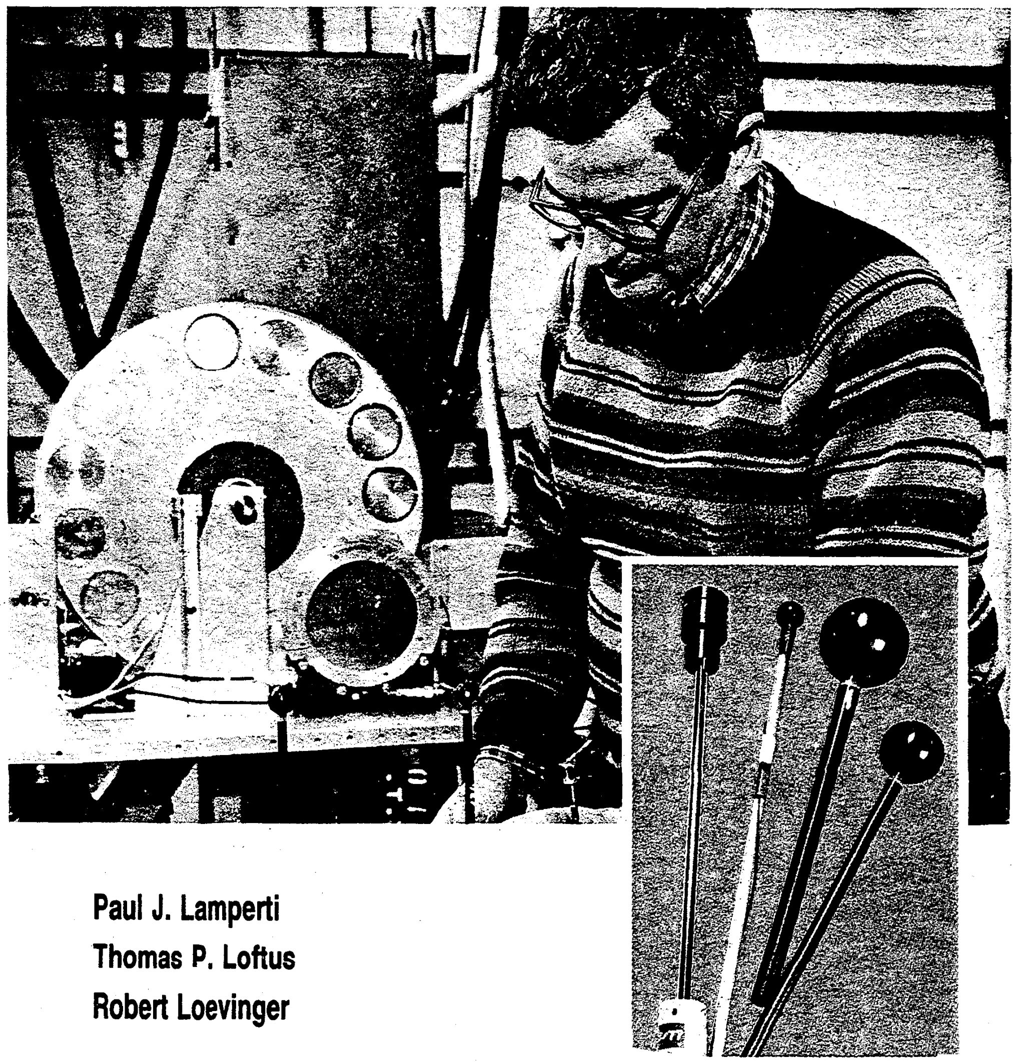
NBS Measurement Services:

Calibration of X-Ray and Gamma-Ray Measuring Instruments



NBS Special Publication 250-16

Paul J. Lamperti
Thomas P. Loftus
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U.S. Department of Commerce
National Bureau of Standards

Center for Radiation Research

The Center for Radiation Research is a major component of the National Measurement Laboratory in the National Bureau of Standards. The Center provides the Nation with standards and measurement services for ionizing radiation and for ultraviolet, visible, and infrared radiation; coordinates and furnishes essential support to the National Measurement Support System for ionizing radiation; conducts research in radiation related fields to develop improved radiation measurement methodology; and generates, compiles, and critically evaluates data to meet major national needs. The Center consists of five Divisions and one Group.

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Carries out basic theoretical and experimental research into the spectroscopic and radiative properties of atoms and highly ionized species; develops well-defined atomic radiation sources as radiometric or wavelength standards; develops new measurement techniques and methods for spectral analysis and plasma properties; and collects, compiles, and critically evaluates spectroscopic data. The Division consists of the following Groups:

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- Radiometric Measurement Services

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- Radiation Theory
- Radiation Chemistry and Chemical Dosimetry
- Neutron Measurements and Research
- Neutron Dosimetry
- Radioactivity
- X-Ray Physics
- Dosimetry

Nuclear Physics Group

Engages in forefront research in nuclear and elementary particle physics; performs highly accurate measurements and theoretical analyses which probe the structure of nuclear matter; and improves the quantitative understanding of physical processes that underlie measurement science.

NBS MEASUREMENT SERVICES: CALIBRATION OF X-RAY AND GAMMA-RAY MEASURING INSTRUMENTS

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PREFACE

The calibration and related measurement services of the National Bureau of Standards are intended to assist the makers and users of precision measuring instruments in achieving the highest possible levels of accuracy, quality, and productivity. NBS offers over 300 different calibration, special test, and measurement assurance services. These services allow customers to directly link their measurement systems to measurement systems and standards maintained by NBS. These services are offered to the public and private organizations alike. They are described in NBS Special Publication (SP) 250, NBS Calibration Services Users Guide.

The Users Guide is being supplemented by a number of special publications (designated as the "SP 250 Series") that provide a detailed description of the important features of specific NBS calibration services. These documents provide a description of the: (1) specifications for the service; (2) design philosophy and theory; (3) NBS measurement system; (4) NBS operational procedures; (5) assessment of measurement uncertainty including random and systematic errors and an error budget; and (6) internal quality control procedures used by NBS. These documents will present more detail than can be given in an NBS calibration report, or than is generally allowed in articles in scientific journals. In the past NBS has published such information in a variety of ways. This series will help make this type of information more readily available to the user.

This document (SP 250-16), NBS Measurement Services: Calibration of X-Ray and Gamma-Ray Measuring Instruments, by P. J. Lamperti, T. P. Loftus, and R. Loevinger, is the sixteenth to be published in this new series of special publications. It describes the calibration and irradiation of x-ray and gamma-ray instruments in terms of the physical quantity exposure, measured in roentgens, or the quantity air kerma, measured in grays (see test numbers 46010C through 46050S in the SP 250 Users Guide). Inquiries concerning the technical content of this document or the specifications for these services should be directed to the authors or one of the technical contacts cited in SP 250.

The Center for Radiation Research (CRR) is in the process of publishing 21 documents in this SP 250 series, covering all of the calibration services offered by CRR. A complete listing of these documents can be found inside the back cover.

NBS would welcome suggestions on how publications such as these might be made more useful. Suggestions are also welcome concerning the need for new calibration services, special tests, and measurement assurance programs.

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Acting Director
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Abstract. The calibration and irradiation of x-ray and gamma-ray instruments are performed in terms of the physical quantity exposure. The calibrations are listed in NBS Special Publication 250 as calibrations 46010C through 46050S (formerly 8.3A through 8.3M). A calibration or correction factor is provided for radiation detectors, charge sensitivity of a high-gain electrometer is tested, and passive dosimeters are given known exposures. Calibration is performed by comparing the instrument against an NBS primary standard of exposure, which is a free-air chamber for x rays and a cavity ionization chamber for cesium-137 and cobalt-60 gamma rays. A variety of quality assurance checks are performed to assure the constancy of the standards and the accuracy of the calibrations and irradiations. The overall uncertainty (considered to have the approximate significance of a 95% confidence limit) is given as 0.7% for exposure rate in the NBS beams, 1% for calibration of a cable-connected chamber and irradiation of passive dosimeters, and 1.5% for calibration of a condenser chamber.

Key words: calibration; cavity chamber; cesium-137 gamma rays; cobalt-60 gamma rays; exposure; free-air chamber; ionization chambers; primary standard; standard; uncertainty estimate; x rays.

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FOREWORD

NBS Special Publications 250-16 and 250-19 can be considered monuments to the skill and dedication of Thomas P. Loftus. Tom came to the Radiological Equipment Section of NBS in 1951, working under Dr. Scott Smith, Section Chief, and Dr. H. O. Wyckoff, Chief, Radiation Physics Laboratory. Tom was involved with and supervised the gamma-ray and brachytherapy calibrations until NBS moved from the Washington, D.C. to the Gaithersburg, Maryland site in 1965. At that time he took on the added responsibility of supervising the x-ray calibration work. He continued in this capacity until his retirement in June 1984. At that time, it was decided to update the documentation of all the dosimetry calibration services, as part of a Bureau-wide program. It was evident that Tom was the ideal person to take on this job, and he was awarded a contract for that purpose. The result was six separate documents entitled "Review of Ionization-Chamber Current-Measurement Techniques in the NBS Dosimetry Group", "Ionization-Current Measurement Console Equipment", "Pre-Calibration Testing of Exposure Instrumentation", "Gamma-Ray Calibration Ranges", "Exposure Calibration of Radiation Instruments at the NBS", and "Brachytherapy Source Calibrations at the NBS".

The first five documents form the basis for SP 250-16, and the last forms the basis for SP 250-19. In order to meet the requirements for the NBS SP 250 series of publications, the Loftus material has been reorganized, rewritten in places, supplemented with additional material, and edited by P. J. Lamperti (SP 250-16), J. T. Weaver (SP 250-19), and R. Loevinger (both documents).

The final documents reflect the knowledge, skill, experience, and careful attention to detail of Thomas P. Loftus. P. J. Lamperti and J. T. Weaver, who worked under Tom for many years, wish to express here their thanks to him for the example he set while at NBS.

P.J.L., R.L., J.T.W.
March 1988

1. Introduction

This report describes the status of the calibration service for x-ray and gamma-ray measuring instruments, as of September 1986. Section 1 defines the physical quantity exposure, in terms of which the calibrations are performed, and also the properties of the x-ray and gamma-ray beams used in the service. Section 2 is a brief definition of calibration by substitution. Section 3 describes in detail the calibration system and its measurement standards, first (section 3.2) the free-air chambers and the x-ray beams, and then (section 3.4) the cavity-chamber standards and the gamma-ray beams. Sections 3.5 and 3.6 describe the instruments and techniques for measuring current and charge, and for storing and analyzing the calibration data. Section 3.7 describes the tests applied to the instruments being calibrated, while section 3.8 covers the tests and calibrations performed on NBS laboratory equipment. Section 4 describes the operating procedures, including the administrative procedures and methods of handling and calibrating the instruments, and irradiating the passive dosimeters. The assessment of uncertainty is covered in section 5, followed by safety considerations in section 6, including radiation, high-voltage, and laser safety. References are listed at the end of the report, in the order in which they were cited. Twenty-one attachments are appended to the report; a list of the attachments gives the number of the section in which the attachment is cited.

1.1 Description of service

The National Bureau of Standards (NBS), Ionizing Radiation Division, Dosimetry Group receives a variety of instruments for calibration, test, or irradiation in x- or gamma-ray beams. These services are Test Nos. 46010C through 46050S (formerly 8.3A through 8.3M) in NBS Special Publication 250 [1],[1] "NBS Calibration Services Users Guide 1986-88," available from the NBS Office of Physical Measurement Services. Calibration factors or correction factors are provided for radiation detectors. The charge sensitivity of a high-gain electrometer can be tested at any one set of switch positions in conjunction with a calibration factor. Passive dosimeters can be given known exposures of x or gamma radiation. Calibrations and irradiations are performed in terms of the physical quantities exposure and air kerma.

The quantity exposure characterizes an x-ray or gamma-ray beam in terms of the electric charge liberated in air by ionization of air molecules. Exposure can be defined qualitatively as the total charge per unit mass liberated in free air by a photon beam. More precisely, the 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 liberated by photons in a volume element of air whose mass is dm are completely stopped in air. Then

$$X = dQ/dm \quad .$$

[1]Numbers in brackets indicate the literature references at the end of this document.

The SI unit of exposure is the coulomb per kilogram (C/kg); the special unit of exposure, the roentgen (R), is equal to 2.58×10^{-4} C/kg (exactly). The ionization arising from the absorption of bremsstrahlung emitted by the secondary electrons is not to be included in dQ. Except for this small difference, significant only at high energies, the exposure as defined above is the ionization equivalent of air kerma.

The quantity kerma characterizes a beam of photons or neutrons in terms of the energy transferred to any material. In the calibration service under discussion, consideration is limited to photon beams and air. Air kerma can be defined qualitatively as the total energy per unit mass transferred from an x-ray or gamma-ray beam to air. More precisely, air kerma (K_{air}) is the quotient of dE_{tr} by dm, where dE_{tr} is the sum of the initial kinetic energies of all electrons liberated by photons in a volume element of air and dm is the mass of the air in that volume element. Then

$$K_{air} = dE_{tr}/dm \quad .$$

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

The relationship between exposure and air kerma can be expressed as a simple equation:

$$K_{air} = X \cdot (W/e)/(1-g)$$

where W/e is the mean energy per unit charge expended in air by electrons, and g is the mean fraction of the energy of the secondary electrons that is lost to bremsstrahlung.

The currently accepted value of W/e is 33.97 J/C. The currently accepted values of g for ^{60}Co and ^{137}Cs beams are 0.32% and 0.16%, respectively. Then, using SI units, X is converted to K_{air} by multiplying by 34.08 and 34.02 for ^{60}Co and ^{137}Cs beams, respectively. The value of g is negligible for the x-ray beams of interest, and the conversion factor is just 33.97.

Any calibration or irradiation performed in terms of exposure can be converted to a calibration or irradiation in terms of air kerma by use of the multiplicative constants given above. Because of the inconvenient form of SI units for exposure and (especially) exposure-rate, the quantity air kerma is being adopted in place of exposure in virtually all countries. NBS has not made this change at the time of writing (June 1986), but expects to do so. The material that follows is written in terms of exposure, but it applies equally well to calibrations and irradiations in terms of air kerma, making use when necessary of a multiplicative constant to convert the former to the latter.

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 carry out beforehand a careful program of stability checks involving redundant measurements in highly reproducible radiation fields, and to repeat those checks after NBS calibration, and again at suitable intervals. Instruments submitted for calibration, and material submitted for irradiation, must be shipped in reusable containers.

An x-ray tube produces bremsstrahlung spectra, highly 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 aluminum, copper, tin, or lead) in order to reduce the unwanted low-energy x rays. 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 exposure rate to 50%, and then again to 25%, of its original value. These thicknesses are called the first half-value layer (HVL) and the second HVL. The measurements must be made using good-geometry attenuation in order to obtain numbers of general significance. The homogeneity coefficient is the ratio of the first to the second HVL, here multiplied by 100 to provide more convenient numbers. A value near 100 indicates that the filtration has produced an approximately homogeneous beam that is approaching monoenergetic conditions.

1.2 Beam qualities for calibration of x- and gamma-ray measuring instruments

The NBS x-ray beam qualities offered for exposure calibration of x- and gamma-ray measuring instruments were revised in Jan 1983. Several previously offered beam qualities were discontinued, a number of new qualities added, and a total of 32 qualities offered. The beam qualities are divided into groups according to filtration, i.e., light, moderate, and heavy filtration. The qualities for each group were chosen so that the x-ray tube constant potentials plotted against HVL fall on or near a smooth curve. Likewise the aluminum and copper homogeneity coefficients plotted against HVL fall on or near a smooth curve. (The homogeneity coefficient is taken as HC = 100 × 1st HVL/2nd HVL.) Figure 1-1 is a graph of the generating constant potential against the aluminum and copper HVLs. Figure 1-2 and 1-3 are graphs of the homogeneity coefficient against the HVL, for aluminum and copper, respectively.

The beam codes consist of the letter L, M, or H, followed by the generating constant potential in kilovolts. For example, M100 indicates moderate filtration and 100-kV constant potential. Table 1-1 gives a complete listing of beam codes offered.

It has been our experience that calibration factors for ionization chambers fall on smooth curves when plotted against HVL, provided that 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 may occur, hence no attempt should be made to interpolate between such calibration factors.

The selection of beam qualities for instrument calibration depends on the situation of interest. The H qualities are usually used for calibration for radiation protection, since 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 for radiation therapy. The L qualities are 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.

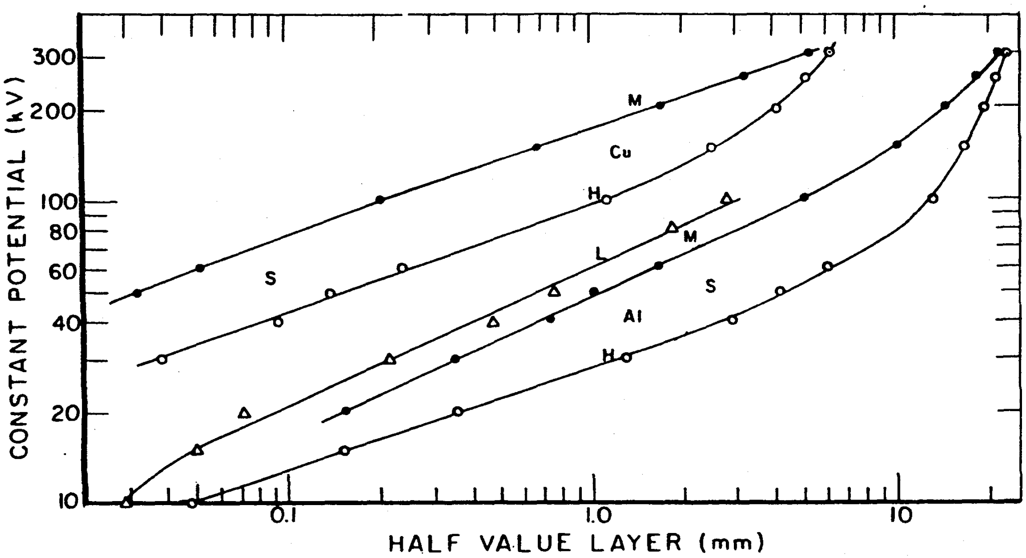


Fig. 1-1. Graph of generating constant potential against half-value layer for the beam qualities used in x-ray calibration. The two upper curves refer to copper half-value layers for the moderate (M) and heavy (H) filtrations. The three lower curves refer to aluminum half-value layers for the light (L), M, and H filtrations. The three S symbols indicate two special filtrations that do not fit in with the L, M, and H filtrations.

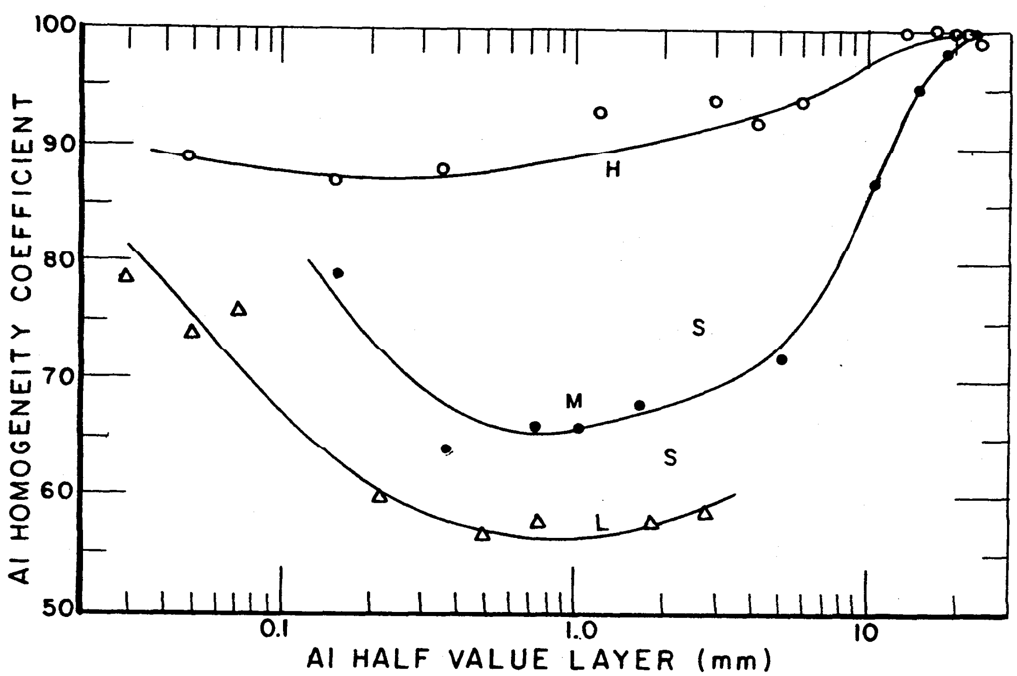


Fig. 1-2. Graph of aluminum homogeneity coefficient against aluminum half-value layer for the L, M, and H filtrations. The two S symbols indicate two special filtrations that do not fit in with the L, M, H filtrations.

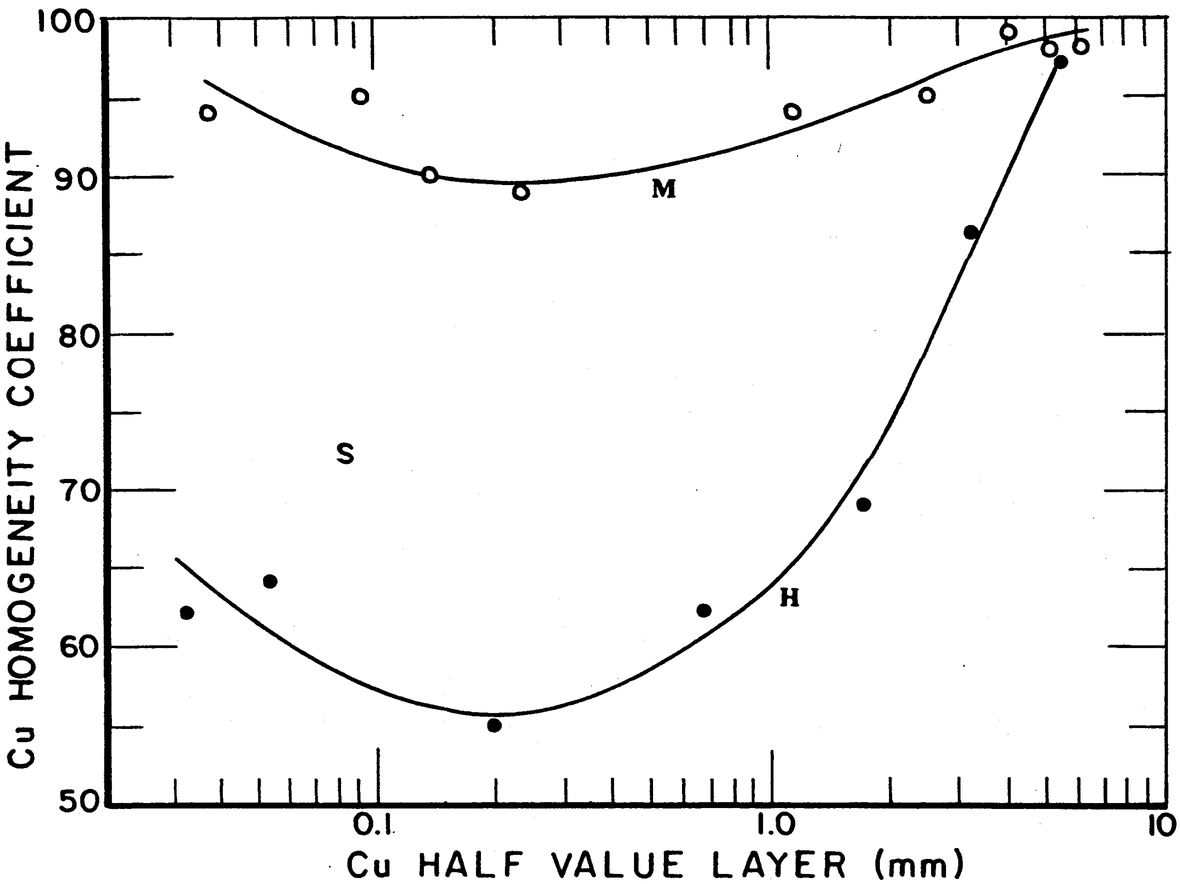


Fig. 1-3. Graph of copper homogeneity coefficient against copper half-value layer for the M, and H filtrations. The S symbol indicates a special filtration that does not fit in with the M and H filtrations.

Table 1-1. Calibration conditions for x-ray and gamma-ray measuring instruments. This is the last page of a computer-generated calibration report.

BEAM CODE	ADDED FILTER AL (MM)	CU (MM)	SN (MM)	PB (MM)	HALF-VALUE LAYER AL (MM)	CU (MM)	HOMOGENEITY COEFFICIENT AL	CU	EFFECT. ENERGY (KEV)	DIS- TANCE (CM)	EXPOSURE RATE MIN. (MR/S)	MAX. (R/S)
L10	0				0.029		79			25	0.001	1.7
L15	0				0.050		74			25	0.001	4.2
L20	0				0.071		76			50	0.001	3.3
L30	0.265				0.22		60			50	0.001	0.4
L40	0.50				0.49		57			50	0.001	0.4
L50	0.639				0.75		58			50	0.001	0.4
L80	1.284				1.83		58			50	0.001	0.4
L100	1.978				2.8		59			50	0.001	0.4
M20	0.230				0.152		79			50	0.001	0.5
M30	0.50				0.36		64			50	0.001	0.3
M40	0.786				0.73		66			50	0.001	0.4
M50	1.021				1.02	0.032	66	62		50	0.001	0.4
M60	1.51				1.68	0.052	68	64			0.8	0.2
M100	5.0				5.0	0.20	72	55			1.0	0.3
M150	5.0	0.25			10.2	0.67	87	62			1.0	0.4
M200	4.1	1.12			14.9	1.69	95	69			1.0	0.3
M250	5.0	3.2			18.5	3.2	98	86			1.0	0.2
M300	4.0		6.5		22	5.3	100	97			0.5	0.08
H10	0.105				0.148		89			25	0.001	0.003
H15	0.500				0.152		87			25	0.001	0.003
H20	1.021				0.36		88			50	0.001	0.003
H30	4.13				1.23	0.038	93	94		50	0.001	0.003
H40	4.05	0.26			2.9	0.093	94	95		50	0.001	0.003
H50	4.0			0.10	4.2	0.142	92	90	38		0.3	0.065
H60	4.0	0.61			6.0	0.24	94	89	46		0.02	0.005
H100	4.0	5.2			13.5	1.14	100	94	80		0.005	0.002
H150	4.0	4.0	1.51		17.0	2.5	100	95	120		0.03	0.010
H200	4.0	0.60	4.16	0.77	19.8	4.1	100	99	166		0.02	0.006
H250	4.0	0.60	1.04	2.72	22	5.2	100	98	211		0.03	0.005
H300	4.1		3.0	5.0	23	6.2	99	98	252		0.04	0.003
S75	1.504				1.86		63			50	0.001	0.4
S60	4.0				2.8	0.089	75	70			0.3	0.06
137CS						10.8			662		1.5	0.1
60CO						14.9			1250		1.5	2.5

FOR THE X-RAY BEAM CODES, THE LETTER INDICATES LIGHT, MODERATE, HEAVY, AND SPECIAL FILTRATION, AND THE NUMBER IS THE CONSTANT POTENTIAL IN KILOVOLTS.

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.

THE HALF-VALUE LAYERS FOR 137CS AND 60CO ARE CALCULATED.
THE HOMOGENEITY COEFFICIENT IS TAKEN AS 100(1ST HVL/2ND HVL).

The revised calibration beam qualities brought NBS practice into line with practice at other national standards laboratories. The H group of qualities agrees with the "narrow spectrum" qualities recommended by the International Standards Organization (ISO) in "X and γ reference radiations for calibrating dosimeters and dose ratemeters and for determining their response as a function of photon energy," ISO Publication 4037-1979 (E) (attachment 1). The ISO recommendations extend from 300 kV to 40 kV, below which the H group has been extended to 10 kV in agreement with practice at the PTB (the standards laboratory of the Federal Republic of Germany). The M group of qualities is in agreement with the recommendation for radiation therapy calibration in "Dosimeters with ionization chambers as used in radiation therapy," IEC Publication 731, 1982 (attachment 2).

The NBS beam codes used since Jan 1983 are shown in table 1-1. The beam codes S60 and S75, and the 5 beam codes that were discontinued have characteristics that are not consistent with those of the L, M, and H groups. The NBS beam codes used prior to Jan 1983 are given in attachment 3.

2. Design philosophy and theory

X-ray calibrations are performed by using the substitution method. Using this method, the exposure or exposure 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. The response of the instrument is determined. The calibration factor is the quotient of the x-ray exposure, in the absence of the chamber, and the charge generated by that radiation in the ionization chamber:

$$\text{Calibration Factor} = X/Q$$

The correction factor is the quotient of the x-ray exposure, in the absence of the chamber, and the electrometer reading with the ionization chamber:

$$\text{Correction Factor} = X/(\text{reading})$$

Gamma-ray calibrations are performed by using previously calibrated beams and correcting for decay. Details of the calibration of gamma-ray beams are given in section 3.4.3.

3. Description of system

3.1. General overall view

Two x-ray calibration ranges are available for instrument calibrations. One range is used for x-rays generated at potentials of 10 kV to 100 kV, the other is used for x-rays generated at potentials of 50 kV to 300 kV. X-rays are produced using constant-potential generators. Gamma-ray calibrations are performed on any one of seven sources, of which three have vertical beams, and four have horizontal beams. A schematic diagram of the 300-kV x-ray calibration range is given in figure 3-1.

3.2. X-ray exposure calibration standards

Standardization of x-ray beams for the quantity exposure is carried out at NBS by means of three free-air ionization-chamber standards (FAC) [2], [3], and [4]. Figures 3-2 to 3-4 show cross-sectional views of the three free-air chambers. The important dimensions of the three free-air chambers are given in table 3-1. With reference to table 3-1, note that the free-air chambers become larger as the x-ray energy increases. The chamber size is dictated by the need, at low x-ray energies, to minimize air attenuation in the path between the FAC defining diaphragm and the collection plate, and the need, at high x-ray energies, to compensate for the downstream loss of electrons from the collection volume by providing sufficient air path length upstream. The latter also eliminates electrons from the diaphragm. At the higher x-ray energies, the plate separation is also made larger in an attempt to allow for complete energy loss for electrons with paths predominantly perpendicular to the x-ray beam direction.

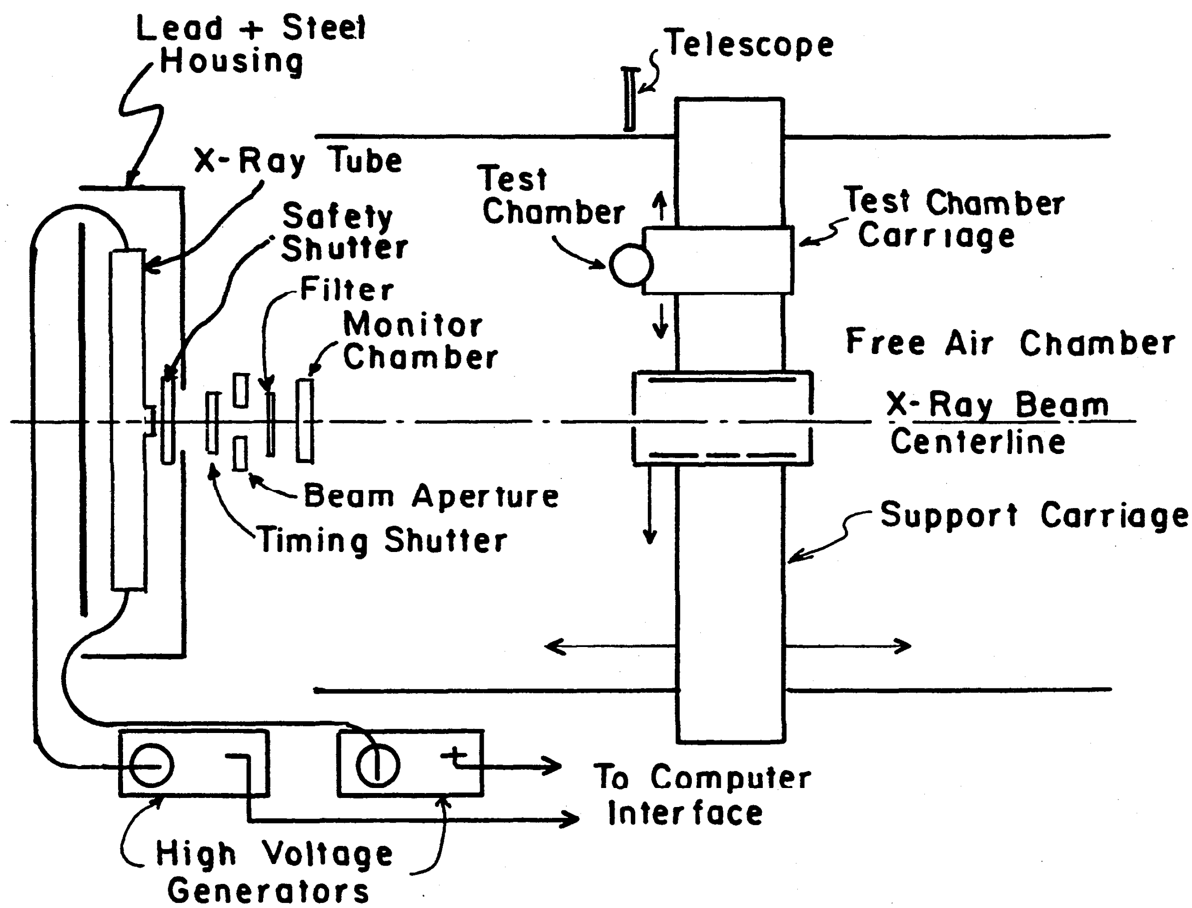


Fig. 3-1. Schematic of 300-kV x-ray set.

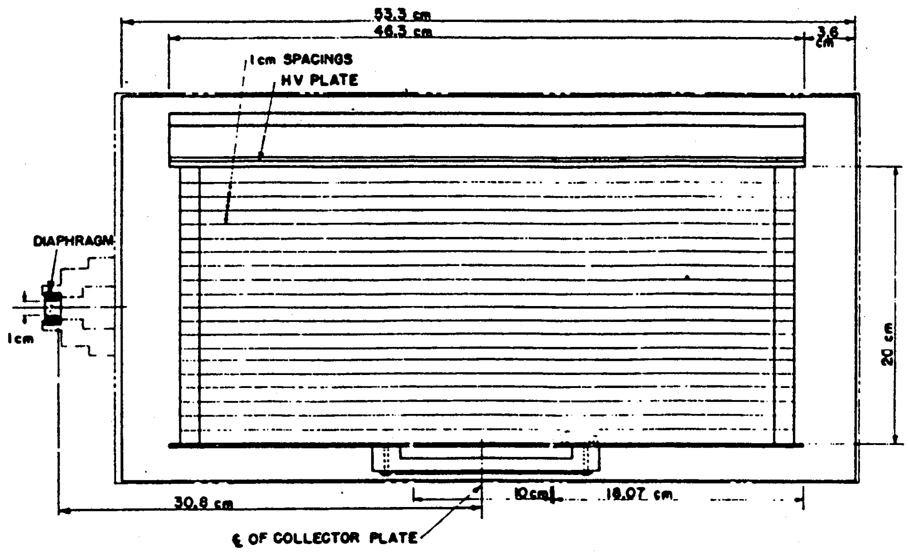


Fig. 3-2. Sectional view of Wyckoff-Attix (50- to 300-kV) free-air chamber.

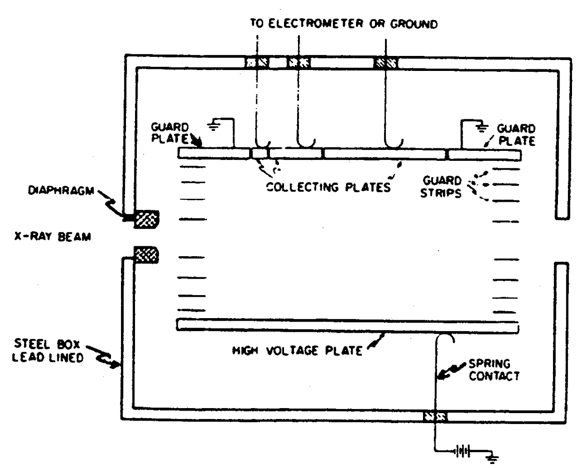
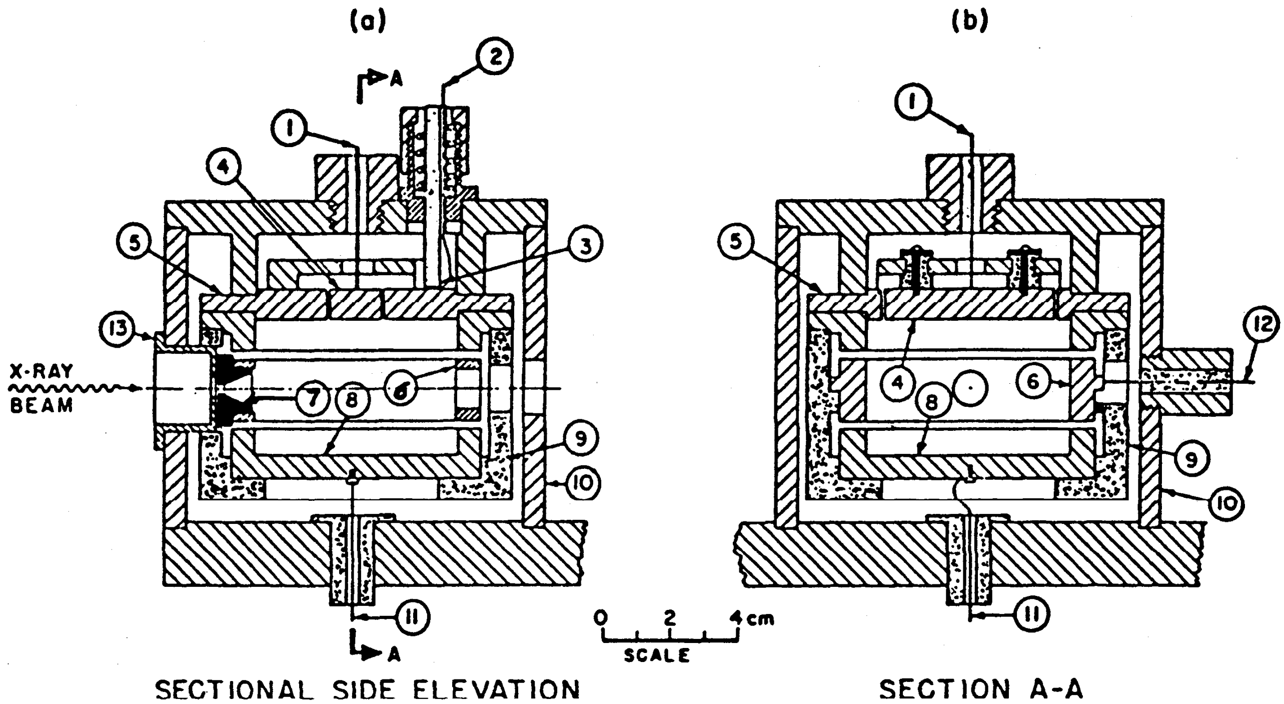


Fig. 3-3. Sectional view of the Ritz (20- to 100-kV) free-air chamber.



1. Lead to current measuring system
2. Lead to thermistor readout
3. Thermistor
4. Collector plate (brass)
5. Guard plate (brass)
6. Guard ring (brass)
7. Diaphragm (tungsten alloy)
8. High voltage plate (brass)
9. Supporting insulator (delrin)
10. Grounded case (brass)
11. High voltage lead
12. Lead to midpoint of potential divider
13. Radiation shield (brass)

Fig. 3-4. Schematic cross-sectional views of the Lamperti (10- to 20-kV) free-air chamber.

Table 3-1. Important dimensions and parameters for the three NBS free-air ionization-chamber standards.

X-ray tube potential (kV)	Plate separation (mm)	Plate height (mm)	Collector length (mm)	Diaphragm diameter/(ID) (mm)	Air absorption length (mm)	Electric field strength (V/cm)
10 to 60	40	50	10.146	4.994/(5S)	39.02	750
20 to 100	90	90	70.030	10.00/(10A)	127.39	555
50 to 300	200	268	100.80	10.00/(10B)	308	250

The 10-to-60-kV FAC is designed for use up to 60 kV but is normally used only up to 15 kV. In column five ID gives the identification number for each diaphram.

Although strenuous efforts were made, by the designers of the free-air chambers, to realize experimentally the quantity exposure, various corrections are still required. The corrections are as follows:

Air attenuation (k_a) - The area of the beam, and the exposure rate, are defined at the position of the FAC diaphragm, but the length of the air volume in which the ionizing electrons of interest are produced is defined by the length of the collector plate. Correction must be made for attenuation of the x-rays in the air path between the position of definition and the position of measurement. The distance for air attenuation measurements is taken to be the distance between the defining plane of the diaphragm and the center of the collector. This correction is energy dependent and at low energies atmospheric temperature and pressure effects become significant.

Photon scatter (k_p) - Ionization produced by electrons resulting from photons scattered out of the diaphragm-defined beam is not included in the definition of exposure.

Electron loss (k_e) - Energetic electrons may leave the collection volume before expending their entire energy in the form of ionization. The volume is defined by the area of the collection plate and the distance between the collection plate and the high-voltage plate (plate separation).

Recombination (k_s) - Ions may recombine before they are collected. This correction is exposure-rate dependent.

Since the quantity exposure is defined as charge per unit mass of air, and the special unit of exposure, the roentgen, is 2.58×10^{-4} C/kg, the calculation of exposure data from standard free-air chamber measurements of charge is accomplished using the equation

$$\dot{X} = \frac{1}{2.58 \times 10^{-4}} \frac{dQ/dt}{\rho V} \Pi k_i$$

where $\dot{X}$ is the exposure rate (R/s).

dQ/dt is the rate of change of the collected charge (C/s).

V is the product of the diaphragm area and collector plate length, the volume (m^3).

ρ is the density of air at the ambient conditions of temperature and pressure.

$$\rho = \rho_0 \, PT_0 / P_0 T \quad (kg/m^3)$$

and ρ_0 is the density of air at the reference conditions, T and P are the ambient temperature and pressure, and T_0 and P_0 are the reference temperature and pressure. (T and T_0 are in kelvins.)

Πk_i is the product of all necessary dimensionless correction factors.

3.2.1. Wyckoff-Attix (50- to 300-kV) FAC corrections

The correction for electron loss is

$$k_e = 1 - \sum A_F E_r / 100$$

and the correction for scattered photon contribution is

$$k_p = 1 - \sum A_F S_r / 100 \quad .$$

In these equations, E_r is the percent electron contribution (a loss) beyond a radius r, S_r is the percent scattered photon contribution (a gain) beyond radius r, and A_F is the fraction of each annular area that contributes to the summation. The calculations of the corrections for electron loss, k_e, and photon contribution, k_p, are based on data from NBS Handbook 64 (HB64) [2] and the work of Ritz [5]. Calculations for the percent loss (E_r) of electron-produced ionization beyond different radii, from a zero diameter x-ray beam, utilize figures 8, 9, and 10 in HB64, (reproduced and recaptioned in figs. 3-5 to 3-7 below) while curves for the percent electron contribution to the ionization per radius increment ($\Delta E_r/r$) at different inner radii are provided in figures 11, 12, and 13 of HB64 (reproduced and recaptioned in figs. 3-8 to 3-10 below).

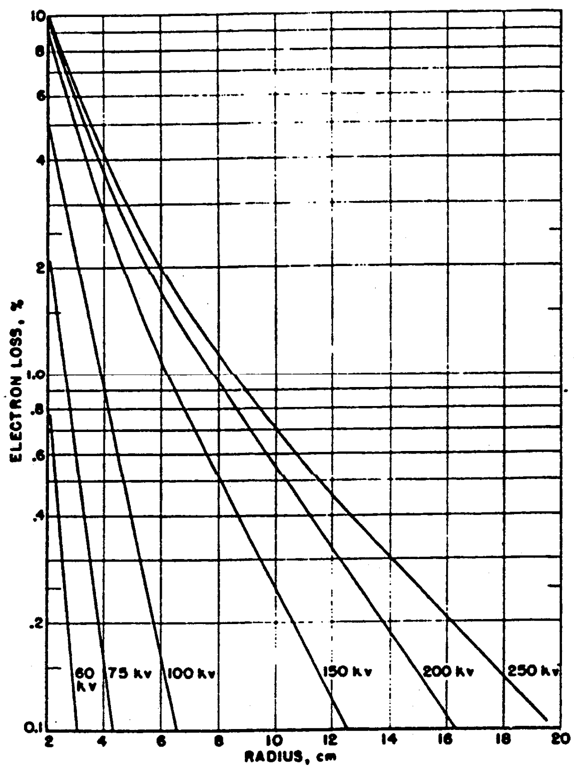


Fig. 3-5. The loss of electron-produced ionization (in percentage of total electron ionization) beyond different radii from a zero-diameter beam of constant potential x-rays.

The x-ray potentials were 60 and 75 kV with zero added filter, 100 kV with 1 mm Al added filter, 150 kV with 0.23 mm Cu + 1 mm Al added filter, 200 kV with 0.5 mm Cu + 1 mm Al added filter, and 250 kV with 1 mm Cu + 1 mm Al added filter. The x-ray tube had an inherent filtration of approximately 3 mm Al.

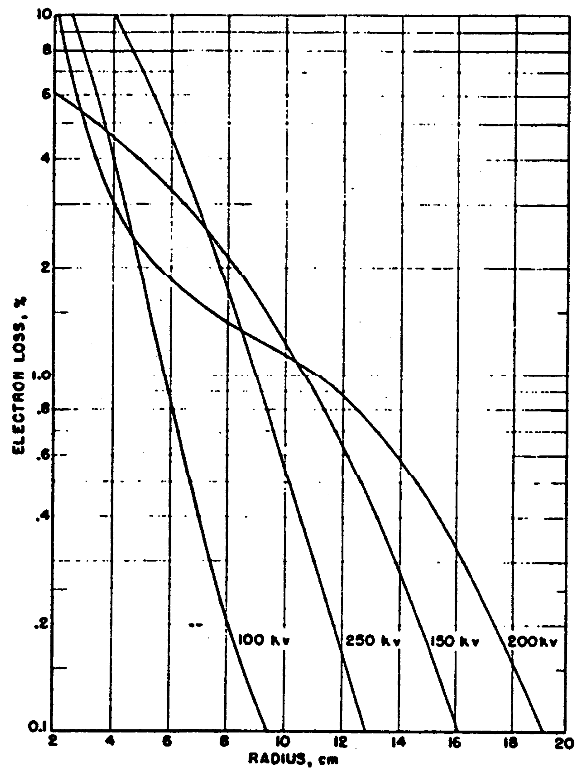


Fig. 3-6. The loss of electron-produced ionization (in percentage of total electron ionization) beyond different radii from a zero-diameter beam of constant potential x-rays.

The x-ray potentials were 100 kV with 0.53 mm Pb added filter, 150 kV with 1.53 mm Sn + 4.0 mm Cu added filter, 200 kV with 0.7 mm Pb + 4.0 mm Sn + 0.59 mm Cu added filter, and 250 kV with 2.7 mm Pb + 1.0 mm Sn + 0.59 mm Cu added filter. The inherent filtration of the beam was approximately 3 mm Al.

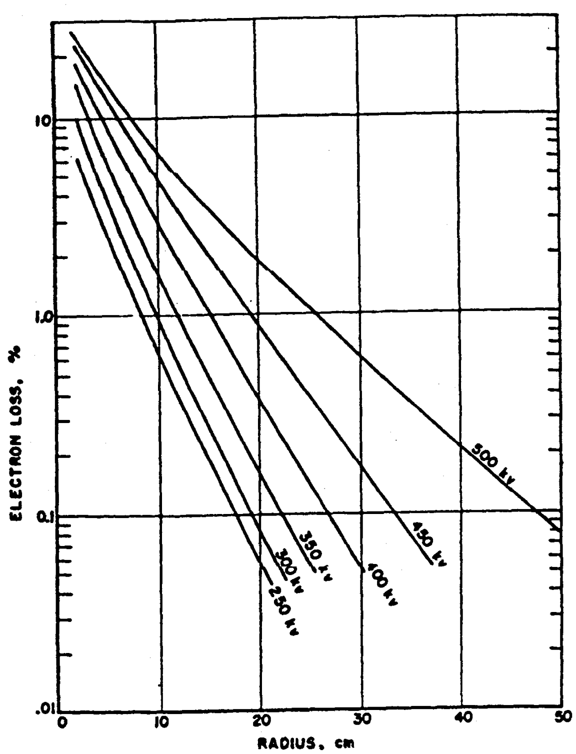


Fig. 3-7. The loss of electron-produced ionization (in percentage of total electron ionization) beyond different radii from zero-diameter x-ray beams of the constant potentials indicated. The inherent filtration of the beam was approximately 3 mm Cu.

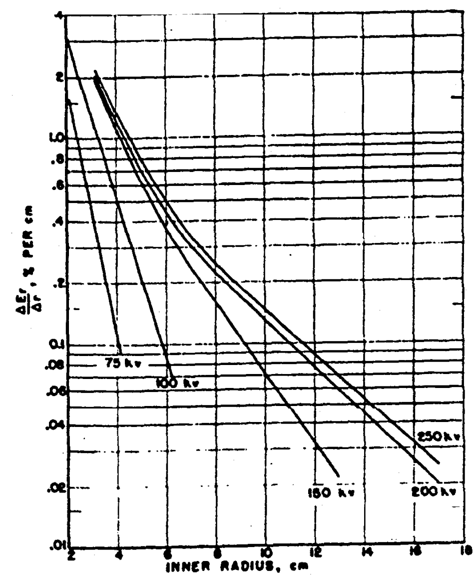
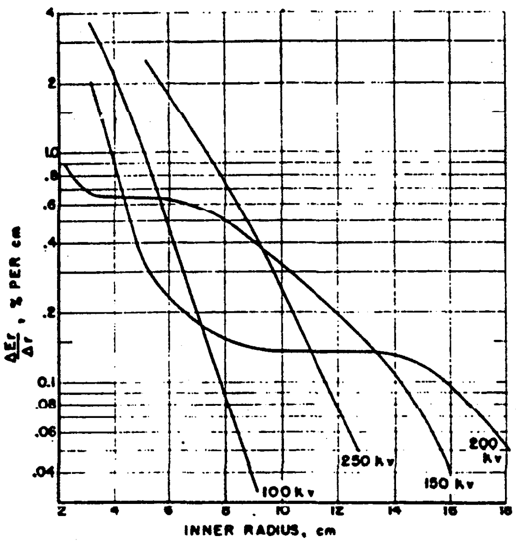


Fig. 3-8 The percent contribution of electron-produced ionization per centimeter for the indicated constant-potential x-ray beams and filtrations given in figure 3-5.

The figures 3.5 and 3.6 form an interesting pair (as do figures 3.8 and 3.9). Both figures show the loss of ionization, as a percent of the total ionization, beyond different radii for zero-diameter x-ray beams generated at the constant potentials shown on the curves. Figure 3.5 refers to very lightly filtered beams, and figure 3.6 refers to heavily filtered beams essentially the same as in table 1-1. The constant potentials 100 kV to 250 kV are the same in the two figures, yet the shapes of the curves are quite different. The experimentally obtained curves represent the resultant of scattering and absorption of photons and electrons, in a series of interactions that appear to be too complicated to allow an easy explanation for the details of the individual curves.



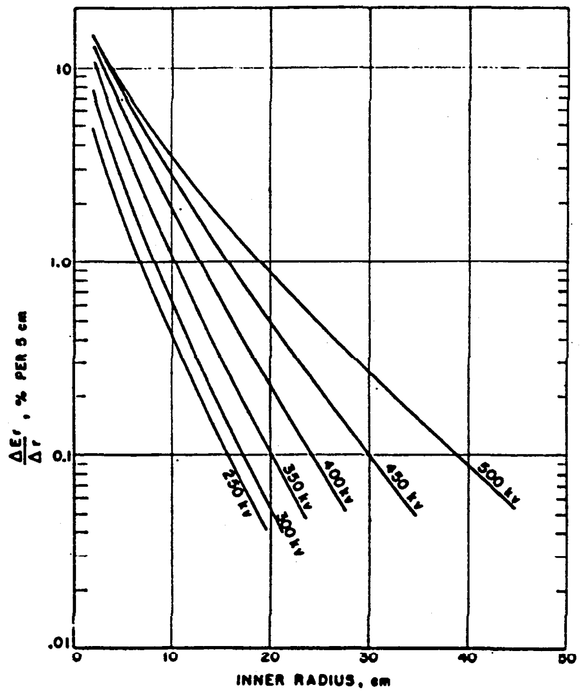


Fig. 3-9. The percent contribution of electron-produced ionization per centimeter for the indicated constant-potential x-ray beams and filtrations given in figure 3-6.

Fig. 3-10. The loss of electron-produced ionization per 5 cm for the indicated constant-potential x-ray beams and an inherent filtration of approximately 3 mm Cu.

In order to calculate the correction for electron ionization loss, it is necessary first to find the percent loss in ionization, E_r, utilizing figures 8, 9, or 10 in HB64 (figures 3-5 to 3-7) for the x-ray beam quality of interest, beyond a radius computed from the FAC plate separation and the diameters of the x-ray beam. For example, the minimum inner radius r_o for the Wyckoff-Attix FAC is 95 mm for a 10-mm diameter beam (see figure 3-11). It is always necessary to decrease the plate separation by the diameter of the beam. It is then necessary to determine the fractions A_F of the annular areas remaining inside the cross section of the FAC collection volume for increasing inner radii. Next, the products are formed for each fractional area and the percent contribution to the ionization per centimeter for the inner radius associated with the fraction. The products are then added algebraically to the percent loss in ionization beyond the minimum inner radius r_o. The net result is the percent loss in FAC ionization for a particular beam quality due to inadequate plate spacing.

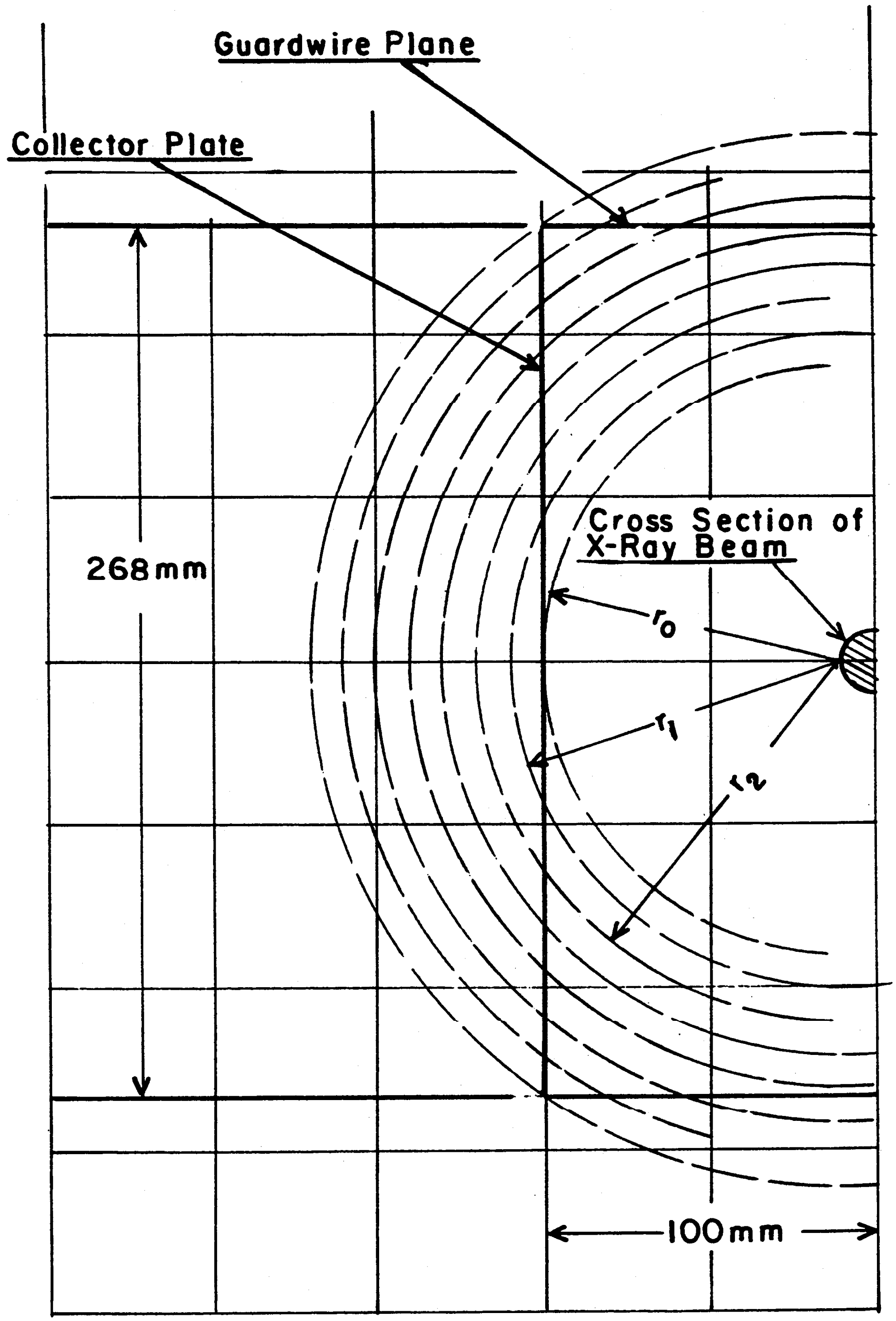


Fig. 3-11. Cross section of Wyckoff-Attix FAC.

The calculations of k_p requires the use of a revised table (on an errata sheet) in HB64 for the percent scattered photon contribution (S_r) to the ionization. The revised table is shown in table 3-2.

Table 3-2. Secondary photon contribution, S_r, in percent

Radius	X-ray tube potential (kV)								
	60	75	100	150	200	250	300	400	500
(cm)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
5	0.44	0.41	0.32	0.21	0.20	0.19	0.18	0.16	0.16
10	0.62	0.59	0.49	0.35	0.33	0.31	0.29	0.27	0.27
15	0.85	0.82	0.70	0.54	0.50	0.46	0.43	0.39	0.39
20	1.09	1.06	0.93	0.73	0.68	0.63	0.57	0.52	0.52
25	1.32	1.29	1.14	0.91	0.85	0.78	0.71	0.64	0.64
30	1.53	1.50	1.34	1.08	1.00	0.92	0.84	0.76	0.76
35	1.73	1.70	1.52	1.24	1.15	1.05	0.96	0.86	0.86
40	1.92	1.89	1.70	1.40	1.29	1.18	1.07	0.96	0.96

The fractions of the annular areas inside the collection plate system of the Wyckoff-Attix FAC were calculated using the following equations:

Annular area $A = \pi(r^2_{n+1} - r_n^2)$

Area of a segment $P_i = (\pi r_i^2/2) - \left(r_o \sqrt{r_i^2 - r_o^2} + r_i^2 \sin^{-1}(r_o/r_i)\right)$

where $\sin^{-1}(r_o/r_i)$ is in radians.

$A_x = 2(P_{n+1} - P_n)$, annular area outside cross section of collection volume.

$A_F = 1 - A_x/A$, fraction of annular area inside cross section of collection volume.

The percent secondary photon contribution S_r changes slowly with distance from the x-ray beam so it is only necessary to consider large differences in radii when calculating $A_F S_r$. The fractional area inside the cross section of the volume defined by the collector plate and the guard wire is just the difference between 2P and the annular area, for the radii 95 mm and 129 mm. It is important to recognize that the difference in percent photon contribution, between the data given for 95 mm and 129 mm, is multiplied by the fractional area to get $A_F S_r$ between those radii. To aid in interpolation for S_r, the data of table 3-2 are plotted in figure 3-12.

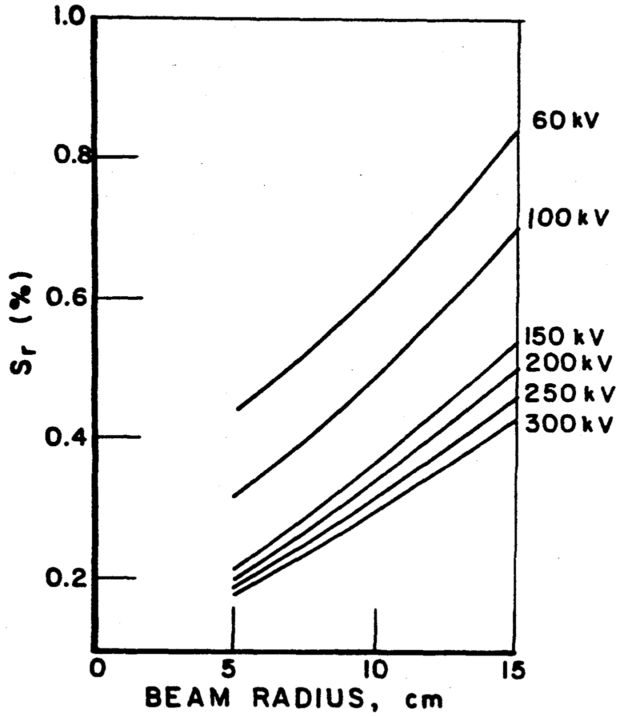


Fig. 3-12. Percent secondary photon contribution within radii from 5 to 15 cm.

Details of the calculations for the loss and gain of ionization in the Wyckoff-Attix FAC are given in tables 3-3 and 3-4 and a summary of the results is given in table 3-5. The beam code designations from table 1-1 are used in table 3-5 to associate the data derived from HB64 with present-day x-ray beam conditions. The corrections for gain of ionization are calculated from a plot of corrections derived from data in HB64 vs Al half-value layer. The corrections for electron loss are calculated from data in HB64 generated for beam conditions very nearly the same as present-day conditions. It is assumed that the differences are not significant. There is one exception to this assumption and that is for H300 for which the HB64 filtrations are not comparable. For a comparison of the present day and HB64 beam filtrations, refer to table 3-6.

The percent corrections, $\Sigma A_F E_r$ and $\Sigma A_F S_r$, presently used for the Wyckoff-Attix FAC and the products of all exposure-rate-independent corrections for each beam code are given in table 3-7. Comparison of columns 3 and 4 of table 3-7 with columns 2 and 3 of table 3-5 shows there is good agreement, in general, between the data calculated in this review from HB64 and the data presently used. The corrections for electron loss ($\Sigma A_F E_r$) for beam M300 and H300 are estimated from figure 9 of reference 2, and may be slightly in error since the filtration of that reference beam is not the same as that of the present-day M300 and H300 beams. The trends in the corrections in this energy range have been considered and an uncertainty in $\Sigma A_F E_r$ of 0.07% has been estimated for M300 and 0.15% for H300.[2]

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[2]Estimated uncertainties are intended to correspond roughly to a 67% confidence-level, as explained in section 5.

Table 3-3. Data from Handbook 64, and fractional areas, used to calculate the percent loss in ionization for moderately (M) and heavily (H) filtered x-rays due to inadequate plate spacing in the Wyckoff-Attix FAC.

Radius			M100		M150		M200		M250		M300*		H100		H150		H200		H250		H300	
Inner (cm)	Outer (cm)	A_F	E_r (%)	A_FE_r (%)	E_r (%)	A_FE_r (%)	E_r (%)	A_FE_r (%)	E_r (%)	A_FE_r (%)	E_r (%)	A_FE_r (%)	E_r (%)	A_FE_r (%)	E_r (%)	A_FE_r (%)	E_r (%)	A_FE_r (%)	E_r (%)	A_FE_r (%)		
0	9.5	1.00	0	0	-0.29	-0.29	-0.61	-0.61	-0.77	-0.77	-1.05	-1.05	-0.10	-0.10	-1.40	-1.40	-1.10	-1.10	-0.68	-0.68	-	-
9.5	10.5	0.81	0	0	0.085	.07	0.14	0.11	0.16	0.13	0.13	0.11	0.03	0.02	0.35	0.28	0.13	0.105	0.32	0.26	-	-
10.5	11.5	0.66	0	0	0.057	.04	0.12	0.08	0.13	0.086	0.108	0.071	0	0	0.28	0.18	0.13	0.086	0.19	0.12	-	-
11.5	12.5	0.58	0	0	0.037	.02	0.089	0.05	0.10	0.058	0.08	0.046	0	0	0.22	0.13	0.13	0.075	0.10	0.058	-	-
12.5	12.9	0.54	0	0	0.010	.005	0.003	0.01	0.03	0.017	0.024	0.012	0	0	0.07	0.04	0.05	0.028	0.024	0.013	-	-
$\sum A_FE_r$				0		-0.16		-0.36		-0.48		-0.81		-0.08		-0.77		-0.81		-0.23		-

*The 300-kV data are for an x-ray beam filtered by 4 mm of Cu.

See table 3-6 for "M" and "H" beam filtrations.

Table 3-4. Data from Handbook 64, and fractional areas, used to calculate the percent contribution to the ionization in the Wyckoff-Attix FAC due to scattered photons. No distinction is made in this table regarding the "M" or "H" type filtration.

Radius Inner (cm)	Radius Outer (cm)	A_F (%)	60 kV S_r (%)	60 kV A_FS_r (%)	100 kV S_r (%)	100 kV A_FS_r (%)	150 kV S_r (%)	150 kV A_FS_r (%)
0	9.5	1.00	0.60	0.60	0.47	0.47	0.34	0.34
9.5	12.9	0.66	0.14	0.09	0.13	0.09	0.11	0.07
ΣA_FS_r				0.69		0.56		0.41
			200 kV		250 kV		300 kV	
0	9.5	1.00	0.32	0.32	0.30	0.30	0.28	0.28
9.5	12.9	0.66	0.10	0.07	0.09	0.06	0.08	0.05
ΣA_FS_r				0.39		0.36		0.33

Table 3-5. Summary of calculations from tables 3-3 and 3-4 for percent loss and gain of ionization due to lack of plate separation and scattered photons, respectively. The data are for the Wyckoff-Attix FAC.

Beam Code	ΣA_FE_r (%)	ΣA_FS_r (%)
M 60	0	0.69
M100	0	0.56
M150	-0.16	0.41
M200	-0.36	0.39
M250	-0.48	0.36
M300	-0.81	0.33
H 50	0	-
H 60	0	*
H100	-0.08	*
H150	-0.77	*
H200	-0.81	*
H250	-0.23	*
H300	**	*

*Same as for "M" beam codes.

**The 300-kV filtration of 4 mm Cu is not comparable with the composite filtration used for H300.

Table 3-6. Comparison of x-ray beam filtrations used for data reported in Handbook 64 with filtrations presently used for conventional calibration conditions.

	Handbook 64					NBS SP-250, May 1984				
X-ray tube potential (kV)	Inherent filter (mm)	Pb (mm)	Added Filter Sn (mm)	Cu (mm)	Al (mm)	Inherent filter (mm)	Pb (mm)	Added Filter Sn (mm)	Cu (mm)	Al (mm)
60	3 Al	-	-	-	-	3 Be	-	-	-	1.51
100	3 Al	-	-	-	1.0	3 Be	-	-	-	5.0
150	3 Al	-	-	0.23	1.0	3 Be	-	-	0.25	5.0
200	3 Al	-	-	0.50	1.0	3 Be	-	-	1.21	4.1
250	3 Al	-	-	1.0	1.0	3 Be	-	-	3.20	5.0
300	3 Cu	-	-	-	-	3 Be	-	6.5	-	4.0
50	-		(No data)			3 Be	0.10	-	-	4.0
60	-		(No data)			3 Be	-	-	0.61	4.0
100	3 Al	0.53	-	-	-	3 Be	-	-	5.2	4.0
150	3 Al	-	1.53	4.0	-	3 Be	-	1.51	4.0	4.0
200	3 Al	0.7	4.0	0.59	-	3 Be	0.77	4.16	0.60	4.0
250	3 Al	2.7	1.0	0.59	-	3 Be	2.72	1.04	0.60	4.0
300	-		(No data)			3 Be	5.0	3.0	-	4.1

For the NBS SP-250 beams, the first 6 entries are moderately (M) filtered and the final 7 entries are heavily (H) filtered.

Table 3-7. Data presently used (May, 1986) to compute corrections for the Wyckoff-Attix standard free-air ionization chamber for conventional calibration conditions. An energy independent correction factor of 1.0015 for noncoplanarity of the guard-collector plate system is included in the product Πk_i.

Beam Code	k_a	$100(1-k_e)$ $\Sigma A_F E_r$ (%)	$100(1-k_p)$ $\Sigma A_F S_r$ (%)	$k_e k_p$	$\Pi k_i / k_s$
M 60	1.0203	-	0.77	0.9924	1.0140
M100	1.0097	-	0.60	0.9940	1.0052
M150	1.0068	-0.15	0.40	0.9975	1.0058
M200	1.0055[a]	-0.40[b]	0.39[c]	1.0001	1.0071
M250	1.0045	-0.50	0.36	1.0014	1.0074
M300	1.0039[a]	-0.62	0.32[d]	1.0030	1.0084
H 50	1.0103		0.63	0.9937	1.0055
H 60	1.0088[a]	-	0.55[d]	0.9945	1.0048
H100	1.0060[a]	-0.04	0.41[d]	0.9963	1.0038
H150	1.0050	-0.68	0.35	1.0033	1.0098
H200	1.0043	-0.82	0.35	1.0047	1.0106
H250	1.0040	-0.26	0.35	0.9991	1.0046
H300	1.0038[a]	-0.62[c]	0.31[d]	1.0031	1.0084
S 60	1.0131	-	0.70	0.9930	1.0075

[a]Estimated from a graph of k_a vs. HVL in mm Cu.

[b]Estimated to be essentially the same beam quality as the previous beam code MFC.

[c]Calculated using figure 9 of reference 1.

[d]Predicted from the least squares fit:

$$\Sigma A_F S_r = 0.9912 + 1.816 \times 10^{-3} \log_e(\text{HVL in mm Al})$$

The corrections given in table 3-7 for air attenuation, k_a, in the Wyckoff-Attix FAC are taken from data in Data Book 848 page 110 (DB 848:110) where reference is made to DB 331 III:92-117 and DB 527:081. The corrections appear to be nearly a linear function of the logarithm of the half-value-layer in copper for the beam qualities of interest. The data points cover the range of Cu HVL's for the "M" and "H" beam qualities except for M60 and H300. The k_a values for those conditions are estimated from a plot of the data on semi-log graph paper.

The data points given in DB 848:110 when fitted to a logarithmic curve using the method of least squares provide the following equation:

$$k_a = 1.0067 - 2.0229 \times 10^{-3} \log_{10}(\text{HVL in mm Cu})$$

The correlation coefficient is 0.96. A comparison of the k_a data, and estimated values, with k_a computed using the least-squares-derived equation is shown in table 3-8.

The only serious discrepancy between the presently used values for k_a, and k_a derived from the least squares equation, is for M60 where the presently used value for k_a appears to be about 0.7% too high. A data point for 0.089 mm Cu HVL, which does not fit in very well with the rest of the data, evidently had an undue influence in estimating k_a for the M60 beam quality. This conclusion is substantiated to some extent by data from figure 15 of HB64 where the air attenuation is shown to be 4.4% per meter at 60 kV for an inherent filtration of 3 mm Al. The inherent filtration for the Seifert 300-kV x-ray tube is 3 mm Be, and for the M60 beam quality 1.51 mm Al is added, giving an effective total filtration (assuming 60-kV x rays) equal to 2.5 mm Al. A thin phenolic protective plate covers the beryllium window, which further adds to the filtration. If the attenuation per meter of air were 5%, k_a would be 1.015, which is 0.5% lower than the value used presently.[3]

The recombination correction, k_s, for the Wyckoff-Attix chamber is computed using a first-degree logarithmic equation, developed using the OMNITAB POLYFIT program, for data resulting from the work of Wyckoff and Lamperti. A copy of the graph of the data plotted in 1969 is shown in figure 3-13. The result can be represented by the equations:

$$k_s = 1 + 6.52 \times 10^{-4}\ \dot{X}^{0.382}, \quad \dot{X} \text{ in R/min}$$

$$k_s = 1 + 3.11 \times 10^{-3}\ \dot{X}^{0.382}, \quad \dot{X} \text{ in R/s}$$

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[3]At the time of writing (June 1986) an investigation of the M60 discrepancy is planned.

Table 3-8. Comparison of the k_a values presently used (May, 1986) with k_a values computed from the least squares equation.

Beam code	Cu HVL (mm)	Present	Least Squares
M 60	0.052	1.0203*	1.0128
M100	0.20	1.0097	1.0100
M150	0.67	1.0068	1.0076
M200	1.69	1.0055*	1.0057
M250	3.2	1.0045	1.0044
M300	5.3	1.0039*	1.0034
H 50	0.142	1.0103	1.0107
H 60	0.24	1.0088*	1.0096
H100	1.14	1.0060*	1.0065
H150	2.5	1.0050	1.0049
H200	4.1	1.0043	1.0039
H250	5.2	1.0040	1.0034
H300	6.2	1.0038	1.0031

*Estimated from graph in DB 848:110

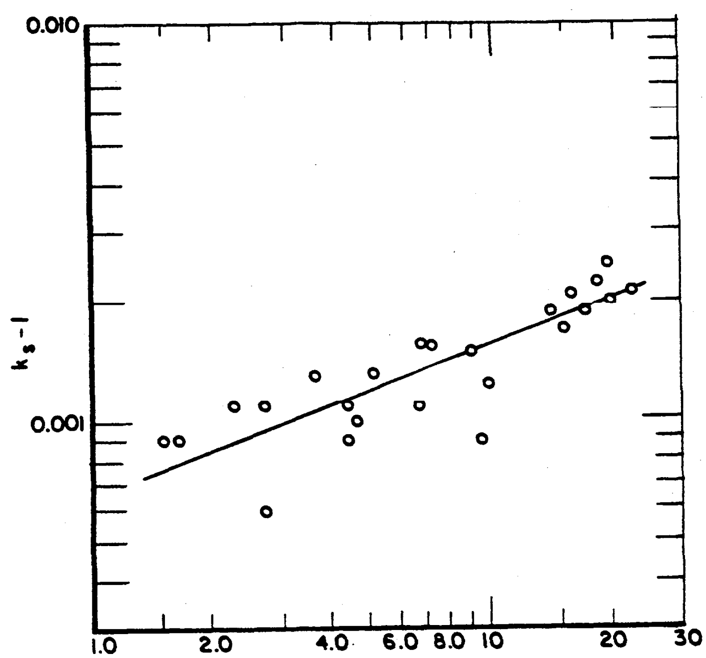

Fig. 3-13. Fractional recombination correction (k_s-1) versus exposure rate for the Wyckoff-Attix FAC.

Representative values of the recombination correction are as follows:

Exposure rate, $\dot{X}$ (R/min)	(R/s)	k_s
1.0	0.0167	1.0006
10.0	0.167	1.0016
100.0	1.67	1.0038

The net result of this review of the corrections for the Wyckoff-Attix FAC is given in table 3-9 where the products of the presently used corrections and those computed in this review are compared. The details regarding the individual corrections are summarized in the following comment section.

Table 3-9. Products of all exposure-rate-independent corrections for each x-ray beam quality in current use (May 1986) with the Wyckoff-Attix FAC, and the products of the corrections based on the data from HB64 and this review.

Beam Code	$\Pi k_i/k_s$ Current	Review	Difference (%)
M 60	1.0140	1.0074	0.65
M100	1.0052	1.0059	-0.07
M150	1.0058	1.0066	-0.08
M200	1.0071	1.0069	+0.02
M250	1.0074	1.0071	+0.03
M300	1.0084	1.0097	-0.13
H 50	1.0055	-	-
H 60	1.0048	1.0042	+0.06
H100	1.0038	1.0032	+0.06
H150	1.0098	1.0100	-0.02
H200	1.0106	1.0096	+0.10
H250	1.0046	1.0036	+0.10
H300	1.0084	-	-

Some comments regarding the Wyckoff-Attix FAC corrections

1. k_a. The presently used correction for air attenuation for M60 appears to be too high, although the comparison is made between two extrapolated values for k_a. This correction should be determined experimentally using well-known techniques. The presently used corrections at M150 and H60 are almost 0.1% different from the values computed from the least-squares-derived equation.

2. k_e and k_p. The methods and sources of data for computing corrections, for ionization loss and gain due to electron loss and scattered-photon contribution respectively, have been provided. The information has been given in such detail that it can be checked and, if newer data become available, it can be revised.

In general, the computations in this review provide data for the electron-loss and scattered-photon gain corrections which are in agreement with the data now used. Some exceptions, where differences are of the order of 0.1%, are (comparing tables 3-5 and 3-7) $\Sigma A_F S_r$ for M60 and $\Sigma A_F S_r$ for H150. The corrections for M300 assume that the rather large difference in filtration between the experimental conditions (4 mm Cu), and the actual filtration for M300 (3 mm Be + 6.5 mm Sn + 4.0 mm Al), will not significantly affect the magnitude of the corrections. The same corrections as are used for M300 are used for H300. While there is some justification for the assumption of equivalence between the experimental and M300 filtrations, the same is not true for H300, and calibrations for this condition have been discontinued until the appropriate data are available. (Refer to fig. 3-14).

3. Non-coplanarity correction. This correction is based on measurements made many years ago. The guard-collector plate assembly should be re-inspected periodically to verify the validity of this correction.

3.2.2. Ritz (20- to 100-kV) FAC corrections

The Ritz FAC is used for standardization of x-ray beams for x-ray tube potentials from 20 to 100 kV [3]. The dimensions of interest for purposes of developing corrections for this FAC are: L, the length of the airpath between the defining-plane of the diaphragm and the mid-plane of the collection plate; and the collection-plate-system separation and height, refer to table 3-1.

The largest FAC correction for "low" energy, lightly filtered x rays is for air attenuation (k_a). This correction is determined with the FAC at particular distances from the x-ray tube, since the intervening air acts as a filter and at low energies can influence the measurements. The procedure for determining the correction involves removal of the FAC diaphragm and setting a fixed diaphragm in the beam independent of the FAC. For a particular set of conditions (distance at which the exposure rate is to be determined, x-ray tube potential, filtration), the ionization current produced in the FAC is measured with the mid-plane of the collection plate at the position where the exposure rate is to be determined, (position 1) and again with the mid-plane moved away from the source by the air absorption distance shown in table 3-1 (position 2). Position 1 is the normal position of the diaphram, and position 2 is the normal position of the collection plate. The diameter of the fixed diaphragm must be such that the defined beam in its entirety is intercepted by the FAC at the two measurement positions. The ratio of the currents measured at position 1 and position 2 is the air attenuation correction factor for the conditions of measurement. These conditions include the atmospheric temperature and pressure since the attenuation is dependent on the density of the air. The attenuation correction is computed for P = 750 mmHg[4]

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[4]One atm = 101.325 kPa = 1013.25 mbar = 760 mmHg. Our laboratory barometers read out in mm of Hg, so all constants in this review are computed using pressure in units of mm of Hg.

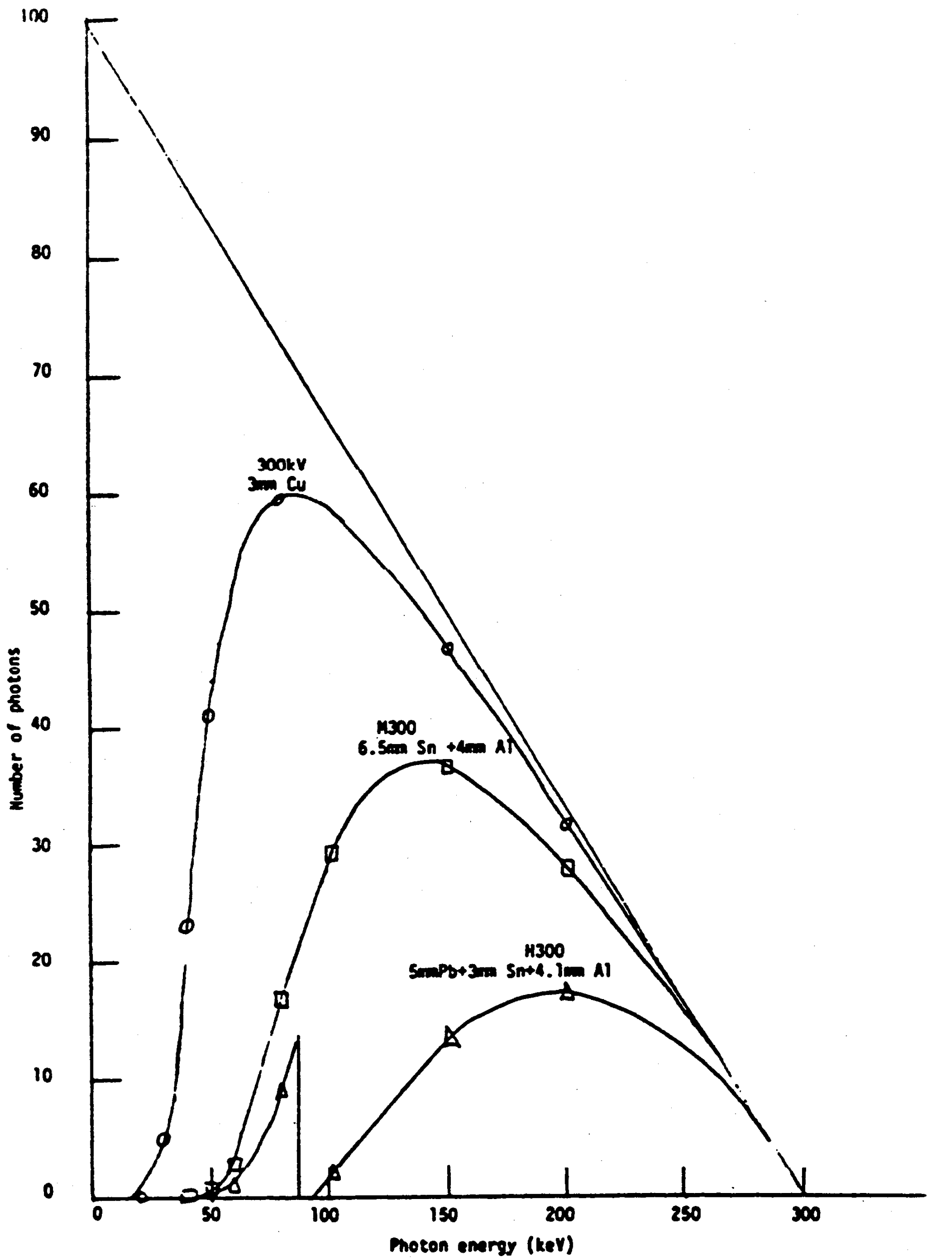

Figure 3-14. 300 kV spectra. Initial triangular spectrum assumed for 300 kV across x-ray tube. Spectrum modified by mass attenuation coefficient from Hubbell [6]. The triangular spectrum is hypothetical and is used to allow calculation of the other spectra.

and T = 293.15 K (dry air density = 1.189 mg/cm^3) to provide a correction factor representative of normal room conditions. If the experimentally determined attenuation coefficients μ/ρ are so large that normal variations in room conditions produce significant differences in the correction, then pressure and temperature must be taken into account. This condition pertains for x ray beams with Al HVL's < 0.22 mm. A list of mass air-attenuation coefficients, experimentally determined using the Ritz FAC, is given in table 3-10. Also included in table 3-10 are air-attenuation corrections, k_a, for the reference conditions P = 750 mmHg and T = 293.2 K. (The data for these calculations are taken from DB 752:075-084, 143-181; DB 848: 170-200; DB 852:5-8.) Values for k_a in table 3-10 differ by less than a few hundredths of one percent from presently used data given in a similar table recorded in DB 852:11.

Table 3-10. Mass air-attenuation coefficients and values of k_a for the Ritz FAC. The defining plane of the FAC diaphragm is 50 cm from the x-ray tube target. For the Ritz chamber, L = 127.39 mm.

Beam Code	HVL (mm Al)	μ/ρ (cm^2/mg)	k_a at 750 mmHg 293.2 K
L20	0.071	8.2293×10^{-3}	1.1327*
L30	0.22	3.2392×10^{-3}	1.0503*
L40	0.49	1.6816×10^{-3}	1.0258
L50	0.75	1.2163×10^{-3}	1.0186
L80	1.83	7.3175×10^{-4}	1.0111
L100	2.8	4.3435×10^{-4}	1.0066
M20	0.152	4.0835×10^{-3}	1.0639*
M30	0.36	1.8811×10^{-3}	1.0288
M40	0.73	1.1051×10^{-3}	1.0169
M50	1.02	7.4192×10^{-4}	1.0113
H20	0.36	1.6190×10^{-3}	1.0248
H30	1.23	5.8048×10^{-4}	1.0088
H40	2.9	3.9028×10^{-4}	1.0059

*These factors can vary significantly with changes in atmospheric temperature and pressure. For ambient conditions, k_a is calculated using $k_a = \exp(\mu L)$.

Note: The experimentally determined attenuation coefficients in column 3 should not be confused with conventional, good-geometry attenuation coefficients.

The effect on k_a of changes in temperature and pressure from reference conditions can be calculated as follows:

$$k_a = \exp(\mu L) = \exp((\mu/\rho)\ \rho L)$$

where L is the air absorption length from table 3-1. Because the air density ρ is proportional to P/T, and μ/ρ is independent of density, it can be shown that

$$dk_a/k_a = (\mu L)\ (dP/P - dT/T) \quad .$$

For Beam Code L20, L = 12.7 cm, and μL = 0.12. Thus a 1% change in P or T gives a 0.1% change in k_a, and a smaller change for the remaining beam codes in table 3-10.

The electron-loss corrections (k_e) for the Ritz FAC are taken from data in the 1959 publication of Ritz [5][5] on the design of free-air ionization chambers. The dimensions of the Ritz FAC are such that the ionization loss due to loss of electrons occurs only at the upper end of the x-ray energy range for which this FAC is used. Therefore, only figures 10 and 14 of reference [5] are required for calculation of the corrections for Beam Codes S75 and L100. These data, used in conjunction with the fractional areas inside the collection-plate system for different radii, provide the required corrections for ionization loss. For this calculation, the plate separation is reduced from 9 cm to 8 cm to account for the 1-cm-diameter FAC beam-defining diaphragm and to simulate the required zero-beam diameter. The results of the calculations shown in table 3-11 do not differ by more than 0.1% from the corrections for electron loss presently used for these conditions (DB 852:11). Since no data are published for the L80 x-ray beam condition, the correction for electron-loss is estimated by interpolation following the curvature of the data for E_r at 60, 75, and 100 kV with 3 mm Al added filtration. The estimated correction is 0.12%, which is not significantly different from the presently used correction. A detailed analysis of the k_e corrections required for the Ritz chamber has been performed. The calculations, which consider x-ray beam penumbra effects on the magnitude of the corrections, are recorded in a loose-leaf binder entitled "Supplement to DB776, FAC Comparisons."

Table 3-11. Computation of electron-loss corrections for the Ritz FAC

Radius Inner (cm)	Radius Outer (cm)	A_F	S75 E_r (%)	S75 $A_F E_r$ (%)	L100 E_r (%)	L100 $A_F E_r$ (%)
0	4.0	1.00	-0.10	-0.10	-0.60	-0.60
4.0	4.5	0.58	0.035	0.02	0.20	0.12
4.5	5.0	0.28	0.024	0.01	0.13	0.04
$k_e = \Sigma A_F E_R$				-0.07		-0.44

[5]All the Ritz data are for a target-to-diaphragm distance of one meter. The assumption is made that, for the present-day operating distance of 0.5 m, the shorter air path will not significantly affect the Ritz data for electron loss and scattered photon contribution corrections.

Corrections for the scattered-photon contribution to the ionization in the FAC are derived from Ritz [5], and Allisy and Roux [7]. The percent scattered-photon contributions within different radii, and appropriate multipliers for several x-ray beam conditions, are given in Ritz [5], figure 15 and table 1, respectively. The data of Ritz, Allisy, and Roux were combined and, by means of least-squares fit for k_p vs. Al HVL in mm, the following logarithmic equation was developed:

$$k_p = 0.9956 + 2 \times 10^{-3} \log_{10}(\text{Al HVL in mm}) \quad .$$

The values of k_p for the Ritz FAC listed in table 3-12 are computed from this equation. For convenience, the products of all rate-independent corrections for the Ritz FAC are provided in the last column of table 3-12.

Table 3-12. Summary of corrections for the Ritz FAC. The values given for k_a are computed using P = 750 mmHg and T = 293.2°K.

Beam code	Added Al filter (mm)	Al HVL (mm)	k_a	k_p	k_e	Πk_i
L20	none	0.071	-	0.9933	1.0000	0.9933*
L30	0.265	0.22	-	0.9942	1.0000	0.9942*
L40	0.50	0.49	1.0257	0.9949	1.0000	1.0205
L50	0.639	0.75	1.0186	0.9953	1.0000	1.0138
L80	1.284	1.83	1.0110	0.9960	1.0010	1.0080
L100	1.978	2.8	1.0065	0.9964	1.0051	1.0080
M20	0.230	0.152	-	0.9940	1.0000	0.9940*
M30	0.50	0.36	1.0289	0.9947	1.0000	1.0234
M40	0.786	0.76	1.0170	0.9952	1.0000	1.0121
M50	1.021	1.02	1.0114	0.9955	1.0000	1.0069
S75	1.504	1.86	1.0076	0.9960	1.0007	1.0043

*These products include only k_p and k_e and must be multiplied by exp(μL).

The recombination corrections for the Ritz FAC are calculated from an equation of the same form as that developed for the Wyckoff-Attix FAC. The corrections are based on measurements of ionization currents at several collection potentials, with exposure rate as a parameter. In accord with the method of Scott and Greening [8], the inverse of the ionization currents are plotted against the inverse of the squares of the collection potentials.

Extrapolation of the plotted data to $1/E^2 = 0$ predicts the inverse of the saturation ionization current. If the ionization currents are normalized to the current measured at the normal operating collection potential, the inverse of the intercept at $1/E^2 = 0$ is the recombination correction for that particular exposure rate.[6]

The Scott and Greening extrapolation procedure for exposure rates ranging from 70 mR/s to 480 mR/s yields the data shown plotted in figure 3-15. The OMNITAB POLYFIT program used to fit the data to a first degree logarithmic equation provides the following equations:

$$k_s = 1 + 9.182 \times 10^{-6}\ \dot{X}^{\ 1.174}, \quad \dot{X} \text{ in R/min}$$

$$k_s = 1 + 1.123 \times 10^{-3}\ \dot{X}^{\ 1.174}, \quad \dot{X} \text{ in R/s} \quad .$$

With reference to figure 3-15, the plotted points are from data derived from measurements with a 1-cm diameter FAC diaphragm (the diaphragm in normal use for calibrations) and from measurements made using a 0.5-cm diameter FAC diaphragm. There appears to be no significant difference in the data sets. Two points using the 0.5-cm diaphragm at ≈ 20 R/min (solid dots) are considered to be outliers and the original data have not been reviewed.

The data plotted in figure 3-15 are based on measurements recorded throughout DB 592, 624, and 638. The data plots used for extrapolations are filed in a file cabinet in Rm. B033 under the general title "FAC Recombination." Further analyses of the data are recorded in a three-ring binder entitled, "Supplement No. 1 to DB 592, 624 and 638. 10-60kV and 20-100 kV FAC Comparison." The three-ring binder is kept in the bookcase in Rm. B033.

3.2.3. Lamperti (10- to 20-kV) FAC corrections

The Lamperti FAC is designed for x-ray exposure standardization in the region 10 kV to 60 kV. In practice, the Ritz FAC, with exposure measurement capabilities overlapping that of the Lamperti FAC, is used for calibrations down to and including 20-kV x rays. The Lamperti FAC is used only for measurements at 10 kV and 15 kV.

Lamperti and Wyckoff [4] have discussed in detail the corrections for the Lamperti FAC. Although many different corrections are identified, the important corrections are for air attenuation, k_a, and scattered photon contribution to the ionization, k_p. The corrections for electron loss, k_e, in the 10-kV to 60-kV region are given as "much less than 0.1%" [4]. For x rays generated at 10 kV and 15 kV, k_e should equal unity since the FAC plate

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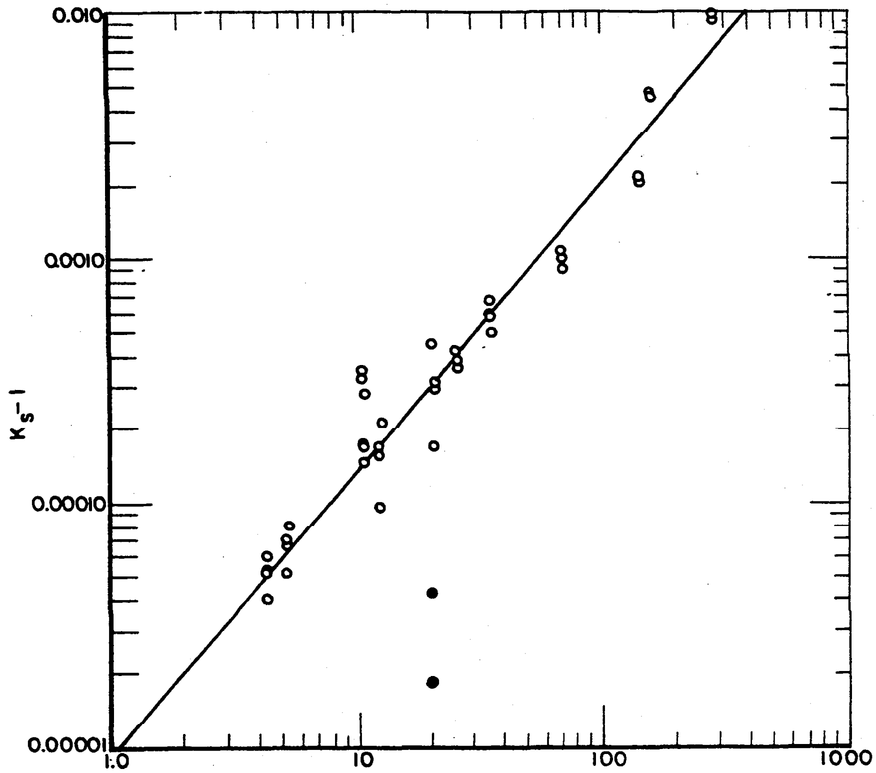
[6] The extrapolation procedure described was also used to determine recombination corrections for the Wyckoff-Attix FAC but the data were plotted with 1/E as the abscissa. According to Scott and Greening, this procedure exaggerates the effects of recombination and is proper only for very low exposure rates. However, the predicted recombination correction for the Wyckoff-Attix FAC is only about 0.2% for the maximum exposure rate tested (about 0.33 R/s (20 R/min)) and the usual operating electric field strength of 250 V/cm.



Exposure Rate(R/min)

Fig. 3-15. Fractional recombination correction (k_s-1) versus exposure rate for the Ritz FAC.

separation is 4 cm (refer to table 3-1) and the continuous-slowing-down-approximation (CSDA) range [9] for 15-keV electrons is only 0.5 cm (air density equal to 1.1888 mg/cm^3). Actually, k_e should be unity for the Lamperti FAC for x rays up to 50 kV since the CSDA range for 50-keV electrons is 4.1 cm for normal room temperature and pressure. (This is a very conservative statement because the assumptions are that the entire energy of the highest energy photon is transferred to an electron, and that the CSDA range is equal to the practical range. According to Katz and Penfold [10], the practical electron range would be only about 80% of the CSDA range for 50-keV electrons.)

The intercomparison of free-air chambers described by Lamperti and Wyckoff [4] was carried out for x rays generated by x-ray tube potentials from 20 kV up to 60 kV, with corrections for the effect of scattered photons, k_p, obtained from Ritz [3] and Allisy and Roux [7]. The data from these two sources differ slightly ($\approx$ 0.1%) in the region below 30 kV and the two sets of data have been combined using the least squares method to arrive at the following equation:

$$k_p = 0.9975 + 1.034 \times 10^{-3} \log_{10}(\text{Al HVL in mm}) \quad .$$

Somerwil [11] investigated a systematic difference between several national FAC standards, intercompared at the Bureau Internationale des Poids et Mesures, and found that the FAC scattered-photon contribution correction for chambers with 40-mm diaphragm-to-collection-plate distances, d, should be less than corrections determined from measurements with chambers having d = 100 mm. (The Ritz FAC has d = 127 mm.) The values of k_p were computed for x rays with Beam Codes L10, L15, H10, and H15 using the above equation. These corrections were reduced by adding 0.15% at L10 and H10 and 0.10% at L15 and H15 because the Ritz and Allisy-Roux measurements were for d = 100 mm. The adjustments to the corrections are the percentages determined by Somerwil.

The air attentuation corrections, k_a for the Lamperti FAC are determined using the Ritz FAC in the two-position, independent-diaphragm technique, already described. In this case, the distance between the two measurement positions is made equal to 39 mm since that is the air attenuation path length in the Lamperti FAC. The Ritz FAC is used because the Lamperti FAC sans-diaphragm aperture is not large enough to encompass the beam defined by the fixed diaphragm. The measurement data are recorded in DB 752:143-162.

The recombination corrections for the Lamperti chamber were determined using the procedure suggested by Scott and Greening. The data are recorded throughout DB 592, 624, and 638, in the three-ring binder entitled "Supplement No. 1 to DB 592, 624 and 638" and in file folders under the general title "FAC Recombination", all filed in Rm. B-033. The equation developed from these studies for determining the recombination correction is:

$$k_s = 1 + 7.08 \times 10^{-6}\, \dot{X}^{0.735}, \quad \dot{X} \text{ in R/min}$$

$$k_s = 1 + 1.435 \times 10^{-4}\, \dot{X}^{0.735}, \quad \dot{X} \text{ in R/S}$$

Recombination corrections for exposure rates commonly encountered in instrument calibration work are provided in table 3-13 and figure 3-16.

Table 3-13. Recombination corrections for the Lamperti FAC

Exposure rate, $\dot{X}$ (R/min)	(R/s)	k_s
10	0.167	1.000
100	1.67	1.0002
1000	16.7	1.0011

The corrections presently used for the Lamperti FAC are given in table 3-14 where most of the air attenuation corrections are shown to be dependent on temperature and pressure and the corrections for photon scatter have been computed from the equation for k_p adjusted for the Somerwil correction. k_e is equal to unity as are all other exposure-rate independent corrections identified by Lamperti [4].

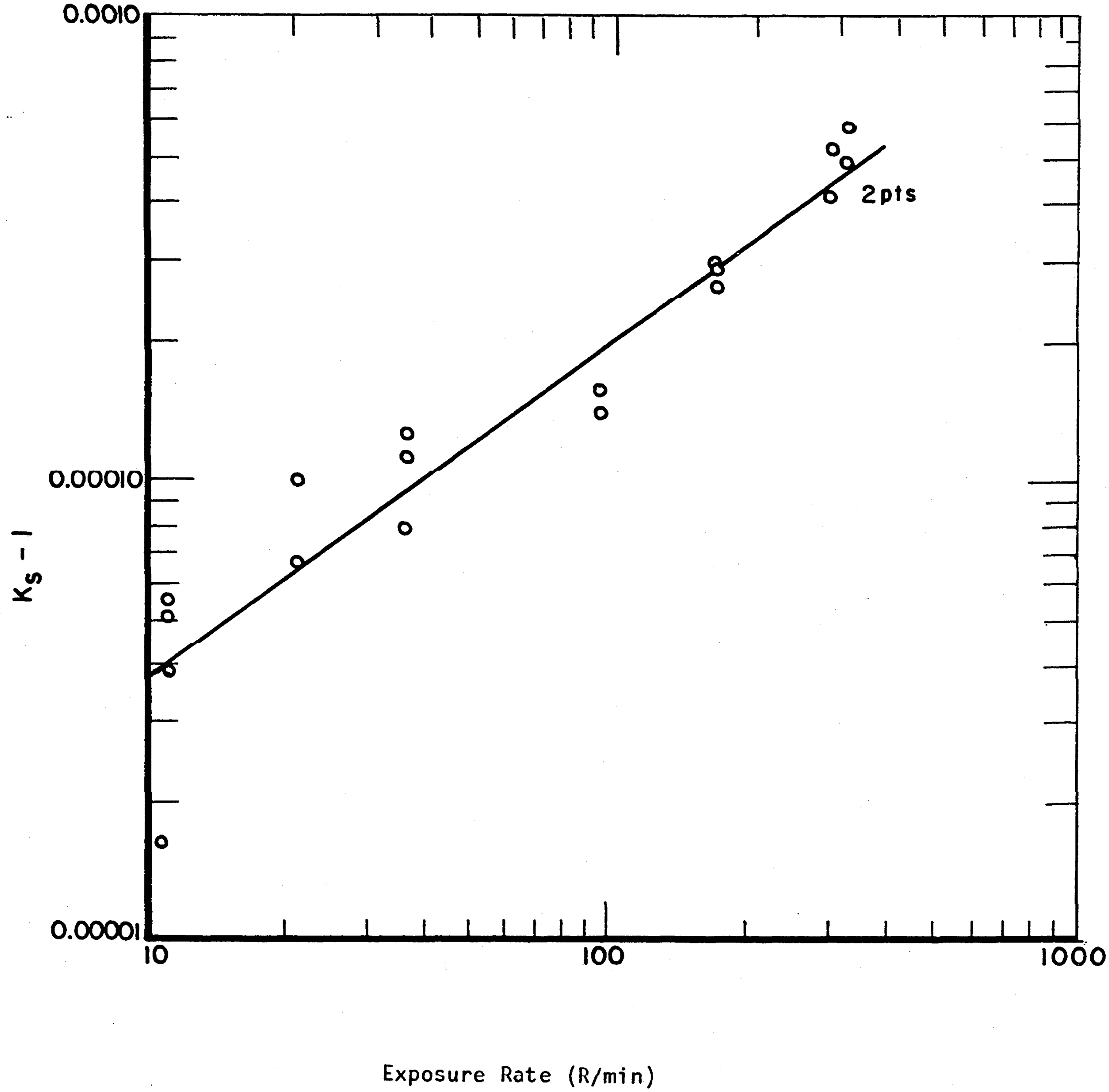


Fig. 3-16. Fractional recombination correction (k_S-1) versus exposure rate for the Lamperti FAC.

Table 3-14. Summary of corrections for the Lamperti FAC. The air attenuation data are for a target-to-diaphragm distance of 250 mm. For the Lamperti FAC, L = 39.02 mm.

Beam code	Added filter (mm Al)	HVL (mm Al)	μ/ρ (cm^2/mg)	k_p	k_a
L10	0	0.029	0.0194	0.9972	*
L15	0	0.050	0.0125	0.9971	*
H10	0.105	0.048	0.0140	0.9975	*
H15	0.500	0.152	---	0.9976	1.0245

*$k_a = \exp(\mu L)$

3.3. Intercomparison of standard free-air ionization chambers

The present NBS standard free-air ionization chambers have been intercompared with the standards of other nations and internally, to test their congruity where their measurement capabilities overlap. It is beyond the scope of this review to discuss in detail the various international intercomparisons except to state that one should expect agreement within 1.2% [2].

Internal intercomparisons of the free-air chambers have been carried out in 1961-62, 1966-67, 1975 and 1976 for the Lamperti and Ritz chambers, and in 1958-59, 1962, 1975-76 for the Wyckoff-Attix and Ritz chambers. The results of these intercomparisons were tabulated in 1977 in a report for the Dosimetry files. The mean difference between the Lamperti and Ritz FAC's in the region 20 kV to 50 kV was found to be 0.41%. The mean difference between the Wyckoff-Attix and Ritz FAC's was found to be 0.51% in the region 60 kV to 100 kV. No adjustment is made for these differences, since they are well within the maximum difference of 1.2% estimated by the ICRU, and the intercomparisons give no indication which member of a pair is to be considered the more reliable. The relatively recent small adjustments to the scattering corrections for the Lamperti-Ritz FAC's will not significantly affect the agreement.

3.4. Gamma-ray exposure standards and calibration ranges

There are seven gamma-ray sources available for the calibration of instruments for the quantity exposure and for delivering known exposures to passive dosimeters. The sources are collimated and the beams have been calibrated using appropriate standard graphite cavity ionization chambers. These chambers have precisely known volumes, so that when exposed to a gamma-ray beam they define the ionization per unit volume of air and, with suitable corrections for wall absorption and other perturbations, the collected charge can be interpreted directly in terms of the quantity exposure.

3.4.1. Cavity-chamber standards, description

The cavity chambers, used for studies leading to the revised (1972 May 1) ^{60}Co and ^{137}Cs exposure-rate standards, were fabricated from reactor-grade, high-purity graphite, following the design of Wyckoff [12], shown in figure 3-17. The spherical shape was chosen in order to allow the standards to be based on a homogeneous group of chambers of different volumes, to avoid the distance effect and the complexity of set-up in measurements with cylindrical chambers, and to present a uniform, symmetrical, chamber aspect to the source. The chambers have been carefully compared in the gamma-ray beams, and the NBS standard of exposure for these radiations is the mean response of all the spherical graphite cavity chambers.

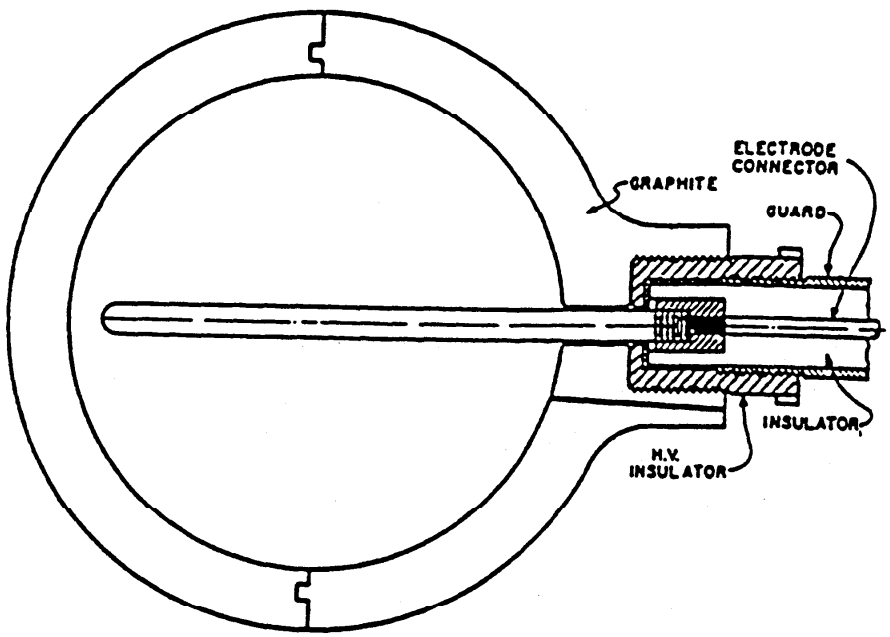


Figure 3-17. Cross-sectional view of typical cavity chamber.

The dimensions of the spherical chambers are given in table 3-15. The three small-volume chambers, identified as 0.5, 1, and 2, were designed to be used as a group to determine a wall correction and provide one measurement of gamma-ray exposure. These chambers have the same nominal outside diameter but different wall thicknesses and thereby different cavity volumes. They were fabricated using ball end-mills of diameters 3/8, 1/2, and 5/8 in. The wall-thickness values given for these three chambers were derived from measurements of outside diameters and the diameters of the end-mills used in their fabrication. The net volumes given in the table are the differences between the cavity volumes and the volumes of the collection electrodes. The electrode diameter for the 50-cm^3 chambers is nominally 0.3 cm but for all other chambers it is nominally 0.1 cm.

Table 3-15. Dimensions of spherical graphite ionization chambers

Nominal volume	Volume	Net volume	Outside diameter	Graphite density	Radial wall thickness	
(cm^3)	(cm^3)	(cm^3)	(cm)	($g\cdot cm^{-3}$)	(cm)	($g\cdot cm^{-2}$)
0.5	0.440	0.431	2.078	1.72	0.563	0.968
1	1.140	1.131	2.065	1.73	0.398	0.688
2	2.029	2.019	2.080	1.74	0.246	0.428
10	10.088	10.069	3.428	1.72	0.3755	0.647
30	30.262	30.24	4.607	1.74	0.3751	0.653
50-1	51.943	51.634	5.34	1.73	0.3652	0.632
50-2	50.425	50.089	5.58	1.73	0.5085	0.880
50-3	50.460	50.155	5.80	1.73	0.6129	1.060

The 50-cm^3 chambers have the same nominal cavity size but different wall thicknesses and can be used as a group to determine the wall correction. The wall correction can also be determined by the addition of closely fitting shells to two of the chambers. With the two methods of wall-absorption measurement available, each of the 50-cm^3 chambers can be considered to provide an independent measurement of exposure.

Of all the spherical chambers, the 50-cm^3 chambers are of the highest quality, great care having gone into their fabrication to insure close tolerances in all dimensions. Measurements of wall thickness at many locations on the periphery of both halves of each 50-cm^3 chamber show that the range of the wall thickness variation is less than 0.025 $g\cdot cm^{-2}$ and the largest difference between the average values for the two halves is 0.016 $g\cdot cm^{-2}$.

The fabrication of the 10-cm^3 and 30-cm^3 chambers was performed with less restriction on the variation of chamber wall thickness with the result that the average wall thicknesses for the two halves differ by 0.016 cm (0.25 $g\cdot cm^{-2}$) for the 10-cm^3 chamber and 0.052 cm (0.089 $g\cdot cm^{-2}$) for the 30-cm^3 chamber. Although these differences seem to infer uncertainties in the chamber wall correction of up to 0.3 percent, in fact the chamber response is related to the average wall thickness and the average is used in plotting the chamber response versus wall thickness to determine the wall correction. The wall thicknesses given in table 3-15 for these two chambers are the overall averages for measurements in a radial direction at a number of positions (see fig. 3-17), and the corrections are determined for the chambers by the addition of closely fitting spherical shells to the chamber walls.

The densities for the 0.5-cm^3 and 2-cm^3 chambers were measured using the principle of Archimedes, while density for the 1-cm^3 chamber was inferred from measurements of another chamber fabricated from the same material. The densities for the 50-cm^3 chambers were determined from a cylindrical block machined from the same material. The densities for the 10-cm^3 and 30-cm^3

chambers were determined using differential weighings in and out of distilled water. The differential weighing method and mechanical measurement of dimensions and weighing of the same graphite block give densities which differ by only 0.01 $g \cdot cm^{-3}$. Further details are contained in a report by Loftus and Weaver [13].

3.4.2. Gamma-ray sources, location, initial activity, and description

The location, year acquired, nominal activity at the time of purchase, and beam orientation of the gamma-ray sources used for instrument calibration are given in table 3-16. Drawings showing the horizontal-beam sources and collimator dimensions are attachments 4 and 5. A sketch of the Theratron "F" head which contains the ^{60}Co source located in room B036 is attachment 6.

Table 3-16. Gamma-ray source locations and nominal activities of sources at time of purchase

Radio-nuclide	Year* acquired	Activity	Location	Beam orientation
^{60}Co	1978	10 kCi	B036	Vertical
^{60}Co	1965	1 kCi	B034	Vertical
^{60}Co	1964	200 Ci	B021B	Horizontal
^{60}Co	1964	20 Ci	B015B	Horizontal
^{137}Cs	1957	1.7 kCi	B036	Vertical
^{137}Cs	1964	300 Ci	B021A	Horizontal
^{137}Cs	1964	30 Ci	B015A	Horizontal

*These dates are supplied only to indicate the approximate ages of the sources. The activities do not take self-absorption into account.

3.4.3. Calibration of gamma-ray beams

The horizontal-beam calibration ranges were calibrated at various distances from the sources. The data were fit to a suitable function which allows accurate computation of exposure rates at selected distances, or of distances for selected exposure rates. The equation used for this purpose was derived by using the inverse square law with correction for air attenuation and buildup. An equation that was found to adequately predict the exposure rate $\dot{X}$ to within a few hundredths of one percent was of the form

$$\dot{X}D^2 = K_1(1 + K_2D + K_3D^2 + K_4D^3)$$

where $D = S + S_0$ and S is the distance from the source to the reference point of the chamber, as read on a scale mounted on an aluminum channel. An

Al-channel scale is associated with each source. The S_o are offset distances, for each source, introduced to improve the fit of the data to the polynomial in D. In practice, the equation is solved for exposure rate by rearranging the equation to:

$$\dot{X} = (A/D^2 + B/D + C + ED)e^{-\lambda T}$$

where λ is the decay constant for the radionuclide, and T is the elapsed time since the source was calibrated.

Tables of exposure rate vs distance are printed out, using the Digital Equipment Corp. 11/23 Computer (DEC), for each month with arguments of three days. In the information at the top of the tables, the letter P is used for S_o. Although the tables are useful for many purposes, the constants for the equations are stored in the "G CF" program for the HP9836 computer and exposure rates are computed, as required, when calibrations are performed using the mobile measurement console. The nomenclature for the constants is different in the DEC program for producing tables, from that used by the HP9836 to compute exposure rates. For ease of translation between programs, values of the constants for 1984 Dec 21 are given in table 3-17 for each source, using both sets of letters.

Table 3-17. Constants* for computing exposure rate corrected for decay for the horizontal beam sources. The reference date is 1984 Dec 31.

DEC: HP9836: Source	A K1 (m^2 mR/s)	B 10^2 K2 (m mR/s)	C 10^4 K3 (mR/s)	P 10^2 K4 (m)	λ 10^5 K5 (d^{-1})	DB:page
B015A-^{137}Cs	2.0323	-0.943	-1.8619	-0.818	6.326	750:118
B021A-^{137}Cs	19.617	-13.84	123.24	-0.304	6.326	744:203
B015B-^{60}Co	0.5924	-0.1657	-1.345	-0.144	36.010	717:127
B021B-^{60}Co	5.2676	0.4764	67.33	-0.528	36.010	717:125

*The constant E equals zero for these four sources. The constant P is the offset distance so distance equals the scale reading plus P in the DEC program. Do not confuse the subscripted K's in the Loftus-Weaver paper with the K1, K2 etc. used in the HP9836 program.

The data for the ^{60}Co sources in table 3-17 are derived from the data in Table 17 of Loftus and Weaver [13]. Checks on the calibration of these sources through the years since 1973 show them to be unchanged. On the other hand, the checks on the ^{137}Cs sources indicate a need for recalibration since they were found to have changed from previous calibrations by several tenths of one percent. The reason for these changes is unknown. The updated constants for the ^{137}Cs source in table 3-17 are based on the newest calibration data. They are derived from a computer program for non-linear least-squares function fitting (SAAM) of measurement data.

The ^{60}Co source in Rm. B034 is not used at present for instrument calibrations. This source, initially 1 kCi, had been used for calibration of small-volume cable-connected chambers and high-range R-meter probes but as of 1985 Jan, has an activity of only about 150 Ci making exposure times for those calibrations too long. However, the source can be utilized for exposures of passive instruments (TLD, Fricke, etc.). The data for two calibrations of this source are given in table 3-18.

Table 3-18. Data and references for calibration of B034 vertical-beam ^{60}Co source. Al-Ch. scale reading: 50 cm. Collimator setting: 10 x 10 on the 100 cm TD scale. Distance to source: 97.9 cm. Date 1979 Dec 31.

DB:page	Standard chamber and exposure rate (mR/s) 1 cm^3	10 cm^3	Mean, all meas.
750:93	56.75	56.65	
817:42-50	56.81	56.66	
817:93	56.72		56.72

Calibrations of the vertical-beam sources are limited to one or two sets of conditions. For the ^{60}Co source located in B034, the reference distance on the Al-channel mounted scale is 50 cm. The offset of the scale-zero from the source center is 47.9 cm. To the best of our knowledge the source consists of one layer of 1 mm × 1 mm cylindrical pellets.

The highest activity ^{60}Co source available for calibration work is located in B036. At the end of 1984, the effective activity of the source was about 3 kCi (computed using XD^2 measurements). The source was calibrated early in 1979 using the 1 cm^3 and 10 cm^3 graphite standard ionization chambers. The mean of those measurements corrected for decay is used at the present time (1986 May). As shown in table 3-19, a later measurement using the 10-cm^3 standard chamber checked the original data.

The vertical-beam ^{137}Cs source in Room B036 is calibrated for several collimator setting-distance conditions. The calibrations rely mainly on measurements with the 1-cm^3 standard chamber although some measurements with the 10-cm^3 and 1-50-cm^3 chambers have also been tried. Some of the 10-cm^3 and 1-50-cm^3 data in table 3-19 are parenthesized to indicate that they are not included in the source calibration. These data are included in table 3-19 to call attention to the need for further study of the measurement problems encountered, and data accumulated, over a period of several years for this source. For example, the agreement between the 1 cm^3 chamber and the 1-50-cm^3 chamber measurements for the 15 × 15 collimator setting show that the standards are consistent for the large field size. But a reason for the discrepancies in the data for the 8 × 8 collimator setting has not been determined.

In the course of using the standard graphite ionization chambers for NBS and other-agency source calibrations, the electrodes in the chambers have either loosened and shorted to the chamber wall or have been over-voltaged.

When this occurs, the electrodes are weakened and carbon is deposited on the high-voltage insulator. The 1-cm^3, 10-cm^3 and 30-cm^3 chambers are particularly prone to this problem since the electrodes are of small diameter (< 1 mm) and, with the present stem design, are difficult to anchor securely in position. It has been necessary on several occasions to straighten or replace these electrodes and to clean or replace the high-voltage insulators and chamber stems. Subsequent checks of source calibrations, in particular using the 1-cm^3 chamber, indicate that the relationship of that chamber to the others, established under ideal conditions in 1972, may no longer hold. Measurements of the high-exposure-rate sources after the last repair of the 1-cm^3 chamber were several tenths of one percent higher than the reference data. This is shown to some extent in table 3-19 where the latest data for the 8 x 8 collimator setting is higher than the previous measurements. Some 1-cm^3 chamber exposure data not included in table 3-19 indicate a difference between present and earlier measurements of as much as 0.4%. On the other hand, measurements at low exposure rates at 1 meter from the ^{137}Cs source in Rm B021A show agreement between the 1-cm^3 standard and the 1-50-cm^3 or the 10-cm^3 standard to be within 0.02% and 0.01% respectively. Referring to DB 817:155, we have

Ratio of exposure rates, B021A, 100 cm:

$$\frac{\dot{X}\ \text{(VIII)}}{\dot{X}\ (1\text{-}50\ \text{cm}^3)} = 0.9998$$

and

$$\frac{\dot{X}\ \text{(VIII)}}{\dot{X}\ (10\ \text{cm}^3)} = 0.9999$$

The net cavity volume for the 1-cm^3 chamber following the last repair (replacement of electrode and refurbishment of the HV electrode) is 1.1297 cm^3. Details can be found in DB 817:94 if needed.

Table 3-19. Data and references for calibration of vertical-beam gamma-ray sources in Rm B036. All data corrected to 1984 Dec 31.

DB:page	Source	Dist. Al-Ch. scale (cm)	Coll. set	Standard chamber and exposure rate 1 cm^3 (mR/s)	10 cm^3 (mR/s)	1-50 cm^3 (mR/s)	Exp. rate used for calib. (mR/s)
799:34	^{60}Co	105	6 x 6	468.8	467.5	-	468.2
817:52	"	"	"	-	467.3	-	
750:201	^{137}Cs	55	8 x 8	105.18	-	-	
799:44,60	"	"	"	105.07	-	-	
817:121, 131,141	"	"	"	105.21	(104.43)	(103.68)	105.21
799:70	"	"	15 x 15	108.42	-	108.21	108.31
817:138	"	"	"	108.19	107.78	-	
817:121	"	38	10.5 x 10.5	167.16	-	-	

The main difficulty in reproducing exposure calibration data centers around the 1-cm^3 chamber. A small-volume standard chamber is required for high exposure-rate measurements, and in beams that may be uniform only over small areas (DB 799:10-11 and DB 817:17), but for small-volume chambers unwanted extra-cameral volumes in the vicinity of the HV insulator and stem can have a large effect on the chamber response to radiation. Additional difficulties of another sort arise in comparing data over a period of years when different measurement equipment may be used. (See for example DB 817:51-52.) The uncertainty statement given by Loftus and Weaver [13] is only representative in the short term and for optimum conditions. If the same overall uncertainty (0.7%) is to apply to a long-term exposure standardization, the primary standards must be carefully preserved and not used as working standards, and the associated equipment (electrometer, capacitor, voltmeter) must be kept in accurate calibration.

3.4.4. Useful beam size

The "useful beam" radius for the gamma-ray sources is defined as the distance from the center of a radiograph of the beam to the point where the density of the film is 90 percent of the center density, minus the difference in distance between the 90 percent and 50 percent density measurements. With R_{90} the radius of the 90-percent density contour, and R_{50} the radius of the 50-percent density contour, the useful beam radius (UB) is computed as follows:

$R_{50} = K6 \times SD + K7$ (called Beam size in "G CF" program)

$R_{90} = K8 \times SD + K9$ (not specifically named in "G CF" program)

$UB = R_{90} - (R_{50} - R_{90})$

$UB = 2R_{90} - R_{50}$ (called useful beam in "G CF" program

In the above equations, K6, K7, etc. are the constants listed in the "G CF" program and SD is the aluminum channel scale reading. The constants for each source are listed in table 3-20

Table 3-20. Constants for computing useful beam radii for the horizontal and vertical beam calibration ranges.

Dist* (cm)	Source	K6	K7	K8 (cm)	K9 (cm)	Useful beam radius (cm)
SD	^{137}Cs - B015A	0.188	0.613	0.143	0.044	Variable
SD	^{60}Co - B015B	0.157	0.237	0.112	-0.106	"
SD	^{137}Cs - B021A	0.207	0.235	0.149	-1.068	"
SD	^{60}Co - B021B	0.191	0.682	0.124	-0.236	"
38	^{137}Cs - B036	0	6.8	0	4.3	1.8
55	^{137}Cs - B036	0	6.4	0	4.05	1.7
105	^{60}Co - B036	0	6.3	0	4.4	2.5

*SD indicates a variable source distance.

Referring to attachments 3 and 4, showing the horizontal-beam sources, note the cavity surrounding each of the sources. Radiographs of these beams indicate a "hot" spot in the center so a conservative computation for the useful beam is justified.

The vertical-beam sources are calibrated at specific distances thus the constants K6 and K8 in table 3-20 are set to zero. The useful beam radii for these sources is very small, less than 2 cm for the ^{137}Cs source and 2.5 cm for the ^{60}Co source. Referring to attachment 5, which shows the Theratron "F" head which contains the B036 ^{60}Co source, note that the sketch shows the distances measured to determine the Al-channel scale offset distance.

Instruments designed for measurement of high-exposure-rate beams are often sensitive to beam size. This effect occurs because the small-volume chambers, used primarily to minimize ion recombination, are subject to the influence of extra-cameral and insulator "soakage" effects, which can constitute a significant fraction of the chamber reading.

Some instruments showing the stem effect are the NPL 0.2-cm^3 and the Farmer-NEL 0.6-cm^3 chambers, and Victoreen chambers of 100-R range and higher. The difference in calibration factors for a Victoreen 100-R chamber, depending on whether or not its stem is protected from radiation, may be as much as 4%. In order to insure that sensitive chamber stems are protected, calibrations of high-exposure-rate chambers are performed only for certain distance and collimator conditions. These conditions are purposely few in number to reduce the primary standardization work required and to minimize the possibility of error in setup. The beams are nominally square and the dimensions have been determined using radiographic film. The 50% density contour is taken as defining the beam size for this purpose. The data are given in table 3-21.

Table 3-21. Beam size defined by 50-percent radiographic density contour for vertical-beam gamma-ray sources, for specific collimator settings.

Source	Al-Ch. scale dist. (cm)	Collimator settings	Beam size (cm)
^{137}Cs - B036	38	10.5 × 10.5*	13.6 × 13.6
^{137}Cs - B036	55	8 × 8*	12.8 × 12.8
^{60}Cs - B036	105	6 × 6	12.6 × 12.6

*Actual setting determined by gauge blocks.

3.5. Ionization-chamber current-measurement techniques

3.5.1. Background and history

Ionization currents as encountered in exposure standardization are currents produced by 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 that 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.

In the normal course of events in dosimetry measurements, ionization currents very rarely reach 50 nA. (An exposure rate of 1 R/s will produce about 0.3 nA/cm^3 in an ideal ionization chamber.) Included in the measurement of these currents are currents not produced by the radiation of interest but by background radiation and insulator leakage. 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 and leakage currents be determined. As a rule of thumb, and without taking special precautions, the leakage current for a good quality ionization chamber should be less than 5 fA. The measurement of leakage 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 to be made of 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.

In the past, various types of instruments have been used for radiation measurements, one of the first being gold-leaf electroscopes, then string electrometers of various types, direct current amplifiers, AC amplifiers (the vibrating-reed electrometer (VRE) with negative feedback), and presently, the direct-coupled high-gain negative-feedback electrometers. (There is a good description of early instrumentation in Hoag and Korff [14].)

3.5.2. Electrometers

Until high-gain negative-feedback amplifiers were introduced, electrometers used for ionization current measurements were used as null detectors. Charge, or current, was measured by manually nulling the signal on the most sensitive range of the electrometer. In the null method of measurement, determination of stray capacitance in the system and voltage calibration of the electrometer are unnecessary but it is necessary in free-air chambers to maintain the null such that the collector plate potential is very near the guard-plate potential. A difference in potential between the guard and collector plates in a free-air chamber distorts the electric field and deforms the defined air volume. Measurements of exposure will then be in error, see [15-17] for a more detailed description of this subject.

The VRE was an improvement over direct-current, vacuum-tube electrometers not only because it utilized negative feedback but, being an AC amplifier, the problem of zero drift was essentially eliminated. Negative feedback automatically maintains the inner electrode of an ionization chamber near the guard potential and minimizes field distortion. For many years, VRE's were used at NBS as null detectors [2,18]. The gain of the VRE's was found on occasion to be much less than the design gain of 1000; gains as low as 250 were found, which could lead to reading errors of up to several percent in the collected charge. Loevinger [19] derived corrections for electrometer current measurements and showed that the gain of several VRE's varied with scale reading and polarity. Sources of information for the following discussion are given in references 19-24.

The high-gain, negative-feedback amplifier is the type of operational amplifier used in electrometers for measurement of small currents from ionization chambers. These amplifiers have a high impedance input and, an essential characteristic for free-air ionization chambers, the input terminal maintains the collector plate virtually at ground potential. A negative-feedback electrometer with resistive feedback element is shown in figure 3-18. The signal current I_{sig} from an ionization chamber impresses a signal on the input terminal of the operational amplifier, which generates an output voltage V_{out}. Part or all of V_{out} is fed back (from the load resistor R_L) through the feedback resistor R_f to the input terminal, so as to oppose the input signal. The output voltage is larger than the resultant input voltage V_{in} in the ratio

$$G = V_{out}/V_{in}$$

where G is the amplifier gain. In modern electrometers, such as the Keithley 616, $G > 10^4$, so for present purposes V_{in} can be neglected compared to V_{out}, and

$$V_{sig} = V_{out} \quad .$$

For operational amplifiers with large input resistance, for which the input voltage $V_{in} \approx 0$, there can be no current through the amplifier, and the current through the feedback resistor is equal to the ionization-chamber current I_{sig}. Therefore

$$V_{sig} = I_{sig} R_f$$

and finally

$$I_{sig} = V_{out}/R_f \quad .$$

This is the relationship used for measuring current when using a resistive feedback element.

For low-current measurements high-megohm resistors are required. For example, a feedback resistor of 20 MΩ is required to develop a feedback voltage of 1 V for the exceptionally large ionization current of 50 nA. Day and Attix [18] found that the high-megohm resistors of several manufacturers changed their values by as much as 1% over a period of six months. Consequently General Radio Corp. air-dielectric capacitors have been used as feedback elements for dosimetry calibration work for many years. A negative-feedback amplifier with capacitative feedback element C_f is shown in figure 3-19. In this case,

$$\Delta V_{sig} = I_{sig} \Delta t/C_f$$

and we get

$$I_{sig} = C_f \Delta V_{out}/\Delta t \quad .$$

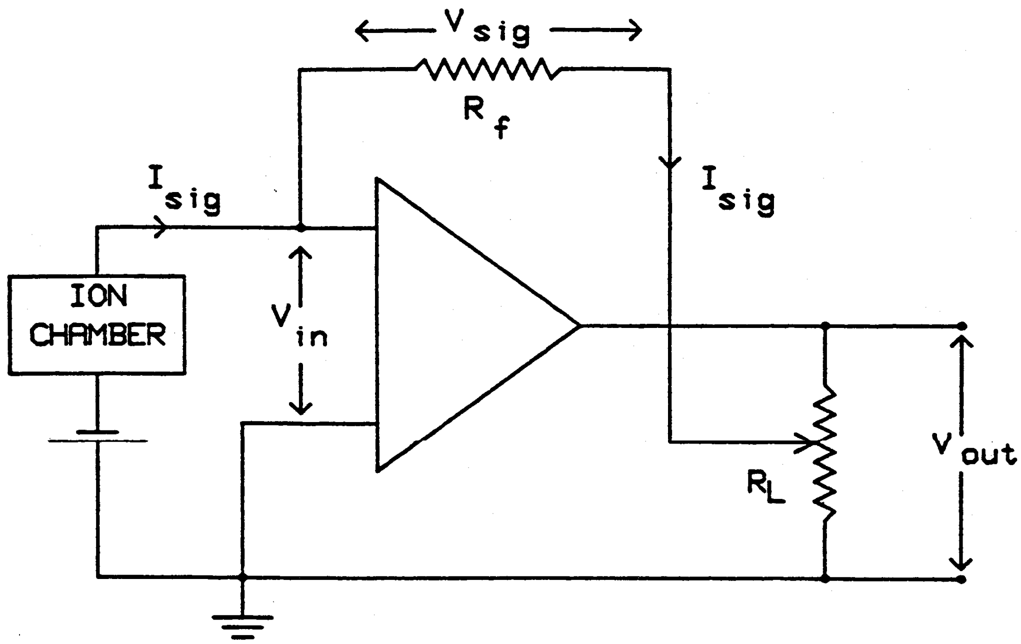


Fig. 3-18. Circuit of a negative-feedback amplifier with resistive feedback element.

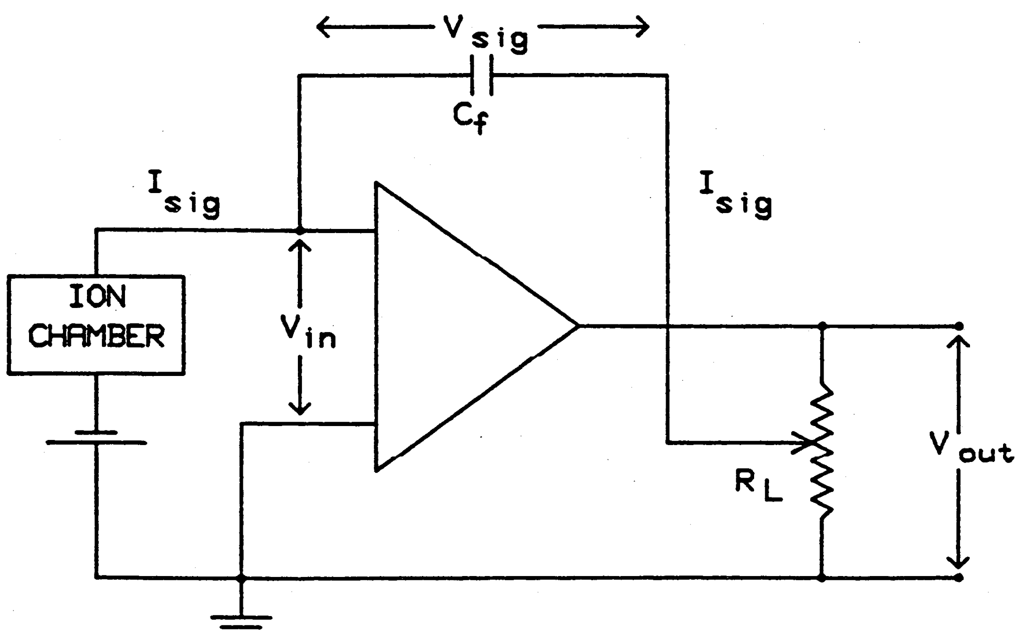


Fig. 3-19. Circuit of a negative feedback amplifier with a capacitive feedback element.

This equation is the basis for all important ionization-current measurements at NBS. The ionization current I_{sig} is determined from measurements of V_{out} using accurate digital voltmeters which can be commanded to sample-and-hold readings of V_{out} at preset time intervals.

The inverting operational amplifier has other advantages worthy of mention since they affect the application of these devices to ionization current measurements. These features are the inherent linearity of the change in V_{out} with time, giving $\Delta V_{out}/\Delta t$ = const., and the ability of the device to transfer essentially all of the charge produced in the ionization chamber to the measurement system. The slope $\Delta V_{out}/\Delta t$ is constant because the input terminal being at virtual ground is essentially isolated from the input circuit, i.e., the magnitude of the voltage on C_f does not affect the ionization current being supplied from the current source. If this were not so, the charge build-up on C_f would be exponential. The almost complete charge transfer from the current source is accomplished because ΔV_{in}, the potential across the capacitance of the current source, is forced to be near zero by the negative feedback and, for an open loop gain of 10,000, $\Delta V_{in} = V_{out} \times 10^{-4}$. Then only $10^{-4}\ V_{out}$ is across the current source capacitance. Other ways to consider this effect are that the capacitance of the current source is degenerated by the open-loop gain or, that the effective capacitance of the electrometer is increased by the open-loop gain.

Personnel safety in the measurement of radiation requires that measuring instrumentation be located in a radiation-safe environment. In addition, it is good practice not to allow radiation to strike instruments which may be susceptible to generation of extraneous currents. These conditions are made possible through the use of "low-noise" coaxial cables for connection between ionization chambers and electrometers. Low-noise cables are manufactured by the Amphenol, Essex, and Microdot companies. The "low-noise" characteristic of these cables is accomplished by coating the surface of the coaxial insulator with a conducting material. In this way the metallic braid used as an electrostatic shield, and the coating, are always at the same potential regardless of cable disturbance. Additionally, the capacitance between the coaxial surfaces remains the same even though the braid may not always be in immediate contact with the surface. Prior to the advent of the low-noise cable, solid-dielectric lead-shielded connections were made to ionization chambers, and later, long tubes with spring-loaded central wires were used. It was necessary to evacuate the air from the tubes to eliminate their contribution to the measured ionization current.

The use of long, low-noise cables and the discontinuance of manual null methods were made possible by the use of the high-gain negative-feedback electrometers. Cables between ionization chambers and electrometers in several of the NBS Dosimetry laboratories are as long as 15 m (50 ft). For a typical low-noise cable capacitance of 30 pF/ft the total capacitance is 1.5 nF. This cable capacitance is degenerated to 0.15 pF if the electrometer gain is 10,000. Since, in most measurements, the electrometer feedback capacitors are 1000 pF or greater, the added capacitance in this instance would cause an error of 0.02%. If the feedback capacitance is less than 1000 pF, say 100 pF, the percent loss of charge trapped on the stray capacitance should be determined. (The open-loop gain may be as high as 50,000.)

Commercial electrometers, such as the Keithley Model 616 used by the Dosimetry Group, are very versatile instruments. Those features of interest, for measurement of ionization currents, are the current-and charge capabilities for currents above about 100 fA. The instrument is operated in the "fast" mode (negative feedback) for the currents of interest here. It has selectable feedback resistors ranging from 0.1 MΩ to 10 TΩ, and selectable feedback capacitors ranging from 100 pF to 100 nF. However ionization current measurement procedures developed over many years in the Dosimetry Group preclude the use of high-megohm resistors as feedback elements and the use of air-dielectric capacitors is preferred where possible. Feedback elements of choice can be selected for this electrometer by setting the range switch to the "Volts" position. There is no built-in feedback element with the switch in this position and a capacitor of choice can be connected between the "guard" terminal at the back of the instrument and the instrument input. (Refer to Electrometer Amp. and Range Switching Circuit No. 25764E in the Keithley Mod. 616 Instruction Manual).

The ionization currents usually encountered in Dosimetry Group calibration work are in the range 0.1 pA to 100 pA. It is necessary, therefore, to have available a range of feedback capacitors in order to efficiently perform measurements of currents. This has been done for Dosimetry instrumentation by mounting air-dielectric capacitors of nominal capacitance, 100 pF and 1000 pF, and good quality 10 nF and 100 nF polystyrene capacitors in chassis, which are then mounted with electrometers in measurement consoles containing other control and measurement equipment.

The capacitors installed in measurement consoles have either been calibrated by the NBS Electrical Measurements and Standards Division or intercompared with such standards. The General Radio capacitors, of nominal values 100 pF and 1000 pF, were modified originally for mounting on VRE preamplifier heads and the polystrene capacitors were mounted in metal cylinders for the same purpose. Since the VRE's are no longer used, connections are made to these capacitors by means of BNC-type connectors. A brass adapter, simulating the VRE preamp spring-loaded connector, is available in B033 for making connections to those capacitors not having BNC connections at each end.

Periodically, several of the available capacitors are submitted to the Electricity Division for calibration. These calibrated capacitors are then used to "calibrate" the remaining capacitors. A detailed explanation of this procedure appears in section 3.8.1.

3.6. Ionization current measurement-console equipment

X- and gamma-ray-produced ionization currents are, for the most part, measured automatically, although capability exists to use manual methods. There are two automatic data acquisition systems (DAS) in use at the time of writing. One system is used exclusively for measurements made with the x-ray sets, and the second system, a portable system, is used for measurements made with the gamma-ray sources.

3.6.1. X-ray calibration data acquisition system

Data are acquired for x-ray standardization by measurement of all conditions relevant to establishing an x-ray exposure at a particular distance from the x-ray tube target for a shutter-open time interval. The data acquired are of three categories: (a) data required for computation of ionization currents, (b) parameter data, and (c) measurement system test and information data. In category (a) are: initial and final electrometer feedback voltages, the atmospheric pressure and pertinent air temperatures, and the shutter-open time interval. In category (b) are: the x-ray tube current and potential, the x-ray tube target-to-reference point distance, and the filter and the diaphragm wheel positions. In category (c) are: measurements of the collection potentials on the standard free-air chamber, the monitor chamber, and the chamber being calibrated (if appropriate). Also in category (c) are the results of tests of accuracy of the system digital voltmeter.

The DAS consists of an input scanner (Hewlett-Packard Model 2901), an integrating digital voltmeter (HP Model 2410C), a coupler (HP Model 2547A), a preset controller (HP Model 5331A), four Keithley Model 616 electrometers, two capacitor selector boxes with a total of sixteen calibrated capacitors, two temperature-measuring devices, and one pressure indictor. Several NIM modules built by NBS are used to control the system. A block diagram of the DAS is given in attachment 7.

The HP input scanner, on command, sequentially connects analog signals from up to 25 sources to the DVM for measurement. The DVM performs each measurement and provides the information to the coupler which also receives from the scanner the channel number identifying the source of the signal.

Digital data from the preset timer and the distance switches for the 300-kV range are supplied to the coupler. The rest of the 300-kV range set-up code (diaphragm, filter, and chamber identity) is supplied directly to a parallel input board (DRV-11J), located in the Digital Equipment Corp. 11/23 computer expansion box. The function of the coupler is to convert all the information supplied to it to a form that can be received by the serial input-board. A different arrangement is used for the 100-kV range where the timer data and set-up code are all supplied to the coupler. The data provided by the coupler to the DLV-11J are in ASCII octal form and are sent serially at a rate of 10 characters per second. The input signals to the scanner for operation of the 300-kV calibration range, as of 1984 December 31, are given in table 3-22.

One important variable not identified automatically is the capacitor used as the feedback element for each electrometer. These are selected from a capacitor value menu for the 300-kV x-ray range. The capacitor values are entered manually for work done on the 100-kV x-ray range. There are four sets of these capacitors, one set for each K616 electrometer. The values for these capacitors, and the instruments with which they are associated are given in table 3-23.

Table 3-22. HP Scanner channel numbers and input signals for 300-kV x-ray machine

Channel No.	Signal
1	Kilovoltage (Seifert control panel)
2	Air temperature, room or inside FAC
3	Feedback voltage, FAC
4	Feedback voltage, monitor chamber
5	Collection potential on monitor chamber
6	Collection potential on FAC
7	Collection potential on test chamber, #1 position
8	X-ray tube current (Seifert control panel)
9	Atmospheric pressure
10	Feedback voltage, test chamber in #1 position
11	Feedback voltage, test chamber in #2 position
12	Positive polarity, standard cell potential
13	Zero, DVM shorted
14	Negative polarity, standard cell potential
15	Collection potential on test chamber, #2 position
16-24	Not used
25	Temperature inside monitor chamber

Table 3-23. Electrometers and capacitors mounted in x-ray standards measurement console.

(Standard Free-Air Chamber) K616 NBS No. 189980		(Monitor Chamber) K616 NBS No. 188889	
Cap. Type	Cap. (pF)	Cap. Type	Cap. (pF)
A	83.67	B	1 038.4
B	1 050.8	C	10 144
C	9 870	2D	197 871
D	99 060		

(Test Chamber #1) K616 NBS No. 179266		(Test Chamber #2) K616 NBS No. 179274	
Cap. Type	Cap. (pF)	Cap. Type	Cap. (pF)
A	81.68	A	100.20
B	988.35	B	1 091.8
C	9 808	C	10 571
D	99 761	D	100 187

The A and B type are air-dielectric capacitors. The C and D type are polystyrene-dielectric capacitors. Ref: DB852: 116-117

The temperature sensors used to measure room, FAC, and monitor air temperatures are two-wire thermistors manufactured by Yellow Springs Inc. (YSI). The sensors for the FAC, and for room air temperature measurement, are switched to the YSI Mod. 43TN readout depending on the in-beam instrument. The YSI readout is a bridge circuit which, when unbalanced, provides a voltage proportional to the temperature. The YSI voltages are monitored on channels 2 (FAC or room) and 25 (monitor). The equations used prior to 1986 Jun 24 for computing temperatures for the 300-kV range were:

$$\text{FAC T (°C)} = 46.59\ (V_i + V_f) + 30.33 \quad \text{(Ref: DB 848:201)}$$

$$\text{Mon. Ch T (°C)} = 43.23\ (V_i + V_f) + 29.46 \quad \text{(Ref: DB 848:201)}$$

$$\text{Room T (°C)} = 46.75\ (V_i + V_f) + 30.13 \quad \text{(Ref: DB 848:201)}$$

where i and f refer to the initial and final voltage measurements, V_i and V_f in volts, for the preset time interval. With the exception of the monitor chambers thermistor, all temperature indicators have been recalibrated. A description of the calibration procedure appears in section 3.8.2. The new equations are:

$$\text{FAC T (°C)} = 48.314(V_i + V_f) + 30.562 \quad \text{(Ref: DB 852:060-061)}$$

$$\text{Room T (°C)} = 49.350(V_i + V_f) + 30.050 \quad \text{(Ref: DB 852:065-066)}$$

The changes in absolute temperature are -.02% and -.05% for the FAC T and the Room T, respectively. The above constants were incorporated into the computer programs on or about 1986 Jun 24.

The atmospheric pressure is measured by means of a capacitance-sensitive device manufactured by the Rosemount Company. The sensor is powered by an NBS power supply serial no. 2561. The output voltage is calibrated for pressure measurements in units of millimeters of Hg. The equation used prior to 1986 May 01 for computing the pressure was:

$$\text{P (mmHg)} = 560.85 + 25.54(V_i + V_f) \quad \text{(Ref: DB 783:23-25)}$$

The pressure sensor was recalibrated and a description of the calibration procedure appears in section 3.8.2. The equation used since 1986 May 01 is:

$$\text{P (mmHg)} = 557.52 + 25.891(V_i + V_f) \quad \text{(Ref: DB 852:095)}$$

This represents a change of -.09%. In the preceding equations, the constants are the result of combining and rounding off the constants stored in the computer.

The Seifert high-voltage supply was calibrated (1984 Aug 22-23) using a calibrated high-voltage divider (DB 852:45-55). The high-voltage divider was calibrated in March 1983 (Test No. 722/G44568; Seifert Voltage Divider SN 720479). The calibration showed some dependence of the HV on the x-ray tube current. In the equations below, the x-ray tube current is equal to the tube current thumbwheel switch setting (maTWS). The relationship between the true potential (TP) and the control panel thumbwheel kV settings (TWS) was established and found to be (1984 Aug 27):

$$\text{TWS} = -4.75 \times 10^{-1} - 4.8 \times 10^{-3}(\text{mATWS}) + (1.01394 + 3.74 \times 10^{-4}\ (\text{mATWS}))\text{TP}$$

The nomenclature in the equation is the same as is used in the DEC computer program. The number of places used for the constants in the above equation is sufficient to calculate values for TWS accurate to 0.1 kV. With the x-ray machine under computer control, the required x-ray tube potential and current are typed into the computer and the thumbwheel settings are (remotely and effectively) set in accord with the solution of the equation for TWS. The x-ray tube potential is monitored on channel 1. The sensor is an impedance transformer and the rectified signal is available from a special module behind the Seifert control panel.

The relationship between the kV analog signal on channel 1 and the true kV was measured for x-ray tube currents (monitored on channel 8) up to the maximum current for each x-ray tube potential of interest (Ref. DB 852:55).

The x-ray tube potential is computed using the second equation below after calculating the x-ray tube current from the voltage signals on channel 8 as follows:

$$(mA)_{calc} = (mATWS)_{calc} = C(V_i + V_f)/2 + D$$

where C = 10.0594 and D = -0.050737
then:

$$\text{Tube Potential (kV)} = B(V_i + V_f) + A$$

where $A = -0.32637 + (0.010391)\ (mATWS)_{calc}$

and $B = 47.7267 - (0.0109295)\ (mATWS)_{calc}$

In the solution for the constants A and B for the x-ray tube potential equation, a linear relationship was assumed, for A and B, with tube current. While this is correct for B, examination of the data for A (DB 852:55) reveals that it is the second differences in A which are nearly constant and therefore a second degree equation would better describe the variation of A with tube current. Considering the datum at 25 mA(TWS) to be an outlier (the value is based on only two points), an equation which closely describes A = f(mATWS) is $A = -0.333 - 0.0013944\ (mATWS) + 0.0011247\ (mATWS)^2$.

A comparison of calculations for Tube Potential, using the first and second-degree equations for A, is given in table 3-24.

The differences shown in table 3-24 are of more academic than practical interest since these signals are used only for monitoring the x-ray tube potential and current. The potential is set either manually or by computer and the result is compared with the information from the filter wheel position to test for consistency and for identification of the appropriate FAC corrections. The signals on channels 1 and 8 of the scanner monitor the x-ray tube condition during the course of a calibration.

The filter wheel position associated with the 300-kV machine calibration beam codes are given in table 3-25. For convenience where the calibration techniques are the same, the previous beam code is listed. (These are provided for ease of reference in response to inquiries regarding past instrument calibrations). The beam codes are also listed in table 1-1.

Table 3-24. Comparison of solutions for true kV using first and second-degree solutions for the constant A.

kV signal (V)	mATWS	X-ray tube potential (kV) A, 2nd degree	A, 1st degree	ΔkV
2.0	5	95.0	95.1	+0.1
2.5	5	118.9	118.9	-
3.0	5	142.7	142.7	-
3.5	5	166.5	166.6	+0.1
4.0	5	190.4	190.4	-
4.5	5	214.4	214.3	-0.1
5.0	5	238.0	238.1	+0.1
5.5	5	261.9	261.9	-
6.0	5	285.7	285.8	+0.1
6.5	5	309.6	309.6	-
		No difference for 10 mATWS		
2.0	15	95.0	95.0	-
2.5	15	118.8	118.7	-0.1
3.0	15	142.6	142.5	-0.1
3.5	15	166.4	166.3	-0.1
4.0	15	190.2	190.1	-0.1
4.5	15	213.9	213.9	-
5.0	15	237.7	237.6	-0.1
5.5	15	261.5	261.4	-0.1
6.0	15	285.3	285.2	-0.1
2.0	20	95.1	94.9	-0.2
2.5	20	118.9	118.7	-0.2
3.0	20	142.6	142.4	-0.2
3.5	20	166.4	166.2	-0.2
4.0	20	190.1	189.9	-0.2
4.5	20	213.9	213.7	-0.2

Table 3-25. Calibration beam code - filter wheel positions for 300-kV x-ray machine. The letters M or H preceding the number in the Beam Code column indicate "moderate" or "heavy" filtration. The number following the letter is the constant potential on the x-ray tube.

Filter Wheel Position	Beam Code Present	Beam Code Old
1	M60	MFB
2	S60	MFC
3	M50	-
4	M100	MFG
5	H100	-
6	M150	MFI
7	M200	-
8	H300	-
9	M250	MFO
10	H50	HFC
11	H60	-
12	H150	HFG
13	M300	-
14	H200	HFI
15	H250	HFK

Calibrations of instruments for lightly filtered x-rays are performed using either the Lamperti or Ritz FAC which are mounted in the low-energy calibration range (100 kV). The measurement console equipment for the 300-kV x-ray machine is also used for the 100-kV range. The switchover to the 100-kV range is accomplished by changing input selector cables and switches on a module located in the HP DAS console. The A and C positions are for the 300-kV range and the 100-kV ranges, respectively. The E position can be used if it became necessary to use the HP DAS for gamma-ray calibrations performed in rooms B034 and B036. This mode is no longer used since there is a portable DAS for the gamma-ray calibrations. A description of this system follows in section 3.6.2. All switches and cables must be set to the same letters to have proper connections. The HP scanner channel and input signals for the 100-kV range are given in table 3-26.

The power supply for the low-energy-range x-ray tube is a 150-kV supply built by Universal Voltronics (Ser. No. 2-6-1486). The output of the supply was calibrated in 1972 by the NBS Electricity Division. A copy of the calibration report is attachment 8, since there is no reference test number. On the basis of this calibration, the DVM in the 100-kV control console is set to provide the required potential on the x-ray tube. The maximum potential allowed across the x-ray tube is 100 kV although the power supply can be operated up to 150 kV.

Table 3-26. HP scanner numbers and input signals for 100-kV calibration range.

Channel No.		Signal
1		X-ray tube HV, analog sig.
2		Room or FAC temp.
3		Feedback voltage, FAC or test ch.
4		Feedback voltage, mon. ch.
5		HV, mon. ch.
6		HV, FAC
7		HV, test ch. (if required)
8		X-ray tube mA, analog sig.
9		Pressure signal
10-11	not used	
12		Std. cell, + polarity
13		HP DVM shorted
14		Std. cell, - polarity
15-16	not used	
17		X-ray tube current meter range selected
18-24	not used	
25		Mon. temp.

The equation used (Ref: DB 764:004) for computing the high voltage on the 100-kV x-ray tube is:

$$\text{Tube Potential (kV)} = 3.206095 \times 10^{-3} + 1.0233975\ V - 1.39388 \times 10^{-4}\ V^2$$

where V is the mean of the analog HV signal measurements taken, on channel 1, at the beginning and end of the preset exposure interval. The calculated kV is corrected by 1.5% because the HP DVM in the data acquisition system loads the signal at the time of measurement.

The x-ray tube current meter has three manually selectable ranges, 2mA, 6mA, and 20mA. The x-ray tube current is determined from signals measured on channels 8 and 17. The signal on channel 17 is a function of the selected meter range and is labeled TCDIV in the computer program. The equation for x-ray tube current is:

$$\text{Tube Current (mA)} = (V_i + V_f)/2(\text{TCDIV}) \qquad \text{(V measured on channel 8)}$$

where (TCDIV) = 0.3. However, if the signal on channel 17 is less than 4 volts, (TCDIV) = 1, and if the signal is less than 2 volts, (TCDIV) = 3.

The filter wheel positions associated with the 100-kV x-ray tube calibration beam codes are given in table 3-27.

Table 3-27. Calibration beam code-filter wheel positions for the 100-kV x-ray range. The letters L, M, or H preceding the numbers refer to the "Light", "Moderate" or "Heavy" filtration, respectively. The number following the letter is the constant potential on the x-ray tube.

Filter wheel position	Beam Code Present	Beam Code Old
1	L10, L15, L20	L-B, L-C, L-D
2	H10	-
3	M20	-
4	L40, M30, H15	- , L-G, -
5	H40	-
6	M50, H20	L-I, -
7	S75	L-K
8	L100	L-M
9	H30	-
10	M40	-
11	L30	-
12	L50	-
13	L80	-
14-15	-	-

Note that since the same filtration is used for several x-ray tube potentials, special means of identifying the technique being used are required.

Where the same filter wheel position is used for several calibration energies, IF statements in the computer program operate on the computed x-ray tube potential. IF statements are required for filter wheel positions 1, 4, and 6. A value of 20 is hard wired to all filter wheel data making the multi-technique positions 21, 24 and 26. If the filter wheel position is identified as 21 and the computed kV is greater than 12.5 kV but less than 17.5 kV, then the code is made equal to 34. Code 34 identifies the beam code as L15 and the appropriate data associated with the Lamperti FAC are used to compute exposure data. If, however, position 21 is identified and the calculated kV is greater than or equal to 17.5 kV, the code is made equal to 35 and the beam code is identified as L20. The same procedure is followed for position 4 (24) which is associated with beam code H15, except where the calculation for kV indicates otherwise, whereupon it is identified as either M30 (code 36) or L40 (code 37) depending on the magnitude of the kV. Position 6 (26) is M50 unless the calculated kV is less than 35, in which case the beam code is identified as H20.

There are four YSI temperature probes used in conjunction with measurements on the 100-kV calibration range. The thermistors for the room, Ritz FAC, or Lamperti FAC are manually switched one at a time to a single YSI readout and are read on scanner channel 2. The temperature of the monitor chamber is determined from measurements on channel 25. The equations for computing these temperatures are:

Monitor temp. $= 30.17 + 45.34(V_i + V_f)$

Room temp. $= 29.86 + 48.47(V_i + V_f)$ (Ref: DB 852:063)

Ritz FAC temp. $= 30.05 + 47.92(V_i + V_f)$ (Ref: DB 852:064)

Lamperti FAC temp. $= 30.17 + 49.48(V_i + V_f)$ (Ref: DB 852:067)

The above constants were incorporated into the computer programs on 1986 Jun 24.

The atmospheric pressure is determined from measurements of the Rosemount transducer for which the pressure equation was given in the discussion of the 300-kV range.

For both the 100-kV and 300-kV ranges, the shutter-open time is determined by a counter which starts, and stops, counting a 1 kHz (optionally 100 Hz) signal as the edge of the shutter crosses the mid-point of the beam port. The signal to the timer is a pulse produced by a photodiode when its light beam is interrupted by a flag on the shutter mechanism. Upon initiating the exposure, counting commences only on receipt of the photodiode pulse. At the end of the preset time interval, the shutter is caused to close but the timer continues to count until the edge of the shutter crosses the portal mid-point. The timing shutters move quickly so the difference between the preset time and the actual exposure time is usually less than 0.1 s. The 300-kV machine also has a safety shutter which opens before, and closes after, the timing shutter. The lead thickness in the timing shutter was minimized for mechanical purposes but is of sufficient thickness to prevent significant effects on instrument readings in the interval between operation of the two shutters.

3.6.2. Gamma-ray calibration data acquisition system

The measurement console and computer controlled equipment described could also be used for instrument calibrations for gamma rays in Rms. B034 and B035. For this purpose, it would be necessary to connect the cables on the input-cable-sector board from common to E and to turn all switches to E. Also, it would be necessary to set up the chamber to be calibrated and make proper connections from the instrument and control panels in B035. This type of operation is inefficient, however, since for integration-type-instruments, it would be necessary to go from room-to-room between readings. In addition, and more importantly, x-ray and gamma-ray calibrations cannot proceed simultaneously. Calibrations as well as other types of measurements using the gamma-ray sources in rooms B034, B036, B021, and B015 are therefore carried out using a mobile measurement console consisting of all instrumentation required for measurement and standardization of ionization currents, and an HP9836-HP3497A computer-controller system which can be made to automatically acquire calibration data for cable-connected instruments, and into which instrument readings can be typed for other types of instruments. The 3497A is the data acquisition unit which incorporates, among other capabilities, a scanner, a digital voltmeter (5 1/2 digits) and a timer. The HP 9836 is a computer which instructs the HP 3497A to perform certain measurements. The computer instructions are in the form of strings of commands addressed to the HP 3497A. A typical command string in a program named "G CF" is:

OUTPUT 709: "SE1TI2AE1AF0AL2VR3AC0VT2S01".

The address of the HP3497A is 709. (7 is the interface select code and 09 is the device select code.) The commands are the two letter codes and a number. The meaning of the above string is as follows:

- SE1 Sets bit 0 of the service request mask (SRQ) to 1. When bit 0 in Status Register is set to 1, indicating Data Ready, both bits are true and an SRQ is sent to the controller.
- TI2 Two seconds after the 3497 receives the string, a pulse is output from the timer port.
- AE1 Enables the external channel increment port.
- AF0 Sets the first channel to be read at channel 0.
- AL2 Sets the last channel to be read, channel 2.
- VR3 Sets the voltmeter range to 10 volts.
- AC0 Closes analog channel 0.
- VT2 Triggers voltmeter on an external trigger pulse.
- S01 Instruction to system to wait until measurement is complete.

The HP3497A sends a service request (an INTERRUPT 7) on the interface bus because the bits 0 in the SRQ mask and the STATUS register are true when the voltmeter has completed the readings on channels 0 through 2. The computer sends a SERIAL POLL message and the HP3497A returns the STATUS BYTE. The computer seeing the measurement data have been acquired will then respond in accord with the actions required by the program.

This mobile console contains a Keithley Model 616 electrometer, a Setra Model 350A digital barometer, and a Digitec Model 5810 digital thermometer. Each instrument provides analog signals to the HP3497A. The feedback elements for the electrometer selector switch in the "Volts" position, are capacitors mounted in a capacitor-selector chassis. The values for these capacitors are given in table 3-28.

Table 3-28. Capacitor values (1986 Jun) in mobile measurement console.

Capacitor	Capacitance (pF)
A-2	78.05
B-18	1 002.4
C-3	10 213

The equations for computing temperature are dependent on the thermistor used and, for measurements in control room B019, the signals are taken from YSI readouts mounted in the source control consoles. These equations, the equation for computing atmospheric pressure from the Setra device, and the data for converting the analog signals from the thermistor probes to air temperatures in each calibration range and from the pressure transducer to atmospheric pressure are stored in the HP9836 "G CF" program. The general equation for air temperature (D1) taken from the "G CF" program listing is:

$$D1 = (K11)\ (V(J,2) + V(J-1,2))/2 + K12 \quad (°C)$$

where V(J-1,2) is the analog signal measured at the start of an exposure and V(J,2) is the same measurement at the conclusion of the exposure. The values of the constants K11 and K12 are given in table 3-29. The disparity in the values of the constants is due to the different models of bridge-type YSI readouts used for B015A and B, and B021A and B, and the Digitec digital thermometer used in the mobile measurement console for B034 and B036.

The equation for computing atmospheric pressure (D2) is listed in the "G CF" program as:

$$D2 = 60\ (V(J,3) + V(J-1,3))/2 + 802 \quad (\text{mbar})$$

$$\text{and } D2h = 760\ D2/1013.25 \quad (\text{mmHg})$$

Table 3-29. Constants in "G" program for computing air temperature in gamma-ray calibration rooms.

Room	K11	K12	DB:page
B015A	-91.87	29.60	852:070
B015B	-92.72	29.85	852:071
B021A	-197.96	42.95	852:068-069
B021B	-197.45	42.82	852:072
B034	13.82	-0.32	852:073
B036	13.77	-0.31	852:076

Finally, the "G CF" program listing for the pressure and temperature correction is:

$$Pt = (760/D2h)\ (D1 + 273.15)/295.15$$

Although all standards measurements are acquired automatically, for other purposes it is sometimes convenient to use manual measurement methods. The instrumentation is the same as for automatic measurements except for controlling charge-integration time and measurement of V_{out}. A DVM controller-timer designed by A. Marella of NBS (Rad. Source and Inst. Div., Drawing ND-3440) replaces the HP9836-3497 system for manual measurements. The essential elements of the controller-timer are: an accurate frequency source (Greenway

Mod. Y819 (1000 pps.)), a digital counter (ERC Mod. 2306A), and a comparator (ERC Mod. 2506-1). The function of the timer is to output a pulse of the required amplitude and width to initiate a sample-and-hold command to a digital voltmeter with that command capability. The Digitec DVM (either Mod. 266 or 287) requires a positive pulse 10 to 40 μs wide and with an amplitude between 2.2 and 5.5 V for a sample and hold command. The DVM responds within 60 ms after the occurrence of the leading edge of the pulse.

The Greenway oscillators are specified as having frequencies of typically 999.9866 pps. and DVM's such as the Digitec Mod. 266, when compared with the Fluke DC Voltage Calibrator, have been found to be accurate to 4 1/2 digits.

3.7. Pre-calibration tests of exposure instruments

Considerable time and effort are expended in setting up to calibrate an instrument for the quantity exposure. Additional man-hours and machine time can be lost if instrument problems are discovered after the calibration procedure has begun. Therefore all instruments submitted for calibration are tested prior to calibration to discover possible defects and to establish certain instrument characteristics in a less time-intensive laboratory facility.

In general, there are two types of instruments submitted for calibration: (a) ionization chambers associated with exposure readers, and (b) ionization chambers to be calibrated in electrical units. Type (a) instruments can be divided into two categories - (1) "condenser" types which consist of a charger/reader and one or more "condenser" probe ionization chambers (probes); and (2) cable-connected types. In general, both types have probes with different ranges, extending the instrument's range from protection-level to therapy-level exposure rates.

3.7.1. Charger/reader scale linearity test

For all practical purposes, the only charger/reader sent to NBS for calibration is the Victoreen Model 570 R-meter, described in section 4.2.1. The first test of a charger/reader is for scale linearity but this cannot be carried out upon arrival. The instrument must be allowed to acclimate itself to the laboratory environment for at least several hours before testing and, in fact, because of scheduling, may not be tested for several days.

Along with testing for scale linearity, the general operation of the charger and the quality of the scale and image of the quartz fiber are evaluated. The image of the string, ideally, should be aligned with the scale markings, and the scale markings and string image should be well-defined from zero to full-scale reading. Evaluation of the image is somewhat subjective, but lack of good focus, double images, or string images with high-lights, should be considered as reasons for returning the instrument to the owner for adjustment or repair. Although minor adjustments can be made at NBS, they are done reluctantly since other, unforseen, problems may arise. In no case are adjustments attempted without contacting the owner for permission.

The scale linearity test is carried out using the Data Precision Model 8200 NBS No. 500302 voltage source (negative polarity, 1000-V range) and a connector which simulates the stem of a probe. The electrometer is connected to the line, turned on, and allowed to come to equilibrium with temperature changes caused by the light which illuminates the scale. With the Data Precision voltage source warmed up and with all voltage switches turned to zero, the negative polarity output is connected to the probe simulator and the simulator is inserted and locked into the charger recess. The voltage source is then turned from "0" to "-". While observing the electrometer scale, the potential from the voltage source is increased until the image of the string coincides with the zero marking on the scale. The potential is recorded for "VO" on the index card and, decreasing the potential, data are recorded for the 20, 40, 50, 60, 80 and 100 percent of full-scale reading.

According to specifications for the electrometer, the potentials required to bring the string image to a zero, and to a full-scale reading, are 525 volts and 275 volts respectively. So the initial setting on the voltage source for a zero reading should be about 525 volts. As a guide as to what might be expected, charging potentials, the difference in potential between zero and full-scale reading, and some statistics for 13 randomly chosen electrometers are given in table 3-30. In those cases where the number of measurements (n) is large, the data have been accumulated over as many as six years, and the charging potentials (V_0) and potential differences (V_0-V_{100}) are mean values. The mean V_0 for the 13 electrometers is 525.2 volts with a standard deviation of 7.7 volts (1.5%); and the mean potential difference, V_0-V_{100}, is 250.4 volts with a standard deviation of 1.7 volts (0.7%). Note that the standard deviations for individual instruments are about half the standard deviations for the group.

Table 3-30. Victoreen Model 570 electrometer charging data. V_0 is the potential required to charge the electrometer to a zero scale reading. V_{100} is the potential for a full-scale reading and S.D. is the standard deviation.

Serial No.	n	V_0 (V)	S.D. (V)	S.D. (%)	V_0-V_{100} (V)	S.D. (V)	S.D. (%)
143	6	518.6	3.6	0.7	251.5	0.73	0.3
265	10	526.9	3.1	0.6	247.6	1.13	0.5
997	7	538.6	3.9	0.7	253.6	1.26	0.5
1275	2	522.4	-	-	252.3	-	-
1285	2	518.6	-	-	251.3	-	-
1506	4	534.6	3.6	0.7	249.7	0.51	0.2
2261	1	531.0	-	-	249.6	-	-
2278	2	533.1	-	-	251.3	-	-
2300	2	521.2	-	-	248.9	-	-
2302	1	531.0	-	-	249.1	-	-
2344	4	515.6	3.7	0.7	248.2	0.53	0.2
2346	3	516.6	-	-	251.8	-	-
3015	6	519.9	3.3	0.6	250.3	0.56	0.2

3.7.2. Leakage tests of condenser probes

The condition of the probes associated with the electrometer is ascertained following the scale-linearity measurements on the electrometer. The thimbles of all probes are checked for one or more of the following: (1) physical damage; (2) integrity at joints; (3) tightly screwed-on thimble; (4) dirt in dust cap that could cause leakage. Assuming the probes are in good condition, they are charged to a zero reading on the electrometer with the time and date of charging recorded on the index card kept with the instrument (see section 4.1 for details). The instruments are then stored in a radiation-free area. This procedure provides a means for quickly determining, on the scheduled calibration date, the leakage condition of each probe.

3.7.3. Testing for atmospheric communication, condenser probes

The Victoreen probes are also tested for communication with the atmosphere since this is essential if air density corrections are to be applied to their readings during calibration. This test is carried out by connecting a probe to a negative-feedback electrometer and placing the probe in a box which can be pressurized while the probe is being irradiated. The measurement is carried out with the electrometer in the "current" mode of operation and readings are taken for room-pressure conditions and at slightly elevated pressures. The percentage change in the electrometer readings should equal (nearly) the percentage change in the air pressure. For most probes, the rate of change of the pressure is of no consequence, however, the pressure should be changed very slowly for thin-window chambers such as the model 651. (This precaution must be observed for any thin-window chamber, not just those manufactured by Victoreen.) Generally, a pressure change of 4 to 5% is sufficient for this test and conveniently, this change is about the same as the change from normal room pressure to a full-scale reading (785 mmHg) on the aneroid barometer in the test stand.

A special connector is available for connecting R-meter probes to the coaxial cable leading to the negative-feedback electrometer. The connector consists of a modified R-meter probe cap which has been fitted with a BNC connector. The ground for the connector is extended along, but is electrically isolated from the cap. In order to minimize the contribution of ionization from air volumes in the vicinity of the connector end, the connector is supported, during the test, in a lead brick. The polarizing potential is connected to the stem of the probe by an independent connection and what is usually at ground potential is now at high voltage. This is important in setting the polarity of the polarizing potential if a triax cable is used in conjunction with the Keithley Model 6169 Ion Chamber Interface. A copy of the Keithley drawing is attachment 9, showing the operating modes of the model 6169 interface.

Protection of the modified probe connector from radiation is especially important when the probe chamber volume is small, such as for "100 R" ($\approx$ 0.5-cm^3) and "250 R" ($\approx$ 0.2-cm^3) chambers. The exposure rate in the pressure test box, which is about 0.5 m from the source in B021A, is about 0.075 R/s (March 1986). The ionization currents produced in these chambers for an exposure rate of 0.075 R/s are 1×10^{-11} A and 5×10^{-12} A, respectively. These small currents and the usual associated noise in the signal sometimes make it difficult to discern with good confidence a 4% difference in reading. An additional difficulty in testing the high-range Victoreen probe is a drift in the reference reading with exposure to radiation. It may be necessary to cycle high-range probes through several pressure changes before firm conclusions can be drawn in regard to communication to the atmosphere.

Other problems arise in testing low-range probes. The exposure rate must be made appropriate for proper operation of low-range probes either by moving away from the source or by attenuating the beam. In large-volume chambers (e.g., 25-mR chambers), if the ionization density is too high, the percentage increase in reading will not be proportional to the increase in air pressure because ions are lost due to recombination.

3.7.4. Testing for atmospheric communication, cable-connected probes

Some instruments have ionization chambers cable-connected to an electrometer with a readout in exposure units. The electrometers are used as null devices or are of the negative feedback type. The scale linearity of these readers is not tested but the associated ionization chambers are tested for communication with the atmosphere. A difficulty often encountered with these tests is incompatability of connectors, requiring a departure from the use of test station instruments. In this case, the readout associated with the chamber is used to determine communication with the atmosphere. Depending on the size of the ionization chamber and its appurtenances, it may be necessary to use one of the special openings in the pressure box or to use another sealable container. A large tray with sealable lid and openings for a pressure hose and cables is available for special uses.

3.7.5. Testing of readers for cable-connected probes

While the scale linearity of this type of reader is not tested, it is important to check the collecting potential used for the probe. Some readers have a switch or button that will permit a "self test". For those instruments where this convenience is not available, one needs to turn on the reader alone, then using a high input impedence meter, carefully measure the collecting potential at the probe input connector. Comparison of the observed value should be made with nominal value given in the instruction book for the instrument.

3.7.6. Testing of instruments to be calibrated in electrical units

The pre-calibration testing of ionization chambers to be calibrated in electrical units is more extensive than for those incorporating an exposure-reading electrometer. The tests are for electrical leakage; time required to equilibrate after application of the collection potential and exposure to radiation; and the change in reading, for constant exposure rate, with reduction of the collection potential by half. In addition, if the request for calibration is for a mean calibration factor for positive and negative collection potentials, the polarity effects are investigated.

Except in those cases where the ionization chamber is quickly shown to be defective (high leakage current, large recombination correction, obviously bad electrostatic shielding) the results of pre-calibration tests are, to some extent, dependent on the time allotted to testing. The currents being measured are extremely small, and changes in measurement data reflect strains in cables and connectors which, in turn, are dependent on the length of time since the connections were made. Superimposed on these effects are insulator "soakage" effects caused by the application, and change, of the collection potential.

Assuming all cable, connector, and chamber insulators are in good condition, the leakage current, after a system has been connected together overnight, should approach the offset current of the electrometer (a Keithley Model 616 has been used at the test station). Typical leakage currents for the electrometer and the electrometer plus cables and connectors are shown in table 3-31. The data in table 3-31 are the result of measurements taken after the system had recovered from transients produced by making the various connections. Under some circumstances, it is difficult to decide when to bring the tests to a conclusion. To alleviate this problem, a "Pre-Calibration Ionization Chamber Test Data" form, which allows measurement data and decisions to be recorded in an organized manner, was prepared by T. P. Loftus. A copy of this proposed form, on which data from an actual test is shown, is attachment 10. The data reflect the real-time condition of the ionization chamber, i.e., the condition existing during calibration, not that of a quiescent state such as would be be case if the system were allowed to settle down overnight.

Table 3-31. Electrometer leakage current and currents induced by adding cables and connectors

Conditions	Current (fA)
Model 616 electrometer and Model 6169 interface Triax connector on interface capped off	< 2.0
Triax cable (≈ 15 m) added and capped off	<29
Triax-BNC adapter added and capped off	<34
NEL adapter added and capped off	<34

Although there are some advantages (reduced noise, single cable) to the use of triax cables for connecting guarded ionization chambers to electrometers, recent tests indicate that the addition of the triax cable insulation, between the guard and the external shield, can contribute to an increase in "insulator soakage time". Insulator soakage is the phenomenon observed in ionization chamber measurements in which a change in collection potential causes a reading transient which disappears exponentially with time. This soakage is of no consequence for chambers designed to be connected by triax cable to their electrometers, and for which the collection potential is always of the same magnitude and polarity. However, in tests designed to evaluate the recombination characteristics of an ionization chamber, additional HV-insulation increases recovery time from the transients introduced by the changing collection potentials. Data showing that low noise coaxial cables are more suitable for pre-calibration tests are recorded in DB 861:12-14.

3.7.7. Summary and comments

Pre-calibration testing is performed not only to detect instrument defects but to provide information required for proper operation during calibration and to provide data for the final calibration report. The pre-calibration test datum that appears on the R-meter calibration report is the open or sealed condition. The Roentgen per Coulomb calibration report contains, in addition to the above item, the leakage current, the ratio of ionization currents for full and half collection potential, and the magnitude of the ionization current observed with full collection potential.

The report information could be made more nearly correct in regard to leakage current if the statement for leakage were changed to the expression "not greater than" as opposed to stating a specific value. This change would save time by allowing a determination of leakage currents relevant to the effect such a current would have on the expected ionization currents during calibration.

The full and half collection potential current ratio could be made more relevant if the expected calibration exposure rate were a consideration in the tests. For low-range ionization chambers, present facilities are adequate and this consideration could be made a requirement in the test procedure. For the present, the testing of high-range instruments at full and half potential needs to be done at the time of calibration.

3.8. Capacitor, pressure indicator, temperature indicator calibration

3.8.1. Capacitor calibration

Periodically, since 1956, several of the available capacitors are submitted to the Electricity Division for calibration. Copies and originals of these reports are kept in the Dosimetry Group office file in a folder marked "Intrabureau Calibrations". (Ref. Test No. 521-02-86, 10-30-85; Test No. 521-07-86, 02-21-86). The letter designations A, B, C and D identify the capacitors as having nominal values of 100, 1000, 10,000 and 100,000 pF, respectively. Following the 1985/1986 calibrations, all available capacitors were compared with either A5, B5, C6, or D4. The data are recorded in DB 852:082-088. Some typical long-term calibration results are given in table 3-32. The uncertainty, including both random and systematic, stated by the Electricity Division is ± 0.02% for A5 and B15, and ± 0.03% and ± 0.05% for C6 and D4, respectively. (These uncertainties are interpreted by the Electricity Division as equivalent to three standard deviations.) The results shown in table 3-31 indicate a reproducibility of 0.02% for capacitors A5 and B5. Capacitor C1 shows a shift of + 0.45% from 1967 to 1980 but only 0.04% from 1980 to 1983. Capacitor C6 shows a smaller change, 0.02%, from 1983 to 1986.

The circuit shown in figure 3-20 is used for Dosimetry calibrations of capacitors. The variable voltage source is a Data Precision Model 8200 and the operational amplifier is a Keithley Model 616 Electrometer (K616). The electrometer is operated with the Range switch in the "Volts" position, and the Fast-Normal switch in the "Fast" position. The capacitor to be calibrated is connected between the feedback (Guard) terminal at the back of the electrometer, and the input terminal at the front of the electrometer. A

Table 3-32. Electricity division calibrations

Serial Number	Calibration Date (month/year)	Capacitance (pF)
A5	12/56	81.16
	10/59	81.16
	3/60	81.16
	3/70	81.174
	8/77	81.19
	2/83	81.189
	10/85	81.197
B5	12/56	962.3
	6/57	963.0
	4/59	963.54
	6/59	963.2
	9/59	963.2
	10/60	963.3
	7/63	963.5
	6/64	963.6
C1	7/67	10533.2
	12/80	10580.6
	2/83	10576.2
C6	2/83	9812.09
	2/86	9813.74

calibrated digital voltmeter (HP Model 3456A) is connected between the feedback and ground terminals to measure V_{out}. The procedure is to clean all connections using a source of dry gas (Aero Duster™, if available) and then connect the system as shown in figure 3-20. The capacitors and cables should be positioned where they will not be disturbed. The voltage source, K616, and DVM are then turned on and warmed up for the recommended times. The recommended K616 warmup time for critical measurements is two hours, and this is sufficient for the voltage calibrator and the DVM. The voltage source polarity switch is turned to "-" with the voltage range selected dependent on the relative values of the standard and unknown capacitors. The unknown capacitor is unshorted using the K616 "Zero Check" switch and the initial value for V_{out} is recorded. The voltage from the voltage source is then changed (ΔV) and the resulting value of V_{out} is recorded. The procedure is repeated as often as is necessary to determine that the measurements are reproducible.

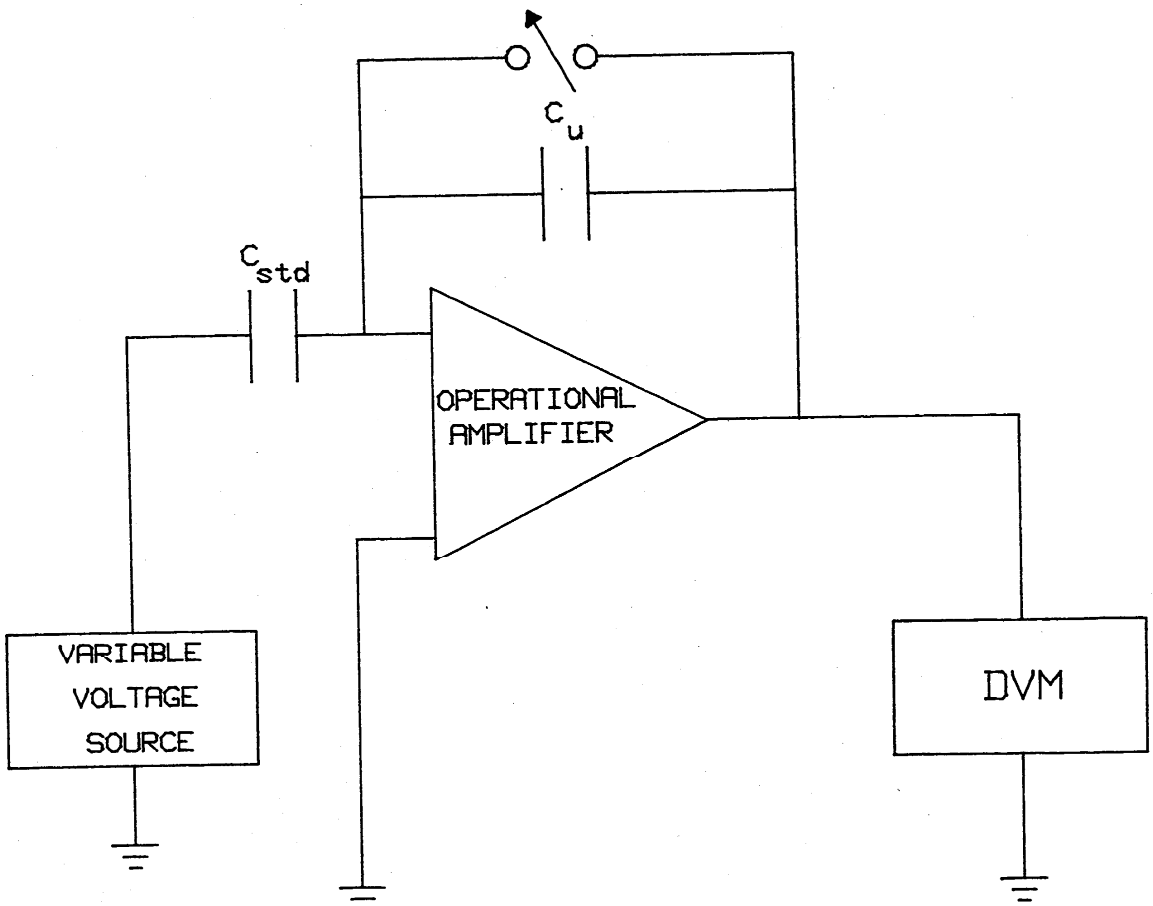


Fig. 3-20. Circuit used for Dosimetry Group calibrations of capacitors.

The charge introduced to the K616 is $\Delta Q = (C\ \Delta V)_{std}$. With a high-gain electrometer, essentially all of the charge is transferred to C_u so C_u can be computed as follows:

$$C_u = (C\ \Delta V)_{std}/\Delta V_{out}.$$

Some precautions to be observed in this procedure are: (a) the integrity of the system must be established, i.e. one must have confidence in the accuracy of the voltage standard and DVM; (b) excessively large potentials should not be used on the standard capacitor, and (c) V_{out} readings should be taken shortly after the voltage is changed on C_{std} but after transients have died away. The last precaution relates to the offset current in the electrometer which can cause V_{out} to change with time. The specifications for the K616 give the offset current as less than 5×10^{-14} A. Assuming that 5×10^{-14} A is the offset current and that C_u is approximately 1 nF, V_{out} will change by 1 mV every 20 seconds. If ΔV_{out} is 1 V, after 20 seconds the reading would be in error by ~0.1%.

3.8.2. Temperature indicator calibrations

A liquid-in-glass thermometer, marked Fishers 815553, was calibrated by the Temperature and Pressure Division in June of 1985 (Ref. Test No. 311-5-85, 6-17-85). The results of this calibration are shown in table 3-33.

Table 3-33. Liquid-in-glass thermometer calibration

Thermometer Reading	Correction (IPTS-68)*
21.000	-.031
23.000	-.111
25.000	-.031

*International temperature scale - 1968

In order to facilitate the temperature indicator calibrations, a calibrated liquid-in-glass thermometer was used to calibrate the Dosimetry Group's quartz crystal thermometer, HP Model 2801A. Attachment 11 is a copy of the liquid-in-glass thermometer calibration report. The results of the quartz crystal thermometer calibration are in DB 852:058. The resulting probe corrections were less than 0.05°C. The procedure for calibrating the individual temperature indicators was to place each indicator in a glass test tube which, in turn, was submerged in a gallon jug filled with circulating water, see figure 3-21. The temperature of the water was lowered by introducing cold water. The temperature of the water was raised by introducing hot water or by energizing a heater wire wrapped around the outside of the jug. A tube inserted into the jug and connected to a fish pump provided the necessary circulation. Since the jug was well insulated, a stable temperature could be achieved without undue waiting. The temperature of the water bath was varied from about 19°C to 26°C. The output data for each temperature probe (either voltage or temperature indication) were recorded, with multiple readings taken at each temperature. These data were then fitted using a least squares technique. The resulting equations are shown in table 3-34. The details appear in DB 852:060 to 077. It should be noted that the individual thermistors do not have any individual markings, and are identified only by their location.

3.8.3. Pressure indicator calibrations

An aneroid barometer, Wallace and Tierman, Model FA 139, Serial Number XX11242, NBS ID P-8020, was calibrated by the Temperature and Pressure Division in November 1985 (Ref. W.O. No. 536-7007, 11-04-85).

Calibrations of individual pressure indicators used at the various sources were made by placing the calibrated barometer alongside the instrument to be tested and connecting both to a variable pressure device. The pressure was varied from about 710 mmHg to about 780 mmHg. This range of pressures is somewhat larger than normally expected. Data was taken with increasing and with decreasing pressure, the comparisons being made directly or via voltage signals. The data were fitted by the method of least squares, and the results are shown in table 3-35.

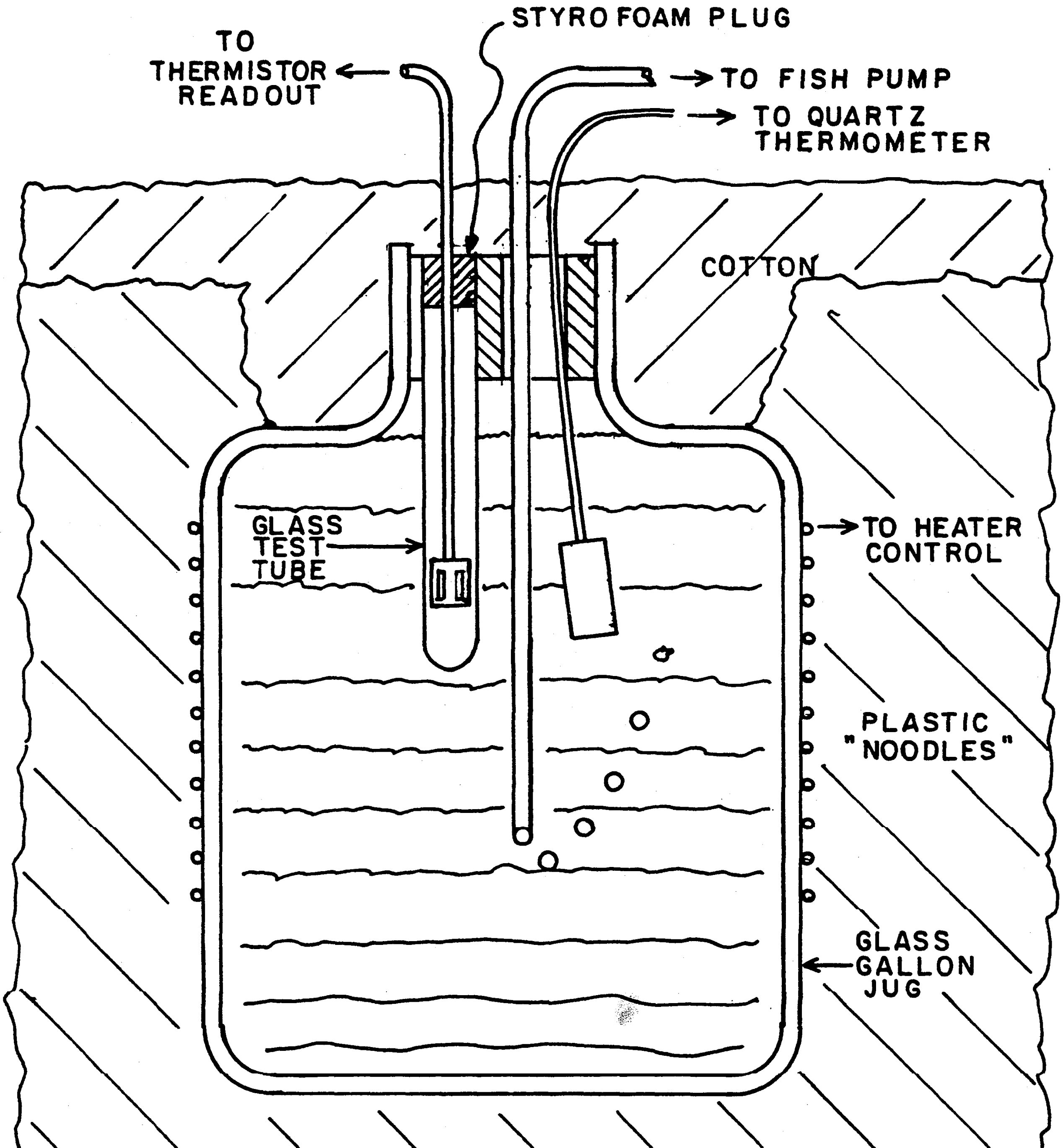


Fig. 3-21. Schematic of thermistor calibration setup.

Table 3-34. Summary of thermistor calibration equations

Thermistor Location	Calibration Equation	DB 852:page
B021A	t= -197.96 V +42.951	68-69
B015A	t= -91.871 V +29.6	70
B015B	t= -92.716 V +29.854	71
B021B	t= -197.45 V +42.815	72
B034*	t= -13.824 V -0.32232	73
B034**	t= -103.73 V +30.464	77
B036*	t= -13.767 V -0.31241	76
Wyckoff-Attix FAC	t= +96.628 V +30.562	60-61
300 kV, Position 1,2	t= +98.700 V +30.35	65-66
100 kV, Position 1,2	t= +96.947 V +29.855	63
Ritz FAC	t= +95.838 V +30.047	64
Lamperti FAC	t= +98.969 V +30.169	67

(V = signal in volts; t = temp in °C)

*Portable computer readout - Digitec Model 5810
**YSI readout in console

Table 3-35. Pressure indicator comparison summary

Pressure Indicator and Location	Equation	Reference
Setra MO 350A, SN 26718 on mobile computer	P=45.176 V + 600.13	DB 852:93-94
Rosemont MO 1332A10 SN 1688, B033	P=51.782 V + 557.52	DB 852:095
Wallace and Tiernan NBS 151998, B019	P=1.008 (Reading) - 6.18	
Wallace and Tiernan SN MM 14869, B033	P=1.008 (Reading) - 6.63	
Wallace and Tiernan NBS 157053, B036	P=1.007 (Reading) - 5.57	

4. Operating procedures

4.1. Administrative procedures

The recommended procedure for requesting an NBS calibration service is outlined in NBS SP 250. In practice, however, customers request calibration service in a variety of ways. Typically a new (first-time) customer will establish contact with the Dosimetry Group by telephone or letter, requesting information regarding techniques offered, charges, backlog time, turnaround time, and shipping/mailing information. At this stage, there is generally an opportunity to discuss with the prospective customer appropriate qualities of radiation for the type of service being requested, methods of shipment to reduce the risk of damage, alternate places to have instruments calibrated, etc. On occasion, contact is with a purchasing agent or buyer. Experience has shown that it is highly desirable to make a record of the name and telephone number of the person or persons requesting the service.

Other variations in calibration requests are:

(a) Purchase order with detailed description of calibration request, including beam quality codes, instrument model and serial numbers, name and telephone number of person to be contacted;

(b) Purchase order with little more than the company name and the statement "calibration required";

(c) Instrument arrives without a purchase order;

(d) Instrument arrives with purchase order fitting into category a, b, or e; and

(e) A letter, with or without sufficient information that can serve as a purchase order.

Regardless of the method used to request a calibration service, a full description of the service being requested should be obtained by whatever means possible.

Initial requests for thermoluminescent dosimeter (TLD) exposures can be more general in nature, since experience has shown that the details of the exposures requested accompany the dosimeters.

The customer's purchase order is then sent to the Office of Measurement Services, requesting a test folder. (At the time of writing, 1986 June, it is sent: OMS, Physics Building, Room B362, Attn: Vickie Weeden.) Each test folder has a unique number and is used as one of the identifiers on the calibration report. After a test folder is received from the Office of Measurement Services, a sequential number is assigned indicating the customer's place on the calibration inventory list.

Information from the purchase order and the test folder number are entered on a calibration inventory form (attachment 12). The calibration inventory list is updated periodically using the program "INV" and the HP9836 computer. Attachment 13 shows a typical calibration inventory list. TLD irradiations are not entered on this inventory.

When instruments arrive for calibration, they are unpacked and inspected for damage. Shipping damage is reported to the NBS Shipping Department. When an instrument arrives in a state of disrepair that is obvious by visual inspection, the customer is notified, and a decision is made whether to return the instrument to the customer, or if the repair is minor, have NBS personnel perform the repair. An index card is filled out, according to the type of instrument, condenser or current type (attachments 14 and 15), using information from the purchase order, or any other source. Each card is then assigned a Dosimetry Group number (DG No.) obtained from the binder marked "Calibration Log" kept in the Dosimetry Group Office. The index card is then filed in the drawer marked "For Test Station" located in room B033. The precalibration tests are described in section 3.7.

Requests for TLD exposure service are typically for periods of one year, and occasionally for a period of two years. The initial handling of the purchase order is the same as for instrument calibration. It has been found convenient to close these test folders approximately every three months. A copy of the original purchase order is then used to open a new test folder for the next three-month period continuing until the purchase order expiration data has been reached.

Most of the time in a calibration procedure is spent in the generation and review of the calibration report. The data-taking techniques used for calibrating instruments are described in sections 3.5 and 3.6. After the data have been taken and analyzed locally, they are transmitted to the NBS Cyber 855 computer via a telephone line or over the NBS NET. At present (June 1986), there are two different programs available for sending data from the laboratory computer to the NBS Cyber 855. One program is used for the data taken using the x-ray sets, and another for the gamma-ray data. Detailed instructions are contained in a binder marked "Computer Instructions for Data Transfer, Editing, and Report Generation" and located in room B033. A duplicate binder is kept with the portable HP9836 computer and another with the Digital Equipment Corporation terminal, Model VT220, located in room C207. Once the data has been transmitted to a file in the main computer, there exists the possibility to make corrections to the data file by using the computer's edit feature. Both of the laboratory computers, the HP9836 and the DEC 11/23, have editing features that make possible the editing of data prior to transmission to the NBS main computer. The computer program stored on the NBS Cyber 855 then generates data reduction and analysis pages (replacing the data books used in the past), calibration summary pages, and a final calibration report. The calibration summary pages, the data reduction and analysis pages, and the final report are printed out using the laser printer located in C29, building 245. Examples of each of these appear as attachments 16-19.

After a calibration report, summary pages, and associated data reduction and analysis pages have been generated, a series of reviews takes place. The data reduction and analysis pages are reviewed and checked for various indicators. For example: appropriate beam size for the chamber being calibrated; spelling of the customer's name and address; chamber and charger/reader name, model and serial number; ratio of the calculated x-ray tube potential and the stored value for the kV at that particular beam code; reproducibility of the data (see column 18 of the attachment); magnitude of the leakage currents; etc. Errors detected at this stage of review can be corrected by editing the data file and rerunning the calibration report program. Instructions for this procedure are contained in the binders marked "Computer Instructions for Data Transfer", etc. Secondly, the calibration summary pages are used to compare present results with previous results, with the customer's instrument when applicable, and always with the NBS check chamber calibrated at the same time as the customer's (as discussed in section 4.2.3). Finally, the report itself is reviewed, and any typographical errors corrected or necessary additions made to the calibration- or correction-factor tables to indicate switch positions or other items of note. The final version of a report contains no erased or retyped information. The reviewer initials the report, then brings it to the Dosimetry Group office for review by the group leader.

After the group leader has reviewed and initialed the report, it is sent to the Division Office for signature. Upon return, three copies are made. One copy plus the original is mailed to the customer and a notation made of the data sent and to whom in the "Calibration Log", one copy is filed in the "DG" file, and one copy goes into the test folder. At this time, if all the requested calibration work has been completed, fees are computed, the NBS Form 64 is filled out and three copies made of it. The original goes to Accounts, A800, Admin. Bldg., one copy goes to the Center Office, one copy goes in the DG file, and one copy goes into the test folder. The test folder is then signed and returned to the Office of Measurement Services.

TLD exposure calibration reports are generated in a different manner. The data are taken and entered in a data book (attachment 20 is a typical page). After review, the data are transferred to a TLD calibration report form (attachment 21) and a DG number is assigned. The secretary then types the appropriate information into the word processor and produces the final report. The report is reviewed for correctness, initialed, then sent for signatures and handled in the same manner as the instrument calibration reports.

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

The index cards are then filed in the "Completed Calibrations" file drawers located in B033, according to type of calibration.

4.2. Calibration of integrating-type instruments

4.2.1. Condenser chambers

4.2.1.1. General considerations

This type of instrument consists of a charger/reader and a variety of removable condenser probes. As mentioned in section 3.7.1, the only charger/reader sent to NBS for calibration is the Victoreen Model 570 R-meter along with appropriate condenser chambers (probes). The Victoreen condenser R-meter has been so widely used in radiation dosimetry for such a long period of time, that it merits a special description. A diagrammatic section through a Victoreen condenser chamber is given in figure 4-1. It consists of an ionization chamber with an air volume of a few cubic centimeters mounted at one end of a shielded stem containing a solid dielectric storage condenser.

Connection with the chamber is made through a contact at the other end of the stem, this being covered by a close-fitting cap when the chamber is in use. For charging the chamber, or reading its potential after irradiation, the cap is removed and the stem is plugged into a socket in the charger/reader. This charger/reader contains a quartz-fiber electrometer, which is observed through a low-power microscope having a scale calibrated directly in roentgens. The probes are of various volumes, allowing for a variety of total exposures ranging from 10 mR to 250 R full scale. The wall thickness varies according to probe model. The calibration techniques appropriate for each model are given in a folder marked "Calibration Technique", located in B033. For those models where the wall thickness is insufficient for the energy of the radiation requested, an equilibrium shell must be added.

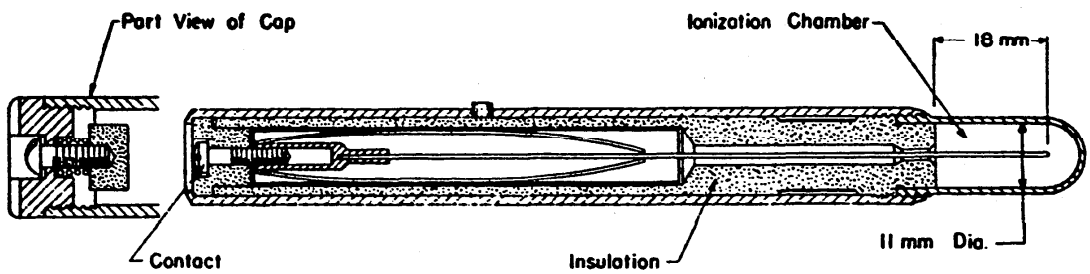


Fig. 4-1. Detailed construction of the 25-r Victoreen condenser ionization chamber.

4.2.1.2. X-ray calibrations

X-ray calibrations are performed using the substitution method: the standard is used to measure the exposure rate at a given point in space, then the instrument to be calibrated is placed at that point and exposed for a known period of time. The probe's response is normalized to 760 mmHg pressure and 22°C. The ratio of known exposure to the normalized response is a dimensionless number, the correction factor.

Prior to calibration, the chamber is first aligned in the x-ray beam. Generally this can be done while the x-ray set is warming up. A variety of holders are available, depending on the probe being calibrated. (In the drawer marked "Chamber Holder", south wall of B033 for 300 kV set; north wall cabinet in 100-kV set area.) The chamber is placed in a holder and the laser beam used to determine vertical and horizontal alignment. The cross-hair reticle of a telemicroscope is set to the defining plane of the appropriate free-air chamber prior to final alignment of the probe. For the Wyckoff-Attix (50- to 300-kV FAC), the defining plane is the white line on the aperture holder. For the Ritz chamber (20- to 100-kV FAC), the defining plane is exactly 15.00 mm (toward the FAC center) from the white line on the aperture holder. For the Lamperti chamber (10- to 20-kV FAC), the defining plane is exactly 20.00 mm (toward the FAC center) from the scribed line on the plastic insert that fits into the removable shield and touches the front face of the aperture. Adjustment of the chamber to the defining plane is accomplished by sighting through the telemicroscope (previously aligned on the defining plane) while using the motorized slide to adjust the chamber center or defining plane to the FAC plane. Control is accomplished using a control box located in the vicinity of each telemicroscope. Condenser-type probes are right cylinders, or have rounded-top cylindrical thimbles or thin end windows. For the first two types, the chamber reference plane is the mid-plane of the thimble. For the latter, the grooved line on the thimble is the reference plane. The thin-window chamber is calibrated with its axis parallel to the beam axis, while the other two types are calibrated with the chamber axes perpendicular to the beam axis.

A further consideration in x-ray calibration is choice of an appropriate beam size. For this purpose a parameter called the "useful beam size", is compared to the largest dimension of the active volume. The general practice is to use a "useful 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 since the chamber stem attenuates the radiation considerably. The "useful beam size" for the 100-kV x-ray calibration range is defined as twice the distance from the center of a radiograph of the beam to the point where the density of the film is 90 percent of the center density, minus the difference in distance between the 90 percent and the 50 percent density measurements. The "useful beam size" for the 300-kV x-ray calibration range is calculated from plots of normalized density readings of radiographs made at 78 cm and 220 cm from the x-ray tube target using apertures ranging from 0.94 cm to 2.54 cm diameter. A limit of 0.5 percent change in density from the density at the beam center appears to have been used as the limit for the "useful beam size." The data used for these calculation are contained in a black loose-leaf binder marked "Seifert + New 100-kV BOC's" and is kept in room B033.

Leakage measurements are taken prior to calibration. If the leakage is a significant fraction of the expected exposure reading, either the probe is cleaned with canned dry gas, rechecked and found to be corrected, or it is not calibrated. In addition, leakage measurements are made at the time of calibration. Again if, the leakage is found to be a significant fraction of the expected reading, the insulators are cleaned using canned dry gas. (The gas is cold due to expansion, so some time must be allowed for the chamber to equilibrate with room temperature.) If the cleaning procedure is not successful, the calibration is terminated.

4.2.1.3. Gamma-ray calibrations

The instruments to be calibrated using gamma-ray beams are of the same type as described in section 4.2.1.1, and are calibrated in essentially the same way as in the x-ray beams. The primary difference is that in the gamma-ray beams, an NBS standard is not used at the time of calibration. Instead, a previously determined value of the exposure rate is corrected for decay to the time of calibration. This procedure is described in section 3.4.

The source-to-chamber distance is set by sighting the telemicroscope on the appropriate scale distance. The standard scale-distance/collimator-beam settings in room B036 are given in table 4-1.

Table 4-1. Standard distance and collimator settings, room B036

Source	Scale Distance (cm)	Collimator (cm^2)
^{137}Cs	38	10 × 10
^{137}Cs	55	8 × 8
^{60}Co	105	6 × 6

All the horizontal sources in rooms B015A, B015B, B021A, and B021B allow scale distances from 35 cm to 300 cm, and have a fixed collimator size. The probe to be calibrated is adjusted to the beam center-line using the laser beam associated with each source. The chamber is then centered in the telemicroscope scale-reticle. An exception to this technique is when the probe is larger than 10 cm. The technique for set-up then involves measuring the probe in the direction of the beam using a metric calipers and determining the radius. The probe is then placed in the beam, aligned as above, and adjusted so that the end of the chamber is coincident with the telemicroscope cross-hairs. The scale distance, entered as SD in the computer program, becomes the scale distance of the cross-hairs plus the probe radius.

4.2.2. Cable-connected instruments

4.2.2.1. General considerations

This type of instrument consists of an electrometer-type readout connected by cable to the probe. Details of the theory of operation, measurement techniques, modes of operation, etc., are best described by the instruction manual for each model. If no manual is provided with the instrument, it is possible that a copy may be available in a Dosimetry Group file of manuals located in room B033. All units provide a collecting potential for the probe. The value of the collecting potential can be obtained from the instruction manual; good operating procedure dictates that this parameter be tested prior to calibrating the probe, preferably upon arrival of the instrument at NBS. If the potential is found to be outside specifications, it may require replacing the batteries (sometimes special types) or returning the instrument to the customer for repair.

4.2.2.2. X-ray calibrations

Alignment of these types of probes is the same as the condenser chambers. A limited variety of probe holders are on hand for this type of instrument. There are occasions when no specific chamber holder exists for a chamber to be calibrated; on these occasions, available holders must be adapted (or modified) accordingly. In all instances, care must be taken to reduce or eliminate scattering material from the beam. Details of the data-taking procedure appear in section 4.2.

The calibration procedure for this type of instrument is only slightly different from that for condenser-type. Having a direct readout makes it convenient to take into account any small leakage/background effects. The procedure used is to unground the reader for the same length of time to be used in the exposure measurements. One can then correct the final value by either adding or subtracting the "leakage". The reason this technique is used for this type of instrument, and not for the condenser-type, is that the readouts on the cable-connected type allow for a more precise reading (the electrometers of condenser-types are generally readable only to 1%).

4.2.2.3. Gamma-ray calibrations

This type of calibration is basically the same as for x-rays, and essentially no different from the gamma-ray calibration of condenser chambers.

4.3. Calibration of current-type instruments

Detailed description of current-type instruments and calibration techniques is given in section 3.5.

4.3.1. X-ray calibrations

Section 3.6 gives a description of the data-acquisition system, ionization current measuring systems, and x-ray-set operation. The setup techniques for these types of chambers is basically the same as for both of the integrating-type probes described above. The additional steps that need to be taken are as follows:

After mounting and aligning the chamber in the fixture and the chamber collecting potential has been turned on, either manually or under computer control (see section 3.6), a hand-held voltmeter is used to check the collecting voltage on the chamber itself. This insures that a connection has been made. Also with certain Triax-to-BNC adapters a short-circuit occurs if the triaxial portion of this adapter (at high voltage) is grounded. It is good practice to insulate this adapter and tape it in place so that motion of the carriage does not cause the cable to shift. It is also important to keep all connections out of the radiation beam, thereby reducing errors due to contributions from extra-cameral volumes.

4.3.2. Gamma-ray calibrations

Section 3.4 contains a general description of the gamma-ray sources and calibration techniques used for these types of instruments. The calibration techniques used for current-type instruments are basically the same as the techniques described above for the gamma-ray calibration of integrating type instruments. As with x-ray calibrations, it is necessary to check the chamber collecting potential at the chamber itself. Care should be taken in shielding the cable connections and preamplifiers from the beam and from scattered radiation. Errors of as much as 5% can be introduced, even in the scattered beam, if lead shielding is not employed.

4.4. In-house calibration checks

The long-term reliability of NBS dosimetry calibrations depends on the stability of the NBS exposure standards. For gamma rays, the NBS exposure standard is the mean response of six spherical graphite ionization chambers, which are periodically intercompared. For x-rays, the NBS exposure standard is the response of the appropriate free-air chamber; the three free-air chambers are also periodically intercompared. The in-house calibration checks are intended to check both the stability of the NBS standards and the reliability of the calibration procedures.

There are two ways to check the validity of a calibration. The first of these is to calibrate an NBS probe or chamber that is either the same as or similar to the customer's and on which NBS has a calibration history. There are two loose-leaf binders (identified as to instrument type) in Room B033 where such histories are kept.

The second check is examination of previous calibrations of the customer's instrument at the same beam quality. Any significant discrepancy, > 0.2% for current-type probes, > 1% for integrating-type instruments, is cause for investigation. Such discrepancies seem to occur approximately once per year out of about 130 routine calibrations, on the average. When there are several previous calibrations of the customer's instrument at any one beam quality, one can estimate the reproducibility and decide whether the current value is acceptable.

For the gamma-ray check chambers, a computer program provides the average value of the previous 10 calibrations and a comparison of that average value with the current value. If accepted by the operator this latest calibration becomes part of a new average of 10 calibrations, subsequently called the "previous 10". (The criteria for acceptance are generally the same as for customers' instruments: within 0.2% for current-type chambers and within 1% for integrating-type chambers.) At the end of each new set of 10 calibrations, the gamma-ray calibration program prints out the results, dates, model numbers, serial numbers, and source identification so that it may be placed in one of the above-mentioned binders.

For the x-ray check chambers, a record is maintained of all calibrations, and the previous three calibrations are compared with the current calibration to detect any trend or measurement discrepancy.

Any discrepancy arising with an NBS check chamber of the order mentioned above should, without exception, give 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, a recalibration is necessary.

The calibration check procedures outlined above carry the danger that a very slight drift in the calibration factor of a check chamber would not be detected, but would accumulate to a significant value over an extended time. In order to investigate this possibility, the entire calibration histories of three different chambers were analyzed for trends and outliers using linear regression. The results showed trends in the calibration factors of no more than 0.09% per year, with an average of 0.04% per year. Twice the standard deviation of the regression is used as a limit to define outliers. Table 4.2 summarizes the results, which are contained in a folder in Room B033. It appears to be worthwhile to expand these analyses to include all the data available and to update them periodically.

Table 4.2. Analysis of three NBS check chambers for the period Sep 1969 to Oct 1987.

Chamber	Shonka/Wyckoff		Exradin		Victoreen
Model No./Serial No.	3CM3,2.5MM/344		A2/134		415A/121
Beam Quality Code	^{60}Co	^{137}Cs	M100	M50	M50
Number of points	151	66	18	29	53
Overall trend (%/year)	0.04	0.04	-0.03	-0.09	0.01
Stand. dev. of trend (%)	0.00	0.01	0.06	0.01	0.02
Stand. dev. of regr. (%)	0.1	0.1	0.3	0.1	0.6
Number of outliers	4	2	1	2	1

4.5. Test of high-quality feedback electrometers

NBS provides a test service for high-quality feedback electrometers that are used in conjunction with current-type ionization chambers. The procedure involves electrically testing the electrometer at one feedback-capacitor position and computing a correction factor, K_Q. A typical report form is attachment 22. As a check on this electrical test, the customer's current-type chamber is calibrated for one beam quality with both the NBS system and with the customer's system. Agreement is usually within 0.2%.

4.6. Irradiation of thermoluminescent dosimeters

4.6.1. General considerations and procedures

Thermoluminescent dosimeters received at NBS for irradiation in terms of exposure have been the type used for personnel protection. Exposures requested have usually been in the 200 mR to 1000 mR range. Until 1985, all the exposures requested were for ^{137}Cs gamma rays. Recently there have been requests to provide exposures at x-ray energies ranging from 50 kV to 150 kV.

4.6.2. Exposure techniques

For both x- and γ-ray exposures, the dosimeters are mounted on a scatter-free frame at a distance such that the beam is uniform over the area of irradiation. Gamma-ray exposures are performed at a scale distance of 300 cm, where the useful beam size is 25.0 cm diameter. The exposure is obtained from the charts associated with each source, corrected for decay.

All irradiation details are recorded in a data book, see DB 828, pp. 177 for a typical record. After review of the results in the data book, the badge identification numbers, exposure levels, and date of irradiation are transferred to a TLD report form, from the desk in B033, along with a DG number obtained from the calibration log in the Dosimetry office. The secretary types the information into the skeleton form residing in the memory of the word processor. Upon completion of this step, the report is then checked for correctness, initialed by the person who performed or who supervised the irradiation. The report is then sent to the Group Leader for review and initialing, and to the Division Chief for signature. Upon return from the Division Chief, three copies are made. One copy plus the original is mailed to the customer (noting P.O. number on envelope), one copy is for the DG file, and one copy for the test folder.

5. Assessment of uncertainty

Uncertainty of dosimetry calibration and irradiation is assessed in several steps. First the uncertainty in the exposure rate of the x-ray and gamma-ray beams is estimated, next the uncertainty in instrument calibration or irradiation in each beam is estimated, and finally the exposure-rate uncertainty is combined with the calibration or irradiation uncertainty to obtain a final estimate.

The method of uncertainty assessment used here follows the recommendation of the Comité International des Poids et Mesures (CIPM). The uncertainty estimates are of two kinds: Conventional statistical estimates of random uncertainties are given as standard deviations of the mean, and for convenience 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 the extensive experience of the calibration staff. The Type B uncertainties are estimated so as to correspond approximately to a 67% confidence limit, i.e., they are estimated with the intent that there be about one chance in three that the "correct" value is outside the chosen limits; they are assumed to have roughly the character of standard deviations. The Type A and Type B estimates are combined according to the usual rule for combining standard deviations, i.e., by taking the square root of the sum of the squares, which is referred to here as the "quadratic sum". The quadratic sum of the two types of uncertainty is then considered to be the combined uncertainty, which is in turn multiplied by two to give an overall uncertainty. The overall uncertainty is considered to have the approximate significance of a 95% confidence limit.

Table 5-1 presents the details of the assessment of uncertainty in the exposure rates determined for x-ray beams by free-air ionization chambers, and as determined for gamma-ray beams by the set of spherical graphite cavity ionization chambers. Table 5-2 presents the details of the assessment of uncertainty in the calibration of current-type ionization chambers and condenser-type chambers used with their electrometers, and also in the irradiation of passive (thermoluminescent) dosimeters. All the entries in tables 5-1 and 5-2 are uncertainties of multiplicative factors, except for radiation background, which is a subtractive correction. Since the uncertainty for radiation background makes a negligible contribution to the final uncertainty, a separate computation is unnecessary.

Table 5-1. Uncertainty analysis for exposure rate.

	Gamma-ray beam		X-ray beam	
	A	B	A	B
Volume	0.06	0.05	0.04	0.01
Charge	0.03	0.1	0.03	0.1
Timing	0.04	0.1	0.04	0.1
Air density	0.01	0.08	0.01	0.08
Recombination loss, k_s		0.1		0.1
Humidity		0.1		0.1
Leakage		0.01		0.01
Radiation background		neg		0.01
Stopping-power ratio		0.25	NA	
Energy-absorption coefficient ratio		0.05	NA	
Stem scatter		0.05	NA	
Mean origin of electrons		0.1	NA	
Effective measurement point		0.05	NA	
Axial nonuniformity		0.02	NA	
Radial nonuniformity		0.01	NA	
Air attenuation, k_a	NA			0.07
Scattered photons, k_p	NA			0.07
Electron loss, k_e	NA			0.01
Electric field distortion	NA			0.2
Polarity difference	NA		0.03	0.1
Penetration of aperture	NA			0.04
Penetration of chamber face	NA			0.01
Quadratic sum	0.08	0.36	0.07	0.33
Combined uncertainty	0.37		0.34	
2 x combined uncertainty	0.74		0.68	
Overall uncertainty	0.7		0.7	

Notes to table 5-1.

The uncertainty estimates are in percent. The columns headed A and B refer to the estimates described in the text as Type A and Type B.

Charge includes uncertainties for both voltage and capacitance.

Air density includes uncertainties for both temperature and pressure.

Recombination loss refers to the uncertainty in correcting for loss of electrons by ion recombination.

Humidity refers to the uncertainty in correcting to dry air.

Radiation background refers to uncertainty in the extent to which the relatively large-volume free-air chambers might be sensitive to ambient radiation background. The much smaller volume cavity chambers are insensitive to radiation background in the NBS calibration laboratory, and the uncertainty is assumed negligible.

Table 5-2. Uncertainty analysis for calibration and irradiation.

	Current-type chambers		Condenser chambers		Irradiation	
	A	B	A	B	A	B
Exposure rate	0.08	0.36	0.08	0.36	0.08	0.36
Scale reading	NA		0.2	0.5	NA	
Charge	0.04	0.1	NA		NA	
Timing	0.04	0.1	0.04	0.1		0.1
Air density	0.01	0.08	0.01	0.08	NA	
Recombination loss		NA		NA	NA	
Humidity		0.05		0.05	NA	
Leakage		0.02		0.1	NA	
Radiation background		neg		neg	NA	
Distance	0.01		0.01			0.1
Radial nonuniformity	NA		NA			0.2
Quadratic sum	0.1	0.4	0.22	0.64	0.08	0.44
Combined uncertainty	0.41		0.68		0.45	
2 x combined uncertainty	0.82		1.36		0.9	
Overall uncertainty	0.8		1.5		1.0	

Notes to table 5-2.

The uncertainty estimates are in percent. The columns headed A and B refer to the estimates described in the text as Type A and Type B.

Exposure rate is from table 5-1.

Charge includes uncertainties for both voltage and capacitance.

Air density includes uncertainties for both temperature and pressure.

Recombination loss is not corrected for in a calibration so uncertainty is not applicable in this table. Recombination loss in the usually much higher exposure rate of the user's beam must be determined by the user.

Humidity refers to the uncertainty arising from the difference between the humidity at the time of calibration and at the time of use.

Radiation background and its uncertainty are assumed negligible, since the relatively small volume chambers being calibrated are insensitive to the ambient background in the NBS calibration laboratory.

Distance refers to uncertainty in setting the secondary instrument at the same distance as the primary standard that established the exposure rate. It does not refer to uncertainty in the magnitude of the source-detector distance.

Estimates of the uncertainty vary slightly for different radiation sources, beam qualities, measurement distances, methods of measurement, etc. A full presentation of all these variations would result in many tables, varying only slightly. In order to simplify the situation, the tables have been assembled by choosing the largest value for each alternative situation. Similarly, table 5-1 shows that the uncertainty in the exposure rate determined by the free-air chambers is slightly smaller than the uncertainty in the exposure rate as determined by the cavity chambers, so the latter uncertainty has been used as the first entry in table 5-2.

For all the entries in tables 5-1 and 5-2, the Type A component is much smaller than the Type B component, so much so that even if the Type A component were neglected, the combined and overall uncertainties would not be significantly changed. This arises from the complexity of the interaction of ionizing radiation with matter: it is never possible to account fully for the numerous second-order effects, but it is usual during exposure calibration at NBS to repeat measurements until the Type A component of the uncertainty is smaller than the Type B component. (The measurement of volume, table 5-1, is an exception, but this is not a routine measurement, and in any event both components are small.) As a result, it is not worthwhile examining in detail the random, Type A uncertainties, beyond noting that the number of degrees of freedom varies between 5 and 15, depending on whether the measurement is part of a particular calibration, or is carried out to evaluate some aspect of the measurement system.

Based on the assessment of uncertainties described here, the following rounded values of the overall uncertainties have been adopted:

exposure rate:	0.7%
calibration of cable-connected chambers:	1%
irradiation of passive dosimeters:	1%
calibration of condenser chambers:	1.5%

6. Safety Considerations

The main safety consideration is radiation protection. As described below, every effort is made to avoid any possibility of radiation exposure, even though it would be highly unlikely that serious exposures could occur accidentally. Another safety consideration is exposed high voltage, such as exists on ionization chambers during calibration. There is no danger of high voltage related to the x-ray generators since the equipment now in use has no exposed high voltage. To a much lesser degree, there is consideration for the safe use of low-wattage laser beams.

6.1. Radiation safety

6.1.1. X-ray calibration ranges

First and foremost, the two x-ray source ranges are designed to eliminate any possible exposure to x-radiation. The 100-kV x-ray tube is interlocked with its power supply in such a way that if the tube is moved from a safe position, i.e., away from a lead shutter, the high-voltage is turned off (or cannot be turned on). Some unavoidable leakage of radiation occurs between the shutter assembly and the x-ray tube window at an angle of 90° from the beam centerline. Prudence dictates that the x-ray set be turned off or a lead sheet be used to block the radiation while working in this particular area. The 300-kV x-ray tube is enclosed in a housing of 19 mm Pb and 6.4 mm steel. There is a 25-mm Pb safety shutter and a 12.7-mm timing shutter in front of the beam portal. At full power, 300 kV, 14 mA, radiation leakage is negligible. Both x-ray calibration ranges are protected by lead- lined doors that are interlocked in a fail-safe manner with the shutters. This means that the shutter or shutters cannot be opened if the door interlock is open; if the shutter is open and the closed doors are opened, the shutter or shutters close. Where no door exits, as in one area of the 300-kV x-ray range, a light beam is used for protection. In addition, a time-delay device inside the 300-keV x-ray range must be actuated upon leaving or the shutter cannot be opened. As a further indication of radiation danger, two red lights are turned on whenever the shutter or shutters are open. A flashing red light associated with the 300-kV x-ray set indicates high voltage is on the x-ray tube.

6.1.2. Gamma-ray calibration ranges

All doors giving access to the gamma-ray calibration ranges have interlocks as per Nuclear Regulatory Commission regulations. The vertical-beam rooms have a time-delay device inside the room that must be actuated before leaving the radiation area. In addition to this, a roped-off area exists at the entrance to B036 to discourage loitering in the vicinity, since the scattered radiation from the large ^{60}Co source is sufficient to be above acceptable levels for long-term exposure in the area outside the door. In addition to the above safety features, a radiation detector with indicator lights and an audible signal is in each gamma calibration range. At each entrance to a gamma-ray calibration range, a set of two red lights indicates a "beam on" condition.

All radiation areas in the building are marked with striped tape and film badges must be worn by all personnel.

6.2. High-voltage safety

The only danger that exists from high voltage has to do with the chambers that are being calibrated, 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.

6.3. Laser safety

The 0.5-mW lasers used for alignment purposes do not pose any serious danger to eyes. Nevertheless, appropriate warning signs are posted.

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International Standard 4037

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION•МЕЖДУНАРОДНАЯ ОРГАНИЗАЦИЯ ПО СТАНДАРТИЗАЦИИ•ORGANISATION INTERNATIONALE DE NORMALISATION

X and γ reference radiations for calibrating dosemeters and dose ratemeters and for determining their response as a function of photon energy

Rayonnements X et γ de référence pour l'étalonnage des dosimètres et débitmètres et pour la détermination de leur réponse en fonction de l'énergie des photons

First edition — 1979-05-15

Attachment 1, Section 1.2. ISO Publication 4037-1979 (E). (Excerpt)

UDC 535-34/-36 : 53.089.6 Ref. No. ISO 4037-1979 (E)

Descriptors : dosimeters, exposure flowmeters, calibrating, electromagnetic radiation, reference materials, test equipment, test results.

TABLE 2 – **Calibration conditions of filtered X reference radiations**

Series	**Mean energy** keV 1)	**Resolution** R_e %	**Constant potential** 2) kVcp	**Additional filtration** 3) mm			**1st HVL$_x$**	**2nd HVL$_x$**	**Homogeneity coefficient**
				Lead	**Tin**	**Copper**	mm of copper		
Narrow spectrum	33	30	40			0,21	0,09	0,12	0,75
	48	36	60			0,6	0,24	0,29	0,83
	65	31	80			2,0	0,59	0,64	0,93
	83	28	100			5,0	1,16	1,2	0,97
	100	27	120		1,0	5,0	1,73	1,74	0,99
	118	36	150		2,5		2,4	2,58	0,93
	161	32	200	1,0	3,0	2,0	3,9	4,29	0,91
	205	30	250	3,0	2,0		5,2	5,2	1,00
	248	34	300	5,0	3,0		6,2	–	–
Wide spectrum	45	48	60			0,3	0,18	0,26	0,69
	58	54	80			0,5	0,35	0,52	0,67
	79	57	110			2,0	0,94	1,16	0,81
	104	56	150		1,0		1,86	2,14	0,87
	134	58	200		2,0		3,11	3,53	0,88
	169	58	250		4,0		4,3	4,38	0,98
	202	58	300		6,5		5,0	–	–

NOTE – As a guide it is pointed out that, for a current of 10 mA and at 1m from the tube, the exposure rate range usually obtained is between $2{,}6 \times 10^{-4}$ C·kg^{-1}·h^{-1} (1 R·h^{-1}) and $2{,}6 \times 10^{-3}$ C·kg^{-1}·h^{-1} (10 R·h^{-1})4) for the narrow spectrum series, and between $2{,}6 \times 10^{-3}$ C·kg^{-1}·h^{-1} (10 R·h^{-1}) and $2{,}6 \times 10^{-2}$ C·kg^{-1}·h^{-1} (100 R·h^{-1})4) for the wide spectrum series.

Lower energy photons outside the main portion of the spectrum, whose shape is given in figures 2 to 17, amounting to less than 2 % of the main spectrum, are not shown.

1) The value of the mean energy adopted with a tolerance of ± 3 %, is taken from the results of a comparison of the spectra obtained in France, Germany and the United Kingdom (reference).

2) The constant potential is measured under load.

3) The total filtration includes, in each case, the fixed filtration adjusted to 4 mm of aluminium (see 3.1.3.3).

4) The actual value depends on the particular conditions of the installation.

Attachment 1, continued.

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Attachment 2, Section 1.2. IEC Publication 731, 1982. (Excerpt) add significantly to the filtration of the beam. The effect on the monitor chamber of back-scattered radiation from the reference chamber and from the chamber under test should be investigated; if this effect is significant, it can be reduced by introducing an additional diaphragm to shield the monitor chamber (this diaphragm should not limit the useful beam).

A monitor chamber is unnecessary if calibrations are carried out by simultaneous irradiation of the reference chamber and the chamber under test; it is also unnecessary in a gamma-ray beam.

Note. — It is good practice to place all the components just listed as close to the target as possible, consistent with the need for a narrow beam penumbra.

C4.8 *Additional shielding*

The effect on the reference chamber or on the chamber under test of scattered radiation:

- from the filter;
- from the front of the beam-limiting diaphragm, or
- from the X-ray tube housing

should be investigated. If this effect is significant, it should be reduced by suitable shielding.

C4.9 *Positioning of the equipment*

In order to reduce the uncertainty of comparison to ±0.2%, it is necessary to place the REFERENCE POINTS of the reference chamber and of the chamber under test at the same distance from the target to an accuracy of ±0.5 mm when calibrating at 50 cm from the target. It is sometimes convenient to have an easily removable and accurately replaceable means of providing a point on the axis of the useful beam close to the chambers, from which the chambers can be accurately positioned.

It should be possible to adjust and to hold the chambers rigidly; no part of the positioning device should be in the useful beam.

C5. **Radiation qualities**

C5.1 The radiation qualities used for calibration should be similar to those used in radiotherapy.

In order to achieve a range of such radiation qualities, a series of X-ray tube voltages may be chosen and the additional filtration adjusted until the half-value layer of the beam lies within one of the two areas bounded by the pairs of dashed lines in Figure C1, page 137.

Data for Figure C1 were supplied by three national laboratories, namely the National Bureau of Standards (USA), the National Physical Laboratory (United Kingdom) and the Physikalisch-Technische Bundesanstalt (Germany).

Aluminium filtration alone may be used for half-value layers up to about 4 mm Al (about 0.15 mm Cu) and copper filtration (with 1 mm Al filter after the copper filter) for higher half-value layers. Tin filtration may also be used for half-value layers above about 2 mm Cu, with about 0.25 mm Cu and 1 mm Al filters after the tin. Aluminium of 99.99% purity should be

Attachment 2, continued.

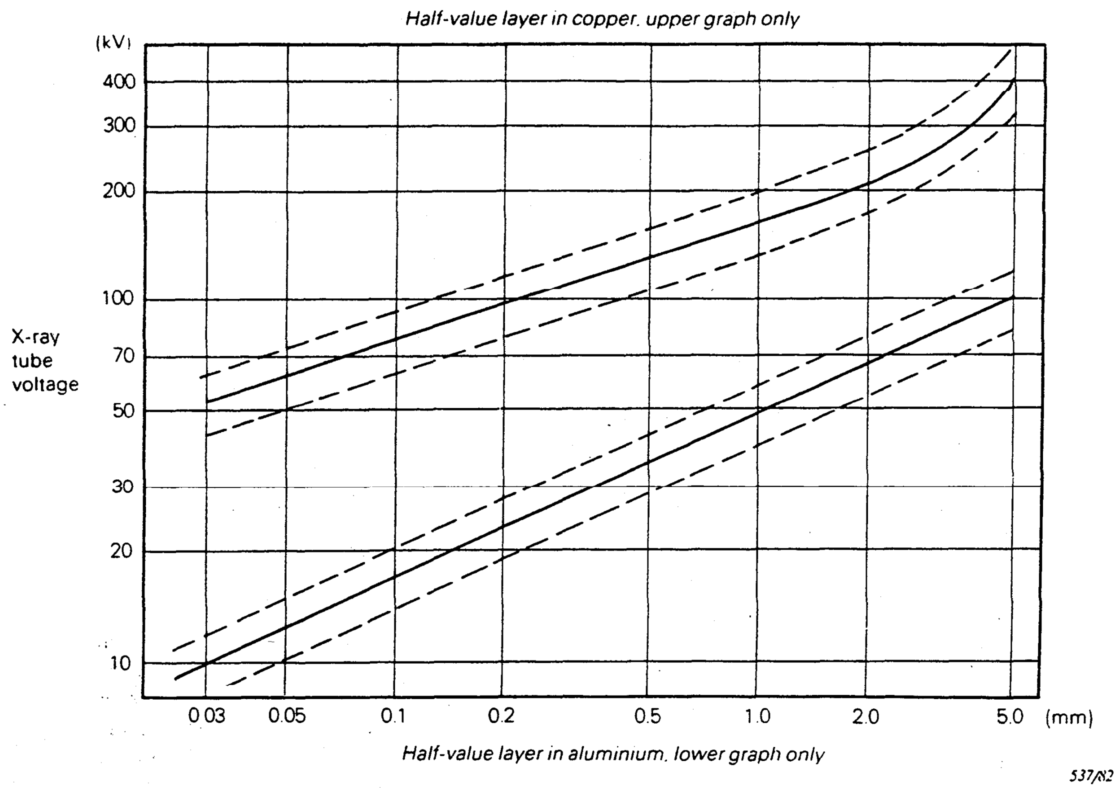


FIG. C1. — X-ray tube voltages (constant potential) and half-value layers of radiation qualities for calibrating exposure meters as used in radiotherapy. For dashed lines, see Sub-clause C5.1.

CONVENTIONAL CALIBRATION CONDITIONS FOR X- AND GAMMA-RAY MEASURING INSTRUMENTS

Lightly Filtered X Rays

Beam Code	Constant Potential (kV)	Distance (cm)	Added Filter[a] Al (mm)	Half-Value Layer Al (mm)	Homogeneity Coefficient 1st Al HVL/ 2nd Al HVL
L-B	10	25	0	.029	0.79
L-C	15	25	0	.050	0.74
L-D	20	50	0	.071	0.76
L-E[b]	20	50	0.5	.23	0.78
L-G	30	50	0.5	.36	0.64
L-I	50	50	1.0	1.02	0.66
L-K	75	50	1.5	1.86	0.63
L-M	100	50	2.0	2.78	0.59

Moderately Filtered X Rays

Beam Code	Constant Potential (kV)	Added Filter[c] Al (mm)	Added Filter[c] Cu (mm)	Half-Value Layer Al (mm)	Half-Value Layer Cu (mm)	Homogeneity Coefficient 1st Al HVL/ 2nd Al HVL
MFB	60	0	0	1.62		0.68
MFC[b]	60	2.50	0	2.79	0.090	0.79
MFE[b]	75	2.51	0	3.391		0.76
MFG	100	3.50	0	5.03	0.20	0.73
MFI	150	3.49	0.25	10.25	0.66	0.89
MFK	200	3.49	0.50	13.20	1.24	0.92
MFM[b]	250	3.50	1.01	15.80	2.23	0.92
MFO	250	3.47	3.20	18.30	3.25	0.98

Heavily Filtered X Rays

Beam Code	Constant Potential (kV)	Added Filter[c] Al (mm)	Added Filter[c] Cu (mm)	Added Filter[c] Sn (mm)	Added Filter[c] Pb (mm)	Half-Value Layer Al (mm)	Half-Value Layer Cu (mm)	Effective Energy (keV)
HFC	50	2.50	0	0	0.10	4.199	0.14	38
HFE[b]	100	2.50	0	0	0.50	11.20	0.74	70
HFG	150	2.50	4.00	1.51	0	16.96	2.45	117
HFI	200	2.47	0.60	4.16	0.77	19.60	4.09	167
HFK	250	2.50	0.60	1.04	2.72	21.55	5.25	210

GAMMA RAYS

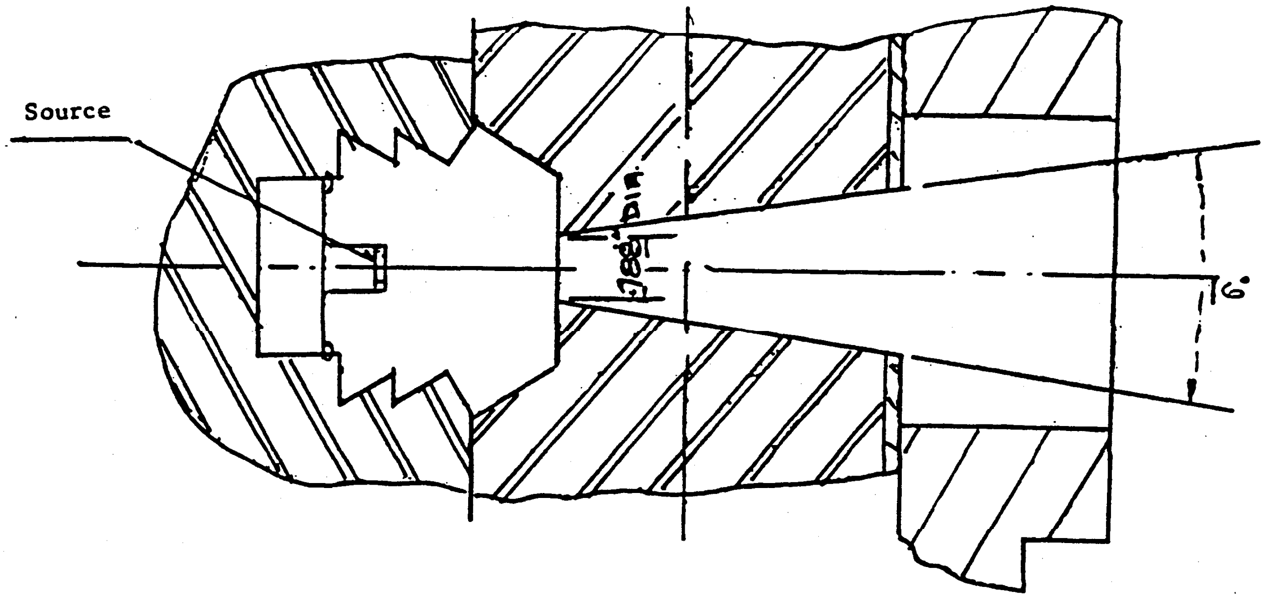
Radionuclide	Energy (keV)	Calculated Cu Half-Value Layer (mm)
^{137}Cs	662	10.8
^{60}Co	1250	14.9

[a]Inherent filtration approximately 1.0 mm Be.

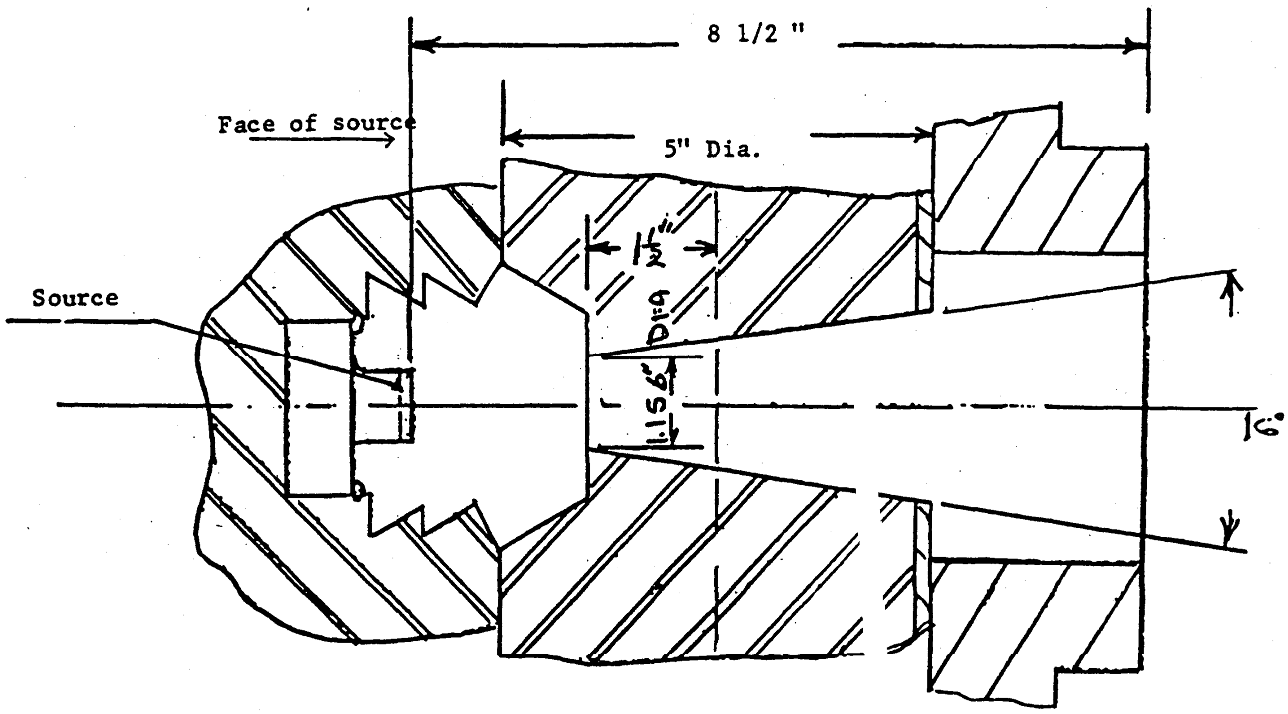
[b]Discontinued beam codes.

[c]Inherent filtration approximately 1.5 mm Al.

Attachment 3, Section 1.2. NBS beam codes used prior to 1986 for calibration of x-ray and gamma-ray measuring instruments.

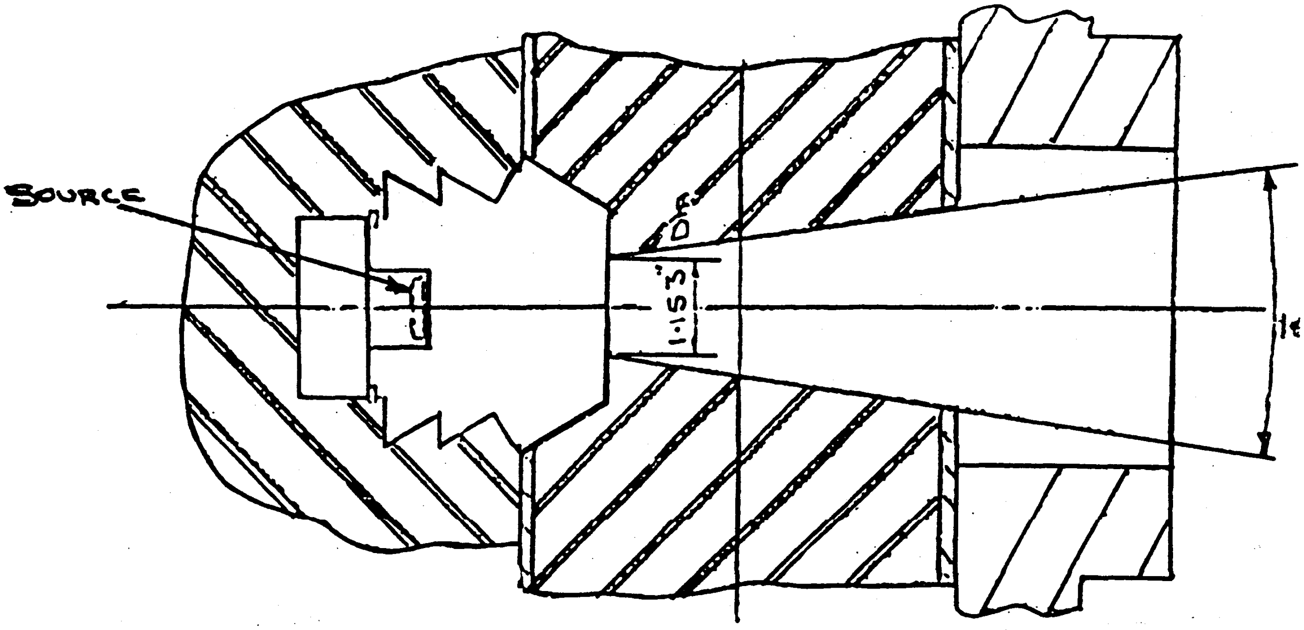


Port detail for 20 Ci Co60 source X 6mm diameter.

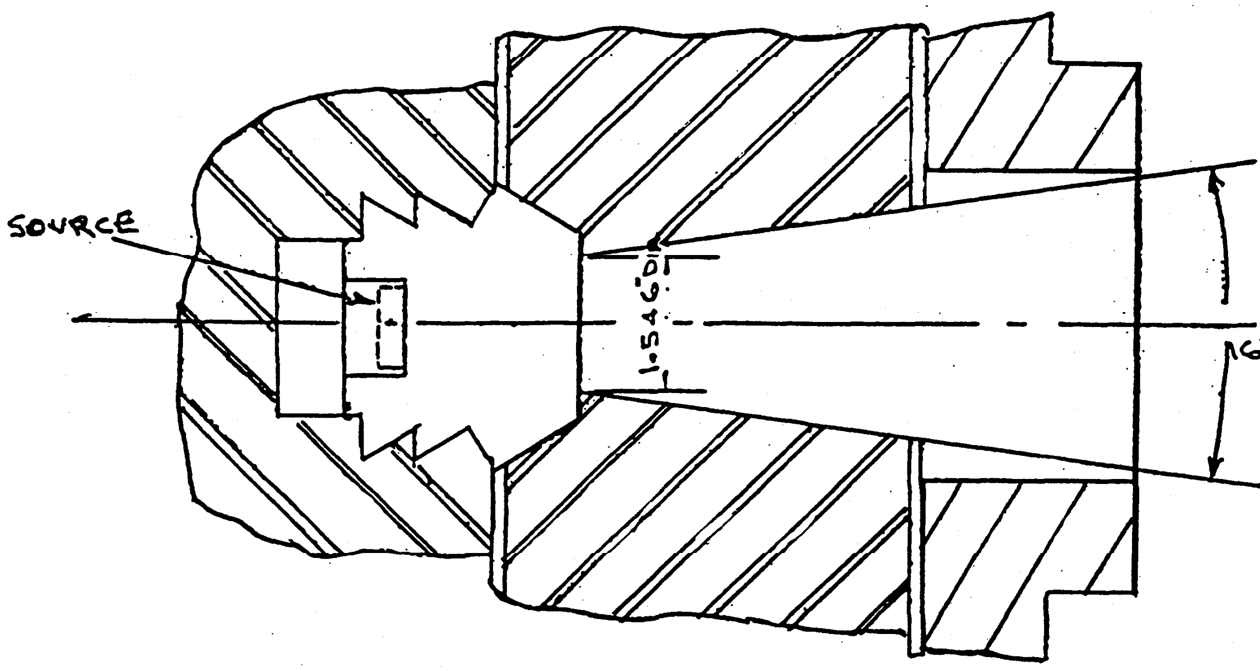


Port detail for 200 Ci Co60 source X 5mm diameter.

Attachment 4, Section 3.4.2. Sketch of horizontal 20-C and 200-Ci ^{60}Co sources.

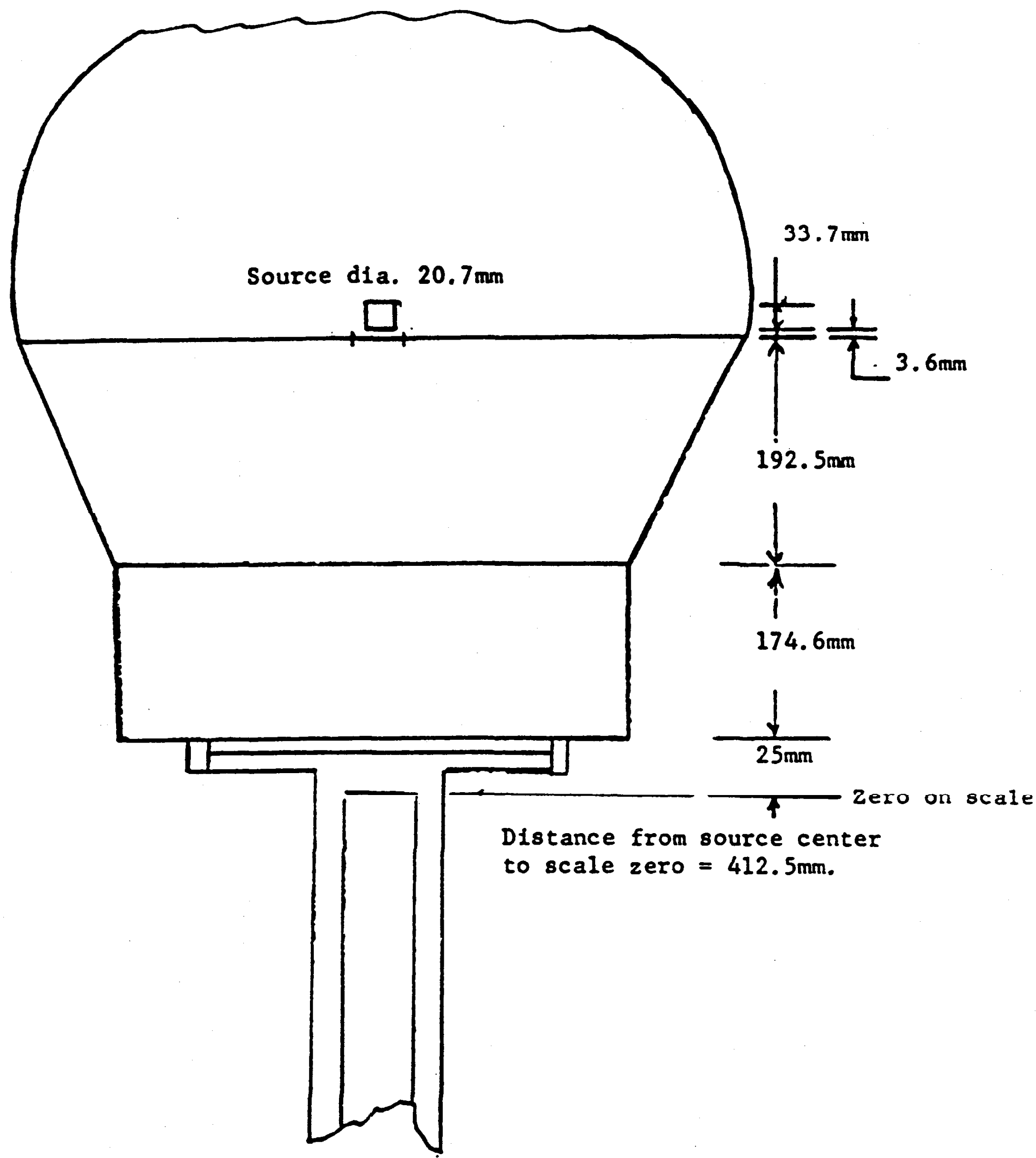


PORT DETAIL FOR 30 Ci Cs137 SOURCE X 15mm DIAMETER.



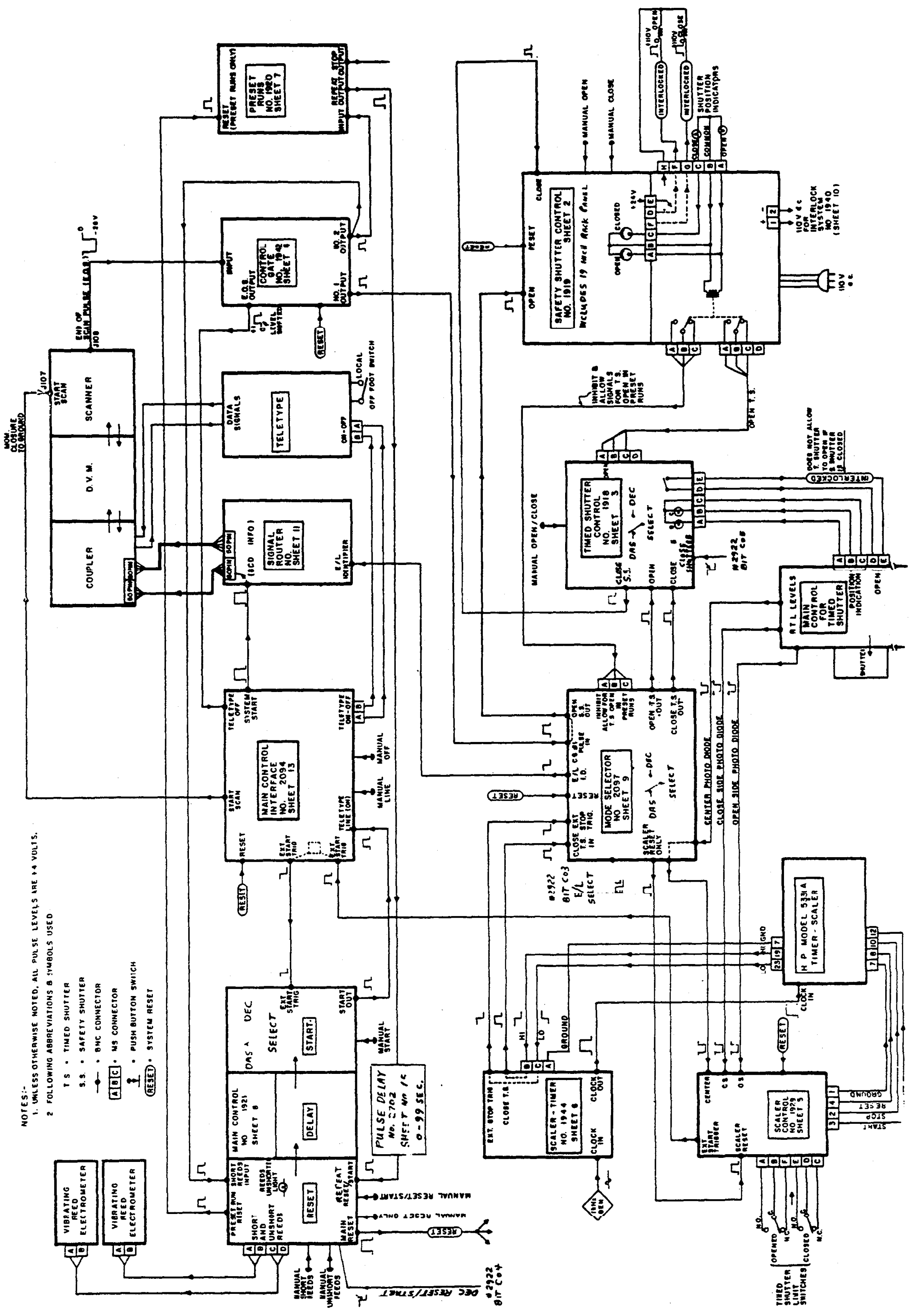
PORT DETAIL FOR 300 Ci Cs137 SOURCE X 25mm DIAMETER.

Attachment 5, Section 3.4.2. Sketch of horizontal 30-Ci and 300-Ci ^{137}Cs sources.



Sketch of 10kCi C060 THERATRON "F" (Super G) head.

Attachment 6, Section 3.4.2. Sketch of vertical 10-kCi ^{60}Co Theratron "F" (Super G) head.



Attachment 7, Section 3.6.1. Block diagram of data acquisition system (DAS).

150 KILOVOLT POWER SUPPLY
Universal Voltronics, Serial No. 2-6-1486

Submitted by

National Bureau of Standards
Division 243
Section 02

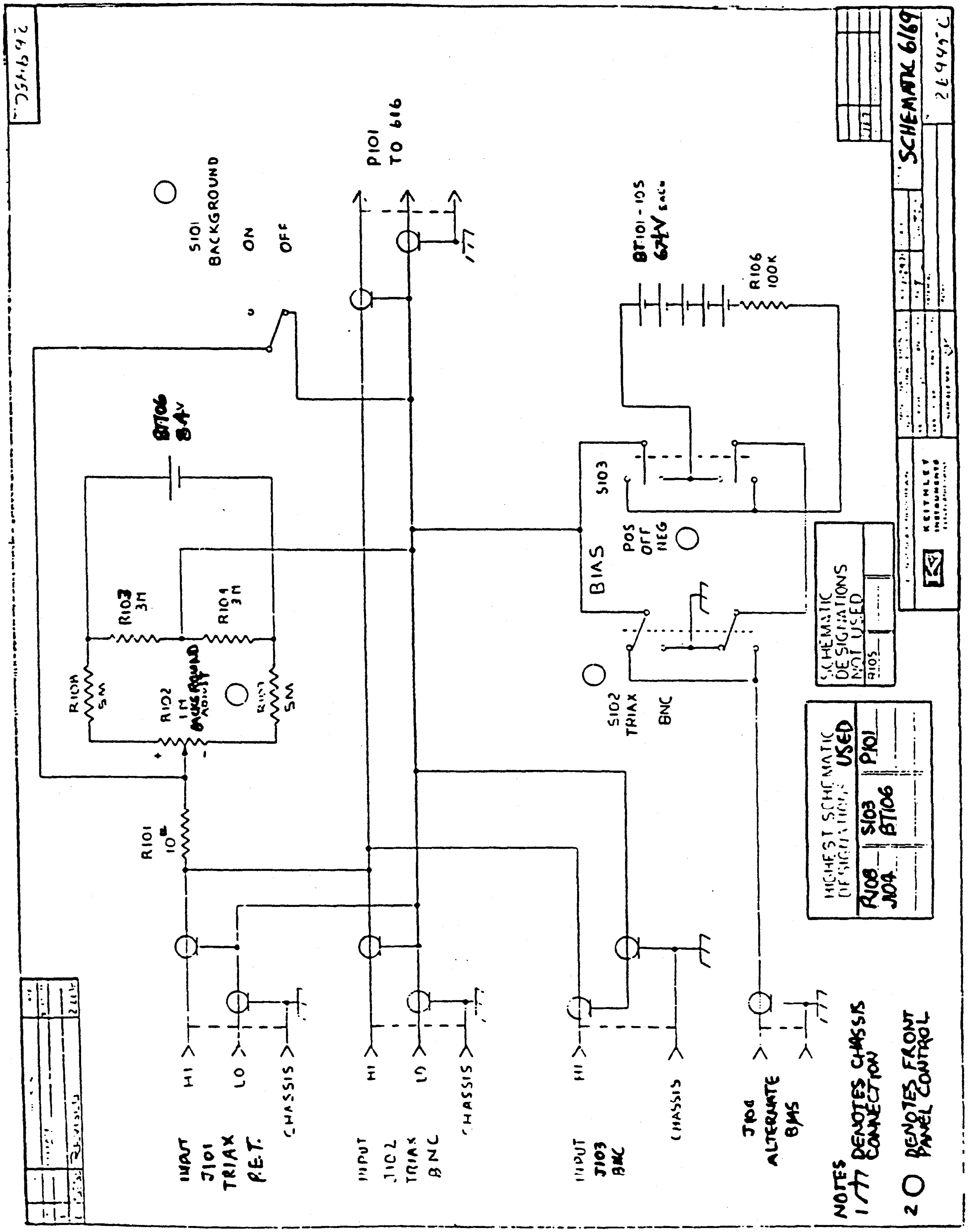
Voltage measurements on this unit were made in September 1972 and the following results obtained:

Console Setting (kilovolts)	Measured Voltage (kilovolts)
5	5.18
5.07	5.25
10.07	10.45
20	19.55
20.07	19.62
30	29.90
40	40.24
50	50.6
60	60.9
70	69.9
80	80.1
90	90.4
100	100.6
100	100.7

The results given above are estimated to be accurate to within ±0.1 percent of the quoted value or ±0.05kV, whichever is greater.

These accuracies refer to the values at the time of measurement and are not indications of long-term stability.

Attachment 8, Section 3.6.1. Universal Voltronics power supply calibration report.



Attachment 9, Section 3.7.3. Schematic drawing of Keithley 6169 chamber-electrometer interface.

PRECALIBRATION IONIZATION CHAMBER TEST DATA

Owner: ____________________

Date: 83 Oct 10 DB 841:137-138

Chamber type: PTW-DAL 1 Mod 7733 SN

MEASUREMENT SEQUENCE ABCD	A	Comments	B	Comments
Coll. Pot. (V)	+100		+50	Chamber has
Initial leakage (A)	+34 fA		-22 fA	been irradiated
Final leakage (A)	-3 fA	Pre-radiation	-16 fA	
Time between initial and final leakage (s)	700		100	
Magnitude of ionization current (A)	300 pA		300 pA	
Percent change in ion current from first to last meas. (%)	0.02		0.01	
Time between first and last ion. current measurement (s)	60		0	
Mean ion current (A)	316.55pA		316.62 pA	
Ratio of ion currents for full and half coll. pot.	0.9998			

MEASUREMENT SEQUENCE ABCD	C		D	
Coll. Pot. (V)	-50		-100	
Initial leakage (A)	-98 fA	Before irrad.	-	
Final leakage (A)	-30 fA	at -50V	-	
Time between initial and final leakage (s)	400		-	
Magnitude of ionization current (A)	300 pA		300 pA	
Percent change in ion current from first to last meas. (%)	0.44	Readings changing. Running out of time.	0.12	Changing. Ran out of time.
Time between first and last ion. current measurement (s)	690		210	
Mean ion current (A)	-		-	
Ratio of ion currents for full and half coll. pot.	(Negative collection potential data not required for calibration report.)			

Attachment 10, Section 3.7.6. Proposed precalibration test form.

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
NATIONAL MEASUREMENT LABORATORY
GAITHERSBURG, MD. 20899

R E P O R T   O F   C A L I B R A T I O N

LIQUID-IN-GLASS THERMOMETER

TESTED FOR: NATIONAL BUREAU OF STANDARDS
DIVISION 533.02
MARKED: FISHER 815553
RANGE: +19 TO +35 DEGREES C IN 0.02 DEGREE

THERMOMETER READING	CORRECTION (IPTS-68)**
21.000 C	-.031 C
23.000	-.111
25.000	-.031

**ALL TEMPERATURES IN THIS REPORT ARE BASED ON THE INTERNATIONAL PRACTICAL TEMPERATURE SCALE OF 1968, IPTS-68. THIS TEMPERATURE SCALE WAS ADOPTED BY THE INTERNATIONAL COMMITTEE OF WEIGHTS AND MEASURES AT ITS MEETING IN OCTOBER, 1968, AND IS DESCRIBED IN ''THE INTERNATIONAL PRACTICAL TEMPERATURE SCALE OF 1968 AMENDED EDITION OF 1975,'' METROLOGIA 12, NO. 1, 7-17 (1976).

ESTIMATED UNCERTAINTIES IN THE ABOVE CORRECTIONS DO NOT EXCEED 0.03 DEGREE UP TO 35 DEGREES C .

FOR A DISCUSSION OF ACCURACIES ATTAINABLE WITH SUCH THERMOMETERS SEE NATIONAL BUREAU OF STANDARDS MONOGRAPH 150, LIQUID-IN-GLASS THERMOMETRY.

IF NO SIGN IS GIVEN ON THE CORRECTION, THE TRUE TEMPERATURE IS HIGHER THAN THE INDICATED TEMPERATURE; IF THE SIGN GIVEN IS NEGATIVE, THE TRUE TEMPERATURE IS LOWER THAN THE INDICATED TEMPERATURE. TO USE THE CORRECTIONS PROPERLY, REFERENCE SHOULD BE MADE TO THE NOTES GIVEN BELOW.

THE TABULATED CORRECTIONS APPLY FOR THE CONDITION OF TOTAL IMMERSION OF THE BULB AND LIQUID COLUMN. IF THE THERMOMETER IS USED AT PARTIAL IMMERSION, APPLY AN EMERGENT STEM CORRECTION AS EXPLAINED IN THE ACCOMPANYING STEM CORRECTION SHEET.

NOT TESTED OVER THE ENTIRE RANGE OF SCALE NOR AT A SUFFICIENT NUMBER OF POINTS.

TEST NUMBER 311-5-85
COMPLETED 6-17-85

Attachment 11, Section 3.8.2. Liquid-in-glass thermometer calibration report.

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
WASHINGTON, D.C. 20234

CORRECTION FOR EMERGENT STEM

This stem correction sheet is designed to explain the process of computing the corrections for emergent stem, but has not been specifically adapted to the individual thermometer with which it is issued.

If a total-immersion thermometer is actually used with a part of the liquid column in the capillary emergent from the bath, a stem correction must be calculated and applied as explained below, making use of the formulas given.

The general formula used in computing the correction for emergent stem is:

$$\text{Stem correction}=k \times n(t_1-t),$$

where k=the differential expansion coefficient of mercury (or other liquid in the thermometer such as alcohol, toluene, pentane, etc.) in the particular kind of glass of which the thermometer is made; (for numerical values see below)

n=number of degrees emergent from the bath;

t_1=temperature of the bath;

t=mean temperature of the emergent stem.

EXAMPLE 1.—Suppose the observed reading was 84.76° C and the thermometer was immersed to the 20° mark on the scale, so that 65° of the column projected into the air, and the mean temperature of the emergent column was found to be 38° C, then—

Stem correction=0.00016×65 (85°—38°)=+0.49° C.

The true temperature is therefore the observed reading, 84.76° C, + tabular correction as interpolated from the report, + emergent stem correction (+0.49° C).

EXAMPLE 2.—Suppose the observed reading was 780° F and the thermometer was immersed to the 200° mark on the scale, so that 580° of the column projected into the air, and the mean temperature of the emergent column was found to be 170° F, then—

Stem correction=0.00009×580(780°—170°)=+32° F as a first approximation.

Since the result shows that the bath temperature was approximately 780° F+32° F, a second approximation should be made, using t_1=812° F instead of t_1=780° F. This gives—

Stem correction=0.00009×580(812°—170°)=+34° F.

The true temperature is therefore the observed reading, 780° F, + tabular correction as interpolated from the report, + emergent stem correction (+34° F).

It will be noted that if the average temperature of the stem is below that of the bulb, the sign of the correction will be +, while if the temperature of the stem is above that of the bulb, the sign of the correction will be —.

EXPLANATORY NOTES ON THE EMERGENT STEM CORRECTION

Some thermometers are pointed and graduated by the maker to read correct, or approximately correct, temperatures when the bulb and the entire liquid index in the stem are exposed to the temperature to be measured, while other thermometers are so pointed and graduated that they will read correct, or approximately correct, temperatures when the bulb and only a short length of the stem of the thermometer are immersed in the bath, the temperature of which is to be measured. Thermometers of the former class are known as "total-immersion thermometers," and those of the latter class as "partial-immersion thermometers."

Total-immersion thermometers are tested under the condition of total immersion and the corrections resulting from such a test will serve to reduce the observed readings of the thermometer to true temperatures only if the thermometer is *used* as a total-immersion thermometer. If such a thermometer is actually used as a partial-immersion thermometer, i.e., with a part of the mercury column emergent into the space above the bath, and with the emergent stem therefore either colder (or warmer) than the bulb, the thermometer will obviously read lower (or higher) than it would under the condition of total immersion. Hence, if a total-immersion thermometer is so used, a so-called stem correction must be applied to the observed reading in addition to the correction taken from the accompanying table of corrections. This stem correction is very large if the number of degrees emergent and the difference of temperature between the bath and the space above it are large. It may amount to more than 20° C (36° F) for measurements made with a mercury thermometer at 400° C (750° F)

The coefficient k is different for different kinds of glass and, even for the same kind of glass, it differs for different temperature intervals, i. e., different values of $(t_1 - t)$. Values for k for two widely used thermometric glasses for use in calculating stem corrections are tabulated as follows

VALUES OF k FOR MERCURY-IN-GLASS THERMOMETERS

For Celsius thermometers			For Fahrenheit thermometers		
Mean temp. $\frac{t_1+t}{2}$	k for "normal" glass	k for "borosilicate" glass	Mean temp. $\frac{t_1+t}{2}$	k for "normal" glass	k for "borosilicate" glass
0°	0.000158	0.000164	0°	0.000088	0.000091
100	158	164	200	88	91
150	158	165	300	88	92
200	159	167	400	89	93
250	161	170	500	90	95
300	164	174	600	92	97
350	---------	178	700	---------	.000100
400	---------	183	800	---------	103
450	---------	188			

If the kind of glass of which the thermometer is made is known, the value of k to be used in computing the stem correction may be taken from the above table. If the kind of glass is not known, use k=0.00016 for Celsius or 0.00009 for Fahrenheit thermometers. High-grade thermometers are now generally made of "normal" or "borosilicate" glasses. If a thermometer is graduated only to about 450° C (850° F), it may be made of either of the above glasses; if it is graduated to 500° C (932° F) and is actually usable at that temperature, it is made of one of the borosilicate glasses or a similar glass.

The expansions of liquids such as alcohol, toluene, etc., vary quite rapidly with the temperature, so that k varies considerably for different temperature intervals. An approximate stem correction for such thermometers may be calculated by taking k in the above equation = 0.001 for Celsius thermometers or 0.0006 for Fahrenheit thermometers.

The value of t, the mean temperature of the emergent stem, is the most difficult of the terms in the above formula to estimate. It may be quite accurately measured by the use of special capillary thermometers. This is, however, very rarely done except in the testing laboratory, and then only when the stem correction *must* be determined with considerable precision (to 10 percent or better). In general, the value of t may be determined to a sufficient approximation by judgment or preferably by suspending an auxiliary thermometer close beside the emergent stem, with the bulb of the auxiliary thermometer somewhat nearer to the top of the bath than to the liquid meniscus.

US COMM—DC 21044—P75

CALIBRATION INVENTORY FORM

OWNER'S NAME (31 characters)	SEQ NO	TFN	INST. RECEIVED
Newark AFS	631	G45168	YES / NO

CHAMBER NAME (31)	MODEL (15)	SN (15)	NO OF PTS X	NO OF PTS G
Exradin	A3	123	0	2
Exradin	A4	136	0	2

ELECTROMETER / READER (31)	MODEL (15)	SN (15)	CONTACT
			Steve Gargas 512-522-7416

****

OWNER'S NAME (31 characters)	SEQ NO	TFN	INST. RECEIVED
Kirtland AFB	632	G45196	YES / NO

CHAMBER NAME (31)	MODEL (15)	SN (15)	NO OF PTS X	NO OF PTS G
Victoreen	555-0.1HA	262	0	1

ELECTROMETER / READER (31)	MODEL (15)	SN (15)	CONTACT
Victoreen Radocon II	555	820	L. Townsend 505-844-9939

****

Attachment 12, Section 4.1. Calibration inventory form.

INVENTORY OF INSTRUMENTS FOR X RAY OR GAMMA RAY CALIBRATIONS
LAST EDIT 1986:07:24:10:23:28 BY PJL

```
                          SEQ NO  TST FLD  INST REC  TST STA  NOTIFY SEND  NOTIFY TO COME  INSTRUMENT    BACKLOG POINTS
                                                              FOR I        INST            TAKEN         X  0, 6  0
                            MODEL          SN                XPTS DONE  GPTS DONE  1180  DENE  TOM  BOB   OTT  MAILED

                          SEQ NO  TST FLD  INST REC  TST STA  NOTIFY SEND  NOTIFY TO COME  INSTRUMENT    BACKLOG POINTS
BARTLETT NUCLEAR           688    238671    YES               FOR I        INST            TAKEN         X  0, 6  0
                            MODEL          SN                XPTS DONE  GPTS DONE  1180  DENE  TOM  BOB   OTT  MAILED
   VICTOREEN .025R CHAMBER  188            13451              0    0     1    0      /     /    /    /     /     /
   VICTOREEN .25R    "      130            13498              0    0     1    0      /     /    /    /     /     /
   VICTOREEN 2.5R    "      552            13492              0    0     2    0      /     /    /    /     /     /
   VICTOREEN 25R     "      553            13406              0    0     2    0      /     /    /    /     /     /
   VICTOREEN 100R    "      621            13370              0    0     2    0      /     /    /    /     /     /
   VICTOREEN R-METER        570            3766            CONTACT  RALPH JACOBS 301 874 2693
                                                           CONTACT  RALPH JACOBS 617 746 6464
   VICTOREEN R-METER        570            1026            CONTACT  M DREWS 206 655 5015

                          SEQ NO  TST FLD  INST REC  TST STA  NOTIFY SEND  NOTIFY TO COME  INSTRUMENT    BACKLOG POINTS
MILL POWER CO              693    238786                      FOR I        INST            TAKEN         X  0, 6  8
                            MODEL          SN                XPTS DONE  GPTS DONE  1180  DENE  TOM  BOB   OTT  MAILED
                                                           CONTACT  AL BOLINGER 704 875 1971 X225

                          SEQ NO  TST FLD  INST REC  TST STA  NOTIFY SEND  NOTIFY TO COME  INSTRUMENT    BACKLOG POINTS
TU ELECTRIC                694    239173                      FOR I        INST            TAKEN         X  0, 6  8
                            MODEL          SN                XPTS DONE  GPTS DONE  1180  DENE  TOM  BOB   OTT  MAILED
   CAPINTEC CHAMBER         PM-500         CII52.1914         0    0     1    0      /     /    /    /     /     /
   CAPINTEC CHAMBER         PR-06C         CII.61657          0    0     1    0      /     /    /    /     /     /
   CAPINTEC CHAMBER         PM-30          CII30.5838         0    0     1    0      /     /    /    /     /     /

                          SEQ NO  TST FLD  INST REC  TST STA  NOTIFY SEND  NOTIFY TO COME  INSTRUMENT    BACKLOG POINTS
NAVAL SURFACE WEAPONS CTR  698    CNTRCT    YES      DONE     FOR I        INST            TAKEN         X  0, 6 11
                            MODEL          SN                XPTS DONE  GPTS DONE  1180  DENE  TOM  BOB   OTT  MAILED
   VICTOREEN 1R CHAMBER     227            12787              0    0     1    0      /     /    /    /     /     /
   VICTOREEN 25R CHAMBER    70-5           51                 0    0     1    0      /     /    /    /     /     /
   VICTOREEN .25R CHAMBER   130            59                 0    0     1    0      /     /    /    /     /     /
   VICTOREEN R-METER        570            3838            CONTACT  DANIEL SAM 394 1566

                          SEQ NO  TST FLD  INST REC  TST STA  NOTIFY SEND  NOTIFY TO COME  INSTRUMENT    BACKLOG POINTS
EG&G IDAHO                 699    239390    YES      DONE     FOR I        INST            TAKEN         X  0, 6 14
                            MODEL          SN                XPTS DONE  GPTS DONE  1180  DENE  TOM  BOB   OTT  MAILED
   MQA TEST                                                   0    0     0    0      /     /    /    /     /     /
                                                           CONTACT  DR CARLSON FTS 583 2143

                          SEQ NO  TST FLD  INST REC  TST STA  NOTIFY SEND  NOTIFY TO COME  INSTRUMENT    BACKLOG POINTS
UNIVERSITY OF WISCONSIN    706    239527                      FOR I        INST            TAKEN         X  0, 6 14
                            MODEL          SN                XPTS DONE  GPTS DONE  1180  DENE  TOM  BOB   OTT  MAILED
   EXRADIN CHAMBER          A2             149                0    0     0    0      /     /    /    /     /     /
                                                           CONTACT  STEVE GOETSCH 608 262 2170
```

Attachment 13, Section 4.1. Typical inventory of instruments for x-ray or gamma-ray calibrations, 1986 July 24. (Excerpt)

1986:07:24:10:23:28PJL

	SEQ NO.	BACKLOG X-RAY POINTS	BACKLOG GAMMA POINTS
		0	0
BALTIMORE GAS & ELECTRIC	710	0	16
BARTLETT NUCLEAR	688	0	0
EG&G IDAHO	699	0	14
KODAK	713	0	21
MILL POWER CO	693	0	8
NAVAL SURFACE WEAPONS CTR	698	0	11
POINT BEACH	712	0	20
PRINCETON UNIVERSITY	709	0	14
TU ELECTRIC	694	0	8
UNIVERSITY OF WISCONSIN	706	0	14
WISCONSIN ELECTRIC	711	0	18

NUMBER OWNERS 12
BACKLOG X-RAY POINTS 1
BACKLOG GAMMA POINTS 22
TOTAL NUMBER POINTS BACKLOGED 23

Attachment 13, continued.

PRIORITY 382	U S DEPARTMENT OF COMMERCE National Bureau of Standards R-METER AND SIMILAR UNITS	MAKE Victoreen	MODEL 570	SERIAL NO. 3675
OWNER Naval Surface Weapons Lab		RECEIVED 1986 JUL 10	REPORT NO. 8524/86	REPORT DATE
ADDRESS Silver Spring, Md 20910		TEST FOLDER Contract	CONTACT: Daniel Sam TEL. NO: 394-1561	

DATE	7/11/86	7/14/86	
DB REF	JJL	ELB	
v-0	523.2	522.2	
v-20	473.3	472.1	
v-40	423.0	422.2	
v-50	398.2	396.9	
v-60	373.0	371.7	
v-80	323.3	321.9	
v-100	273.5	271.9	
v0-v100	249.7	250.3	

COMMENTS:

SWITCH		SWITCH	
ID	SETTING	ID	SETTING

CHAMBERS	RANGE	250 R						
	MODEL	154						
	SERIAL NO.	95						
CS137	CORRECTION FACTOR	x1.099						
	BEAM DIAMETER (CM)	6.4						
	EQUILIBRIUM SHELL	Added						
	ROOM	B036						
CO60	CORRECTION FACTOR							
	BEAM DIAMETER (CM)							
	EQUILIBRIUM SHELL							
	ROOM							

NBS-199 (Rev. 3-84) USCOMM-NBS-DC

RANGE	MODEL	S/N	L-10	L-15	L-20	L-30	L-40	L-50	L-80	L-100	M-20	M-30	M-40	M-50	M-80	M-100	M-150	M-200	M-250	M-300	H-10	H-15	H-20	H-30	H-40	H-50	H-80	H-100	H-150	H-200	H-300	S-60	S-75	Comments:

Attachment 14, Section 4.1. Condenser-type instrument record (Side 1 and 2 of card).

Make	Model	Serial Number	Owner, City, State, and ZIP Code	Priority No
Exradin	A4	136	Department of the Air Force Newark AFS	631

Previously calibrated: ☑ Yes ☐ No

Test Folder Number	Date Received	Report Number	Report Date
G45168	1986 JUN 04	DS 8552/86	

Chamber Information

Wall collecting potential and polarity: −500

Stem orient. to beam: ☑ perpen. ☐ parallel

Identifying mark toward source: white line

Comments:

Readout Information

Make	Model	Serial Number

Switch Name	Switch Setting
Range	
Mode	
Sensitivity	
Input	
Background	
DVM Range	

K_0 DB REF:

For information, please contact:

Name	Telephone Number

NBS-200
(Rev. 3-84)

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards

GUARDED-FIELD IONIZATION CHAMBER RECORD

BQC	CALIBRATION FACTOR R/C	BQC	CALIBRATION FACTOR R/C
L-10		H-60	
L-15		H-100	
L-20		H-150	
L-30		H-200	
L-40		H-250	
L-50		H-300	
L-80		S-60	
L-100		S-75	
M-20			
M-30		CS137	
M-40			
M-50		CO60	
M-60			
M-100			
M-150			
M-200			
M-300			
H-10			
H-15			
H-20			
H-30			
H-40			
H-50			

PRE-CALIBRATION TEST RESULTS

1. Initial leakage, femto amps: 7.2
2. Guard-to-central - electrode leakage: Not done
3. Equilibration time, T = T(rad. on) - T(.999 V-final): < 1 min
4. Current for current ratios: 291.15
5. ☑ Open ☐ Sealed
6. Full V/Half V (neg) (pos): 1.001 Neg V/Pos V (full) (half V)

Attachment 15, Section 4.1. Current-type instrument record (Side 1 and 2 of card).

NBS 533. CALIBRATION SUMMARY

CHAMBER NAME: 0.250 R CHAMBER MODEL: 130 SERIAL NUMBER: 3464
ELECTROMETER: VICTOREEN R-METER MODEL: 570 SERIAL NUMBER: 2990
TIME: 15:50:23
OWNER: DG 8770/87 CR DATE: 1987 NOV 10
RECEIVED: 1987 OCT 14

STEM PERPENDICULAR TO BEAM. THE 0.25 RNUMBER FACED THE SOURCE OF RADIATION.
PREVIOUS CALIB: YES
CHAMBER OPEN TO ATMOSPHERE WHEN TESTED

1 BEAM QUALITY CODE	2 BEAM SIZE (CM)	3 CALIB DIST (CM)	4 EXPOSURE RATE (R/S)	5 LEAKAGE (R/S)	6 (%)	7 EXPOSED READING (%) FS	8 CORR FACTOR	9 TUBE POT (KV)	10 CORR FACTOR RATIO	11 AL HVL (MM)
137CS	62.3	300.0	2.0E-03	.000E+00	.00	50.0	* 1.032		1.0149	
60CO	37.9	195.0	9.4E-04	.000E+00	.00	50.0	* 1.017		1.0000	

BQC	REF.	CR	PAGES	3 LAST PREVIOUS FACTORS	RESPECTIVE DATES	AND % FULLSCALE
137CS	1	1	2			
60CO	5	5	6			

CHAMBER DATA IN CDATA:	MODEL	RANGE(R)	L CH DIM(CM)	CT TO STEM(CM)	STEM LENGTH(CM)	OD(CM)	EST LTR(%)
	130	.250	12.50	6.00	13.60	5.09	.00

ALL ZEROS USUALLY MEANS NO DATA FOR THAT POINT.
C.F. PREFIX INDICATES IF CHAMBER WALL WAS INCREASED AND POTENTIAL USED ON WALL IN RESPECT TO C. ELECTRODE:
(NO INCREASE,+-) (* INCREASED,+-) (+ NO INCREASE,+) (P INCREASED,+) (- NO INCREASE,-) (N INCREASED,-)

COMMENTS: CR CHECKED BY

Attachment 16, Section 4.1. Calibration summary page (typical).

GROUP NO. 2

DATA REDUCTION AND ANALYSIS TABLE

CR PAGE 2

SET UP CODE 282142 BQC L100 KVCP 100 — NBS 120KV FAC — CR DATE 1986 JUL 02
DIAPHRAGM .500 INCHES OR 1.270 CM — TIME 09:22:45
DISTANCE 50.000 CM

MONITOR CHAMBER ELECTROMETER -MOD/SN K616/188889
EXTERNAL INTERNAL CAP.
197975.000 + .000 = 197975.000(PF)

FAC CHAMBER ELECTROMETER -MOD/SN K616/189980
EXTERNAL INTERNAL CAP.
1050.600 + 0. = 1050.600(PF)

MEASUREMENT DATE 1986 JUN 11

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
OIL	RATIO		EXPOSURE		*		MONITOR CHAMBER				*		120KV FAC CHAMBER				*	TIME
TEMP DEG C	KV/ TECH	I/ FIRST	TIME (S)	PRESSURE (MM HG)	DELTA V(V)	TEMP DEG C	PR CF 0,760	FBM CF OR SEC	I/ FIRST	HV/ -425.0	DELTA V(V)	TEMP DEG C	PT CF 0,760	FBM CF OR SEC	I/ FIRST	HV/ 5000	C16/10	OF DAY
LEAKAGE																		
.00	.9999	1.0000	60.000	745.5	.000	21.71	1.1005	1.0000	1.0000	.9444	.00105	22.41	1.1031	1.0000K	1.0000	-1.0255	1.0000	16.15
.00	.9998	1.0000	60.000	745.5	.000	21.63	1.1002	1.0000	.7070	.9444	.00067	22.41	1.1031	1.0000K	.6349	-1.0254	.8981	16.18
EXPOSURE																		
.00	.9990	1.0000	60.089	745.4	10.370	21.58	1.1001	1.0000	1.0000	.9444	45.86	22.40	1.1031	1.0000K	1.0000	-1.0254	1.0000	16.20
.00	.9991	1.0001	60.087	745.4	10.371	21.52	1.0999	1.0000	.9998	.9443	45.87	22.40	1.1031	1.0000K	1.0002	-1.0255	1.0004	16.22
.00	.9991	1.0001	60.088	745.4	10.377	21.62	1.1003	1.0000	1.0008	.9444	45.90	22.39	1.1031	1.0000K	1.0009	-1.0253	1.0001	16.24
.00	.9991	1.0003	60.091	745.4	10.380	21.54	1.1000	1.0000	1.0008	.9443	45.92	22.38	1.1031	1.0000K	1.0011	-1.0253	1.0004	16.26
.00	.9991	1.0003	60.093	745.4	10.381	21.54	1.1001	1.0000	1.0009	.9444	45.93	22.37	1.1031	1.0000K	1.0013	-1.0253	1.0004	16.28
.00	.9991	1.0003	60.092	745.3	10.379	21.55	1.1001	1.0000	1.0008	.9443	45.92	22.36	1.1031	1.0000K	1.0011	-1.0256	1.0003	16.30

MON XI = 3.7607E+04 PA % SD = .05 TUBE I = 7.916 — FAC XI = 8.8527E+02PA % SD = .054
MON LI = 8.6776E-01PA, % SD = 24.28, M LI % = .00 — FAC LI = 1.6563E-02PA % SD = 31.582 F LI % = .00
NET ABS I = 3.7606E+04PA — NET ABS I = 8.8526E+02PA

ROWS USED FOR XI AVERAGE 3, 4, 5, 6, 7, 8, N = 6
ROWS USED FOR LI AVERAGE 1, 2, N = 2
DVM CK +1 VOLT = .999678 ; DVM+1,ROW 1 2 3 4 5 6 7 8
DVM CK 0 VOLT = .000003
DVM CK -1 VOLT = -.999817 ; DVM-1,ROW 1 2 3 4 5 6 7 8

PR 746.20 RH 52. ENTERED AT 16:34 **** PR INDEXED AND CALC. 745.34 EXCEEDS 0.3 MMHG, LN= 8 ****
RATIO FAC I / MON I =.23540E-01

Attachment 17, Section 4.1. Data reduction and analysis page (typical).

U. S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

GAITHERSBURG, MD 20899

REPORT OF CALIBRATION

EXRADIN CHAMBER

MODEL A4 SERIAL NUMBER 136

MANUFACTURED BY EXRADIN INC.
LOCKPORT, IL 60441

SUBMITTED BY

RECEIVED AT NBS ON 1987 OCT 05

THE CALIBRATION FACTORS GIVEN IN THIS REPORT ARE QUOTIENTS OF THE X- OR GAMMA-RAY EXPOSURE AND THE CHARGE GENERATED BY THAT RADIATION IN THE IONIZATION CHAMBER. THE AVERAGE CHARGE USED TO COMPUTE THE CALIBRATION FACTOR IS BASED ON MEASUREMENTS WITH THE WALL OF THE IONIZATION CHAMBER AT THE STATED POLARITY AND POTENTIAL. LEAKAGE CORRECTIONS WERE APPLIED IF NECESSARY. IF THE CHAMBER WAS OPEN TO THE ATMOSPHERE THE 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. THE NORMALIZING FACTOR F IS COMPUTED FROM THE FOLLOWING EXPRESSION:

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

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)

THE EXPOSURE RATE AT THE CALIBRATION POSITION WAS MEASURED BY A FREE-AIR IONIZATION CHAMBER FOR X RADIATION, AND BY GRAPHITE CAVITY IONIZATION CHAMBERS FOR COBALT-60 AND CESIUM-137 GAMMA RADIATION. THE GAMMA-RAY EXPOSURE RATES WERE CORRECTED TO THE DATE OF CALIBRATION, FROM PREVIOUSLY MEASURED VALUES, BY DECAY CORRECTIONS BASED ON HALF-LIVES OF 5.27 AND 30.0 YEARS, FOR COBALT-60 AND CESIUM-137 RESPECTIVELY.

Attachment 18, Section 4.1. Cable-connected chamber Report of Calibration.

THE OVERALL UNCERTAINTIES OF THE CALIBRATION DESCRIBED IN THIS REPORT IS 1%, OF WHICH 0.7% IS ASSIGNED TO THE UNCERTAINTY IN THE EXPOSURE RATE OF THE NBS BEAM. THE OVERALL UNCERTAINTY WAS FORMED BY TAKING TWO TIMES THE QUADRATIC SUM 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.

THE CALIBRATION FACTOR IS GIVEN TO FOUR DIGITS TO PREVENT ROUNDING ERRORS UP TO 0.5 PERCENT WHEN THE FIRST DIGIT IS UNITY.

INFORMATION ON TECHNICAL ASPECTS OF THIS REPORT MAY BE OBTAINED FROM P. J. LAMPERTI, RADIATION PHYSICS C214, NATIONAL BUREAU OF STANDARDS, GAITHERSBURG, MD 20899, (301) 975-5591.

REPORT REVIEWED BY

REPORT APPROVED BY R. LOEVINGER

FOR THE DIRECTOR
BY

DAVID M. GILLIAM, DEPUTY CHIEF
IONIZING RADIATION DIVISION
CENTER FOR RADIATION RESEARCH
NATIONAL MEASUREMENT LABORATORY

Attachment 18, continued.

NATIONAL BUREAU OF STANDARDS REPORT OF CALIBRATION

DEPARTMENT OF THE AIR FORCE
NEWARK AFS, OH 43055

****
* SEE NOTE BELOW ON *
* EXPOSURE RATES *
****

EXRADIN CHAMBER
MODEL A4 SERIAL NUMBER 136
OPEN TO THE ATMOSPHERE WHEN TESTED
WALL POTENTIAL WAS -500 VOLTS WITH RESPECT TO INNER ELECTRODE

BEAM CODE	HALF-VALUE LAYER AL (MM)	CU (MM)	CALIBRATION FACTOR 22 DEG C AND 1 ATM	DIST (M)	BEAM SIZE (MM)	EXP RATE (R/S)
137CS		10.8	*1.235E+08 R/C	1.95	C406	4.8E-03
60CO		14.9	*1.219E+08 R/C	1.50	C293	1.6E-03

DURING CALIBRATION THE CAVITY WAS POSITIONED IN THE CENTER OF THE BEAM WITH THE STEM PERPENDICULAR TO THE BEAM DIRECTION. THE WHITE LINE FACED THE SOURCE OF RADIATION.

9.E-15 AMPERES WAS THE LEAKAGE CURRENT MEASURED BEFORE CALIBRATION.

1.002 WAS THE RATIO OF THE CURRENT MEASURED FOR FULL COLLECTION POTENTIAL TO THE CURRENT FOR HALF COLLECTION POTENTIAL FOR A CURRENT OF 2.5E-10 AMPERES. A DETAILED SATURATION STUDY WAS NOT CARRIED OUT AND NO CORRECTION FOR LACK OF SATURATION WAS APPLIED TO THE DATA.

* THE CHAMBER WALL THICKNESS WAS INCREASED FOR THIS BEAM QUALITY BY ADDITION OF THE SHELL SUPPLIED WITH THE CHAMBER.

NOTE: ON 1986 JAN 01 THE EXPOSURE RATES OF NBS EXPOSURE STANDARDS WERE ADJUSTED. DETAILS ARE GIVEN AT THE END OF THE REPORT.

CHECKED BY

Attachment 18, continued.

EXPLANATION OF CHAMBER CALIBRATION TABLE

THE BEAM CODE IDENTIFIES IMPORTANT BEAM PARAMETERS. FOR X RADIATION THE LETTERS L, M, H, AND S STAND FOR LIGHT, MODERATE, HEAVY, AND SPECIAL FILTRATION, RESPECTIVELY, AND THE NUMBER FOLLOWING THE LETTER IS THE CONSTANT POTENTIAL ACROSS THE X-RAY TUBE. FOR GAMMA RADIATION THE BEAM CODE IDENTIFIES THE RADIONUCLIDE.

THE HALF-VALUE LAYERS IN ALUMINUM AND IN COPPER HAVE BEEN DETERMINED BY A FREE-AIR CHAMBER FOR X RADIATION. THE CU HVLS FOR 60CO AND 137CS ARE CALCULATED. THE CALIBRATION FACTORS OR CORRECTION FACTORS ARE LISTED IN ORDER OF INCREASING AL HVL.

THE CALIBRATION FACTOR OR CORRECTION FACTOR IS DEFINED ON THE FIRST PAGE OF THIS REPORT. IF THE CHAMBER WAS OPEN TO THE ATMOSPHERE, THE FACTOR HAS BEEN NORMALIZED TO THE TEMPERATURE AND PRESSURE SHOWN AT THE TOP OF THE COLUMN. WHEN THE ENTRY IS A CALIBRATION FACTOR, IT IS IN SPECIAL UNITS (ROENTGENS PER COULOMB). WHEN THE ENTRY IS A CORRECTION FACTOR, IT IS DIMENSIONLESS. IF THE CORRECTION FACTOR IS FOLLOWED BY A NUMBER, THE NUMBER GIVES THE APPROXIMATE PERCENT OF FULL-SCALE ELECTROMETER READING AT WHICH THE CALIBRATION WAS PERFORMED.

THE DISTANCE SHOWN IS THAT BETWEEN THE RADIATION SOURCE AND THE DETECTOR CENTER OR THE REFERENCE LINE. FOR THIN-WINDOW CHAMBERS WITH NO REFERENCE LINE, THE WINDOW SURFACE IS THE PLANE OF REFERENCE.

THE BEAM SIZE IS THE PERPENDICULAR DISTANCE FROM THE CENTER LINE OF THE CALIBRATION BEAM TO THE 50 PERCENT INTENSITY LINE. FOR CIRCULAR FIELDS THE LETTER C PRECEDES THE DIMENSION. FOR SQUARE FIELDS THE LETTER S PRECEDES THE DIMENSION, AND THE CHAMBER AXIS IS PERPENDICULAR TO A SIDE OF THE SQUARE. IF NO LETTER PRECEDES THE DIMENSION, A SPECIAL FIELD WAS USED AND ITS DIMENSIONS ARE GIVEN IN A NOTE AT THE BOTTOM OF THE TABLE.

THE EXPOSURE RATE AT WHICH THE CALIBRATION WAS PERFORMED IS GIVEN IN THE LAST COLUMN. IF THE CHAMBER IS USED TO MEASURE AN EXPOSURE RATE THAT IS SIGNIFICANTLY DIFFERENT FROM THAT USED FOR THE CALIBRATION IT MAY BE NECESSARY TO CORRECT FOR RECOMBINATION LOSS.

THE EFFECTIVE ENERGY IS GIVEN ON THE NEXT PAGE OF THIS REPORT FOR THOSE BEAMS FOR WHICH IT IS BELIEVED TO BE A MEANINGFUL CHARACTERIZATION OF THE BEAM QUALITY. FOR GAMMA RADIATION THE EFFECTIVE ENERGY IS THE PHOTON ENERGY.

FOR X RADIATION THE EFFECTIVE ENERGY IS COMPUTED FROM GOOD-GEOMETRY COPPER ATTENUATION DATA. THE INITIAL SLOPE OF THE ATTENUATION CURVE IS USED TO DETERMINE AN ATTENUATION COEFFICIENT, AND THE PHOTON ENERGY ASSOCIATED WITH THIS COEFFICIENT IS THE "EFFECTIVE ENERGY".
THE ENERGY VS ATTENUATION-COEFFICIENT DATA USED FOR THIS PURPOSE ARE TAKEN FROM J. H. HUBBELL, INT. J. APPL. RADIAT. ISOT. 33, 1269 (1982). FOR BEAM CODES H50 TO H300, THE EFFECTIVE ENERGY IS WELL REPRESENTED BY (EFFECTIVE ENERGY) = 0.861V - 6.1, WHERE V IS THE CONSTANT POTENTIAL IN KILOVOLTS.

Attachment 18, continued.

CONVENTIONAL CALIBRATION CONDITIONS FOR X- AND-GAMMA RAY MEASURING INSTRUMENTS

BEAM CODE	ADDED FILTER AL (MM)	ADDED FILTER CU (MM)	ADDED FILTER SN (MM)	ADDED FILTER PB (MM)	HALF-VALUE LAYER AL (MM)	HALF-VALUE LAYER CU (MM)	HOMOGENEITY COEFFICIENT AL	HOMOGENEITY COEFFICIENT CU	EFFECT. ENERGY (KEV)	DIS-TANCE (CM)	EXPOSURE RATE MIN. (MR/S)	EXPOSURE RATE MAX. (R/S)
L10	0				0.029		79			25	0.001	1.7
L15	0				0.050		74			25	0.001	4.2
L20	0				0.071		76			50	0.001	3.3
L30	0.265				0.22		60			50	0.001	0.4
L40	0.50				0.49		57			50	0.001	0.4
L50	0.639				0.75		58			50	0.001	0.4
L80	1.284				1.83		58			50	0.001	0.4
L100	1.978				2.8		59			50	0.001	0.4
M20	0.230				0.152		79			50	0.001	0.5
M30	0.50				0.36		64			50	0.001	0.3
M40	0.786				0.73		66			50	0.001	0.4
M50	1.021				1.02	0.032	66	62		50	0.001	0.4
M60	1.51				1.68	0.052	68	64			0.8	0.2
M100	5.0				5.0	0.20	72	55			1.0	0.3
M150	5.0	0.25			10.2	0.67	87	62			1.0	0.4
M200	4.1	1.12			14.9	1.69	95	69			1.0	0.3
M250	5.0	3.2			18.5	3.2	98	86			1.0	0.2
M300	4.0		6.5		22	5.3	100	97			0.5	0.08
H10	0.105				0.148		89			25	0.001	0.003
H15	0.500				0.152		87			25	0.001	0.003
H20	1.021				0.36		88			50	0.001	0.003
H30	4.13				1.23	0.038	93	94		50	0.001	0.003
H40	4.05	0.26			2.9	0.093	94	95		50	0.001	0.003
H50	4.0			0.10	4.2	0.142	92	90	38		0.3	0.065
H60	4.0	0.61			6.0	0.24	94	89	46		0.02	0.005
H100	4.0	5.2			13.5	1.14	100	94	80		0.005	0.002
H150	4.0	4.0	1.51		17.0	2.5	100	95	120		0.03	0.010
H200	4.0	0.60	4.16	0.77	19.8	4.1	100	99	166		0.02	0.006
H250	4.0	0.60	1.04	2.72	22	5.2	100	98	211		0.03	0.005
H300	4.1		3.0	5.0	23	6.2	99	98	252		0.04	0.003
S75	1.504				1.86		63			50	0.001	0.4
S60	4.0				2.8	0.089	75	70			0.3	0.06
137CS						10.8			662		1.5	0.1
60CO						14.9			1250		1.5	2.5

FOR THE X-RAY BEAM CODES, THE LETTER INDICATES LIGHT, MODERATE, HEAVY, AND SPECIAL FILTRATION, AND THE NUMBER IS THE CONSTANT POTENTIAL IN KILOVOLTS.

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.

THE HALF-VALUE LAYERS FOR 137CS AND 60CO ARE CALCULATED.
THE HOMOGENEITY COEFFICIENT IS TAKEN AS 100(1ST HVL/2ND HVL).

Attachment 18, continued.

ATTACHMENT CONCERNING ADJUSTMENT OF NBS EXPOSURE RATES.

EXPOSURE RATES WERE ADJUSTED AT NBS ON 1986 JAN 01 TO TAKE INTO ACCOUNT RECENT REFINEMENTS IN SOME OF THE PHYSICAL PARAMETERS. EXPOSURE RATES IN ALL REPORTS ISSUED AFTER 1986 JAN 01 ARE LOWER THAN THE EXPOSURE RATES IN REPORTS ISSUED BEFORE THAT DATE. THE CHANGES ARE AS FOLLOWS:

NBS PRIMARY STANDARD:	CAVITY CHAMBERS			FREE-AIR CHAMBERS
RADIATION:	60CO	137CS	192IR	125I AND X RAYS
HUMIDITY	-0.3	-0.3	-0.3	-0.2
ENERGY-ABSORP. COEF. RATIO	-0.1	0.0	0.0	N.A.
STOPPING-POWER RATIO	-0.7	-0.5	-0.4	N.A.
TOTAL CHANGE	-1.1	-0.8	-0.7	-0.2

LABORATORIES WITH INSTRUMENTS CALIBRATED PRIOR TO 1986 JAN 01 CAN BRING THEIR INSTRUMENTS INTO AGREEMENT WITH THE NEW EXPOSURE RATES BY REDUCING THE EARLIER CALIBRATION FACTORS BY THE ABOVE TOTAL CHANGES IN PERCENT.

HUMIDITY. BEFORE 1986 NO CORRECTION WAS MADE FOR THE EFFECT OF WATER VAPOR IN THE AIR, SINCE EARLY NBS WORK HAD INDICATED A NEGLIGIBLE EFFECT. MORE RECENT WORK AT SEVERAL NATIONAL LABORATORIES HAS DETERMINED THIS EFFECT WITH GOOD ACCURACY. THE VALUES USED ARE TAKEN FROM ICRU REPORT 31, PAGE 31, FIGURE 5.14. THESE FACTORS ARE APPLIED TO THE EXPOSURE RATE DETERMINED BY THE NBS PRIMARY STANDARD. NO CORRECTION IS MADE FOR THE EFFECT OF WATER VAPOR ON THE INSTRUMENT BEING CALIBRATED, SINCE 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.

ENERGY-ABSORPTION COEFFICIENT RATIO. THE MOST RECENT VALUES (J.H. HUBBELL, RAD. RES. 70, 58, 1977, AND INT. J. APPL. RADIAT. ISOT. 33, 1269, 1982) WERE COMPARED WITH EARLIER VALUES USED IN ESTABLISHING NBS EXPOSURE STANDARDS (J.H. HUBBELL, NAT. STAND. REF. DATA SER. 29, NAT. BUR. STAND. (U.S.), 1969). ONLY ONE APPRECIABLE CHANGE WAS FOUND.

STOPPING-POWER RATIO. THE MOST RECENT VALUES (ICRU REPORT 37, 1984) WERE COMPARED WITH THE EARLIER VALUES USED IN ESTABLISHING NBS EXPOSURE STANDARDS (M.J. BERGER AND S.M. SELTZER, NASA SP-3012, 1964). THE COMPARISONS FOR 60CO GAMMA RADIATION WAS MADE BY THE STAFF OF THE BUREAU INTERNATIONAL DES POIDS ET MESURES, AND CONFIRMED AT NBS. THE COMPARISON FOR THE OTHER RADIONUCLIDES WERE MADE AT NBS.

THE LAST PREVIOUS CHANGE IN NBS EXPOSURE STANDARDS WAS MADE ON 1972 MAY 01. AT THAT TIME THE EXPOSURE RATES FOR COBALT-60 AND CESIUM-137 GAMMA RAYS WERE LOWERED BY 0.7% AND 0.6% RESPECTIVELY, DUE TO ADOPTION AS AN NBS EXPOSURE STANDARD OF SIX SPHERICAL GRAPHITE CAVITY IONIZATION CHAMBERS (LOFTUS, T.P., AND WEAVER, J.T., J. RES. NAT. BUR. STAND., 78A, 465, 1974).

Attachment 18, continued.

U. S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

GAITHERSBURG, MD 20899

REPORT OF CALIBRATION

VICTOREEN R-METER
MODEL 570 SERIAL NUMBER 2990

MANUFACTURED BY VICTOREEN INSTRUMENT CO.
CLEVELAND, OH 44104

SUBMITTED BY BROOKHAVEN NATIONAL LABORATORY
UPTON, NY 11973

RECEIVED AT NBS ON 1987 OCT 14

THE CORRECTION FACTORS GIVEN IN THE TABLE OF CALIBRATION DATA ARE QUOTIENTS OF THE X- OR GAMMA-RAY EXPOSURE AND THE ELECTROMETER READING WITH A GIVEN IONIZATION CHAMBER. IF THE CHAMBER WAS OPEN TO THE ATMOSPHERE, THE READINGS WERE NORMALIZED TO ONE STANDARD ATMOSPHERE AND 22 DEGREES CELSIUS. USE OF THE CHAMBER AT OTHER PRESSURES AND TEMPERATURES REQUIRES NORMALIZATION OF THE READINGS TO THESE REFERENCE CONDITIONS. THE NORMALIZING FACTOR F IS COMPUTED FROM THE FOLLOWING EXPRESSION:

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

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)

THE EXPOSURE RATE AT THE CALIBRATION POSITION WAS MEASURED BY A FREE-AIR IONIZATION CHAMBER FOR X RADIATION, AND BY GRAPHITE CAVITY IONIZATION CHAMBERS FOR COBALT-60 AND CESIUM-137 GAMMA RADIATION. THE GAMMA-RAY EXPOSURE RATES WERE CORRECTED TO THE DATE OF CALIBRATION, FROM PREVIOUSLY MEASURED VALUES, BY DECAY CORRECTIONS BASED ON HALF-LIVES OF 5.27 AND 30.0 YEARS, FOR COBALT-60 AND CESIUM-137 RESPECTIVELY.

THE OVERALL UNCERTAINTIES OF THE CALIBRATION DESCRIBED IN THIS REPORT IS 1.5%, OF WHICH 0.7% IS ASSIGNED TO THE UNCERTAINTY IN THE EXPOSURE RATE OF THE NBS BEAM. THE OVERALL UNCERTAINTY WAS FORMED BY TAKING TWO TIMES THE QUADRATIC SUM 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.

IF SUITABLE CONNECTIONS WERE ACCESSIBLE IN THE ELECTROMETER, THE DIFFERENCES IN POTENTIAL BETWEEN CERTAIN SCALE READINGS WERE DETERMINED AND ARE GIVEN IN THE ELECTROMETER CALIBRATION TABLE.

THE CHARGE-READ PROCEDURE FOR VICTOREEN R-METERS, FOR THIS CALIBRATION, WAS AS FOLLOWS:

1. INSERT THIMBLE CHAMBER AND ADJUST TO ZERO READING.
2. UNLOCK CHAMBER AND REMOVE TO THE POSITION WHERE THE LOCKING PIN IS AT THE EDGE OF THE CHARGING SOCKET. NOTE ANY DEFLECTION OF ELECTROMETER READING FROM ZERO FOR THIS REFERENCE POSITION.
3. FOLLOWING EXPOSURE INSERT CHAMBER TO THE REFERENCE POSITION, IF NECESSARY ADJUST FIBER TO DEFLECTION NOTED, THEN INSERT CHAMBER FULLY TO DETERMINE READING.

INFORMATION ON TECHNICAL ASPECTS OF THIS REPORT MAY BE OBTAINED FROM P. J. LAMPERTI, RADIATION PHYSICS C214, NATIONAL BUREAU OF STANDARDS, GAITHERSBURG, MD 20899, (301) 975-5591.

REPORT REVIEWED BY

REPORT APPROVED BY R. LOEVINGER

FOR THE DIRECTOR
BY

DAVID M. GILLIAM, DEPUTY CHIEF
IONIZING RADIATION DIVISION
CENTER FOR RADIATION RESEARCH
NATIONAL MEASUREMENT LABORATORY

Attachment 19, continued.

NATIONAL BUREAU OF STANDARDS REPORT OF CALIBRATION

BROOKHAVEN NATIONAL LABORATORY
UPTON, NY 11973

ELECTROMETER MODEL SERIAL NUMBER

ELECTROMETER READING N (% FS)	POTENTIAL DIFFERENCE V(O)-V(N) (V)	RELATIVE SENSITIVITY S(N)/S(50)
20	49.0	1.004
40	97.6	1.000
50	122.0	1.000
60	146.6	1.001
80	195.4	1.001
100	245.0	1.004

533 V = V(O) WAS THE POTENTIAL MEASURED FOR AN ELECTROMETER READING AT N = O. THE VALUE OF V(O) GENERALLY SHOWS A LARGER VARIATION THAN V(O)-V(N). LONG-TERM MEASUREMENTS ON SIMILAR INSTRUMENTS INDICATE THAT THE PERCENT STANDARD DEVIATION OF V(O)-V(N) SHOULD NOT EXCEED 1.0%

THE ELECTROMETER SENSITIVITY IS S(N) = (V(O)-V(N))/N.

IF THE RELATIVE SENSITIVITY S(N)/S(50) DIFFERS SIGNIFICANTLY FROM UNITY, THE ELECTROMETER SCALE IS NON-LINEAR. IN THIS CASE, THE ELECTROMETER READING SHOULD BE MULTIPLIED BY THE APPROPRIATE RELATIVE SENSITIVITY.

IF THE CORRECTION FACTOR (COLUMN 4 OF THE CHAMBER CALIBRATION TABLE) WAS DETERMINED FOR A SCALE READING OTHER THAN 50%, THE RELATIVE SENSITIVITY SHOULD BE RENORMALIZED TO UNITY FOR THAT SCALE READING BEFORE CORRECTING FOR SCALE NON-LINEARITY.

CHECKED BY

Attachment 19, continued.

NATIONAL BUREAU OF STANDARDS REPORT OF CALIBRATION

BROOKHAVEN NATIONAL LABORATORY
UPTON, NY 11973

****
* SEE NOTE BELOW ON *
* EXPOSURE RATES *
****

VICTOREEN 0.25R CHAMBER
MODEL 130 SERIAL NUMBER 3464
OPEN TO THE ATMOSPHERE WHEN TESTED
ELECTROMETER MODEL 570 SERIAL NUMBER 2990

BEAM CODE	HALF-VALUE LAYER AL (MM)	CU (MM)	CORRECTION FACTOR 22 DEG C AND 1 ATM CF	% FS	DIST (M)	BEAM SIZE (MM)	EXP RATE (R/S)
137CS		10.8	*1.03	50	3.00	C623	2.0E-03
137CS		10.8	1.01	50	3.00	C623	2.0E-03
60CO		14.9	*1.02	50	1.95	C379	9.4E-04

DURING CALIBRATION THE CAVITY WAS POSITIONED IN THE CENTER OF THE BEAM WITH THE STEM PERPENDICULAR TO THE BEAM DIRECTION. THE RANGE NUMBER FACED THE SOURCE OF RADIATION.

* THE CHAMBER WALL THICKNESS WAS INCREASED FOR THIS BEAM QUALITY BY ADDITION OF THE SHELL SUPPLIED WITH THE CHAMBER.

NOTE: ON 1986 JAN 01 THE EXPOSURE RATES OF NBS EXPOSURE STANDARDS WERE ADJUSTED. DETAILS ARE GIVEN AT THE END OF THE REPORT.

CHECKED BY

Pages 5 and 6 have the same form as page 4.
Pages 7 to 9 are the same as pages 4 to 6 of attachment 18.

Attachment 19, continued.

7/7/86
828

Fifteen Landauer badges to irradiate and two controls.
Controls are 00037 and 00292
Source is BORIA (Cs^{137}), Scale Distance 300 cm.
From chart $\dot{X}$ = 2.060261 mR/s for 188 days of decay.

8130 $^{520}_{874}$ }	KKT1
040795 P	00024 } 00332
7/01/86 Landauer	

Report for m up for typing 7/23/86

Badges

Badges	
00271, 00053, 00211, 00083, 00225	Time Started: 1405 Switch Setting: 31.141 sec. Exp. Time: 31.970 sec. Exposure mR: 65.88 mR
00184, 00024, 00161, 00294, 00114	Time Started: 1415 Switch Setting: 96.243 sec Exp. Time: 97.069 sec Exposure mR: 200.0 mR
00065, 00262, 00332, 00050, 00107	Time Started: 1425 Switch Setting: 193.317 sec. Exp. Time: 194.141 sec. Exposure mR: 400.0 mR

NBS Victoreen Mo 500 SN 156 Probe 550-4 SN 894
ES-A, Range 2, 33 cm^3, Outer Neg., -348 V Test

Switch Setting	Exposure Time	Temp °C	Pressure mm Hg	Reading mR	Corr Reading	Exp. mR	Correction Factor
60.000	60.810	23.6	754.5	127.4	129.0	125.3	.971
60.000	60.828	"	754.4	127.5	129.1	125.3	.970
60.000	60.836	"	"	127.5	129.1	125.3	.971

Attachment 20, Section 4.1. Typical page in databook for TLD irradiation.

DG 8782/87
DB 874:032
1987 Nov 18

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MD 20899

REPORT OF IRRADIATION

Irradiation of 15 Landauer TLD Badges

Submitted by

Irradiated on 1987 November 17.

The TLD badges were supported on a plastic frame and held such that the radiation was incident normal to their front surfaces. The badges were positioned at a distance of 3.00 m from a cesium-137 gamma-ray source. The exposure rate was 2.00 mR/s. The overall uncertainty of the irradiations described in this Report is 1%, of which 0.7% is assigned to the uncertainty in the exposure rate of the NBS beams. The overall uncertainty was formed by taking two times the quadratic sum 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 irradiations are given in the attached table.

Information on technical aspects of this report may be obtained from P. J. Lamperti, Radiation Physics C214, National Bureau of Standards, Gaithersburg, MD 20899, (301) 975-5591.

Irradiation performed by E. L. Bright

Irradiation supervised by P. J. Lamperti

Report approved by R. Loevinger

For the Director
by

David M. Gilliam, Deputy Chief
Ionizing Radiation Division
Center for Radiation Research
National Measurement Laboratory

Attachment 21, Section 4.1. TLD Report of Irradiation

NATIONAL BUREAU OF STANDARDS REPORT OF IRRADIATION

Submitted by

Badge Numbers*	Exposure (mR)
00171	150
00157	150
00226	150
00334	150
00090	150
00057	275
00086	275
00204	275
00117	275
00291	275
00266	475
00065	475
00251	475
00078	475
00261	475

There were 2 control badges: serial numbers 00135 and 00103.

Irradiations performed between 0839 h and 0851 h.

*The badges are labeled with several groups of numbers. The numbers given in the table are sufficient for purposes of identification.

Checked by

Page 3 is the same as page 6 of Attachment 18.

Attachment 21, continued.

DG 8775/87
TFN N/A
DB 819:172-173
1987 Nov 10

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MD 20899

REPORT OF TEST

Keithley Digital Dosimeter
Model 35614
Manufactured by Keithley Instrument Company
Cleveland, OH 44137

Serial Number 20368

Submitted by

Received at NBS on 1987 November 10

The referenced electrometer has been tested for use with the ionization chamber covered by Report of Calibration DG 8776/87. The system was tested for the following combination of switch positions:

Switch	Position
Function	10^{-8} C
Range	20 V
Current Suppress	Off

When the electrometer measurements were corrected by K_Q, where

$$K_Q = 1.002,$$

measurements with the system using Beam Code ^{60}Co were found to be consistent with the calibration factor in DG 8776/87. K_Q was determined by injecting a known charge into the electrometer input and observing the corresponding change in the charge reading. The value of the injected charge is believed to have an uncertainty of less than 0.1%.

Attachment 22, Section 4.5. Electrometer Report of Test.

The exposure in air at the reference point of the ionization chamber, with the chamber replaced by air, is given by

$$X = K_Q \, F \, Q \, N = 1.002 \, F \, Q \, N$$

where

N is the chamber calibration factor in terms of exposure per unit charge, for the stated conditions of calibration;

Q is the change in charge on the electrometer system as indicated by the digital panel-meter readings, using the tested combination of switch positions; and

F is a factor that normalizes the measurements to the temperature and pressure reference conditions for N. F is defined in Report of Calibration DG 8776/87.

Information on technical aspects of this report may be obtained from P. J. Lamperti, Radiation Physics C214, National Bureau of Standards, Gaithersburg, MD 20899, (301) 975-5591.

Measurements performed by E. L. Bright

Measurements supervised by P. J. Lamperti

Report approved by R. Loevinger

For the Director
by

David M. Gilliam, Deputy Chief
Ionizing Radiation Division
Center For Radiation Research
National Measurement Laboratory

Attachment 22, continued.