

Absolute Calibration of X-Ray Ionization Chambers

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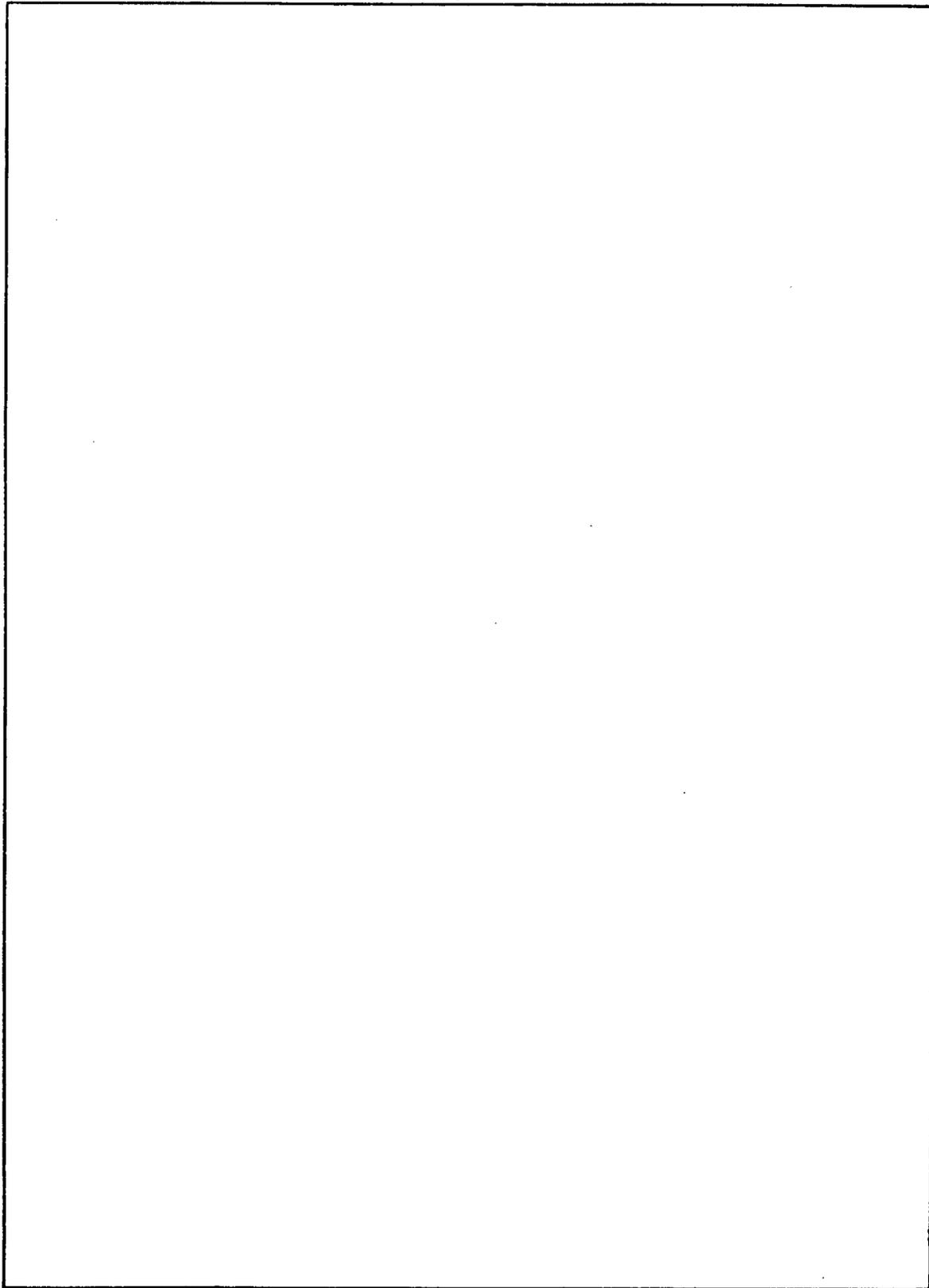
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ABSOLUTE CALIBRATION OF X-RAY IONIZATION CHAMBERS

INTRODUCTION

An ionization chamber, in its simplest form, consists of a gas-filled chamber containing two electrodes (one of which may be the chamber wall) maintained at an essentially constant potential difference. Absorption of radiation by the gas creates a number of electron-ion pairs. Upon collection of these electron-ion pairs, a current is produced between the electrodes that is proportional to the absorbed power. A typical ionization chamber designed for measuring soft x radiation from the sun is shown in Fig. 1. The window and gas are chosen in combination so as to produce a chamber sensitive over a given spectral range. The electronics schematic is shown in Fig. 2. The current between the two electrodes (anode and Faraday cage) is measured by the voltage drop across the resistor. With present ionization chamber designs, currents in response to solar x radiation are 10^{-9} to 10^{-12} A. Typical applied voltages for ion chambers range from 25 to 100 V.

To observe solar soft x radiation, it is necessary to place the measuring instrument above the highly absorbent atmosphere of the earth. The working instrument and its associated electronics are therefore not subject to any but minor changes, and long-term stability must be considered a fundamental requirement. Ionization chambers generally require polarization voltages of less than 100 V, the exact value of which is not critical. All other known measuring devices sensitive to soft x rays require polarizing voltages $\lesssim 1000$ V, the exact value of which is critical. The ionization chamber has the advantage, therefore, of inherent long-term stability. On the other hand, it has the disadvantage of producing small currents requiring sophisticated measuring devices.

A PRIORI CONSIDERATIONS

Let us now consider the response of the ionization chamber to soft x radiation in detail. Let us suppose we have F_0 photons per unit of time per area of wavelength λ incident on the ionization chamber. If the window of the chamber is of area A , the number of photons per unit of time incident on the window is $F_0 A$. The number passing through the window per unit of time is $F_0 A T_W$, where T_W is the transmission of the window(s); the number passing through the sensitive gas volume per unit of time is then $F_0 A T_W T_G$, where T_G is the transmission of the gas. The number absorbed per unit of time in the sensitive gas volume is thus $F_0 A T_W (1 - T_G)$. In the soft x-ray portion of the spectrum, photoelectric absorption accounts for essentially all the absorption that takes place. Then the transmission is given by

$$\begin{aligned} T &= \exp(-\Sigma \sigma N d) \\ &= \exp(-\Sigma \mu_m \rho x), \end{aligned}$$

Note: Manuscript submitted November 12, 1973.

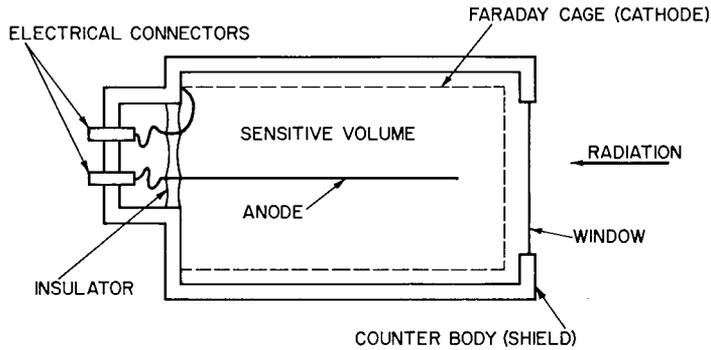


Fig. 1—Cross-sectional view of a typical ionization chamber

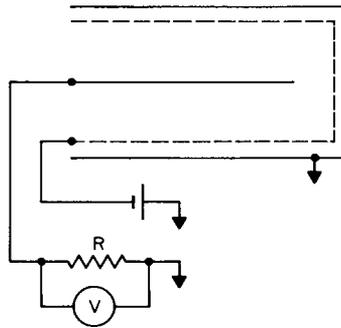
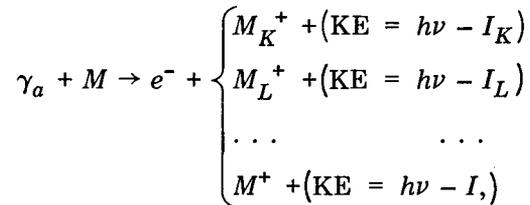


Fig. 2—Electronics schematic for an ionization chamber and its attendant circuitry

where σ is the photoelectric absorption cross section, N is the atomic number density, d is the distance through the medium, μ_m is the photoelectric mass absorption coefficient, and ρx is the area density. The sum is taken over all constituents of the material through which the photons pass.

Suppose we have a monomolecular gas M , photons γ of wavelength λ and incident energy $h\nu$, and ionization potentials I_J for ionization of the gas from the J shell. Upon the absorption of a photon, an electron-ion pair will be formed,



where M_J^+ indicates an ion with an electron vacancy in the J shell. The kinetic energy (KE) is eventually distributed, through collisions, until approximate energy equipartition is reached between ionization and kinetic energy of the ions and electrons; i.e.,

$$NI \simeq (\text{KE})_{e^-} \simeq \text{kinetic energy of ions}$$

for N additional electron-ion pairs formed. We have ignored rotational and vibrational modes of molecular kinetic energy. Thus,

$$h\nu - I_J \simeq 3NJ$$

and eventually we find

$$\gamma_a + \left\{ \begin{array}{l} (N_K + 1)M \\ (N_L + 1)M \\ \dots \\ (N + 1)M \end{array} \right\} \rightarrow \left\{ \begin{array}{l} (N_K + 1)e^- + M_K^+ + N_K M^+ + \text{kinetic energy} \\ (N_L + 1)e^- + M_L^+ + N_L M^+ + \text{kinetic energy} \\ \dots \\ (N + 1)e^- + (N + 1)M^+ + \text{kinetic energy.} \end{array} \right\}$$

Now we also note that

$$M_K^+ \rightarrow \left\{ \begin{array}{l} M_L^+ + \gamma_{KL} \\ \dots \\ M^+ + \gamma_K. \end{array} \right.$$

These results hold for M_L^+, \dots

The characteristic x-ray photons γ_{JI} may be absorbed or they may reach the walls. If they reach the chamber walls, they bring with them energy equal to $h\nu_{JI}$, which is effectively removed from further interactions. In practice, the only γ_{JI} that have a high probability of escaping to the chamber walls are for $J \equiv K$. Obviously, no γ_{KI} will be formed unless $h\nu \geq I_K$. So for $h\nu < I_K$, the number of electron-ion pairs formed for each photon absorbed is

$$N \simeq \frac{h\nu}{3I}. \tag{1}$$

For $h\nu \geq I_K$,

$$N \simeq (1 - \alpha) \frac{h\nu}{3I} + \alpha \frac{h\nu - h\nu_K}{3I} = \frac{h}{3I} (\nu - \alpha\nu_K), \tag{2}$$

where α is the product of the characteristic K x-ray fluorescence yield and its probability of reaching a chamber wall. Because the probability of reaching a chamber wall depends on the position of formation of M_K^+ , α is not independent of the incident photon energy.

While these N electron-ion pairs are being formed, they also tend to recombine. To measure the number of ion pairs, we must apply sufficient voltage to our electrodes to remove the electrons from the neighborhood of the ions before recombination can take place. On the other hand, we do not wish to give the electrons so much energy that other electron-ion pairs will be formed during a collision (gas multiplication). Figure 3

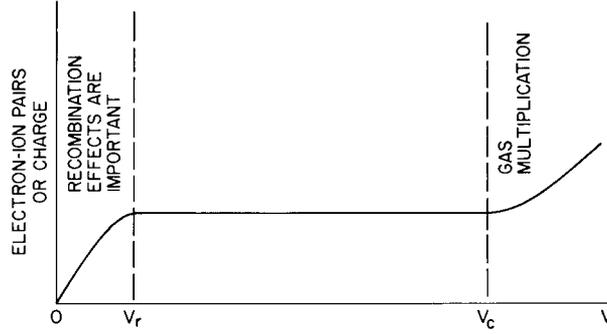


Fig. 3—Dependence of collected charge on polarizing voltage V

shows the relationship between the number of electron-ion pairs collected by the electrodes and the applied voltage. Experimentally, the determination of V_r and V_c is not difficult, and there is nearly always a very comfortable range of operating voltages.

Let us now return to our analysis of the ionization chamber response to an F_0 flux of incident photons of wavelength λ . The number of photons absorbed per unit of time was $F_0 A T_W (1 - T_G)$. The number of electron-ion pairs formed per unit of time is then

$$F_0 A T_W (1 - T_G) \frac{hc}{3I\lambda} \quad \text{for} \quad \frac{hc}{\lambda} < I_K$$

and

$$F_0 A T_W (1 - T_G) \frac{hc}{3I} \left(\frac{1}{\lambda} - \frac{\alpha(\lambda)}{\lambda_K} \right) \quad \text{for} \quad \frac{hc}{\lambda} > \frac{hc}{I_K}.$$

Thus, for an applied voltage between V_r and V_c , we would observe a current between the electrodes of

$$\bar{I} = e F_0 A T_W (1 - T_G) \frac{hc}{3I\lambda} \cdot \begin{cases} 1 & \text{for } \lambda > \frac{hc}{I_K} \\ 1 - \alpha(\lambda) \frac{\lambda}{\lambda_K} & \text{for } \lambda \leq \frac{hc}{I_K} \end{cases} \quad (3)$$

Note that the photon energy flux is $(hc/\lambda)F_0$.

We have assumed in our discussion that we have only one species of gas, that no electrons are released from the walls if a photon is absorbed there, and that only translational kinetic energy is imparted to the electron-ion pairs. Furthermore, $\alpha(\lambda)$, I , and the combination $T_W(1 - T_G)$ are difficult, if not impossible, to determine except by direct measurement of the particular ionization chamber *and* its component parts. In any case, only the ratio

$$R(\lambda) = \frac{\bar{I}}{F_0 A h c / \lambda} \quad (4)$$

must be determined to make the ionization chamber a useful instrument. Previous to the development of the following technique, this ratio was calculated, based on the properties of the material used, as measured by other workers in many fields.

DETERMINATION OF $R(\lambda)$

For later convenience we will modify Eq. (3) to read

$$\bar{I} = \epsilon_{IC}(\lambda) W Q(\lambda) \frac{F_0 h c}{\lambda} A, \quad (5)$$

where $\epsilon_{IC}(\lambda) = T_W(1 - T_G)$, the quantum efficiency of the ionization chamber;

$$W = \frac{e}{3I}$$

and

$$Q(\lambda) = \begin{cases} 1 & \text{for } \lambda > \frac{hc}{I_K} \\ 1 - \frac{\lambda \alpha(\lambda)}{\lambda_K} & \text{for } \lambda \leq \frac{hc}{I_K} \end{cases}$$

≈ 1 in most cases of interest.

Equation (4) then reads

$$R(\lambda) = \epsilon_{IC}(\lambda) W Q(\lambda). \quad (6)$$

If we had a means of measuring both the current \bar{I} and the total power $F_0 h c A / \lambda$ incident to the chamber, calibration could be accomplished; i.e., $R(\lambda)$ would be determined. The first requirement is a source of monochromatic soft x rays of convenient wavelengths λ . Typical x-ray generators bombard a target of suitable material with electrons. The radiation from the target is then of the form of continuum (Bremsstrahlung) and characteristic line radiation. If we use such a generator, the measured current from our chamber \bar{I} will include the response from both the line radiation and continuum. In this case, $R(\lambda)$ is impossible to calculate. Some means must therefore be employed to suppress the continuum, or at least separate the response to the line radiation.

If we irradiate a material with x rays from an x-ray generator (continuum and line radiation), the material will fluoresce completely in its own characteristic x rays. In addition, there will be a very small amount of reflected radiation from the generator. For the lighter elements, atomic number $Z \leq 10$, only characteristic K x rays will be emitted, and reflection will be very small. Unfortunately, the only pure elements of $Z \leq 10$ that are

solids are Li, Be, B, and C, of which only B and C give K x rays $< 100\text{\AA}$ (67\AA and 44\AA respectively). Characteristic L x rays could also be used ($Z \geq 15$), but the emission is very small unless the undesirable K x rays are also produced. So for wavelengths $< 44\text{\AA}$ some other means must be found to produce a monochromatic x-ray beam. This is most easily accomplished with an x-ray generator and a Bragg crystal spectrometer, diffraction from which obeys the relation

$$n\lambda = 2d \sin \theta$$

where n is the order of diffraction, d is a constant of the crystal, and θ is the angle between the crystal diffraction planes and the incident (and the diffracted) beam. With such a device, continuum as well as characteristic line radiation can be used; but continuum did not prove useful in our measurements. Care must be taken to insure that the measured response \bar{I} , is due only to the radiation of interest (line radiation, in this case), not to any other (e.g., radiation at some other order of diffraction). We found that the response due to continuum was easily discernible from that due to the line radiation by scanning over a range of angles θ .

Now that we have means to find the response \bar{I} to x rays of given wavelengths, we must determine $F_0 A h c / \lambda$, the incident energy per unit of time, or, alternatively, $F_0 A$, the number of incident photons per unit of time. There are a number of instruments capable of counting photons, the most useful in our case being a proportional counter that, with its associated electronics, was capable of rates as high as 10,000 absorbed photons per second. We now have a further difficulty: we can only hope to determine the product $F_0 A$ or, if the incident beam is nonuniform, $\int F_0 dA$. We are calibrating the ionization chamber with a proportional counter, and the geometries (hence the areas A) are (and must be) different. We may then either produce a uniform beam (F_0 constant) over the windows of both the ion chamber and proportional counter (in which case we need only the ratio of window areas) or produce a beam small enough that $\int F_0 dA$ is the same for both the proportional counter and the ionization chamber. The former is used in the case of the fluorescent source; the latter in the case of the crystal spectrometer (by introducing appropriate stops).

The number of absorbed photons per unit of time in the proportional counter is, in general,

$$N_t = \epsilon_{PC} (\int F_0 dA)_{PC}$$

(where ϵ_{PC} is the proportional counter quantum efficiency), while

$$\bar{I} = \epsilon_{IC} W Q \frac{hc}{\lambda} (\int F_0 dA)_{IC}$$

in response to monochromatic radiation. We may then write

$$\begin{aligned}\epsilon_{\text{IC}} WQ \frac{hc}{\lambda} &= R(\lambda) \frac{hc}{\lambda} \\ &= \epsilon_{\text{PC}} \frac{\bar{I}}{N_t} \frac{(fF_0 dA)_{\text{PC}}}{(fF_0 dA)_{\text{IC}}}\end{aligned}$$

For the case of the fluorescent source,

$$R(\lambda) \frac{hc}{\lambda} = \epsilon_{\text{PC}} \frac{\bar{I}}{N_t} \frac{A_{\text{PC}}}{A_{\text{IC}}}, \quad (7)$$

and for the spectrometer case,

$$R(\lambda) \frac{hc}{\lambda} = \epsilon_{\text{PC}} \frac{\bar{I}}{N_t}. \quad (8)$$

The one remaining unknown is ϵ_{PC} . A description of the proportional counter and the method used to determine ϵ_{PC} are contained in Appendix A.

To better understand the problem, let us insert some typical values. For most gases, $hcW = (3 \text{ to } 6) \times 10^{-17} \text{ C-Å}$; therefore,

$$\bar{I} = \frac{(3 \text{ to } 6) \times 10^{-17}}{\lambda} \frac{\epsilon_{\text{IC}}}{\epsilon_{\text{PC}}} \frac{(fF_0 dA)_{\text{IC}}}{(fF_0 dA)_{\text{PC}}} N_t,$$

where λ is in Angstroms.

For a fluorescent source,

$$\bar{I} = \frac{(3 \text{ to } 6) \times 10^{-17}}{\lambda} \frac{\epsilon_{\text{IC}}}{\epsilon_{\text{PC}}} \frac{A_{\text{IC}}}{A_{\text{PC}}} N_t,$$

and for the spectrometer,

$$\bar{I} = \frac{(3 \text{ to } 6) \times 10^{-17}}{\lambda} \frac{\epsilon_{\text{IC}}}{\epsilon_{\text{PC}}} N_t.$$

Because of electronic limitations, we are restricted to $N_t \lesssim 2 \times 10^4$ per second; and in order for either device to be useful,

$$0.05 \lesssim \epsilon_{\text{IC}} \leq 1$$

and

$$0.05 \lesssim \epsilon_{\text{PC}} \leq 1.$$

With these restrictions, we find expected upper limits of

$$\bar{I} = \lesssim \frac{10^{-11} A_{IC}}{\lambda A_{PC}}$$

for the fluorescent source and

$$\bar{I} \lesssim \frac{10^{-11}}{\lambda}$$

for the spectrometer source. In fact, because of power limitations in the x-ray generator, typical currents were more nearly 10^{-14} A in x-ray line peaks and 10^{-14} to 10^{-15} A in the continuum to be subtracted. Such low currents are difficult to measure even with vibrating capacitor electrometers, and great care must be taken to minimize contact potentials, signal lead motion, and all other sources of stray currents. For our measurements we used a Keithley Model 640 Vibrating Capacitor Electrometer. This has a remote head containing the vibrating capacitor and its attendant high impedance circuitry. To reduce atmospheric effects and electronics noise, the remote head was encased in a dry nitrogen atmosphere and placed as close to the ionization chambers under test as possible. (In the spectrometer case, this was within the vacuum enclosure containing the spectrometer.)

Using Eqs. (7) and (8), we have determined the value of $R(\lambda)$ for several ionization chambers at several wavelengths, as shown in Figs. 4-9. We then set (see Eq. (6))

$$R(\lambda) = T_W(1 - T_G)W, \quad (9)$$

where

$$T = \exp(-\sum \mu_m \rho x).$$

Here μ_m is the mass absorption coefficient and ρx is the area density. The sum is taken over all the constituents of the material through which the photons pass. Curves of the form of Eq. (9) were fitted to the data (also shown in Figs. 4-9), giving us an *effective* conversion factor, relating energy flux and current. The parameters resulting from the fitting procedure are shown in Table 1 together with the parameters previously used. The values of the mass absorption coefficients used in the fitting are from Veigele.*

CONCLUSIONS

We can draw several general conclusions from the parameters in the table even though the fitted parameters lack meaning except when used in Eq. (9). In every case, there is a

*W.J. Veigele, Photon Cross Sections from 0.1 keV to 1 MeV for Elements Z=1 to Z=94. *Atomic Data* 5, 51-111 (1973).

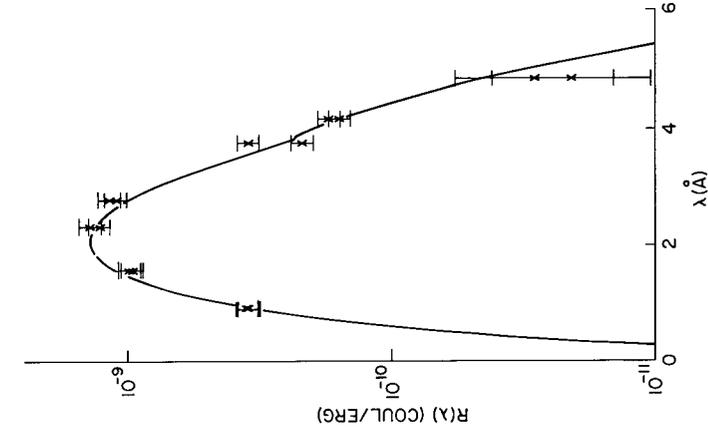


Fig. 5—Dependence of the conversion factor $R(\lambda)$ on wavelength for two 1- to 5-Å ionization chambers. x = data point. Approximate error bars are shown.

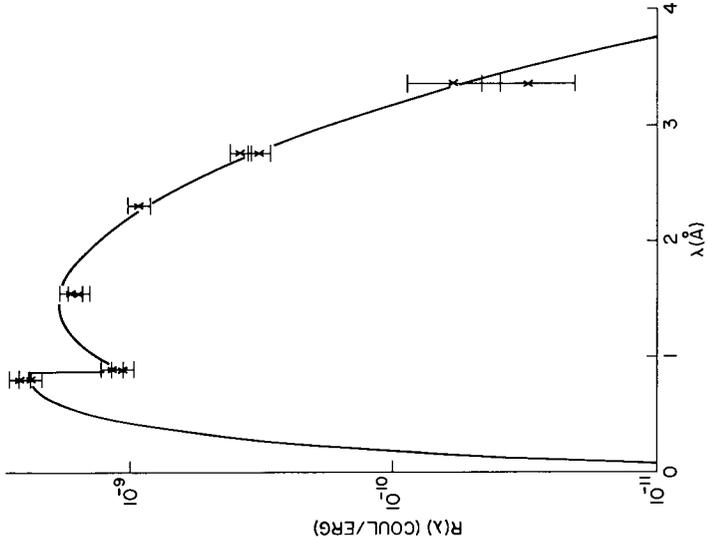


Fig. 4—Dependence of the conversion factor $R(\lambda)$ on wavelength for two 0.5- to 3-Å ionization chambers. x = data point. Approximate error bars are shown.

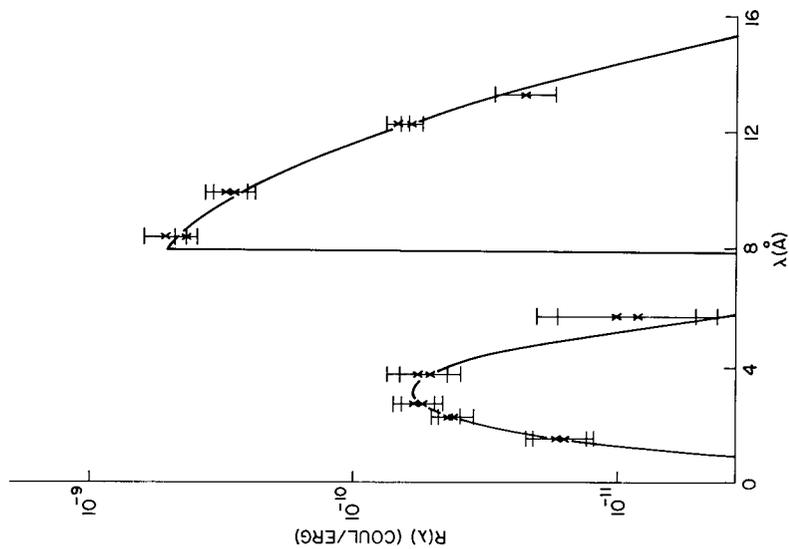


Fig. 7—Dependence of the conversion factor $R(\lambda)$ on wavelength for two 8- to 16- \AA ionization chambers. x = data point. Approximate error bars are shown.

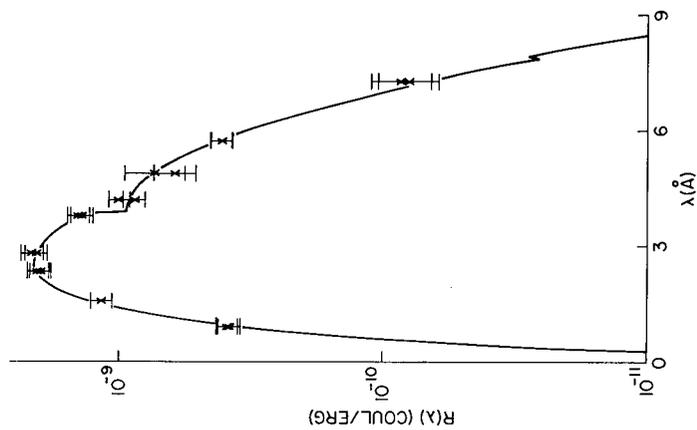


Fig. 6—Dependence of the conversion factor $R(\lambda)$ on wavelength for two 1- to 8- \AA ionization chambers. x = data point. Approximate error bars are shown.

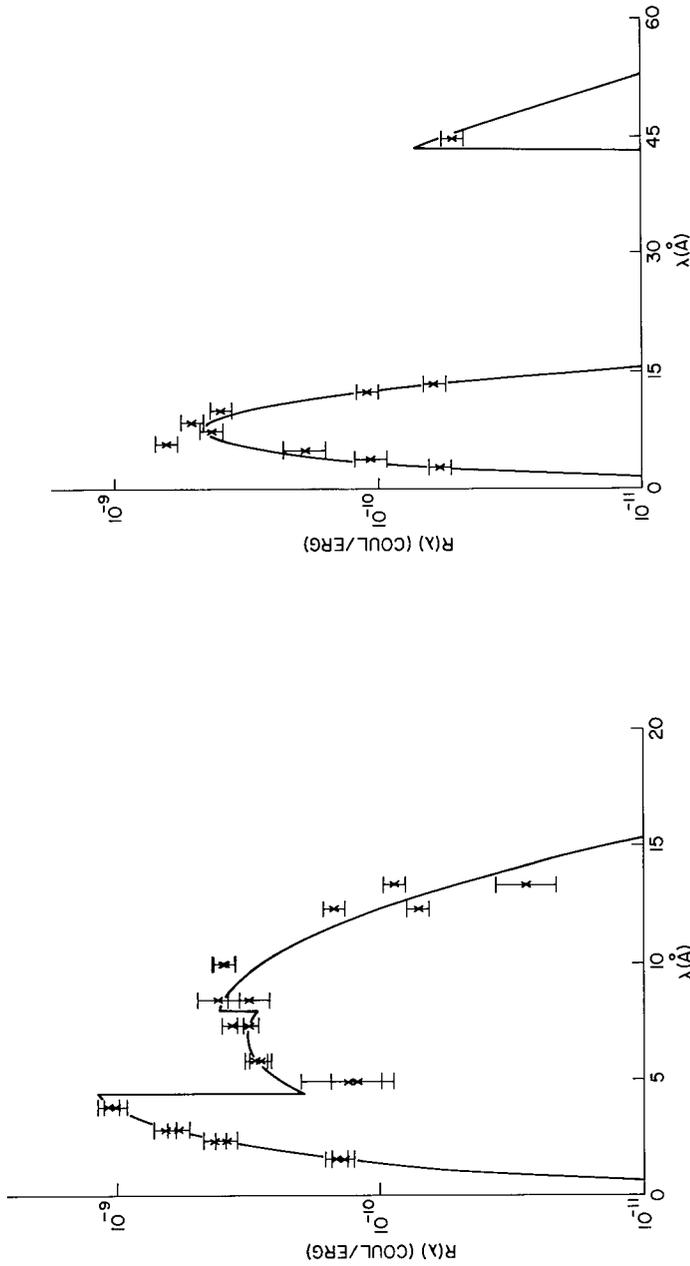


Fig. 9—Dependence of the conversion factor $R(\lambda)$ on wavelength for a 44- to 60-Å ionization chamber. x = data point. Approximate error bars are shown.

Fig. 8—Dependence of the conversion factor $R(\lambda)$ on wavelength for two 1- to 20-Å ionization chambers. x = data point. Approximate error bars are shown.

Table 1
Comparison of Fitted and Previously Assumed Parameters

Ionization Chamber Range (Å)	Constituents*	Previously Assumed Parameters*		Fitted Parameters		Figure Number
		Area Density (g/cm ²)	W/e (ion pairs/erg)	Area Density (g/cm ²)	W/e (ion pairs/erg)	
0.5 to 3	Windows: Be Al Kr Sensitive gas: Kr	0.247 2.7 × 10 ⁻⁵ 7.0 × 10 ⁻⁴ 1.89 × 10 ⁻²	2.57 × 10 ¹⁰	0.301 1.59 × 10 ⁻⁴ 8.62 × 10 ⁻⁴ 2.38 × 10 ⁻²	1.94 × 10 ¹⁰	4
1 to 5	Windows: Be Al Ar Sensitive gas: Ar	0.1003 2.7 × 10 ⁻⁵ 1.7 × 10 ⁻⁴ 4.52 × 10 ⁻³	3.38 × 10 ¹⁰	0.105 1.80 × 10 ⁻⁵ 4.38 × 10 ⁻⁴ 6.40 × 10 ⁻³	1.54 × 10 ¹⁰	5
1 to 8	Windows: Be Al Ar Sensitive gas: Ar	2.63 × 10 ⁻² 2.7 × 10 ⁻⁵ 1.7 × 10 ⁻⁴ 4.52 × 10 ⁻³	2.38 × 10 ¹⁰	2.82 × 10 ⁻² 4.48 × 10 ⁻⁵ 1.51 × 10 ⁻⁴ 5.97 × 10 ⁻³	1.70 × 10 ¹⁰	6
8 to 16	Windows: Al N ₂ Sensitive gas: N ₂	2.44 × 10 ⁻³ 1.42 × 10 ⁻⁴ 1.67 × 10 ⁻³	1.8 × 10 ¹⁰	2.75 × 10 ⁻³ 1.49 × 10 ⁻⁴ 1.25 × 10 ⁻³	1.38 × 10 ¹⁰	7
1 to 20	Windows: Mylar Al CCl ₄ Sensitive gas: CCl ₄	8.5 × 10 ⁻⁴ 6.3 × 10 ⁻⁵ 5.27 × 10 ⁻⁵ 6.19 × 10 ⁻⁴	2.13 × 10 ¹⁰	9.87 × 10 ⁻⁴ 8.58 × 10 ⁻⁵ 5.22 × 10 ⁻⁵ 5.83 × 10 ⁻⁴	1.63 × 10 ¹⁰	8
44 to 60	Windows: Mylar N ₂ Sensitive gas: N ₂	8.5 × 10 ⁻⁴ 6.05 × 10 ⁻⁵ 7.1 × 10 ⁻⁴	1.8 × 10 ¹⁰	9.58 × 10 ⁻⁴ 6.75 × 10 ⁻⁵ 6.18 × 10 ⁻⁴	1.63 × 10 ¹⁰	9

*D.M. Horan and R.W. Kreplin, "The SOLRAD 10 Satellite, Explorer 44, 1971-058A," NRL Report 7408, July 12, 1972.

shift in the sensitive range of the ionization chambers to shorter wavelengths (indicated by the larger area densities). The number of ion pairs formed per erg is also consistently lower than previously assumed. These effects can be accounted for by assuming that the photons, upon collision with the back wall of the chamber, release energy to the gas; that the absorbing gas is not pure, but rather contains unknown contaminants; and that the windows are more absorbent than previously assumed. In any case, measurement of the conversion factor $R(\lambda)$ is necessary for the accurate determination of incident photon fluxes.

Appendix A

DESCRIPTION OF THE STANDARD PROPORTIONAL COUNTER

We will first describe the method used to determine the proportional counter quantum efficiency ϵ_{PC} because its experimental determination affects the design of the proportional counter itself. We use two counters, one behind the other, as shown in Fig. A1. The standard counter is detector 1, the quantum efficiency of which we desire to determine. We will see that the double windows (one behind the other) of detector 1 are required and must be identical. In common with an ionization chamber, a proportional counter must contain two electrodes. To produce a measurable pulse upon absorption of a photon, however, the proportional counter must be operated in the gas multiplication region. For gas multiplication to take place, very high fields must be produced. This is customarily accomplished by making the anode diameter very small, placing it within the cathode, and applying potentials in excess of 1000 V. There are many other general requirements of a good proportional counter that we will not discuss in this document.*

We used organic gas quenches and thin wires for our anodes, resulting in a very stable proportional counter with an operating range in excess of 500 V. From Fig. A1, it is obvious that the anodes could not be placed between the two windows because the x-ray beam would then be obstructed. The quantum efficiency of detector 1 to soft x rays is then simply given as

$$\epsilon_{PC} = T_W(1 - T_G) \quad (A1)$$

where T_W and T_G are the transmission of one window and the gas, respectively. We first measure the count rate of detector 2 with detector 1 out of the x-ray beam. This gives

$$R_1 = \epsilon_2 F_0.$$

We next measure the response of detector 2 with detector 1 in the beam, but having no gas filling:

$$R_2 = \epsilon_2 T_W^2 F_0.$$

Finally, we measure the response of detector 2 with detector 1 filled to its operating gas pressure:

$$R_3 = \epsilon_2 T_W^2 T_G F_0.$$

*The reader is referred to J. Sharpe, *Nuclear radiation detectors*, W.L. Worsnop, editor, Methuen and Co., London, 1964.

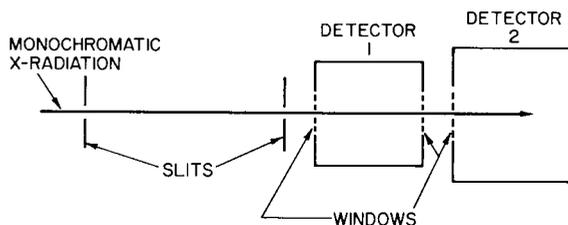


Fig. A1—The arrangement used to determine the quantum efficiency of detector 1

Then we find

$$\epsilon_{PC} = \left(\frac{R_2}{R_1}\right)^{1/2} \left(1 - \frac{R_3}{R_2}\right). \tag{A2}$$

We also note that the response of detector 1 is

$$R = F_0 \epsilon_{PC};$$

hence,

$$\epsilon_2 = \epsilon_{PC} \frac{R_1}{R}.$$

Great care must be taken to insure that F_0 remains constant for all measurements and that when used, all of the photons absorbed in the proportional counter must be electronically counted. With our particular instruments, the error in counted pulses was less than 1 percent.

Placement of the anode wires is shown in Fig. A2. The one possible drawback of this design is that ion pairs formed within the square defined by the anode wires might suffer no acceleration because the electric field may be zero there. In the vicinity of the anode wires, the field is inversely proportional to the distance from the center of the wire, so that once the electrons move to the vicinity of the wire, gas multiplication takes place just as in any counter with only one anode. We describe our detector as a box grounded at $x = 0, y = 0, z = 0, x = b, y = b,$ and $z = c$. The box contains wires parallel to the z axis of radius a and potential V . Then the potential throughout the counter is given by

$$\begin{aligned} \phi = & -\frac{16V}{\pi} \sum_{\substack{n=1 \\ \text{odd}}}^{\infty} \frac{1}{n} \sin \frac{n\pi z}{c} \\ & \sum_{\substack{l,m=1 \\ \text{odd}}}^{\infty} (-1)^{\frac{l+m}{2}} \frac{\sin l\pi x/b \sin m\pi y/b \cos m\pi/4 \cos l\pi/4}{l^2/b^2 + m^2/b^2 + n^2/c^2} \\ & \times \frac{J_0(K_{lm} a)}{\sum_{\substack{l,m=1 \\ \text{odd}}}^{\infty} \frac{J_0(K_{lm} a)}{l^2/b^2 + m^2/b^2 + n^2/c^2}} \end{aligned}$$

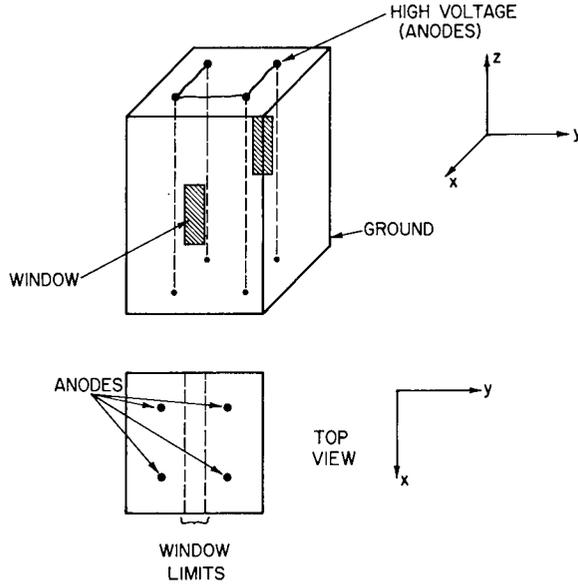


Fig. A2—The proportional counter used as a reference

if $a \ll b$ and $a \ll c$ and where J_0 is the Bessel function of order zero and

$$K_{lm} = \frac{\pi}{b} (l^2 + m^2)^{1/2}$$

If c is large enough ($\gtrsim 4b$), the series on n may be ignored for $z \simeq c/2$. The potential has been mapped for this case in Fig. A3. Figure A4 shows the potential as a function of y for $x = b/4$. Note the minimum at $y = b/2$.

We wish to find the force on electron-ion pairs formed between the two windows. In particular, we desire to determine the component of the force away from the plane $y = b/2$. This force is proportional to the y component of the electric field E_y . We find that in the immediate vicinity of $y = b/2$, E_y is proportional to the distance from the plane, so that if electron-ion pairs are formed in the plane $y = b/2$, there is no y component of the force; but the electron-ion pairs are in a condition of unstable equilibrium and in fact will be collected eventually. By making V large enough, the collection will take place before recombination can occur. We have checked the counter configuration empirically by comparing the results obtained with the counter as shown in Fig. A2 with the results obtained after inserting a ground plane in the counter to one side of the windows. No significant ($\gtrsim 1$ percent) difference was observed.

The proper operating voltage V is found experimentally by simply increasing the applied voltage until no increase in the number of counted pulses is observed. We define this as the threshold voltage V_T , as shown in Fig. A5. When the ions reach the cathode, they recombine, but their excess energy may take the form of ultraviolet (uv) photons. These may be absorbed in the gas (a process that may also occur when electrons reach the anode), or—if the excess energy is higher than the work function of the cathode material—it may take the form of electrons, which are accelerated to the anode. These

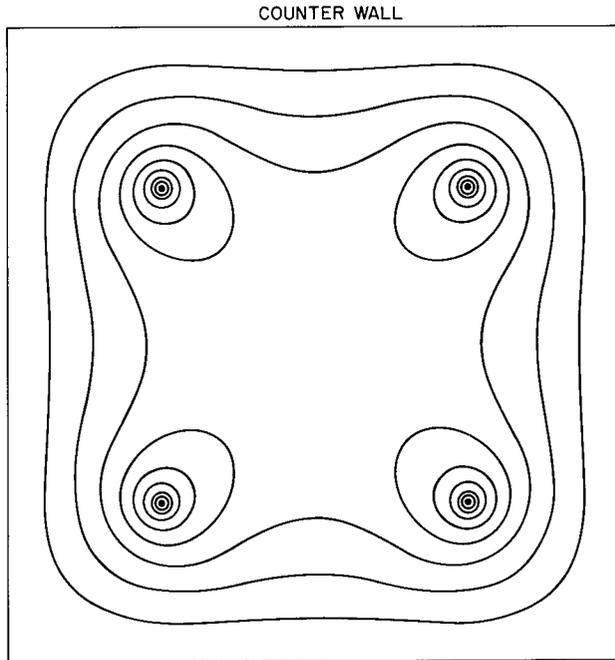


Fig. A3 — Potential contours of the reference proportional counter. The contour levels are in steps of $1/10$ the applied voltage, the 0 contour being the counter walls (the $9/10$ contour has been deleted for clarity). The anode wires are indicated by the heavy dot in the center of the innermost contours. Compare with Fig. A2.

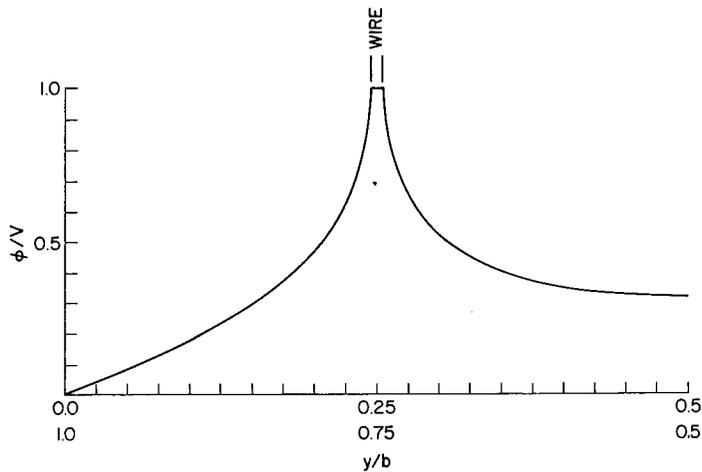


Fig. A4 — The potential of the reference proportional counter as a function of y when $x = b/4$ or $x = 3b/4$. Compare with Figs. A2 and A3. Because of symmetry, x may be interchanged with y .

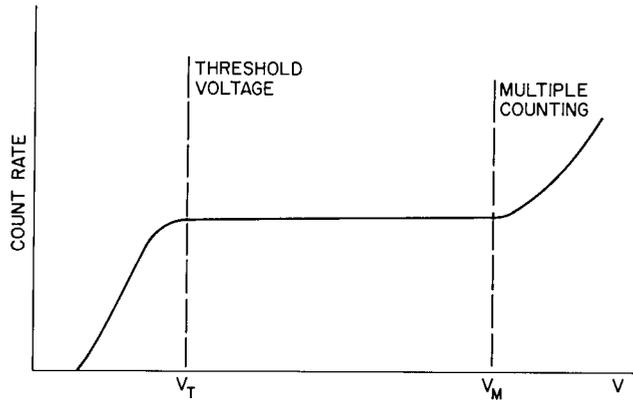


Fig. A5—Count rate in a proportional counter as a function of applied voltage

electrons and uv photons can produce counts in addition to and triggered by the initial event (multiple counting, $V > V_M$). The proper choices of quench and cathode and anode materials suppress these effects unless the excess energy (a function of V) is too high. The proper operating voltage is somewhere between V_T and V_M ; and as long as the slope of the plateau is small, the relation given by Eq. (A2) will be correct to well within 1 percent.