MEDICAL DOSIMETRY STANDARDS PROGRAMME OF THE NATIONAL BUREAU OF STANDARDS

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Abstract

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In the field of radiation dosimetry for medicine and radiation protection, the National Bureau of Standards has the responsibility to establish, verify, maintain and make available suitable measurement standards, and to carry out studies to assure that dosimetry measurements made in the United States of America are in adequate agreement with NBS standards. The physical quantities involved are exposure and absorbed dose, and the measurement standards are free-air chambers, graphite cavity chambers, calorimeters, extrapolation chambers, and radium standards. These NBS standards have been verified after construction, and periodically since that time, by comparison with each other, and with other national and international standards. Calibration services based on the NBS standards are offered for X-ray and gamma-ray measuring instruments, beta-particle and gamma-ray brachytherapy sources, and X-ray penetrameters; irradiation of passive dose meters is offered in photon beams with maximum energies from 10 keV to 1 MeV. Exposure-measuring and absorbed-dose-measuring instruments are subjected to a variety of pre-calibration tests. Calibration data are handled by an automatic data acquisition system and are processed by computer. Measurement assurance studies have been carried out for cobalt-60 teletherapy sources and for high-energy electron beams by means of passive dose meters irradiated by the medical user and evaluated at NBS; measurement assurance studies are being made to test the calibration of a limited number of medical beams by taking the NBS portable calorimeter directly to the medical beam and comparing the calorimeter measurement with a conventional calibration. Traceability to NBS standards of the calibration of instruments used in medicine and radiation protection is established in part by three Regional Calibration Laboratories accredited by the American Association of Physicists in Medicine, in part by direct calibration of field instruments at NBS, and in part by informal calibration procedures about which little information is available.

1. INTRODUCTION

It is the responsibility of the Dosimetry Section of the National Bureau of Standards (NBS) to establish, maintain, and make available dosimetry measurement standards for the United States, and to perform appropriate measurement assurance studies as needed. *Establishment* of standards refers to the design, construction, and verification of measurement standards of a quality adequate to serve as primary national standards. Verification of these standards involves appropriate theoretical and experimental tests, and then comparison with comparable primary standards

of other national and also international laboratories. *Maintenance* of standards refers to periodic tests of their constancy and reliability, both by means of internal tests and by occasional comparison with other primary standards. Standards are *made available* by calibration of suitable instruments and sources, as needed to meet the needs of the U.S., and also by bringing the resources of NBS to bear on measurement problems that are of current importance. *Measurement assurance* refers to the performance of tests to assure that our constituents are actually performing measurements that are consistent with the national measurement standards to the accuracy needed.

2. DOSIMETRY QUANTITIES AND THEIR MEASUREMENT STANDARDS

2.1 Free-air chambers (exposure)

Exposure is a point quantity, defined for a photon beam in terms of the expectation value of the quotient of the total charge liberated in free air by electrons liberated in a small volume of air, and the mass of the small volume [1]. As is well known, the free-air chamber measures the charge liberated in air in a direction perpendicular to the photon beam, in accordance with the definition of exposure. In a direction parallel to the photon beam the free-air chamber depends on electron compensation to achieve the appropriate charge measurement. The close relationship between the free-air chamber and the quantity exposure is not accidental -- the latter has been carefully defined to describe what the former measures. The design and construction of free-air chambers has been the subject of an NBS handbook [2].

There are three free-air chambers at NBS, covering the x-ray generating potentials 10 to 60 kV, 20 to 100 kV, and 60 to 250 kV. (These are conveniently referred to as 60-kV, 100-kV, and 250-kV chambers.) The 250-kV chamber was constructed in 1953 by H. O. Wyckoff, F. H. Attix, and L. DeLaVergne. It was taken to the National Physical Laboratory (NPL) in the U.K., and comparison with the NPL primary standard chamber showed differences of a few percent [3]. Subsequent studies by Wyckoff and Attix [2], and V. H. Ritz [4] refined the use of the chamber, after which comparison in Washington with a new British standard showed agreement to about 0.5%. In 1959 a direct comparison was made in Washington with the newly constructed Canadian standard, from the National Research Council (NRC). Again the instruments agreed to within about 0.5% [5].

Construction and testing of the 100-kV chamber was completed in 1959 by Ritz [4]. This chamber has not been compared directly with standards from other national laborabories, but comparisons have been made with the other NBS free-air chambers, as indicated in Table I.

The 60-kV chamber was constructed in 1963 by P. J. Lamperti following investigation of the necessary parameters by Lamperti and Wyckoff [6]. In 1963 the chamber was taken to the BIPM at Sèvres and compared there with a similar chamber of the BIPM, and one of the NRC [7]. Once again, the results agreed to within about 0.5%.

The three NBS free-air chambers have been intercompared among themselves a number of times. It is our present plan to carry out this intercomparison periodically, about every second year. In Table I are shown the results of the recent comparisons, and also the one earlier comparison in which all three were intercompared at about the same time. The stability of the free-air chambers is very satisfactory. The values given in Table I

TABLE I. COMPARISON OF NBS FREE-AIR CHAMBERS

Date of comparison	Free-air chamber 10 to 60 kV	20 to 100 kV	60 to 250 kV
1962	0.11	- 0.24	0.13
1975 March	0.05	- 0.35	0.28
1976 Nov.	0.05	- 0.32	0.28

The table gives the difference of the response of each chamber from the response of all the chambers, expressed in percent.

must not, however, be taken as representing accurately the relative responses of the chambers, since these are to a limited extent a function of the energy of the x-ray beam.

Indirect comparisons of the NBS free-air chambers with other national standards have been made on several occasions at the BIPM by means of transfer standards. Once again the NBS standards agreed within about 0.5% with the BIPM standards and with the mean of the other national standards. The spread of the national standards was such however that an occasional difference nearly as large as 1% has been observed from another national standard.

2.2 Graphite cavity chambers (exposure)

For calibration at medical-level exposure rates, the free-air chamber at atmospheric pressure is limited to photon energies less than about 300 keV. This limitation arises mainly from the fact that with increasing photon energy the maximum secondary electron range increases, reaching a value of nearly 5 meters for the photons of cobalt-60. Since an atmospheric-pressure free-air chamber for such photons would be far too large, high-pressure free-air chambers are used at several national laboratories, and were studied at NBS [8]. It is now generally believed that a better solution is the use of graphite cavity ionization chambers as standards of exposure for the gamma rays of cesium-137 (0.66 MeV) and cobalt-60 (1.2 MeV). Cavity chambers which serve as primary measurement standards are not calibrated, instead their response is calculated from the measured volume of the chamber and the properties of the wall material. Such cavity-chamber standards do not of course realize the unit of exposure according to its definition -- they more nearly realize the unit of absorbed dose -- nevertheless they are used to determine the unit of the quantity exposure.

The graphite cavity chambers which provide the NBS standard of exposure for gamma radiation are a set of six spherical chambers with active volumes from 1 cm^3 to 50 cm^3 [9]. Several of these chambers were constructed by H. O. Wyckoff and his colleagues during 1958 and 1963, and the remainder were constructed by T. P. Loftus during 1970-71, using the Wyckoff design. All the chambers are made of high-purity graphite, including the central electrode. The NBS exposure standard is the mean response of the six chambers.

Intercomparison of the chambers in the NBS cobalt-60 beam showed agreement within 0.1%, except for the 1-cm^3 chamber, which showed a response about 0.3% different from the mean response. The 1-cm^3 chamber

was taken to Paris for comparison with the BIPM standard chamber [10], which has itself been compared with a number of other national standard chambers. In general the agreement between the national standard graphite cavity chambers is about the same as for free-air chambers -- for the most part they agree within about 0.5%, but there are occasional differences between national standards as large as 0.7%. The NBS cavity chambers have not been compared with other national standards since the initial comparison, but occasional internal comparison between the chambers gives assurance that the NBS gamma-ray standard has not changed. An uncertainty of 0.7% is assigned to the exposure rate in the cobalt-60 beam, as determined by the graphite cavity ionization chambers [9].

At photon energies above a few million electron volts, it becomes difficult to make satisfactory standards of exposure, due to the increase in the range of the secondary electrons relative to the mean free path of the photons. In a wall thickness adequate to provide secondary electron equilibrium, the attenuation of the photon beam would be so great that appropriate wall corrections would be uncertain. Thus at NBS we make no attempt to establish standards for the quantity exposure for photon beams with energies higher than the gamma rays of cobalt-60. We turn instead to another quantity and another measurement standard.

2.3 Graphite calorimeters (absorbed dose)

Absorbed dose is also a point quantity, defined for a photon or particle beam in terms of the mean energy imparted per unit mass at the point of interest in some stated material [1]. Energy imparted to matter results in a rise in temperature, and the natural primary standard for realization of the unit of absorbed dose in terms of its definition is then a calorimeter. For a number of reasons, high-purity graphite is the preferred material, and NBS has two graphite absorbed-dose calorimeters. The first was designed and constructed by S. R. Domen starting in 1968, and is in a 40x40x30-cm cube of graphite; it is permanently located in one of the experimental areas of the NBS 100-MeV linear accelerator. The other calorimeter, designed and constructed by Domen a few years later, is in a 15-cm diameter by 10-cm deep graphite cylinder [11]; it is the "portable" calorimeter which has been used for all NBS calorimeter measurements except those made on the NBS linac. These two calorimeters make use of a unique "heat-loss-compensation" principle discovered by Domen, which provides a method of measuring nearly all the heat lost from the central core to its surrounding jacket at the time of calibration [12].

Interpretation of the response of a calorimeter is in principle simpler than interpretation of the response of a cavity ionization chamber. On the other hand, the calorimeter is considerably more delicate and complex to build than is a cavity chamber. A comparison of their sensitivities is instructive: an absorbed dose of 3 Gy (300 rad) produces a temperature rise of about 4 mK (4×10^{-3} °C) in graphite; an exposure of the same magnitude, 75 mC/kg (300 R) liberates in air about 100 nC of charge in an ionization chamber with a volume of 1 cm^3. Thus if we desire to measure this magnitude of radiation with a precision of 0.1%, we must in effect be able to detect differences of 4 μK (4×10^{-6} °C) for the calorimeter, and about 100 pC for the ionization chamber. Those with experimental experience will recognize that such a charge measurement is not too difficult, but such a temperature measurement requires complex, sensitive, and expensive equipment, as well as unusual skill, experience, and patience. To repeat: a calorimeter is simpler in principle, but considerably more complicated in practice than an ionization chamber. The latter is of course just the reason that the ionization chamber is used for routine dosimetry, while the calorimeter is not.

TABLE II. CALIBRATION CONDITIONS AND BEAM QUALITIES FOR CALIBRATION OF X-RAY MEASURING INSTRUMENTS

Lightly filtered x rays

Constant Potential (kV)	Distance (cm)	Added Filter* Al (mm)	Half-Value Layer Al (mm)	Homogeneity Coefficient (1st HVL/ 2nd HVL)	Exposure Rate Min (μR/s)	Exposure Rate Max (R/s)
10	25	0	0.029	0.79	1.0	1.7
15	25	0	0.050	0.74	1.0	4.2
20	50	0	0.071	0.76	1.0	3.3
20	50	0.5	0.23	0.78	1.0	0.13
30	50	0.5	0.36	0.64	1.0	0.3
50	50	1.0	1.02	0.66	1.0	0.4
75	50	1.5	1.86	0.63	1.0	0.4
100	50	2.0	2.78	0.59	1.0	0.4

*The inherent filtration is approximately 1.0 mm Be.

Moderately filtered x rays

Constant Potential (kV)	Added Filter** Cu (mm)	Added Filter** Al (mm)	Half-Value Layer Cu (mm)	Half-Value Layer Al (mm)	Homogeneity Coefficient (1st HVL/ 2nd HVL)	Exposure Rate Min (mR/s)	Exposure Rate Max (mR/s)
60	0	0	--	1.62	0.68	7	120
60	0	2.50	0.090	2.79	0.79	7	40
75	0	2.51	0.116	3.39	0.74	7	70
100	0	3.50	0.20	5.03	0.73	15	100
150	0.25	3.49	0.66	10.25	0.89	15	130
200	0.50	3.49	1.24	13.20	0.92	30	220
250	1.01	3.50	2.23	15.80	0.92	40	280
250	3.20	3.47	3.25	18.30	0.98	20	150

Heavily filtered x rays

Constant Potential (kV)	Added Filter** Pb (mm)	Sn (mm)	Cu (mm)	Al (mm)	Half-Value Layer Cu (mm)	Half-Value Layer Al (mm)	Effective Energy (keV)	Exposure Rate Min (mR/s)	Exposure Rate Max (mR/s)
50	0.10	0	0	2.50	0.14	4.19	38	0.3	1.5
100	0.50	0	0	2.50	0.74	11.20	70	0.8	4
150	0	1.51	4.00	2.50	2.45	16.96	117	0.7	4
200	0.77	4.16	0.60	2.47	4.09	19.60	167	0.5	4
250	2.72	1.04	0.60	2.50	5.25	21.55	210	0.5	4

** The inherent filtration is approximately 1.5 mm Al.

3. CALIBRATION SERVICES BASED ON DOSIMETRY STANDARDS

3.1 Calibration of x-ray measuring instruments

NBS has two x-ray calibration ranges, one providing calibration for generating potentials from 10 kV to 100 kV using the 60-kV and the 100-kV free-air chambers, and the other providing calibration for generating

TABLE III. MEDICAL-LEVEL GAMMA-RAY CALIBRATION BEAMS

Radionuclide	Activity		Exposure rate*		Absorbed dose rate to water**	
	(kCi)	(TBq)	(R/s)	(μA/kg)	(rad/s)	(mGy/s)
cobalt-60	10	370	2.5	650	2.2	22
cobalt-60	0.25	10	0.07	20	0.06	0.6
cesium-137	1.3	50	0.10	25	--	--

* at one meter
** at one meter, at a depth of 5 cm, 10 cm x 10 cm field

potentials from 50 kV to 250 kV using the 250-kV free-air chamber. Both ranges have highly regulated, constant-potential power supplies. Both have beam-limiting apertures and filters mounted on wheels close to the x-ray tube, followed by a transmission monitor. All measurements are made relative to the monitor. Each calibration range has tracks parallel to the x-ray beams on which a carriage is mounted, supporting the free-air chambers and the test chambers. Calibrations can be performed at distances from about 0.3 m to 4 m. The test instruments and the free-air chambers are on tracks that are perpendicular to the x-ray beams, so that they can be positioned alternately on the beam axis, which is marked with a low-power laser beam. The detector position is set very accurately by means of a cathetometer, which is referenced to the plane of definition of the diaphragm of the free-air chamber. All data are handled by an automatic data acquisition system that is described in Section 3.4. Calibrations are performed for cable-connected ionization chambers without associated electrometers, in terms of exposure per unit charge, and for both cable-connected and condenser chambers with associated electrometers, in terms of exposure per scale division. Table II lists the calibration conditions and beam qualities for which calibrations are performed at the present time.

3.2 Calibration of gamma-ray measuring instruments

There are two gamma-ray calibration ranges for medical-level calibration, with three sources listed in Table III. The sources are mounted overhead about 3 m from the floor with their beams directed down into beam traps to reduce backscattered radiation. The 370-TBq cobalt-60 source and the 50-TBq cesium-137 source are mounted together on a horizontal track so that either can be centered over the beam trap. The 10-TBq cobalt-60 source is mounted over a separate beam trap. The sources are in conventional therapy heads with variable collimators; calibrations are generally performed in 10-cm x 10-cm fields at approximately 1 m from the source. The three beams are standardized in terms of exposure rate by means of the standard graphite cavity chambers. A cathetometer is used to position both the standard chamber and the test chamber being calibrated. The beams are standardized with the standard chambers about once a year, and conventional half-lives are used to correct for source decay since the time of the last standardization.

The cobalt-60 beams are also standardized in terms of absorbed dose rate to water. This was accomplished as follows. The beam was first

standardized in terms of absorbed dose rate to graphite using the portable graphite calorimeter. A specially-built graphite transfer chamber [20] was then calibrated in a graphite phantom in terms of absorbed dose to graphite in graphite. The graphite phantom was replaced with a water phantom, and the same chamber then gave absorbed dose rate to graphite in water. Application of the mean energy-absorption coefficient ratio then gave the beam standardization in terms of absorbed dose rate to water.

Calibrations in a water phantom are performed at 1 m from the source, at the center of a 10-cm x 10-cm field. The ionization chamber to be calibrated is inserted in a horizontal plastic tube the center line of which is 5 cm below the water surface. Any good-quality ionization chamber can be calibrated if its outside diameter is less than 25 mm, and if its silhouette is such that it can be inserted into the plastic tube without excessive air gaps. The water phantom is mounted on a cantilevered platform so that it can readily be moved out of the way when the beam is used for other purposes.

It has been our experience so far that, for a given model chamber, the ratio of the absorbed-dose calibration to the exposure calibration is a constant, as accurately as we can measure. It is very likely that, after we have verified this constancy with further measurements, it will be unnecessary to perform both in-air and in-phantom calibrations, since either one alone will give the necessary information.

In standardizing the cobalt-60 beam, measurements were made in graphite using the calorimeter and several ionization chambers. The chamber calibration factors were independent of depth, to the accuracy of the measurements, from about 1 to 9 g/cm^2. With the plane-parallel chamber, using a stopping-power ratio of 1.0068, we obtained for the mean energy expended per unit charge $\bar{W}/e = 33.6 \pm 0.2$ (m.e.), in good agreement with the accepted value of 33.7 J/C. These measurements were made on the 10-TBq cobalt-60 source, at a dose rate of about 1 mGy/s; they will be reinvestigated using the newly installed 370-TBq source with its much higher dose rate.

The overall uncertainty in the calibration of a good-quality cable-connected ionization chamber in the cobalt-60 beam is estimated to be about 0.8% for a calibration in terms of exposure, traceable to our graphite cavity ionization chambers. The corresponding figure for a calibration in terms of absorbed dose, traceable to the graphite calorimeter, is estimated to be about 1.0%, a figure that we expect to reduce when we have completed standardization of the beam of our new 370-TBq cobalt-60 source.

3.3 Pre-calibration tests of x-ray and gamma-ray measuring instruments

All ionization chambers are put through a variety of tests before they are calibrated. These tests are performed in the cable-connected mode using an NBS electrometer, and condenser chambers are adapted by a special connector for this purpose. The tests are performed at a test bench outfitted with an electrometer, power supplies, a chart recorder, a small pressure pump with valves and pressure gauge, adaptors for all common cable connectors, etc. Before subjecting the chamber to radiation, the following tests are performed:

electrostatic shielding of the central electrode;
leakage, central electrode to polarizing electrode;
stabilization time after application of polarizing potential;
leakage, central electrode to guard electrode; and
leakage, guard electrode to polarizing electrode.

The chamber is then placed in a sealed plastic chamber in a cesium-137 gamma-ray beam where the exposure rate is about 2 R/s. The following tests are then performed:

stabilization time, simultaneous radiation and polarizing potential; saturation test from full-potential and half-potential currents; and communication to the atmosphere.

Individuals performing such tests learn to spot a defective chamber very quickly. If the problem is a minor one, we may choose to remedy it ourselves after consulting with the owner. If however it is a serious deficiency that precludes satisfactory calibration, the chamber is returned to the owner. Frequently we radiograph the chamber and stem, if we suspect some mechanical problem, or if we are curious about the inner structure of a new chamber. The performance of each ionization chamber at these tests is recorded on a card which accompanies the chamber to the calibration range. This serves to alert the individual performing the calibration to any aspect of the chamber behavior that needs special attention.

Before these tests were instituted, it happened on occasion that preparatory work and set-up time would be spent on an instrument that proved to be defective. It is also possible that some chambers were calibrated that would be found unsuitable at this time. Our motives in establishing these tests were to avoid these inefficient and frustrating occurrances, to alert our own personnel to the special characteristics of the instruments we handle, and to inform the owners of the instruments of problems that existed or that they might encounter in their equipment.

3.4 Automatic data acquisition and processing

X-ray and gamma-ray instrument calibration reports are processed by computer. Some of the data must of course be entered by hand, but most of the data are recorded by means of an automatic data acquisition system. Analog (i.e. current) input signals go first to an analog scanner which transmits them sequentially to the analog-to-digital converter (i.e. digital voltmeter). These signals, along with digital input signals, go to a digital scanner, which transmits them sequentially to a teleprinter that generates a punched-tape record of the data. Data entered by hand are entered directly into the teleprinter. The data on the punched tape are transferred to magnetic tape and processed on the NBS central computer (Univac 1108). The input data can be categorized as follows:

Essential digital input signals
- Irradiation time
- Source identification
- Filter identification
- Chamber station identification
- Distance (x rays)

Essential analog input signals
- Variable collimator setting (gamma rays)
- Pressure
- Temperature
- Electrometer feedback potential

Essential input data entered by hand
- Distance (gamma rays)
- Electrometer feedback capacitance
- Electrometer reading if special electrometer

Verification signals
- Tube potential (x rays)
- Tube current (x rays)
- Beam-limiting aperture (x rays)
- Monitor, test, free-air chamber polarizing potentials
- ±1-volt and 0-volt test on digital voltmeter

Information about instrument being calibrated, entered by hand
- Owner
- Manufacturer
- Name, model, serial number
- Date received
- Previous calibrations
- Orientation in beam
- Open to atmosphere at NBS test?
- Requested polarizing potential and polarity (+, -, ±)
- Equilibrium wall inherent or added
- Voltage sensitivity (R-meter electrometers only)

Other information entered by hand
- File identification number
- Serial number of NBS electrometer
- Date and time of day
- Special notes
- Person doing calibration

Using these input data, the computer provides four printouts, as follows.
- Echo of input data with line numbers
- Data reduction and analysis table
- Calibration summary for NBS records
- Calibration report for owner of instrument

The line numbers are given in the echo of the input data to identify locations for insertion or deletion of data, making it possible to repeat only part of a calibration run if desired. The data reduction and analysis table presents the data in readable form, and gives the results of tests of the data for reproducibility and for agreement with nominal or expected values; error messages print out if required data are missing or if the data spread is outside pre-assigned limits. The calibration summary for NBS records gives all the important information about the calibration, some of which is not passed on to the owner of the instrument, since its purpose is only to insure that the calibration has been carried out correctly.

The calibration report for the owner consists of four or more sheets. We try to give all information necessary to interpret the calibration report without ambiguity. We define all terms not immediately apparent. We do not make a complete study of each instrument being calibrated, but we state with care what we have and have not done. For example, we state the calibration distance, beam size, and exposure rate for each ionization chamber calibration. If the owner of the instrument believes that the calibration factor is dependent on these parameters, he can investigate the dependence for himself and thus utilize the calibration factor for other conditions than those for which the instrument was calibrated.

3.5 Irradiation of passive dosimeters

Passive dosimeters are irradiated in terms of exposure in any of the photon beams for which an exposure calibration is offered as a regular service. Such irradiations generally are performed on thermoluminescence dosimeters that are submitted to NBS for irradiation to various exposure levels and at various energies. Irradiation in terms of absorbed dose is also offered, but at the present time is limited to the cobalt-60 beam and water phantom used for absorbed-dose calibration.

3.6 Calibration of gamma-ray brachytherapy sources

Brachytherapy sources of cobalt-60 and cesium-137 are calibrated in terms of exposure rate at one meter in air. The method is to calibrate a representative source of each type as a working standard, using open-air geometry and the graphite cavity chambers [21]. The source to be calibrated is then compared to the working standard using a 2.5-liter spherical aluminum ionization chamber. The chamber is supported on a track in the radium range. The source to be intercompared, and the working standard, are alternately placed in a plastic trough at the same height as the center of the chamber, and at an appropriate distance away, usually about 1 m. The trough can be rotated through 180° to test for possible nonuniform source loading. Radium sources are calibrated in the same manner using a lead-aluminum-walled chamber, except that the working standards have been calibrated in terms of mass of radium, as described in Section 2.5.

Iridium-192 sources are also calibrated in terms of exposure rate at 1 m in air, but the procedures are somewhat different. Iridium-192 seeds are too weak for determination of individual exposure rates using our standard cavity chambers, so it is necessary to assemble a composite source of adequate strength, in some cases consisting of as many as 50 seeds. The exposure rate of this composite source is then measured in open-air geometry at 1 m, as for the cobalt-60 and cesium-137 sources. Each iridium-192 seed is then measured individually in a re-entrant ionization chamber designed for this purpose, and the sum of the individual ionization currents combined with the total exposure rate from the composite source serves to calibrate the re-entrant chamber in terms of exposure rate at 1 m in air. Subsequently individual seeds of the same type can be calibrated in the re-entrant chamber, as long as one can be confident the chamber retains its calibration. One of the radium working standards is used to check the constancy of the re-entrant chamber.

Measurement of radium sources was the first activity in the field of radiation measurement at NBS, starting around 1914. Over the years it has given way in importance to measurement of x rays, other gamma rays, and particle beams, until now we have fewer calls for radium calibration than for any other dosimetry calibration. We now calibrate perhaps one or two radium sources a year. This is due in part to the long life of radium, since a radium source once calibrated can serve as a reliable local standard for a very long time. Perhaps equally important is a decline in the use of radium compared to other brachytherapy sources that are believed to be less dangerous from the viewpoint of handling and storage. It is planned to calibrate radium sources in the same manner as other gamma-ray emitters, namely in terms of exposure rate at one meter in air.

The overall uncertainty in the calibration of a gamma-ray source of cobalt-60, cesium-137, or radium is estimated to be about 0.9%. No estimate has been made of the uncertainty in the calibration of an iridium-192 source.

3.7 Calibration of beta-particle brachytherapy sources

The beta-particle applicators that NBS is called on to calibrate have so far been strontium-yttrium-90 ophthalmic applicators. They are calibrated in terms of absorbed dose to water at the applicator surface using an extrapolation ionization chamber with two interchangeable graphite collecting electrodes. The smaller electrode has a diameter of about 1 mm, and is used to scan the applicator surface. It provides a relative profile of current per unit mass of air across the face of the applicator. The relative measurements are normalized to true specific current by measurements with the larger collecting electrode, that has a diameter of 30 mm, large enough to collect all of the ionization. Specific current is in turn converted to absorbed dose rate using conventional values of the mean energy expended per unit charge in air, the mean stopping-power ratio of water to that of air, and a correction factor to account for the excess of graphite albedo over that of water.

All of the measurements must be made close to the applicator surface, but contact between the applicator and the chamber must be avoided, as it distorts the thin polarizing electrode. This problem is avoided by making measurements at several source distances and several air gaps, so that a single extrapolation corrects the measurements to zero source distance and zero air gap. There are many problems in these measurements, and we assign an overall uncertainty of 10% to the calibration factor in terms of dose rate to water at the applicator surface.

3.8 Calibration of x-ray penetrameters

Penetrameters of the Ardran-Crooks type [22] are special x-ray cassettes that contain a metal step wedge and an optical attenuator so arranged that, after exposure to an x-ray beam, the constant potential or the peak potential can be determined by finding on the developed film the positions of equal density under the step wedge and under the optical attenuator. The result is independent of development parameters, over a wide range. Penetrameters of this type can be calibrated at NBS in terms of constant potential up to 250 kV. Penetrameter calibrations performed to date have generally been in the range of 60 to 120 kV. The NBS tube potentials are believed known to 1%, based on potential calibration by the NBS High Voltage Measurements Section.

While calibration of x-ray penetrameters is not based on dosimetry standards, it is an appropriate calibration service for the Dosimetry Section to offer, since it is readily performed by our standard x-ray generators with their stable and well-calibrated power supplies.

4. MEASUREMENT ASSURANCE STUDIES

"Measurement assurance" is a phrase used at NBS to describe procedures designed to test whether measurements made in the field are in agreement with national measurement standards to the accuracy needed. NBS has carried out two extensive measurement-assurance programs to test the ability to deliver a prescribed absorbed dose to water, in both cases using passive dosimeters distributed by common carrier. M. Ehrlich, C. G. Soares, and G. L. Welter have recently made such a survey for cobalt-60 teletherapy beams using thermoluminescence dosimeters, and Ehrlich and P. J. Lamperti have for some years made a biannual survey for high-energy electron-therapy beams using Fricke chemical dosimeters. Since these two programs have been described in detail in another paper in this Symposium, they need no additional discussion here.

A rather different kind of measurement-assurance study is planned using the portable graphite calorimeter. The calorimeter will be taken to a limited number of medical institutions to calibrate the therapy beams directly in terms of absorbed dose. This "primary" calibration will then be compared to a calibration performed in the usual manner using a calibrated ionization chamber. We expect that a good-quality ionization chamber, calibrated at NBS in terms of absorbed dose, will provide a calibration of a cobalt-60 beam that agrees closely with that of the portable calorimeter. For electron beams, or for photon beams of energy higher than that of cobalt-60 gamma rays, the situation is more complex, and is beyond the limits of this talk. We do plan to make such measurements with the calorimeter and with suitable ionization chambers. This program is just getting started, the first measurements outside NBS are now underway, and results must await a future report.

5. DISSEMINATION OF DOSIMETRY UNITS

There exists in the United States no official method for dissemination of the dosimetry units established at NBS. Until about 1970, NBS calibrated (against the national standards of exposure) all suitable dosimetry instruments submitted to it, but was otherwise not associated with dissemination activities. It became clear that this was inadequate to meet the needs of the country, but there was then and there is now no way in which NBS can certify, or otherwise authorize dosimetry calibration activities outside NBS. In 1970 NBS requested the American Association of Physicists in Medicine (AAPM) to organize secondary dosimetry calibration laboratories for medical-level calibration. The rationale for this was that the responsibility for accrediting the laboratories would be taken by the AAPM, since NBS could not legally do so. The AAPM accepted the responsibility and appointed a task group to carry it out. One representative of NBS is on the task group, but the authority is firmly held by the AAPM. The task group has written criteria for requirements that must be met by a Regional Calibration Laboratory (RCL), requires a written application from a prospective RCL, makes a site visit before accreditation, gives first a provisional accreditation for six to twelve months, and makes another site visit before final accreditation. If at any time there is a major change in personnel or equipment which might impair the quality of the calibration, the accreditation is dropped to provisional again, and the site visits are repeated. (This procedure has in fact been used twice.)

The RCLs fully accredited by the AAPM are at Memorial Hospital in New York City, M.D. Anderson Hospital in Houston, Texas, and at the Victoreen Instrument Division in Cleveland, Ohio. Since each is described in a separate paper at this Symposium, further description here is unnecessary.

The three RCLs have been tested by NBS by sending ionization chambers for them to calibrate and comparing the result with the NBS calibration. The experience so far has been excellent, their calibrations agreeing to within 1% with NBS. So far these have all been open tests, that is each RCL knew that it was being tested. It has been proposed that blind tests, in which the RCL does not know that it is being tested, be occasionally performed in the future.

In discussing the dissemination of dosimetry calibrations, we differentiate between secondary and tertiary instruments. *Reference-class (secondary) instruments* are those whose performance and stability are sufficient for calibration of other instruments, or for measurements of unusually high precision and accuracy. *Field-class (tertiary) instruments*

are those whose performance and stability are sufficient for routine medical beam calibrations. In principle, it is the intention of NBS to limit its dosimetry calibration to reference-class instruments, while field-class instruments are calibrated at accredited RCLs. At present, the three RCLs calibrate perhaps three or four times as many field-class instruments as does NBS, but about half the calibrations performed at NBS are still on field-class instruments. For a variety of reasons, it has not yet been possible for NBS to refuse these instruments, but we hope that in the future it will be possible to divert field-class instruments to accredited RCLs.

Not all field-class instruments in the United States are calibrated at either NBS or an RCL. It seems to be the case that many such instruments are calibrated by an informal comparison with another field-class instrument, using a convenient therapy beam. The result of such a comparison is perhaps a quaternary or a quintenary instrument, surely an undesirable status for so important an instrument. Finally, going one step further, there may be field-class instruments that are not calibrated at all. We have at present very little information about this situation, but perhaps more will soon be known, since calibration needs in the United States is the subject of another paper in this Symposium.

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DISCUSSION

J.C. McDONALD: How many ionization chambers for medical use have been calibrated in terms of absorbed dose by NBS so far?

R. LOEVINGER: About ten. Only preliminary calibration factors have been issued, since we want to be very sure that our calibration factors are correct.

Y. MORIUCHI: Is NBS doing anything about the dissemination of photon energy fluence rate standards?

R. LOEVINGER: No, there is no distribution of photon fluence standards at NBS. In the past we have constructed P-2 chambers and quantameters and have co-operated with other institutions in using them, but these instruments are now very little used at NBS.

P. NETTE: You assign an uncertainty of ± 0.8% to the calibration factor of a reference-class dose meter calibrated for exposure with ^{60}Co in your primary laboratory. The PTB in the Federal Republic of Germany assigns ± 4% for ^{60}Co. This discrepancy raises difficulties for the secondary laboratories. How can one solve this problem?

R. LOEVINGER: Unfortunately there are indeed major differences between primary laboratories in the method of expressing the uncertainty of calibration factors. The problem has been recognized and will be the subject of a meeting between representatives of the national laboratories in the near future. We hope that the differences can be resolved.

G.P. HANSON: To what extent do you think the information you presented concerning the intercomparison study for cobalt-60 radiotherapy units using thermoluminescent dose meters reflects the true situation throughout the USA? Might there not be a bias if the institutions which agree to participate are in fact those which have better dosimetry practices?

R. LOEVINGER: We are quite aware that, in any survey in which participation is voluntary, those who agree to participate form a different statistical population from those who do not. We have selected a random sample of 10% of those who declined and are now endeavouring to persuade all members of the random sample to participate. If we succeed, it will presumably give us valid information on the former non-participants.

D.E. JONES: We were asked by the Nuclear Regulatory Commission to perform a survey of their licensed ^{60}Co therapy installations that were not participating in the voluntary TLD intercomparison programme. We surveyed approximately 430 installations and found in general that their calibrations were satisfactory. A paper on this subject was presented by Bruce Dicey of NRC at the Joint Meeting of the Radiological Society of North America and the American Association of Physicists in Medicine, Chicago, 27 November to 2 December 1977. We are currently surveying approximately 300 additional ^{60}Co sources that are covered by state licences in the USA.