 mm Be.
[c]The HVL values were determined for the tubes installed in 2008 and 2015.

Dosimetry Group Number DG: #####-20
NIST ID 46011C Order Number: 682.02/O-0000000###-20
Report Date: 00/00/2020
Page 6 of 8

Explanation of Terms Used in the Calibration Procedures and Tables (o)

Air Kerma: (g) The air–kerma rate at the calibration position is realized by a free-air ionization chamber for x radiation and is expressed in units of gray per second (Gy/s). **(m)** This realization of the air kerma establishes the national standard for air kerma which can be transferred through a suitable measuring instrument, thus establishing traceability to the national standard. 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 value is 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 K, in gray (Gy), is related to exposure X, in roentgens (R), by the following 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 8.76E-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. The mammography beam codes are a combination of the chemical symbol of the anode and the filter respectively, followed by the constant potential, in kilovolts across the x-ray tube. The exit beam qualities, which represent the transmission of the x-rays through the breast, are created by an additional filtration of 2.0 mm of aluminum. The letter "x" ends the beam codes which refer to exit beam qualities.

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 diameter at the stated calibration distance is appropriate for the chamber dimensions.

Calibration Coefficient: (g,m,o) The calibration coefficients given in this report are quotients of the air kerma and the charge generated by the radiation in the ionization chamber, in units of Gy/C. 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). **(q)**The calibration coefficients listed in this report can be used to calculate the air kerma through the quantification of charge collected from the test instrument in calibration conditions that approximate NIST beam codes. A detailed study of ionization recombination was not performed. No recombination 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.

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.

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.

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

Dosimetry Group Number DG: #####-20
NIST ID 46011C Order Number: 682.02/O-0000000###-20
Report Date: 00/00/2020
Page 8 of 8

Appendix C: Proficiency Test Requirements for ISO 17043:2010 Conformity assessment –

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 identified by the corresponding letter in red font.

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. Since the NIST QA procedure requires stability for the chamber measurements, any change in the reproducibility above 0.2 % may require an investigation into the chamber and/or the support equipment. If the chamber completes the procedure at NIST with acceptable stability and is found to become unstable at the participant's facility, using the acceptable stability limits of the said 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 during all calibrations at NIST. 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 will not provide the normalized error or the Z-score.

Assigned values

The calibration coefficient determined through the proficiency test process is clearly explained in the calibration service, the proficiency test protocol and the proficiency test report. The details are repeated here. The air–kerma rate at the calibration position is realized by a free-air ionization chamber for x radiation and is expressed in units of gray per second (Gy/s). This realization of the air kerma establishes the national standard for air kerma which can be transferred through a suitable measuring instrument, thus establishing traceability to the national standard. The calibration coefficient is the quotient of the air kerma and the charge generated by the radiation in the ionization chamber, in units of Gy/C. The calibration coefficients used for the proficiency test are revealed at the end of the test in the form of a report issued to the participant. Early disclosure of the results is not allowed.

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 at the distance listed in the protocol, typically 1 meter.

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 with the required elements identified by the corresponding letter in red font. 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

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. The communication with the participant is documented in the data file associated with the proficiency test. If statements of participation or performance are issued by a NIST ***proficiency testing*** program, the statements will contain sufficient information as to not be misleading.

Sample Protocol

PROFICIENCY TEST PROTOCOL
FOR AIR KERMA MEASUREMENTS

Participants complete name and address

Radiation Detection Chamber: Exradin A4 Sn XP######

A NIST proficiency test is being conducted to test the ability of your calibration facility to transfer a measurement of air kerma and to provide NIST traceability.

NIST Technical Coordinator (b)**:** Csilla Szabo-Foster

Laboratory Technical Contact (e): Name of Contact

Start Date of Test: Month, Year (k)

Anticipated Completion Date of Test: Month, Year (k)

Information on technical aspects of this measurement comparison may be obtained from (b) Csilla Szabo-Foster, National Institute of Standards and Technology, 100 Bureau Drive Stop 8460, Gaithersburg, MD 20899, csilla.szabo-foster@nist.gov, (301) 975-4334.

Report format 6/2022

Dosimetry Group Number DG:#####-20
NIST ID 46050S Order Number: 682.02/O-0000000###-20
Report Date: 00/00/2020
Page 1 of 6

Sample Protocol

PROFICIENCY TEST PROTOCOL
FOR AIR KERMA MEASUREMENTS
Participants complete name and address
Radiation Detection Chamber: Exradin A4 Sn XP######

Scope, Method and Traceability (a, d, e, f, g and q)
This (e) single participant proficiency test has been requested to fulfill the testing requirement for **accreditation body**, if applicable. An ionization chamber (g) was calibrated using the NIST primary free-air ionization chamber in the (a) NIST x-ray calibration facility in building 245, room H127. The air kerma rate, in terms of Gy/s, at the calibration position is realized by a NIST free-air ionization chamber. (q) This realization of the air kerma establishes the National standard for air kerma, which can be transferred through a suitable measuring instrument, thus establishing traceability to the National standard.

A NIST reference class ionization chamber has been sent for the requested proficiency test with NIST. 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 results of the calibration coefficient(s) for the NIST chamber found at said facility in units of Gy/C in terms of the HVL of the NIST beam quality(s) specified, including uncertainty. The chamber is re-calibrated upon arrival at NIST, to ensure that no damage occurred while in transit. The participant's calibration coefficient(s) should be provided to NIST, normalized to one standard atmosphere (101.325 kPa) and 295.15 K (22 ^{o}C) for a direct comparison with the average of the NIST calibration coefficients. The comparative results will be included in a proficiency test report issued upon the completion of the test. The results will 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. Questions or concerns should be directed to the NIST contact.

The criteria (d) for the test is that the participant must have a linking traceable measurement of air-kerma. Using the participant's established measurement methods and procedures, the participant should provide NIST with the (f) calibration coefficient(s) for the chamber found at their facility for each beam in units of Gy/C. The average current used to compute the calibration coefficient is based on measurements with the chamber at the stated polarity and potential. At the conclusion of the test, each calibration coefficient will be compared to the NIST calibration coefficient and the results will be provided as a percent difference from the NIST measured value. The results reveal the degree to which the participating calibration facility can demonstrate proficiency in calibrating an ionization chamber under the conditions of the said facility at the time of the test. The comparative results and the NIST uncertainty will be included in a NIST report issued upon the completion of the test.

Dosimetry Group Number DG:#####-20
NIST ID 46050S Order Number: 682.02/O-0000000###-20
Report Date: 00/00/2020
Page 73 of 6

Sample Protocol

PROFICIENCY TEST PROTOCOL
FOR AIR KERMA MEASUREMENTS
Participants complete name and address
Radiation Detection Chamber: Exradin A4 Sn XP######

Conditions for the Chamber and Sources in the NIST Facility: **(k and m)**

The values of the calibration coefficients are determined using the procedures outlined in the NIST quality measurement system for service ID 46011C. The chamber is open to the atmosphere and all measurements were normalized to one standard atmosphere and 22 degrees Celsius. Use of the chamber at other pressures and temperatures requires normalization of the ion currents to these reference conditions. No correction is made for the effect of water vapor on the instrument being calibrated. 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. Leakage corrections are applied. A detailed study of ion recombination was not performed. No recombination 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.
The safe handling procedures of the chamber manufacturer are used, and the chamber is kept at safe laboratory conditions between 20° C and 24° C and relative humidity < 50 %. The results relate only to the instrument calibrated in this report.

Chamber	**Exradin A4 Sn XP######**
Bias	500 V (negative charge collected on electrometer)
Rotation	The white mark faced the source of radiation.
Orientation	The chamber was positioned in the center of the beam with the base of the chamber perpendicular to the beam direction
Distance	100 cm to center of volume
Beam size	10 cm diameter
Air Kerma rates and Beam Codes	1.9 E-5 Gy/s (H200) and 4.6E-4 Gy/s (M250)

Dosimetry Group Number DG:#####-20
NIST ID 46050S Order Number: 682.02/O-0000000###-20
Report Date: 00/00/2020
Page 3 of 6

Sample Protocol

PROFICIENCY TEST PROTOCOL
FOR AIR KERMA MEASUREMENTS
Participants complete name and address
Radiation Detection Chamber: Exradin A4 Sn XP######
Participant Shipping Address and Dates (b and u)

Following is the contact information required for the proper shipment of the chamber. After the request for the proficiency test by the participant was processed through the NIST payment system, an agreed upon date was established for the shipment of the chamber, at the owner's expense. At the completion of the proficiency test measurements at the participant's facility, the results should be provided to NIST electronically, prior to returning the chamber to NIST. Once NIST deems the test complete, the chamber should be returned to NIST in the reusable container. The tracking information will be provided by the participant using shipping insurance which would cover loss or damage.

Ship to participant:
Ship Date: month/day/year
Shipped to:
complete address
Email:
Telephone:

Return to NIST:
Ship Date: month/day/year
Shipped to:
NIST,100 Bureau Dr.,Bldg 245, Rm H127, Stop 8460 Attn: Csilla Szabo-Foster
Gaithersburg, MD 20899-8460
Phone: 301-975-4334
Email: csilla.szabo-foster@nist.gov

Dosimetry Group Number DG:#####-20
NIST ID 46050S Order Number: 682.02/O-0000000###-20
Report Date: 00/00/2020
Page 4 of 6

Sample Protocol

PROFICIENCY TEST PROTOCOL
FOR AIR KERMA MEASUREMENTS
Participants complete name and address
Radiation Detection Chamber: Exradin A4 Sn XP######

Format of Participant Results (s) (o and r)
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, normalized to 295.15 K (22 °C) and 101.325 kPa (1 Atm) limiting the value to significant digits. The equipment used for the measurement should be provided in a report with details to include the model and serial number of the chamber, most recent calibration history, the bias potential and the electrometer identification. The date of the calibration, the complete uncertainty budget and a description of the geometry should be included in the participant's results. The method the participant used to calculate the calibration coefficient should be included in the report.

Format of Final NIST Report
The results presented to the participant, at the conclusion of the test, will be in a table similar to that below. The NIST value for each coefficient is an average. The uncertainty is determined by the standard deviation of the mean of the charge measurements.

Comparative Results for the NIST Transfer Standard

NIST Beam Code	**NIST Calibration Coefficient 295.15 K (22 °C) and 101.325 kPa (1 Atm) (Gy/C)**	Participant Calibration Coefficient **295.15 K (22 °C) and 101.325 kPa (1 Atm) (Gy/C)**	**Difference in Percent**
M250	1.###E+06	1.###E+06	0.31
H200	1.###E+06	1.###E+06	0.24

Confidentiality, Collusion and Falsification of Results (j and t)
The identification of the test results will stay confidential and secure on the NIST server, with limited access by the authorized quality management system QMS 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 participant to provide the proficiency test results to the accreditation organization. If collusion or falsification of the results is suspected then the test will be terminated, fees applied and another test, with an associated fee, will be required.
Dosimetry Group Number DG:#####-20
NIST ID 46050S Order Number: 682.02/O-0000000###-20
Report Date: 00/00/2020
Page 5 of 6

Sample Protocol

PROFICIENCY TEST PROTOCOL
FOR AIR KERMA MEASUREMENTS
Participants complete name and address
Radiation Detection Chamber: Exradin A4 Sn XP######

Potential Source of Errors (h)
Differences in geometry can contribute to errors. Failure to normalize data to 295.15 K (22 ^{o}C) and 101.325 kPa (1 Atm) will result in an error. The same voltage bias used by NIST should be used by the participant.

Statistical Design (d, p and r)
Each chamber is measured at least three times by NIST in each beam and the average is used. 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 will not provide the normalized error or the Z-score.

Initial Stability Check and Quality Control of Ionization Chambers (i and n)
Only stable and reproducible ionization chambers are accepted for use for proficiency testing. NIST prepares the ionization chamber through a series of redundant measurements in highly reproducible radiation fields prior to using the chamber for the proficiency test and repeats those checks at suitable intervals. Since the NIST QA procedure requires stability for chamber measurements, any change in the reproducibility above 0.2 % may require an investigation into the chamber or support equipment. If the chamber is found to become unstable at the participant's facility, using the acceptable stability limits of the said facility, NIST should be notified, and the chamber should be excluded from the measurement comparison and a replacement chamber will be provided.

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.

Evaluation of proficiency testing scheme results

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.

Dosimetry Group Number DG:#####-20
NIST ID 46050S Order Number: 682.02/O-0000000###-20
Report Date: 00/00/2020
Page 6 of 6

Sample Report

REPORT OF PROFICIENCY TEST FOR AIR-KERMA CALIBRATIONS

Participants complete name and address

Radiation Detection Chamber: Exradin A4 Sn XP######

Calibrations performed by Csilla Szabo-Foster (c)

Report technical review by Ronaldo Minniti (c)

Report approved by Michael G. Mitch, Dosimetry Group Leader (c)

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

Information on technical aspects of this report may be obtained from Csilla Szabo-Foster, National Institute of Standards and Technology, 100 Bureau Drive Stop 8460, Gaithersburg, MD 20899, csilla.szabo-foster@nist.gov, or (301) 975-4334. (a, b)

Report format version 6/22.

Dosimetry Group Number DG:#####-20
NIST ID 46050S Order Number: 682.02/O-0000000###-20
Report Date: 00/00/2020
Page 78 of #

Sample Report

REPORT OF PROFICIENCY TEST FOR AIR-KERMA CALIBRATIONS

Participants complete name and address

Radiation Detection Chamber: Exradin A4 Sn XP######

Proficiency Testing Scheme (i, q)

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

Only stable chambers are used for the NIST proficiency test. The NIST QA procedure requires stability for the chamber and primary chamber measurements. Any change in the reproducibility of the charge above 0.2 % will be investigated.

Statistical Design (l, n, r)

The chamber is measured at least 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.

Dosimetry Group Number DG:#####-20
NIST ID 46050S Order Number: 682.02/O-0000000###-20
Report Date: 00/00/2020
Page 79 of #

Sample Report

REPORT OF PROFICIENCY TEST FOR AIR-KERMA CALIBRATIONS

Participants complete name and address

Radiation Detection Chamber: Exradin A4 Sn XP######

Calibration Conditions at NIST

Date Chamber shipped to participant: dd/mm/yr
Chamber return date to NIST: dd/mm/yr
Calibration dates: dd/mm/yr
Calibration distance: The center of the volume was positioned 100 cm from the source.
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: 500 volts to collect a negative charge on the electrometer
Chamber rotation: The white mark faced the source of radiation.
Temperature range: 293.2 K (20 °C) to 294.6 K (21 °C)
Pressure range: 99.2 kPa to 101.4 kPa
Background current: less than 0.02 % of signal
The results relate only to the instrument calibrated in this report.

Calibration Results from the NIST Facility

Beam Code	Half –Value Layer (mm Al)	Calibration Coefficient 295.15 K (22 °C) and 101.325 kPa (1 Atm) (Gy/C)	Air- Kerma Rate (Gy/s)	Beam Diameter (cm)	Calibration Distance (cm)
M250	18.49	1.###E+06	#.##E-04	10	100
H200	19.72	1.###E+06	#.##E-05	10	100

Expanded, Combined Uncertainty, in Percent

NIST Beam Code	Air-Kerma Rate (Gy/s)	NIST Calibration Coefficient (Gy/C)

Dosimetry Group Number DG:#####-20
NIST ID 46050S Order Number: 682.02/O-0000000###-20
Report Date: 00/00/2020
Page 80 of #

Sample Report

REPORT OF PROFICIENCY TEST FOR AIR-KERMA CALIBRATIONS
Participants complete name and address
Radiation Detection Chamber: Exradin A4 Sn XP######

Participant's Calibration Conditions as reported by Participant (d, j)

Calibration distance: The center of the volume was positioned 100 cm from the source.
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: -500 volts to collect a negative charge on the electrometer
Chamber rotation: The white mark faced the source of radiation.
Beam size: Used the reference delivery system for the 30 cm x 30 cm field with optimized uniformity across the central 15 cm x 15 cm area.
Nominal Air-Kerma rates: 5.0 E-04 Gy/s (M250) and 2.3 E-05 Gy/s (H200)

Comparative Results for the NIST Transfer Standard

NIST Beam Code	NIST Calibration Coefficient 295.15 K (22 °C) and 101.325 kPa (1 Atm) (Gy/C)	Participant Calibration Coefficient 295.15 K (22 °C) and 101.325 kPa (1 Atm) (Gy/C)	Difference in Percent
M250	1.###E+06	1.###E+06	0.31
H200	1.###E+06	1.###E+06	0.24

Dosimetry Group Number DG:#####-20
NIST ID 46050S Order Number: 682.02/O-0000000###-20
Report Date: 00/00/2020
Page 81 of #

Comments and advice: (p, s, t)
Generally, NIST commentary is not provided, since that is left to the accrediting body which would analyze the results applying the established criteria. The expectations are on the PT customer and their accrediting body to use the purchased PT report as they find necessary within their own quality system. The NIST PT results do not mean, and should not be implied to mean, evaluation, endorsement, or certification of commercial firms' products and services.

Confidentiality, Collusion and Falsification of Results (g)
The identification of the test results will stay confidential and secure on the NIST server, with limited access by the authorized quality management system (QMS) 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 participant to provide the proficiency test results to the accreditation organization. If collusion or falsification of the results is suspected then the test will be terminated, fees applied and another test, with an associated fee, will be required.

All beam code tables provided but not shown here for efficiency.

Dosimetry Group Number DG:#####-20
NIST ID 46050S Order Number: 682.02/O-0000000###-20
Report Date: 00/00/2020
Page 82 of #

Explanation of Terms, Establishment of Assigned Values and Metrological Traceability (m)

Air Kerma: The air–kerma rate at the calibration position is realized by a free-air ionization chamber for x radiation and is expressed in units of gray per second (Gy/s). This realization of the air kerma establishes the national standard for air kerma which can be transferred through a suitable measuring instrument, thus establishing traceability to the national standard. 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 value is 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 K, in gray (Gy), is related to exposure X, in roentgens (R), by the following 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 8.76E-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. The mammography beam codes are a combination of the chemical symbol of the anode and the filter respectively, followed by the constant potential, in kilovolts across the x-ray tube. The exit beam qualities, which represent the transmission of the x-rays through the breast, are created by an additional filtration of 2.0 mm of aluminum. The letter "x" ends the beam codes which refer to exit beam qualities.

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 diameter at the stated calibration distance is appropriate for the chamber dimensions.

Dosimetry Group Number DG:#####-20
NIST ID 46050S Order Number: 682.02/O-0000000###-20
Report Date: 00/00/2020
Page # of #

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, in units of Gy/C. 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 calibration coefficients listed in this report can be used to calculate the air kerma through the quantification of charge collected from the test instrument in calibration conditions that approximate NIST beam codes. A detailed study of 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.
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.
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.
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: (m) 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: Lamperti, P.J., O'Brien, M., "Calibration of X-Ray and Gamma-Ray Measuring Instruments," NIST Special Publication 250-58 (2001).

Dosimetry Group Number DG:#####-20
NIST ID 46050S Order Number: 682.02/O-0000000###-20
Report Date: 00/00/2020
Page # of #