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Determination of Total X-Ray Beam Energy With a Calibrated Ionization Chamber



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With a Calibrated Ionization Chamber

John S. Pruitt and Steve R. Domen



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Determination of Total X-Ray Beam Energy With a Calibrated Ionization Chamber*

John S. Pruitt and Steve R. Domen

This report describes the use of an air-filled aluminum-alloy ionization chamber to determine the energy transported by a bremsstrahlung beam with maximum photon energy in the range 6 to 170 Mev. The experimental calibrations of this chamber over this energy range are given, as well as the results of calibration experiments made with a 250-kv constantpotential X-ray tube and with Cs^{137} and Co^{50} gamma-rays. Information is presented about the change in calibration when the chamber is used with different experimental conditions, and when either its dimensions or its alloy composition are changed slightly. This report can be used to construct a replica chamber and to determine its absolute calibration between 6 and 170 Mev under a variety of experimental conditions.

1. Introduction

The proper evaluation of most experiments performed with a betatron or synchrotron X-ray beam requires knowledge of the absolute number of incident photons of each energy. This knowledge can be obtained by calculating the relative spectral intensity distribution as a function of photon energy, which can be predicted theoretically with reasonable accuracy [1],¹ and determining the total beam energy with a calibrated monitor. This energy is proportional to the area under the spectral distribution curve, and can be used to assign absolute values to the distribution at each photon energy.

The proper calibration of the beam monitor is an important task in most radiation experiments, where the accuracy of the results depends upon the accuracy with which the incident energy is known. Several different techniques for performing this task have been described, relying either upon theoretical descriptions of the interaction of X-rays with matter, or upon experimental energy measurements [2]. The theoretical descriptions require knowledge of atomic parameters which are not accurately known for highenergy bremsstrahlung beams, such as average electronic stopping powers, but the experimental techniques of beam energy measurement have now been developed to the point where a monitor can be calibrated experimentally to within a few percent.

2. Description of the P2 Chamber

Detailed shop drawings of the P2 chamber accompany this Monograph (figs. 17, 18, 19), but its principal features, the thick front wall and the multicellular ionization-collection assembly, are shown in the schematic cross section of figure 1 and the photographs of figures 2 and 3. These chambers were designed for use in X-ray beams up to 20 cm in diameter and with intensities ranging This report concerns the experimental method used in the High Energy Radiation Section of the National Bureau of Standards for rapid and accurate calibration of X-ray monitors for beams with maximum photon energy between $E_{\text{max}}=6$ and $E_{\text{max}}=170$ Mev. The method is based upon results obtained in a series of experiments [3], performed with two instruments which determine the total beam energy in absolute units, a refined version of the lead calorimeter described by Laughlin and Beattie [4], and a large scintillation crystal [5].

These absolute beam-energy measurements were used to calibrate an ionization chamber of a type labeled P2, so that a measurement of the ionization charge collected during an X-ray exposure determines the total beam energy incident on the front face of the chamber. This chamber has been classified as a Standard Instrument, and its calibration is expressed as the energy in joules required to produce one coulomb of ionization charge inside the chamber when it contains dry air at 20 °C and a pressure of 760 mm of mercury. The calibrated chamber is used in this laboratory either to transfer the absolute calibration to special monitors used in radiation experiments, or as a continuous-duty monitor in cases where its large dimensions are not inconvenient.

from 0.5 to 1,000 μ w/cm². The manner in which the design was affected by these criteria is described below.

The diameter of the chamber was chosen to be large both to allow its use with large-diameter X-ray beams and to reduce the dependence of the calibration on beam diameter. The calibration depends on the size of the beam because a part of the radiation scattered in the thick front wall misses the air cavity, and the fraction escaping increases with increasing beam diameter. The

^{*}This work was supported in part by the Atomic Energy Commission. ¹ Figures in brackets indicate the literature references at the end of this Monograph.

diameter of the internal plates is 29.2 cm, large enough so that the calibration decreases by no more than 0.1 percent as the beam diameter increases from 0 to 4 cm, and by no more than 3 percent for an increase to 20 cm.



FIGURE 1. Schematic cross section of a P2 chamber.

The front wall is made of 2024 Dural, an aluminum alloy whose composition is shown in table 1. Its thickness was chosen to minimize the dependence of the calibration, joules/coulomb, on the maximum photon energy of the bremsstrahlung beam. The calibration depends on the maximum photon energy because it is a function of the spectral distribution of the incident photons, which changes with the maximum energy. The spectral distribution is also a function of the beam filtration, so although it is possible to minimize the variation with maximum energy for a given filtration, there is no choice which will make this variation small for all filters. The thickness chosen is 9.4 cm, which reduces this

TABLE 1. Composition of 2024 Dural a

Element	Percentage by weight			
	Nominal	Límits		
Aluminum	93. 4 4. 5	90, 9-94, 7		
Magnesium Manganese	$1.5 \\ 0.6$	$\begin{array}{c} 1.2 - 1.8 \\ 0.3 - 0.9 \end{array}$		
Sílicon Iron		$ \begin{array}{cccc} 0 & - & .5 \\ 0 & - & .5 \\ 0 & - & .5 \end{array} $		
Chromium		0 = .25 0 = .10 0 = .15		

* This alloy was ealled 24S Dural prior to 1954.



FIGURE 2. External view of a P2 chamber.

FIGURE 3. Ionization-collection assembly of a P2 chamber.

variation to 10 percent between 6 and 170 Mev, with a filtration of 4.5 g/cm^2 of aluminum.²

The internal plate assembly, where ionization is produced and collected, contains dry air at atmospheric pressure. It was designed to have high sensitivity and low leakage, so that it could be used with low-intensity beams, and a small probability for ion recombination, so that it could also be used with high-intensity beams. These divergent requirements were met by using a thick air cavity (5 cm), divided into 12 segments by thin Dural plates. These are alternately high-voltage and collector plates, mounted in two interleaved stacks. The two outer plates are high-voltage plates, and are considerably heavier than the inner plates. The plates within each

Figure 4 is a schematic diagram of the experimental arrangement during a typical calibration transfer from a P2 chamber to a thin-walled monitor used with the 180-Mev synchrotron. X-rays incident on the P2 chamber are filtered by one wall of the donut (the evacuated electronacceleration tube) and the monitor. The size and shape of the direct beam in such an arrangement are determined by the aperture in the main lead shield, but radiation scattered in the main shield, the monitor walls, and the air adds a second, more divergent component to the beam. The auxiliary lead shields shown in figure 4 were inserted to reduce the spurious effects produced by this second component. The one in front of the monitor reduced its response to this scattered component, a precaution which increased the reliability of the monitor calibration, since it has

stack are separated by ground steel spacers, which serve to connect them electrically. Each stack is mounted on Kel-F insulators, which are in turn mounted on the grounded front cover, so that there is no direct leakage path between the two stacks. This style of construction insures that the total thickness of the air cavity remains fixed, and that the calibration will not change even if the assembly is dismantled and reassembled. These advantages, plus the relative compactness of the P2 chamber, are the reasons this design was chosen in preference to the design of Wilson [6], where ionization is sampled at several depths in an absorbing medium of essentially infinite thickness.

3. Use of the P2 Chamber

been found that the secondary to primary intensity ratio is a function of changes in operating conditions.³ The auxiliary shield behind the monitor guards against backscattered radiation.

The auxiliary shield in front of the P2 chamber served to limit the fraction of this scattered component incident on the chamber. In this particular experiment, it was necessary to know the amount of radiation energy incident on an area 9 cm in diameter and 70 cm behind the monitor. The P2 chamber was mounted with its front face at this position with a 9-cm-diam hole in the lead shield in front of it. The beam was only 4.2 cm in diameter at this position, but this technique included a 9-cm-diam scattered-

³ For instance, the monitor response, per unit energy in the direct beam, increases by about 3 percent when the synchrotron donut air pressure increases from 6×10^{-6} to 35×10^{-6} mm of mereury. This is caused by an increase in the relative number of secondary electrons from the main shielding aperture, which is in turn caused by an increase in the size of the X-ray source. A sizable fraction of the monitor response (of the order of 50 percent) is caused by these seattered electrons, so it will change when the relative electron-intensity changes. The P2 response is much less affected by these electrons, although it is affected by scattered photons, as discussed in the text.



FIGURE 4. Experimental arrangement during a typical monitor calibration.

² If the ehamber is used with a different filter, or at maximum energies outside this range, the variation of the ealibration with peak energy may be large in the region of interest. It ean usually be reduced over a limited range by ehanging the front-wall thickness.



FIGURE 5. Electrical circuit used for ionization-charge measurement.

photon beam in the energy determination. The need to consider this secondary beam decreases as the distance between P2 and the monitor increases, but at the small separation shown in figure 4, the secondary beam may contribute as much as 1 percent to the energy incident on the P2 chamber. Although this scattered component has been slightly degraded in energy, the chamber calibration varies too slowly with energy to be noticeably changed by this degradation.

The ionization charge collected in the P2 chamber during an X-ray exposure is measured with the modified Townsend balance circuit shown in figure 5. The required components are a high-quality polystyrene capacitor, C, a stable source of high voltage, E_I , a slide-wire potentiometer which is used as a source of compensating voltage, $E_{\mathcal{C}}$, and a vibrating reed electrometer. Coaxial cables with a solid polyethylene dielectric are used to connect the P2 chamber to the power supply and to the electrometer. The electrometer cable is of the lownoise variety, with a semiconductor coating on the dielectric.

The electrometer used in this laboratory is a three-terminal model divided into two components, which are mounted in separate rooms and connected by a 100-ft cable. The head of the electrometer is mounted in the experiment room close to the P2 chamber, to reduce the length of the input cable. The head contains two amplifier tubes and supports a grounded metal box covering the external capacitor, C, which must be carefully shielded against stray radiation. C is mounted between the input and feedback terminals of the electrometer, in parallel with a small internal capacitor, C' (about 10 pf). The amplified signal enters the main body of the electrometer through the 100-ft cable. This component contains most of the electronic circuitry, the zeroing controls, range selector, and output meter. It is located in the accelerator control room, where the calibration data are recorded.

The potentiometer is a commercial 1.6-v model, constructed so that it can be periodically and

easily calibrated with a self-contained standard cell. It is connected in series with the electrometer feedback loop by means of an external connector on the electrometer. It is used as a source of accurately known voltage, which can be conveniently varied from $E_c=0$ to $E_c=1.6$ v.

The source of high voltage, E_I , is a battery power supply consisting of 67.5-v dry cells connected in series. They are mounted in a temperatureregulated box to reduce the electrometer drift currents caused by changes in the ambient temperature. A total of 1,200 v is normally used with high-intensity X-ray beams in this laboratory. This voltage is large enough to reduce the error caused by ion recombination to about 0.1 percent with a synchrotron beam intensity⁴ of 400 μ w/cm². This was determined by plotting the measured ratio E_c /monitor-volt as a function of the ratio relative-intensity/ E_I , and making a linear extrapolation to zero intensity [7].

Values of E_I as large as 2,200 v have been used with no evidence of gas multiplication, but the electrometer drift currents were too large for convenient operation. With $E_I=1,200$ v, this drift current is normally less than 10^{-13} amp. Larger currents signify direct leakage between the electrodes, which is usually caused by lint in the air cavity. This can often be corrected by removing the plate assembly and blowing-it out with a high-pressure jet of nitrogen, but on occasion it is necessary to dismantle and clean the components to achieve a drift current as small as this.

When the P2 chamber is used with low-intensity X-ray beams, recombination problems are less severe, and $E_I = 800$ v is usually used. This reduces the chamber leakage, and electrometer drift currents of the order of 10^{-14} amp are typical.

The electrometer is always used as a null instrument rather than as a deflection instrument, so that accurate charge measurements can be made without knowing the leakage capacitances to ground or the absolute electrometer calibration. With the compensating voltage $E_c=0$, C is discharged with the shorting switch before an X-ray exposure. The electrometer is then zeroed on a sensitive scale and the exposure begun. During exposure, the electrometer needle may be kept on scale either by continuously increasing E_c or by switching to a less sensitive scale.

After an exposure has been completed, the needle is returned to its initial position by adjusting E_c . The ionization charge collected in the P2 chamber during the exposure can be calculated from the equation

$$q \text{ (coulomb)} = [C \text{ (farad)} + C' \text{ (farad)}] \times E_{\mathcal{C}} \text{ (volt)},$$
(1)

where C and C' are the capacitances of the external and internal capacitors in the electrometer head

 $^{^4}$ The synchrotron produces 60 X-ray pulses per second, and with this intensity, each pulse produces an ionization density of about 2 \times 10⁻¹² coulombs/cm³.

and E_c is the compensating voltage required to return the electrometer needle to its initial position. E_c can be obtained directly from the calibrated potentiometer, and (C+C') can be determined by the d-c comparison method described below.

Absolute knowledge of (C+C') can be obtained with the equipment of figure 5, plus a standard air capacitor of known capacitance, C_s , and a second potentiometer used as a variable source of voltage, E_s . The comparison eircuit is similar to that of figure 5, except that the P2 chamber is replaced by C_s and the high-voltage supply by E_s , to form a simple series loop between terminal I and ground. The polarity of E_s must be such that an increase of $E_{\rm s}$ will move the electrometer needle in the opposite direction from that caused by an increase of E_c . The measurement is made by first zeroing the electrometer needle with the condensers dis-charged and $E_c = E_s = 0$, and then determining the value of one (say E_s) required to return the needle to its initial position after the other (E_c) has been changed. Then

$$C + C' = \frac{E_s}{E_c} C_s \tag{2}$$

and (C+C') is known in terms of C_s .⁵ The P2 chamber can itself be used as a continuous-duty exposure monitor, or it can be used to calibrate a different monitor, as in the situation shown in figure 4. The auxiliary monitors used in this laboratory are usually transmission-ionization chambers, of the general type shown in figure 6. This is a thin-walled chamber for use in relatively high-intensity beams. The walls and air gaps as shown are thin enough to prevent

The ionization charge collected in a P2 chamber is related to the incident radiation energy by

Energy (joules) = q (coulombs)

 \times Cal (joules/coulomb) (3)

where q (coulombs) is the measured ionization charge and Cal (joules/coulomb) is the chamber calibration, a number which varies with maximum photon energy. One of the NBS chambers, P2–4, has been calibrated in bremsstrahlung beams between 6 and 170 Mev in a series of four experiments performed with the two NBS eircular electron accelerators, a 50-Mev betatron, and a 180-Mev synchrotron. Each experiment consisted of two measurements at a variety of maximum energies. The first part was a determination of the ionization charge collected in a



FIGURE 6. Schematic cross section of anionizationchamber monitor.

noticeable ion recombination in the X-ray beams used in this laboratory, but if the charge liberated per pulse of X-rays is larger in another laboratory, the recombination probability may increase enough to make even smaller dimensions mandatory.⁶ The high voltage normally used with this type of monitor is about 150 v.

Monitor voltage measurements are always made with the same type of circuit as that shown in figure 5 for the P2 chamber, so that the transfer of a P2 calibration to a transmission chamber requires two electrometers and additional capacitors. The monitor calibration can be expressed in joules/monitor-volt, so that there is no need for absolute knowledge of the capacitances used with the monitor.

4. Calibration of Chamber P2-4

P2 chamber per unit monitor response, using an experimental arrangement similar to that of figure 4. The second part was a determination of the total incident beam energy per unit monitor response, and was performed by replacing the P2 chamber by an absolute energy-measuring instrument.

These four experiments are compared in table 2. The first experiment was performed with a seintillating crystal [5], covering the energy range between 20 and 170 Mev. The next two experiments were performed with a calorimeter [3], between 18 and 42 Mev and between 20 and 170 Mev, respectively. Experiment 4 was performed with a crystal [3] to investigate energies between 6 and 19 Mev, a region of great importance to nuclear physics, but one where the intensities of the NBS accelerators were too small for calorimeter measurements. The data from experiment

⁵ Alternate-current measurement of (C+C') will not give the proper value to use in eq (1) if these capacitors are not air dielectrie. For polystyrene capacitors, measurements at 1,000 e/s underestimate the capacitance by as much as several tenths of one percent. Alternate-current measurements are also more eumbersome because three measurements are required to eliminate the effects of capacities to ground.

⁶ According to the theory presented in reference [7], the probability of recombination is a function of the charge liberated per pulse, which can be taken as proportional to the ratio of the time average X-ray intensity to the pulse repetition rate.

Experiment No.	1	2	3	4
Date of experiment	1957	1958	1959	1959
Participants Aceelerator Target material Energy range <i>Mer</i> Apparatuss Filtrationg/cm ² Beam diametercm	$ \begin{cases} J. E. Leiss, \\ R. A. Schraek_, \\ J. S. Pruitt, \\ synchrotron, \\ tungsten, \\ 20-170 \\ crystal, \\ 4.5 \\ 1.5 \end{cases} $	J. S. Pruitt S. R. Domen betatron tungsten 18-42 ealorimeter 3.0 4.2	J. S. Pruitt S. R. Domen synchrotron tungsten 20–170 calorimeter 4. 5 4. 2	E. G. Fuller E. Hayward betatron tungsten 6-19 erystal 7.3 5.5

TABLE 2. High-energy calibration experiments

1 yielded a calibration eurve with an estimated error of ± 3 percent, that from experiments 2 and 3 a eurve with an estimated error of ± 2 percent, and the data of experiment 4 has been assigned an error of ± 2 percent. These errors are not maximum errors, but they are all considerably more eonservative than probable errors. In the calorimeter experiments, for example, both the net systematic error (the square root of the sum of the squares of six different systematic errors) and the standard deviation of the mean of the ealorimeter measurements at each energy were of the order of 0.5 percent. The quoted ± 2 percent error was obtained by adding the former to three times the latter.

The calibrations of P2-4 obtained in these four experiments are listed in table 3 and plotted in figure 7. They are in good agreement where the energy ranges overlap, except at high energies. Even in this region, however, they agree to within the stated errors except at 110 Mev. They have all been eorrected to refer to the beam size and filtration used in experiment 3, 4.2 cm diam and 4.5 g/cm² of aluminum,⁷ using data presented in section 6. These eorrections were larger than 0.2 percent only for experiment 4, and the maximum was 1.0 percent at 6 Mev.

The solid curve in figure 7 is considered a best fit to the experimental points (the significance of

⁷ The filtration in each experiment included a donut wall, 4.1 g/em^2 of Pyrex for the synchrotron, and 1.6 g/em^4 of eeramic for the betatron. Caleulations have shown that the filtration corrections are changed by less than 0.1 percent if the donut wall is treated as an equivalent g/em² of aluminum.



FIGURE 7. P2-4 calibration at 20 °C and 760 mm of mercury in a 4.2-cm-diam bremsstrahlung beam filtered by 4.5 g/cm² of aluminum.

TABLE 3. Absolute calibrations of chamber P2-4 in a 4.2-
cm-diam X-ray beam filtered by 4.5 g/cm² of aluminum, at
20 °C and 760 mm of mercury

Crystal	experiments	Calorimet	er experiments	
Maximum energy	CaI (12-4)	Maximum cnergy	Cal (P2-4)	
Expe	eriment 1	Experiment 2		
Mev	joules/coulomb	Mev	joules/coulomb	
19.6	4.04×10*	18.2	4. 19×10 ⁵	
24.6	4.14	19.8	4.18	
29.6	4.10	21.7	4. 17	
34.6	4.10	25.9	4.15	
39.6	4.07	31.3	4.13	
44.7	3.96	36.7	4.11	
49.7	3.86	42.1	4.14	
59.7	3.82			
69.8	3.73			
89.8	3.71	Expe	riment 3	
109.9	3.60	·		
130.0	3.64			
150.1	3.69	20	4.12×10^{5}	
170.2	3.71	25	4.08	
		30	4.11	
		35	4.10	
Exp∈	eriment 4	40	4.05	
		45	4.02	
		50	3.99	
6	4.10×10^{5}	60	3.94	
8	4.17	70	3.86	
10	3.99	90	3.80	
13	4.07	110	3.84	
16	4.09	130	3.81	
19	4.17	150	3.82	
		170	3.87	

the other two curves is explained in the following section). Above 20 Mev, its shape was obtained from a weighted average of ealorimeter and crystal points, where the weights were inversely proportional to the quoted errors. Below 20 Mev, the shape of the eurve was influenced by the results of additional experimental calibrations made with γ -rays and X-rays of energy less than 1.5 Mev. These extra ealibrations were made to help determine the sensitivity of P2-4 to monoenergetie photons, as described in the following section.

The 34.5-Mev calibration plotted in figure 7 is based on ealorimeter measurements made at the Max Planek Institut für Biophysik in Frankfurt [8]. They were made to ealibrate P2-6, a repliea chamber belonging to this institute, and were transferred to P2-4 by direct comparison of the two ehambers, as described in section 6. The plotted point has been corrected to a beam diameter of 4.2 em and a filtration of 4.5 g/em² of aluminum.

The 146-Mev calibration is based on ealorimeter measurements made at the University of Illinois

The solid curve is a best fit to the experimental data, and the dashed curves are postulated extremes in the shape of the curve.

[9]. They were transferred to P2-4 by constructing a replica of the Illinois chamber and comparing it with P2-4 at the NBS. No corrections have been made for differences in beam filtration and diameter, but these corrections should be very small.

The P2-4 calibration was also determined at low energies, in experiments using radioactive sources and a 250-kv constant potential X-ray tube, and the results are listed in tables 4 and 5.

TABLE 4. Absolute calibration of chamber P2-4 in a 4.2cm-diam γ -ray beam at 20 °C and 760 mm of mercury

Source	Photon energy	Cal (P2-4)
Cs ¹³⁷ Co ⁶⁰	Mev 0.66 1.25	<i>joules/coulomb</i> 4. 59×10 ⁵ 4. 14

TABLE 5.Absolute calibration of P2-4 in a 4.2-cm-diamlow-energy X-ray beam at 20 °C and 760 mm of mercury

Emax		Filter th	nickness		Cal (P2-4)
	Al	Pb	\mathbf{Sn}	Cu	
Mev 0. 050	mm 3	mm 0.125	mm	m m	joules/coulomb
.100 .150 .200	3 3 3	. 53	1.54 4.0	$\begin{array}{c}4.15\\ 0.61\end{array}$	72×10^{6} 12.4 8.34
. 250 . 250	3 6. 18	2.7 2.7	$\begin{array}{c} 1.0\\ 1.0 \end{array}$. 59 11. 85	7.03 6.91

In each case, the photon-beam intensity was obtained from measurements of the exposure dose in roentgens/min, and the calibration was taken to be the product of intensity (watts/cm²) and beam cross section (cm²), divided by the ionization current (amperes). The beam was 6.4 cm in diameter in each experiment, but small corrections have been applied to the calibrations listed in tables 4 and 5 so that they refer to a 4.2-cm beam.

In the experiments with radioactive sources, measurements of roentgens/min were made with a carbon cavity chamber [10], and the beam intensities were calculated using the conversion factors of 2,959 ergs/cm²/roentgen for Cs¹³⁷ [11] and

5. Sensitivity of P2-4 to Monoenergetic Photons

The calibration of an ionization chamber can be calculated from the equation

$$\operatorname{Cal} = \frac{\int_{0}^{E_{\max}} I(E, E_{\max}) dE}{\int_{0}^{E_{\max}} S(E) I(E, E_{\max}) dE}$$
(5)

where $I(E, E_{max})$ is the differential intensity spectrum at the face of the chamber, and $S(\dot{E})$ is the chamber sensitivity for photons of energy



FIGURE 8. Relative spectral-intensity distributions for filtered X-ray beams obtained from a 250-Kv constantpotential X-ray tube.

The small peak between 0.07 Mev and the K absorption edge of lead at 0.088 Mev belongs to the lightly filtered 0.250-Mev spectrum.

 $3,391 \text{ ergs/cm}^2$ /roentgen for Co⁶⁰ [12]. In the X-ray tube experiments, measurements of roentgens/min were made with a free-air ionization chamber [13], and the beam intensities were calculated from the equation

$$\frac{\text{watts/cm}^2}{\text{coentgen/min}} = \frac{1}{6} \times 10^{-8} \frac{\int_0^{E_{\text{max}}} I(E, E_{\text{max}}) dE}{\int_0^{E_{\text{max}}} \frac{I(E, E_{\text{max}}) dE}{R(E)}}$$
(4)

where $I(E, E_{\text{max}})$ is the differential intensity spectrum in units proportional to watts/cm²/Mev, and R(E) is the conversion factor ergs/cm²/roentgen for photons of energy E. $I(E, E_{\text{max}})$ was calculated by assuming that at these low energies, the unfiltered intensity spectra are proportional to $(E_{\text{max}}-E)$ [1], and correcting for filtration with published total attenuation coefficients [14]. The filtered spectra are shown in figure 8. R(E) was taken from the literature [15].

E, the ionization charge produced by unit incidentradiation energy. Knowledge of the sensitivity is a prerequisite for calculation of the manner in which the calibration depends on the X-ray spectrum.

The sensitivity of P2–4 to monoenergetic photons is plotted as a function of photon energy in figure 9. The solid curve was obtained by solving eq (5) for S(E), using the calibrations described in the previous section. With the data of table 5, $I(E, E_{max})$ was taken from figure 8. In this case the solution was obtained by assigning



FIGURE 9. Sensitivity of P2-4 to a 4.2-cm-diam beam of monoenergetic photons, at 20 °C and 760 mm of mercury.

The solid curve is a best fit to the experimental data, and the dashed curves postulated extremes in the shape of the curve.

an average photon energy to each of these spectra, plotting 1/Cal (P2-4) at this energy, in figure 9, drawing a smooth curve through these points, and calculating Cal (P2-4) from eq (5). The discrepancy between calculated and measured calibrations was removed by adjustment of the average energies.

The values of S(E) plotted at 0.66 and 1.25 Mev in figure 9 are simply the inverse of the calibrations listed in table 4 for Cs¹³⁷ and Co⁶⁰, respectively, since the spectra are approximately delta functions. At higher energies, eq (5) was solved for S(E) by the inverse-matrix technique described in reference [16]. In this case, the calibrations came from the solid curve in figure 7, and $I(E, E_{\text{max}})$ was taken from tabulations of Schiff integrated-over-angles differential-intensity spectra [17], corrected for a filtration of 4.5 g/cm² of aluminum [18]. Examples of the predicted spectra are shown in figure 10. This high-energy solution for S(E) reproduces the solid-calibration curve of figure 7 to a few tenths of 1 percent.

The estimated uncertainties in the sensitivity curve are indicated by vertical lines at low photon energies. The radioactive source errors include uncertainties of ± 3 percent, ± 1 percent in the determination of roentgens/min,⁸ and errors in the conversion to intensity units of ± 1.5 percent for Cs¹³⁷ and ± 1.2 percent for Co⁶⁰. The X-ray tube errors include ± 1 percent for the roentgens/ min determinations, ± 3 percent for the conversion to intensity units, and ± 1 percent for uncertainty in the average energies. The plotted errors are the sums of these individual errors.





FIGURE 10. Relative spectral-intensity distributions for bremsstrahlung beams filtered by 4.5 g/cm² of aluminum.

The estimated errors in S(E) above 2 Mev were obtained by making the trial distortions of the calibration curve shown by dashed lines in figure 7. These curves lie within ± 2 percent of the solid best-fit curve, but include changes in curvature which affect the sensitivity curve more drastically than a simple change in absolute magnitude does. They change the predicted sensitivity curve as shown by the dashed lines in figure 9. It is possible to predict values of S(E) outside of the dashed curves by postulating additional oscillations of the calibration curve, but this would be difficult to justify because all of the physical interactions which determine the calibration vary slowly with energy. This analysis of the uncertainty in S(E) shows that the precise shape of the sensitivity curve is not very well known at high energies, but the presence of two maximums appears to be well established, and this can be qualitatively explained with the following arguments.

At low photon energies, the shape of S(E) is determined by the photon-attenuation coefficients in Dural, which decrease rapidly with increasing E, so that an increasing fraction of the incident energy penetrates the thick front wall of the chamber. In the neighborhood of a few Mev, the product of attenuation coefficient and wall thickness is of the order of unity, and the exponential absorption is less sensitive to changes in energy. In this region, the predominant effect is a decrease in the efficiency of converting photon energy into electron energy, giving rise to the lowenergy maximum in S(E).

At higher photon energies, the increasing range of the secondary electrons means that the region in the Dural where the electrons producing air ionization are generated moves toward the front of the chamber. This decreases the effective wall attenuation and increases S(E). This increased electron range also means that a larger volume of Dural is contributing to air ionization, but this change does not affect the calibration because it is compensated by a decrease in the fraction of its energy which each electron deposits in the air cavity. At energies where the electron ranges are comparable with the front-wall thickness (40 Mev electrons), the volume of Dural contributing to the ionization no longer increases with energy, but the fraction of energy deposited by each electron continues to decrease with increasing energy. At the same time, bremsstrah-

6. Variations of the P2 Calibration

The P2-4 bremsstrahlung calibration curve of figure 7 cannot be used directly for an arbitrary X-ray exposure, because the calibration depends upon the value of several experimental parameters, which may differ from the values used during the calibration experiments. These are

- 1. The temperature and pressure of the air in the chamber.
- 2. The thickness and atomic number of the filters in the X-ray beam.
- 3. The diameter and intensity distribution of the incident beam.

The variation with air temperature and pressure obeys the ideal gas laws, and the calibration may be corrected for this variation by multiplying it by the factor

$$F_{tp} = 2.592 \,\frac{(t+273.2)}{p},\tag{6}$$

where t and p are respectively the temperature (°C) and pressure (mm of mercury) of the air in the chamber during an exposure. t can be read from the attached thermometer, but p must be determined from a measurement made outside the chamber. This factor would also include a small humidity correction except for the use of drier in the chamber air inlet.

The variation with filter thickness and atomic number must be calculated with the help of eq (5), and with $I(E,E_{max})$, the Schiff unfiltered spectrum [17], corrected for absorption by the materials in the beam. These corrections multiply the unfiltered spectrum by an exponential of the form $e^{-\Sigma_i \gamma_i(E)t_i}$, where t_i is the thickness of the *i*th

FIGURE 11. Ratio of P2-4 calibration in a beam filtered by t g/cm² of aluminum to P2-4c alibration in a beam filtered by 4.5 g/cm² of aluminum.

lung production increases, and an increasing fraction of the secondary electron energy is reconverted into photons and becomes unavailable for ionization production. These two effects in combination cause a drop in S(E) and lead to the high-energy maximum.

filter and $\gamma_i(E)$ is its attenuation coefficient for photons of energy E. The values of S(E) used in this calculation may be taken directly from figure 9. The correction for filtration multiplies the calibration of figure 7 by a second factor:

$$F_f = \frac{\text{Cal} (t_i, Z_i)}{\text{Cal} (4.5 \text{ g/cm}^2 \text{ of Al})}.$$
 (7)

These calculations have been performed for the special cases of aluminum and copper filters using total attenuation coefficients from references [14] and [18], which assume that no scattered photons from the filter reach the P2 chamber. The values of F_f obtained are shown in figures 11 and 12 as a function of filter thickness, $t(g/cm^2)$, for a few representative values of E_{max} . The variation with energy in the aluminum curves is quite regular, but the copper curves exhibit a maximum near 100 Mev for large t, related to the minimum in S(E) at 14 Mev. These curves are almost independent of errors in the assumed spectra and absorption coefficients, but they do depend on the precise shape of S(E). If S(E) lies within the limits shown in figure 9, figures 11 and 12 are accurate to within ± 0.2 percent for $t \leq 4.5$ g/cm² of aluminum and 2 g/cm² of copper, respectively. The uncertainties for thicker filters increase approximately linearly with t and are about ± 0.8 percent at 50 g/cm², for energies less than 50 Mev. They are smaller for high energies, and are only about ± 0.3 percent at 170 Mev, for t=50 g/cm².

The variation with beam diameter and intensity distribution was investigated by observing the



FIGURE 12. Ratio of P2-4 calibration in a beam filtered by t g/cm^2 of copper to P2-4 calibration in a beam filtered by 4.5 g/cm^2 of aluminum.





FIGURE 13. Relative dependence of P2-4 calibration on radius of beam incidence.



FIGURE 14. Energy-dependent multiplier used to calculate dependence of P2-4 calibration on radius of beam incidence.



FIGURE 15. Ratio of P2-4 calibration in an X-ray beam of diameter D to that in a 4.2-cm-diam beam, for beams of uniform intensity.

change in response when a P2 chamber was bombarded at different radii by 1.5-cm-diam beams of various E_{max} , and of unit total energy. This change depended on the E_{max} used, but it was found that the dependence on radius, r (cm), could be separated from the dependence on E_{max} , and the relative response could be expressed as

$$R(r, E_{\max}) = 1 - f_1(r) f_2(E_{\max}).$$
(8)

The functions $f_1(r)$ and $f_2(E_{\text{max}})$ are plotted in figures 13 and 14, respectively. The latter has been arbitrarily normalized to unity near 10 Mev.

The beam-size correction multiplies the calibration of figure 7 by the factor

$$F_{D} = \frac{\int_{0}^{2.1 \text{ cm}} rI(r, E_{\max}) R(r, E_{\max}) dr \int_{0}^{\frac{D}{2}} rI(r, E_{\max}) dr}{\int_{0}^{\frac{D}{2}} rI(r, E_{\max}) R(r, E_{\max}) dr \int_{0}^{2.1 \text{ cm}} rI(r, E_{\max}) dr}$$
(9)

where $R(r, E_{\text{max}})$ comes from eq (8) and $I(r, E_{\text{max}})$ is the relative intensity of the incident beam at radius r. These calculations have been performed for the ideal case where the beam intensity is uniform (for $r < \frac{D}{2}$), and the results are shown ⁹

as a function of D in figure 15 for several values of E_{max} .

The corrections for beam filtration and diameter for the calibration experiments came directly from figures 11 and 15, respectively. The beam intensity was not uniform in these experiments, but the corrections for beam diameter were almost negligible, and are quite insensitive to the precise shape of $I(r, E_{max})$.

The three factors of eqs (6), (7), and (9) arc enough to correct the P2-4 calibration for use in most experimental situations, but a fourth factor is required if a different P2 chamber is used. This is

$$F_{c} = \frac{\text{Cal (replica chamber)}}{\text{Cal (P2-4)}}, \quad (10)$$

a factor which is most reliably determined by direct experimental comparison of the replica chamber with either P2-4 itself or another chamber which has been compared with P2-4. The comparisons are made with the experimental arrangement of figure 4, measuring the P2 ionization charge collected per unit monitor response for each of the chambers in turn. At the present time there are eleven P2 chambers which have been experimentally intercompared.

The first four, P2-1 to P2-4, belong to the National Bureau of Standards, and the measured

⁹ These curves are based on measurements with a beam filtered by 4.5 g/cm² of aluminum and may change slightly if the filtration is changed.

values of F_c for these chambers are listed in table 6 for several maximum photon energies between 6 and 170 Mev. The remaining seven chambers belong in various institutes around the world. Their locations are shown in table 7, along with the measured values of F_c and the energies at which these measurements were made [19]. Their labels, P2-n, correspond to the order in which they were calibrated.

TABLE 6. Measured calibration ratios, Fc, of NBS P2
chambers

Emax	6 Mev	14 Mev	3 2 Mev	70 Mev	170 Mev
P2-1 P2-2 P2-3 a P2-4	$\begin{array}{c} 0.994 \\ .994 \\ .996 \\ 1.000 \end{array}$	$\begin{array}{c} 0.\ 996 \\ .\ 995 \\ .\ 999 \\ 1.\ 000 \end{array}$	$0.996 \\ .995 \\ .998 \\ 1.000$	$0.994 \\ .994 \\ .998 \\ 1.000$	0. 998 . 996 . 998 1. 000

^a Equal to unity by definition of F_{ϵ} .

TABLE 7. Measured calibration ratios of other P2 chambers

Chamber	Institute	E_{\max}	F_{c}
P2-5	Institut National d'Hygiene, Paris, France.	Mev 18 22	0. 994 . 994
P2-6	Max Planek Institut für Biophysik, Frankfurt-am-Main, Germany.	$\begin{array}{c} 20\\ 34.5 \end{array}$	$\begin{array}{c} 1.\ 001 \\ 0.\ 999 \end{array}$
P2-7	Kantonsspital Zürieh, Zürich, Switzer- land.	31	. 991
P2-8	Inštitut Jožef Stefan, Ljubljana, Yugoslavia.	18 to 30	1.028
P2-9 P2-10	Tohoku University, Sendai, Japan.	$32 \\ 32$	$1.000 \\ 1.001$
P2-11	University of Illinois, Urbana, Illinois, U.S.A.	38	1.008

The calibrations of these chambers differ for several reasons. The calibration is a function of X (g/cm²), the mass thickness of the front wall, T (cm), the total thickness of the air cavity in the ion collection assembly, and Z, the atomic number of the front-wall alloy. It is a simple matter to predict the variation with X and T. For chambers made of the same alloy, where X and T are only slightly different from the X and T for P2-4, the change in calibration is a linear function of these differences:

$$F_c = 1 + a(X_i - X_4) - b(T_i - T_4), \qquad (11)$$

where subscript *i* refers to the dimensions of chamber P2-*i*. The coefficient *a* has been determined at several values of E_{max} between 6 and 170 Mev by measuring the change in the response of P2-4 when X is changed, and is plotted in figure 16. The coefficient $b=0.20 \text{ cm}^{-1}$, the inverse of the nominal value of T.



FIGURE 16. Fractional decrease in P2-4 calibration per g/cm^2 increase in front-wall thickness.

In using eq (11), it is convenient to define X and T in terms of thicknesses and densities of the individual chamber components:

$$X = X(1) + X(4) + X(10) + 5.5X(11);$$

$$X(j) = \rho(j)t(j) \quad (12)$$

$$T = 6[\overline{T(14)} - \overline{T(11)}]$$
(13)

where the numbers in parentheses refer to the corresponding pieces in the chamber plans. $\rho(j)$ and t(j) are respectively the density (g/cm^3) and thickness (cm) of piece No. j.¹⁰ Note that eq (12) includes half the total thickness of the eleven inner plates, so that the front-wall thickness is measured to the center of the ion-collection assembly. The quantities $\overline{T}(14)$ and $\overline{T}(11)$ in eq (13) are, respectively, the average thicknesses of the spacers in the high-voltage stack of plates and of the inner plates in the collector stack.

The values of X and T are known for several of the chambers which have been intercompared, and these are listed in table 8, along with the values of F_c calculated from eq (11). The alloy densities listed indicate that the alloy compositions of these chambers are approximately the same. It can be seen from this table that the predicted F_c 's agree with the measured values to within a few tenths of one percent, which is within the uncertainties inherent in the measurements of F_c , X, and T.

TABLE 8. Physical parameters and calibration ratios of
scveral P2 chambers

Chamber	Emax	X	T	F	c	ρ
				Calculated	Measured	
P2-1 P2-2 P2-3 P2-4 P2-5 P2-9 P2-9 P2-10	Mev 32 32 32 32 32 32 32 32 32	$\begin{array}{c} g/cm^2\\ 27,30\\ 27,30\\ 27,43\\ 27,41\\ 27,25\\ 27,38\\ 27,39\end{array}$	$\begin{array}{c} cm \\ 5, 061 \\ 5, 063 \\ 5, 069 \\ 5, 062 \\ 5, 073 \\ 5, 060 \\ 5, 052 \end{array}$	$\begin{array}{c} 0.\ 998\\ .\ 997\\ .\ 999\\ 1.\ 000\\ 0.\ 995\\ .\ 999\\ 1.\ 000\\ \end{array}$	0, 996 , 995 , 998 1,000 0,994 1,000 1,001	g/cm ³ 2, 786 2, 786 2, 790 2, 790 2, 790 2, 787 2, 793 2, 794

 $^{^{10}}$ t(1), t(4), and t(10) should be measured near the centers of the corresponding pieces ,since their faces are seldom flat.

The abnormally large F_c for P2-8 (table 7) is caused by changed dimensions, since the inner plates used in this chamber are 1 mm thick instead of 0.8 mm, as specified in the chamber plans. This change should reduce T by 0.12 cm and increase X by 0.3 g/cm², which would be expected to increase the calibration by about 3 percent, in reasonable agreement with the measured increase.

The dependence of the calibrations on Z is more difficult to analyze quantitatively, since the physical interactions which determine the calibration depend upon Z in different ways. Per atom, the probability of a Compton interaction varies as Z, that for pair production varies as Z^2 , and the electron stopping power varies as Z. As an alternative approach, this effect has been investigated at several energies by replacing the removable plates of P2-4 (piece No. 4) by plates made of two different alloys, 1100 Dural (99%) pure aluminum; $\rho = 2.713$ g/cm³) and 7178 Dural (2.0% copper, 2.7% magnesium, 6.8% zinc, 0.3%) chromium; $\rho = 2.827$ g/cm³), and observing the change in calibration. The plates were machined to have the same mass thickness as the plates they replaced (19.82 g/cm^2) to eliminate the effects of changes in X. The measured changes are listed in table 9. They indicate that an increase in the alloy purity will decrease the chamber calibration below about 100 Mev and will increase it at higher energies. It must be remembered that pieces Nos. 1, 10, and 11 were not changed in these tests, so that the effect of using either of these alloys throughout the chamber will be even larger. If each of the numbers in table 9 is expressed as $1+\epsilon$, the proper number to be used for chambers constructed completely of these alloys should be about 1+1.4 ϵ , where 1.4 is the ratio [X(1)+X](4) + X(10)]/X(4).

It is tempting to use the alloy density, ρ , which can be relatively easily measured, as a rough measure of Z. There is no exact proportionality between these quantities, but addition of heavy metals usually increases both ρ and Z. Then an empirical term like

$$c(\rho_i - \rho_4)^k \tag{14}$$

could be added to eq (11) in an attempt to account for changed alloy composition. The 32-Mev data in table 9 indicates that c=0.13 and k=0.95, at least at this energy. This term would subtract 0.001 from the calculated F_c listed for P2-1, P2-2, and P2-5 in table 8 and add 0.001 to the calculated F_c for P2-9 and P2-10. These changes improve the agreement between the calculated and measured F_c in each case, but the improvement is fortuitous. It is felt that this empirical correction term should only be used as a rough indication of

TABLE 9. Effect of changing the alloy composition of the P2-4 front wall

$E_{ m max}$	$\frac{\text{Cal (1100)}}{\text{Cal (2024)}}$	Cal (7178) Cal (2024)
$\begin{array}{c} Mev \\ 6 \\ 11 \\ 18 \\ 32 \\ 70 \\ 90 \\ 120 \\ 150 \\ 170 \end{array}$	$\begin{array}{c} 1.\ 000\\ 0.\ 998\\ .\ 995\\ .\ 992\\ .\ 996\\ .\ 995\\ 1.\ 002\\ 1.\ 002\\ 1.\ 006\end{array}$	1.004

the change resulting from use of a different alloy, and should be treated skeptically if it is larger than about 0.002. The safest way to predict F_c is to use an alloy with approximately the same composition and density as 2024 Dural, so that this term is negligible.

In summary of the information presented in this section, the calibration of an arbitrary P2 chamber is related to the P2–4 calibration by

Cal (replica) =
$$F_{tp}F_fF_DF_c$$
 × Cal (P2-4). (15)

The factors F_{tp} , F_f , and F_D correct for changes in experimental conditions and can be calculated from eq (6), (7), and (9), respectively. F_c comes from eq (10) and should be measured experimentally, but can be predicted with reasonable accuracy from eq (11) if the composition of the aluminum alloy is close to that of P2-4.

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