

Ionization Chambers IV

Ion-Chamber Saturation and Ionic
Recombination

Ionization, Excitation, and W

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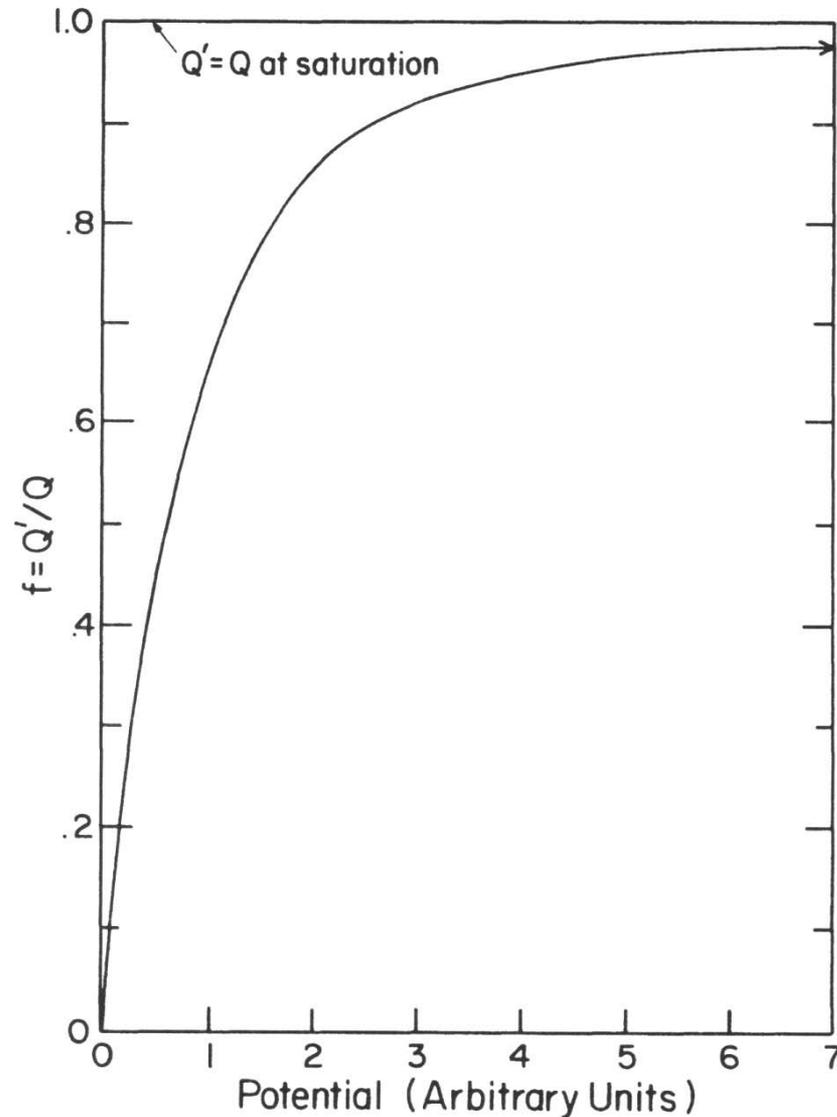
Charge Produced vs. Charge Collected

- The absorbed dose deposited in a gas by ionizing radiation is proportional to the charge Q *produced* in the gas
- In any practical case the charge Q that is *collected* by the biased electrode in the chamber and measured by the electrometer circuit is less than Q , because of recombination of some positive and negative ions within the gas

Charge Produced vs. Charge Collected (cont.)

- An ion chamber is said to be *saturated* to the degree that such ionic recombination is absent
- Increasing the ion-collecting potential applied to the chamber generally reduces recombination and asymptotically approaches saturation
- The following diagram illustrates the typical variation of the collected charge Q as a function of applied potential

Variation of ionization charge Q collected from an ion chamber vs. applied potential. Q is the charge produced by radiation.



Charge Produced vs. Charge Collected (cont.)

- It is not possible to increase the applied potential indefinitely to eliminate recombination altogether, because of the onset of either
 - a) electrical breakdown of insulators, or
 - b) gas multiplication, in which the free electrons gain enough kinetic energy from the electrical field within their mean free path in the gas to ionize the next atom they encounter

Charge Produced vs. Charge Collected (cont.)

- It is necessary to estimate the magnitude of the charge deficiency $Q - Q_c$, or of the *collection efficiency* $f = Q_c / Q$, and make a correction to obtain the charge Q produced in an ion chamber
- This can be done simply in practice in most cases, assuming that the ion-chamber volume does not contain low-field “pockets” of persistent recombination as a result of poor geometry
 - Internal corners should be rounded, not sharp, and the ends of a cylindrical chamber should be hemispherical rather than flat

Initial or Columnar Recombination

- This process occurs when the + and – ions formed in the same charged-particle track meet and recombine
- It is independent of dose or dose rate, since the number of tracks occurring per unit volume of gas does not influence the recombination within a given track, unless the space-charge density becomes so great that the electric field strength is weakened, or the tracks begin to overlap

Initial Recombination (cont.)

- Initial recombination is most likely to occur in densely ionized tracks, that is, for high-LET tracks such as those of α -particles
- It may also be important for electron tracks in high-pressure gases, but is negligible for electrons at 1 atm or less with collecting fields > 100 V/cm

General or Volume Recombination

- This occurs when ions from different tracks encounter each other on their way to the collecting electrodes
- The amount of this type of recombination that occurs depends on how many ions are created per unit volume and per unit time
- Consequently general recombination is dose-rate-dependent, since a greater density of ions of both signs moving past each other increases the probability that they will recombine

Types of Gases

- A free electron produced in an ionizing event may become attached to a neutral gas atom, thus making a negative *ion*
- This is likely to happen in *electronegative* gases, for example, O₂, air, SF₆, Freon 12, and other gases containing even small amounts of O₂, H₂O, NH₃, HCl, SiF₄, or the halogens

Types of Gases (cont.)

- It is difficult in practice to be certain that a gas is free enough of unwanted impurities to allow nonelectronegative behavior (no electron attachment)
- However in pure form N_2 , CO_2 , H_2 , Ar, He, methane, ethylene, BF_3 , butane, and methane-based TE gas are nonelectronegative

Types of Gases (cont.)

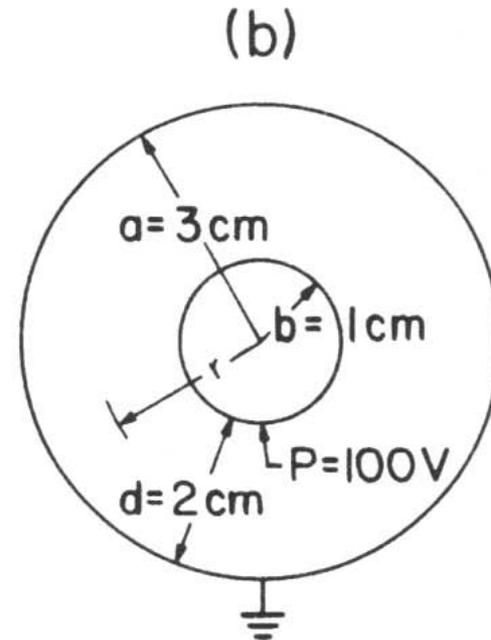
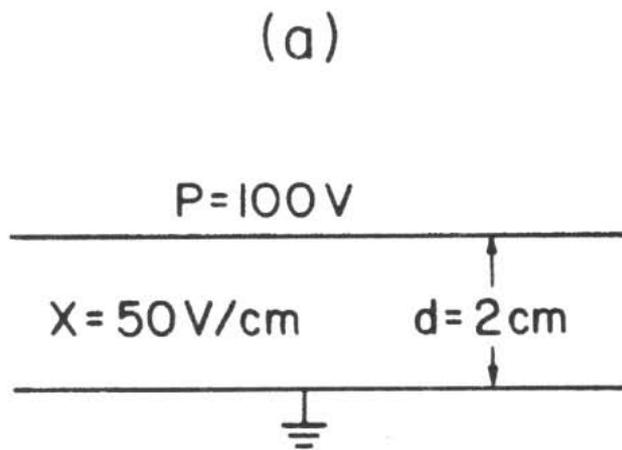
- In general it is much easier to saturate an ion chamber containing a nonelectronegative gas
- This is because the drift velocity of a free electron under normal ambient conditions is $\sim 10^3$ cm/s per V/cm, while that of a negative ion is only about 1 cm/s per V/cm
- Free electrons can be cleared out of the ion chamber so rapidly that they have little chance to recombine with the positive ions, even with usual applied potentials ($\sim 10^2 - 10^3$ V/cm)

Electric Field Strength vs. Chamber Geometry

1. Plane-parallel chambers have uniform field strength $E = P/d$ throughout the chamber volume
2. Cylindrical chamber geometry can be characterized in terms of a , the radius of the outer electrode; b , the radius of the inner electrode; $E(r)$, the field strength at radius r ; and the applied potential P

$$E(r) = \frac{P}{r \ln(a/b)}$$

Comparing electric field strengths in plane-parallel vs. cylindrical vs. spherical ion chambers: (a) plane-parallel geometry, (b) cylindrical or spherical geometry.



Electric Field Strength (cont.)

3. Spherical geometry is also illustrated by *(b)* in the diagram

In that case the field at radius r is given by

$$\mathbf{E}(r) = \frac{Pab}{r^2 (a - b)}$$

Electric Field Strength (cont.)

- The weakening of the electric field throughout a large part of the volume in cylindrical and spherical chambers, compared to plane chambers of the same electrode separation, requires a higher value of P to produce the same ion-collection efficiency, as will be discussed in the next section

Boag's Treatment of Mie's Theory of General or Volume Recombination for Constant Dose Rate in an Electronegative Gas such as Air

- The general equation for the charge-collection efficiency $f = Q / Q$ for constant dose rate in a continuous radiation field is

$$f = \frac{1}{1 + \frac{1}{6} \xi^2}$$

in any ion chamber containing electronegative gas (e.g., air), and where $f \geq 0.7$

Mie's Theory (cont.)

- For plane-parallel chambers, the dimensionless quantity ξ is given by

$$\xi = \sqrt{\frac{\alpha}{ek_1k_2}} \cdot \frac{d^2 \sqrt{q}}{P} \equiv m \frac{d^2 \sqrt{q}}{P}$$

where $m =$ a gas constant, $36.7 \text{ V}^{s1/2} \text{ cm}^{-1/2} \text{ esu}^{-1/2}$ for air at STP,

$d =$ plate separation (cm),

$q = Q/vt$ (esu/cm³ s),

$P =$ applied potential (V),

$\alpha =$ recombination coefficient (cm³/s),

$e =$ electron charge = 4.8032×10^{-10} esu,

$k_1 =$ mobility of positive ions (cm²/Vs),

$k_2 =$ mobility of negative ions (cm²/Vs),

$v =$ volume of ion chamber (cm³), and

$t =$ irradiation duration, assumed to be long compared to the ion-transit time of ~ 1 ms

Mie's Theory (cont.)

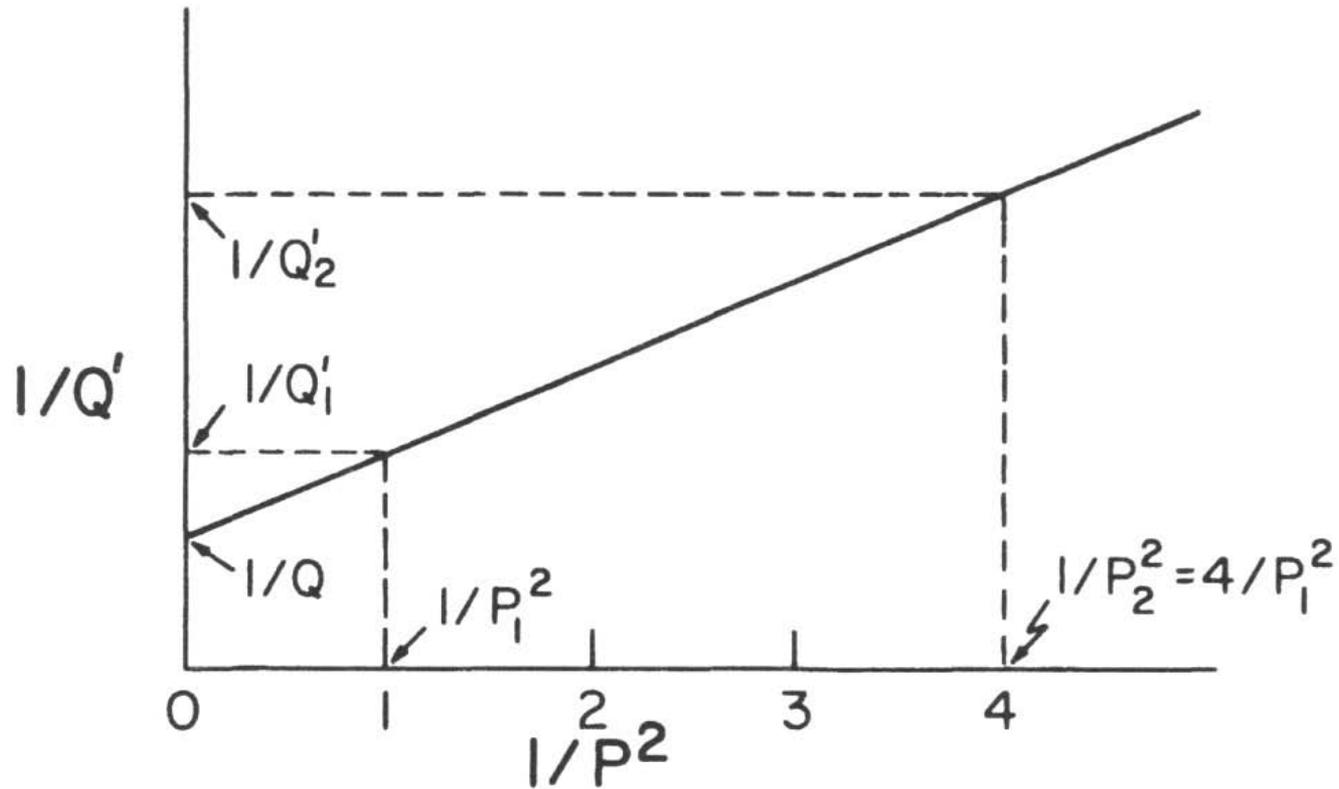
- The equation for f reduces to

$$\frac{1}{Q'} = \frac{1}{Q} + \frac{m^2 d^4}{6vt} \cdot \frac{1}{P^2} = \frac{1}{Q} + \frac{c}{P^2}$$

where $c = m^2 d^4 / 6vt$ is a constant

- This equation predicts that $1/Q$ values measured at several values of P can be extrapolated to $1/P^2 = 0$ to obtain $1/Q$, that is, to correct for general recombination in the case of continuous irradiation
- The following diagram illustrates this

Graph of the equation for $1/Q$, illustrating the extrapolation to $1/P^2 = 0$, yielding $1/Q$



Mie's Theory (cont.)

- For cylindrical chambers ξ is given by

$$\xi_{\text{cyl}} = m \frac{\left[(a-b) K_{\text{cyl}} \right]^2 \sqrt{q}}{P}$$

where a and b are the outer and inner electrode radii, respectively, and K_{cyl} is given by

$$K_{\text{cyl}} = \left\{ \frac{(a/b) + 1}{(a/b) - 1} \cdot \frac{\ln(a/b)}{2} \right\}^{1/2}$$

Mie's Theory (cont.)

- For spherical-geometry chambers the corresponding ξ is given by

$$\xi_{\text{sph}} = m \frac{\left[(a-b) K_{\text{sph}} \right]^2 \sqrt{q}}{P}$$

in which K_{sph} is defined as

$$K_{\text{sph}} = \left\{ \frac{1}{3} \left(\frac{a}{b} + 1 + \frac{b}{a} \right) \right\}^{1/2}$$

Mie's Theory (cont.)

- In cylindrical and spherical geometries, increasing the applied potential to a value of $K^2_{\text{cyl}}P$ or $K^2_{\text{sph}}P$, respectively, produces the same collection efficiency as for a plane chamber with $d = a - b$ and potential P

Extrapolation for Initial Recombination

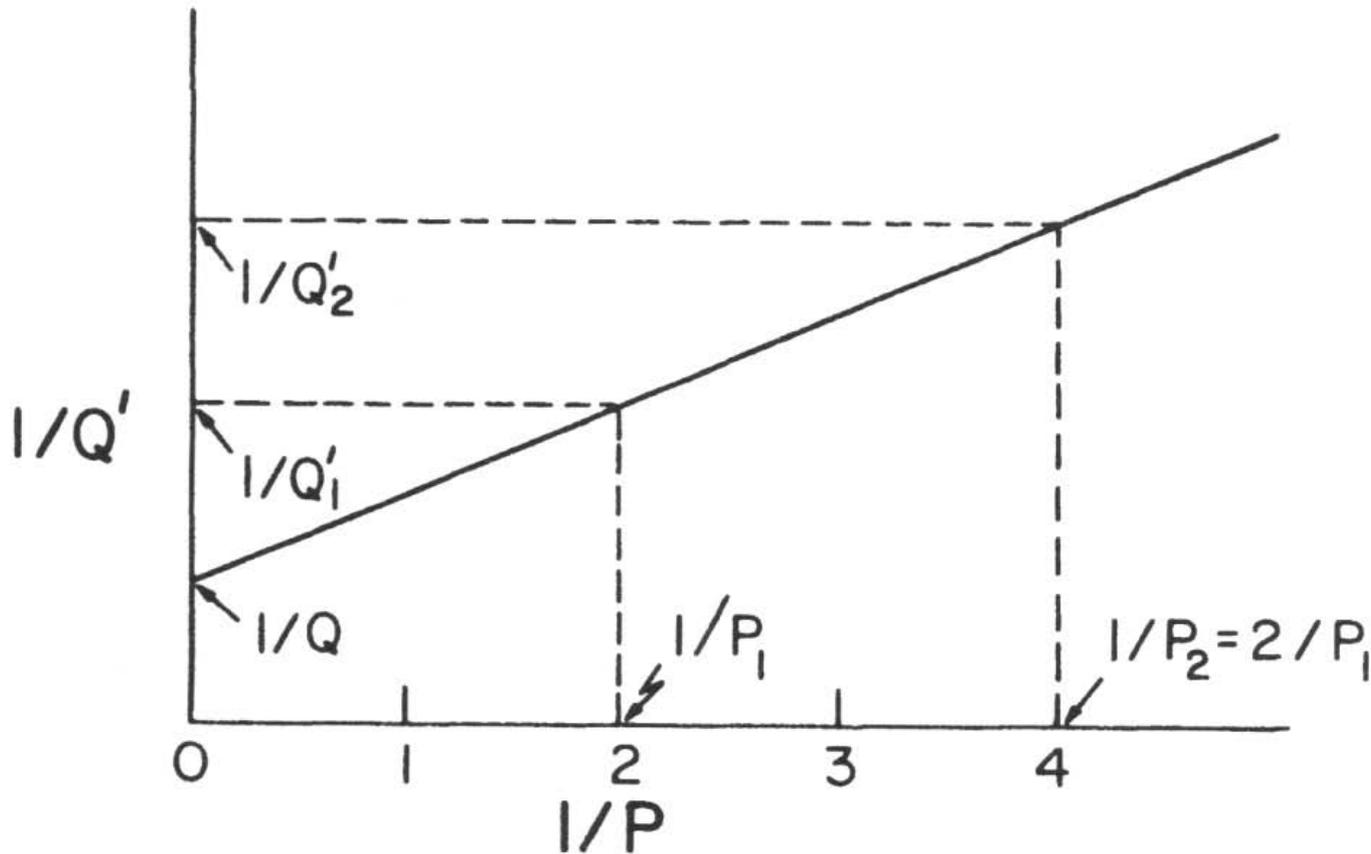
- In case volume recombination is negligible and only initial recombination remains, the Jaffe-Zanstra theory predicts for an electronegative gas that

$$\frac{1}{Q'} = \frac{1}{Q} + \frac{c'}{P}$$

where c is a constant and P is the applied potential

- In this case the type of plot shown in the following diagram is used in obtaining Q

Graph of $1/Q$, illustrating the extrapolation to $1/P = 0$, yielding $1/Q$. The charge Q can be determined for initial recombination with either pulsed or continuous radiation, or for general recombination with pulsed radiation only.



Initial Recombination (cont.)

- A straight-line region of $1/Q$ vs. $1/P$ occurs when the potential gets large enough to virtually eliminate volume recombination, leaving some initial recombination
- This is only significant for high-LET radiation, high-pressure gas, or both

Pulsed Radiation

- The pulses are assumed to be short compared to the ion transit time ($\sim 10^{-3}$ s), and the repetition rate must be slow enough so ions can clear out between pulses
- For the case where many pulses occur during the ion transit time, one can approximate by using the continuous radiation theory of ionic recombination, referred to the *time-averaged* value for q
- If pulses are very long compared to the transit time, continuous radiation theory applies

Pulsed Radiation (cont.)

- In Boag's treatment of short pulses

$$f = \frac{1}{u} \ln(1 + u)$$

where

$$u = \frac{\alpha / e}{k_1 + k_2} \cdot \frac{\rho d^2}{P}$$

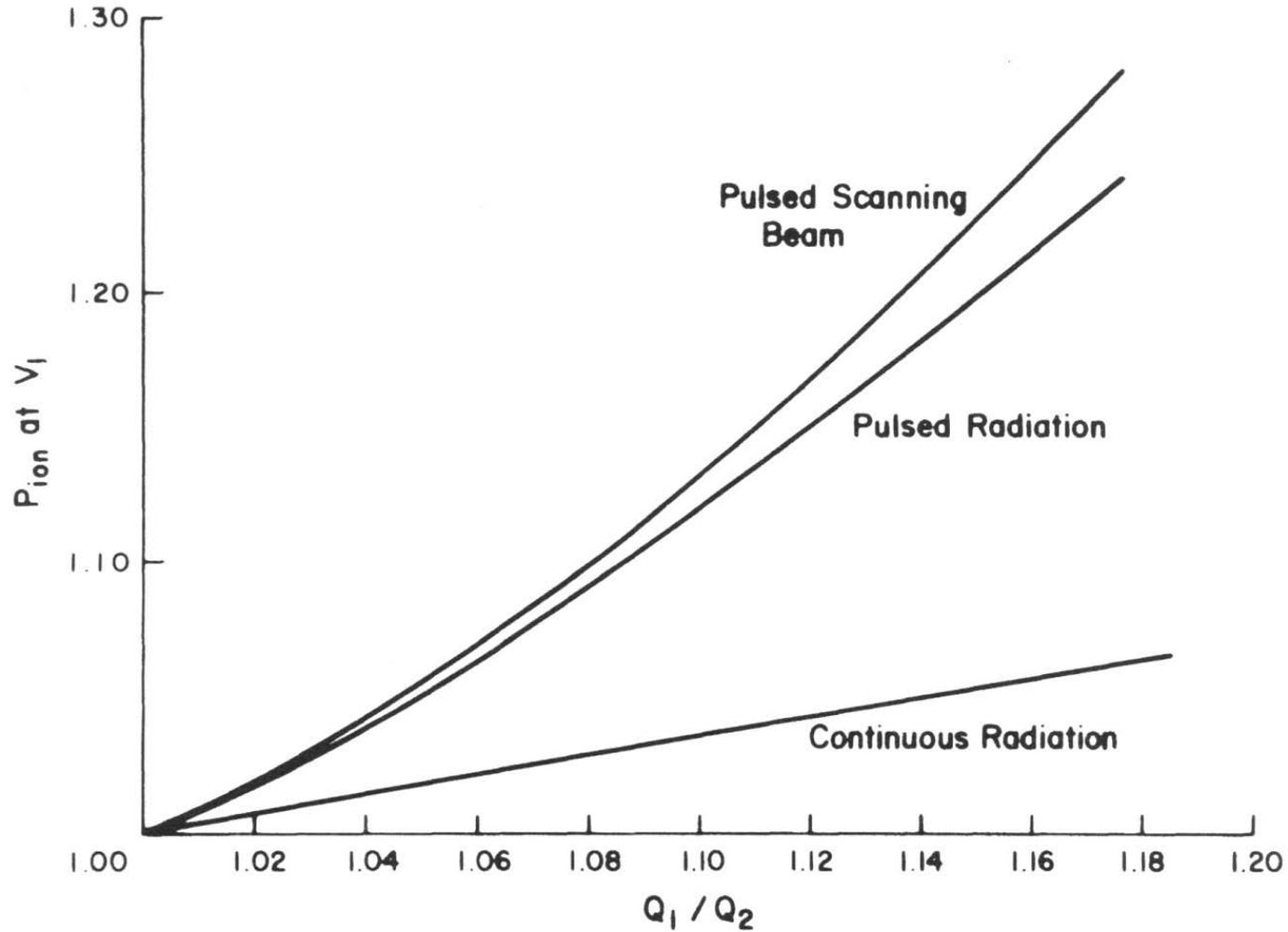
in which ρ is the initial charge density of positive or negative ions created by a pulse of radiation (esu/cm³), d is the electrode spacing

- For cylindrical or spherical chambers, d is to be replaced by $(a - b)K_{\text{cyl}}$ or $(a - b)K_{\text{sph}}$, respectively

Pulsed Radiation (cont.)

- The AAPM protocol has provided a graph of P_{ion} , the reciprocal of the ion-collection efficiency f at the given chamber voltage P_1 , as a function of the charge ratio Q_1/Q_2 observed when the voltage is halved to $P_2 = P_1/2$
- Data are given for continuous radiation, pulsed radiation, and a pulsed *and* magnetically scanned electron beam

Ionization-recombination correction factors



Pulsed Radiation (cont.)

- In conclusion, one should keep in mind that if saturation losses are excessive, the chamber may be malfunctioning (e.g., poor HV connection, or short to ground)
- Besides electrical continuity checks, a radiograph of the chamber may reveal a fault
- If the chamber is found to be normal, the substitution of pure N_2 (or other nonelectronegative gas) for air will greatly decrease the amount of recombination observed

Definition of W and \overline{W}

- An atom can be ionized in a variety of ways, but collision by charged particles interacting with the atomic electrons through Coulomb forces is the most important in dosimetry, since the dose is deposited almost entirely by charged particles
- Such collisions also produce excitation of atoms, in which an electron is raised to a higher energy level, and this energy is also part of the dose

Definition of W and \overline{N} (cont.)

- The energy going into excitation decreased the ionization efficiency of a charged particle, so that one cannot compute the number of ions by dividing the initial kinetic energy T_0 by the ionization potential of an atom (i.e., the minimum energy to ionize)
- Instead this efficiency is expressed in terms of W , the mean energy (in eV) spent by a charged particle of initial energy in producing each ion pair:

$$W = \frac{T_0}{\overline{N}}$$

where \overline{N} is the expectation value of the number of ion pairs produced by such a particle stopping in the medium (usually a gas) to which W refers

Definition of W and \overline{W} (cont.)

- Alternatively W was also defined by the ICRU as

$$W = \frac{T_0(1-g)}{\overline{N}(1-g')}$$

where g is the fraction of T_0 spent by the particle in bremsstrahlung production, and g' is the fractional number of ion pairs produced by the bremsstrahlung

- This definition assumes the escape of the bremsstrahlung; therefore it is consistent with the definition of exposure in any dosimetry situation in which the bremsstrahlung energy is lost from the system

Definition of W and \bar{W} (cont.)

- For a large number n of charged particles having a multiplicity of starting energies, and average value of \bar{W} may be defined:

$$\bar{W} = \frac{\sum_{i=1}^n T_i (1 - g_i)}{\sum_{i=1}^n N_i (1 - g'_i)}$$

where $T_i(1 - g_i)$ is the kinetic energy of the i th particle, exclusive of energy given to bremsstrahlung, and $N_i(1 - g'_i)$ is the number of ion pairs created by the i th particle, exclusive of ionization resulting from the bremsstrahlung

Definition of W and \bar{W} (cont.)

- For charged particles heavier than electrons, g_i and g_{-i} may be taken as zero
- Furthermore $g_i \approx g_{-i}$ if T_i is high enough so that W is constant
- When one speaks of a \bar{W} -value for uncharged radiation, the definition above, applied to all the secondary charged particles that result from the interactions by the uncharged radiation in the medium in question, is what is commonly meant, assuming that bremsstrahlung escapes

Calculation of W

- In general W cannot be calculated for a gas, because of lack of knowledge of the relevant physical quantities
- From conservation of energy for an electron stopping in He, Platzman calculated $W = 41.8$ eV, which approximately equals the value (41.3 eV) obtained experimentally for pure He

Calculation of W (cont.)

- From Platzman's calculations, about three-fifths of the energy spent goes into ionization, one-fifth into excitation, and a similar fraction is lost to subexcitation electrons, which heat the gas without creating further excitation or ionization
- All three components are included in the energy imparted as absorbed dose
- \overline{E}_{se} has no biological consequences, and \overline{E}_{ex} certainly has much less effect than \overline{E}_i per unit energy spent

Calculation of W (cont.)

- The following table compares first ionization potentials (E_1) with measured values of W for several gases
- The ratio of E_1 to W_e (for electrons) tends to have a value of about 0.58 ± 0.03 for the noble gases, and a somewhat lower value (0.43 ± 0.02) for the molecular gases
- This is an indication that the ionization efficiency is lower in the molecular gases, which have more excitation modes than the noble gases

TABLE 12.1 First Atomic Ionization Potentials E_1 and W-Values in Several Gases for Electrons (W_e) and for 5-MeV α -Particles (W_α)

Gas	E_1 (eV) ^b	W_e (eV/i.p.) ^a	$\frac{E_1}{W_e}$	W_α (eV/i.p.) ^a	$\frac{W_\alpha}{W_e}$
He	24.6	41.3	0.60	42.7	1.034
Ne	21.6	35.4	0.61	36.8	1.040
Ar	15.8	26.4	0.60	26.4	1.000
Kr	14.0	24.4	0.57	24.1	0.988
Xe	12.1	22.1	0.55	21.9	0.991
H ₂	15.4	36.5	0.42	36.43	0.998
N ₂	15.6	34.8	0.45	36.39	1.046
O ₂	12.1	30.8	0.39	32.24	1.047
CO ₂	13.8	33.0	0.42	34.21	1.037

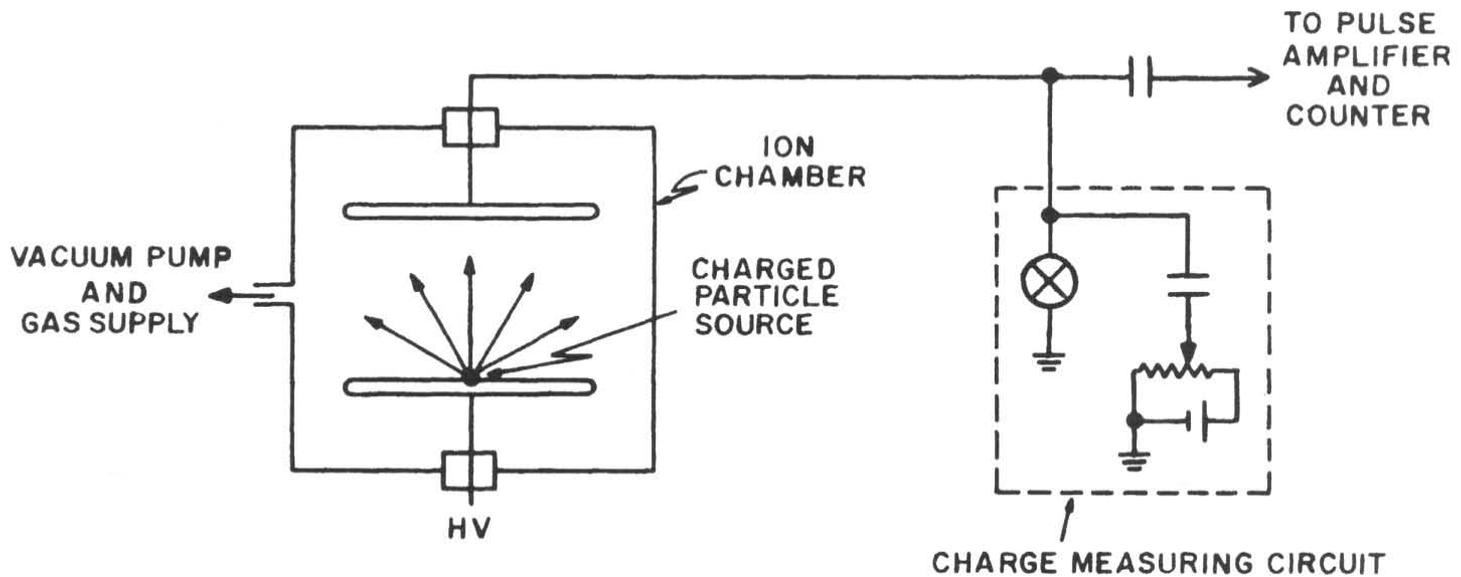
^a Excerpted from ICRU (1979b). Reproduced with permission.

^b Excerpted from the *Handbook of Chemistry and Physics*, 64th edition, CRC Press, Inc. (1983). Reproduced with permission.

Experimental Measurement of W or \bar{W}

- In measuring W for a gas, charged particles of known kinetic energy T_0 are allowed to run their full range within an ion chamber containing the gas
- The particles are counted (n), and simultaneously the ionization charge Q that they produce is measured
- A typical apparatus is shown schematically in the following diagram

Schematic diagram of an experimental setup for measuring W/e



Experimental Measurement of W or \overline{W} (cont.)

- The value of W/e is given in J/C by

$$\frac{W}{e} = \frac{nT_0}{Q}$$

where T_0 is expressed in joules and Q in coulombs

- If the particles are not monoenergetic, their average energy T_0 is substituted in the equation thus determining $\overline{W/e}$

Experimental Measurement of W or \overline{W} (cont.)

- In place of a simple ion chamber, a proportional counter of gas gain G may be required to give pulses large enough to count
- The measured charge must then be divided by the gain factor G in determining W/e

Experimental Measurement of W or \overline{W} (cont.)

- If the charged particles being used in the experiment are electrons, the bremsstrahlung produced practically all escapes from the chamber, which is made just large enough to accommodate the electron ranges
- Thus Q does not include a significant amount of ionization from bremsstrahlung, and T_0 alone must therefore be diminished accordingly:

$$\frac{W}{e} = \frac{nT_0(1-g)}{Q/G}$$

Energy Dependence of W

- W is practically constant above energies for which the charged-particle velocity v is more than 10 times the velocity v_0 of an electron in the first Bohr orbit, where

$$v_0 \cong \frac{2\pi e^2}{h}$$

and h is Planck's constant

- For lower values of v , W tends to increase because of the decreasing probability of ionizing reactions

Energy Dependence of W (cont.)

- Experimentally it is found that over the electron range above 1 keV, W varies by $\approx 2\%$ or less, and above 10 keV, W is found to be constant
- That constancy is assumed in most cases involving photons or electrons, for which a low-LET radiation value is tabulated for a variety of gases [see ICRU Report 31, “Average energy required to produce an ion pair” (1979)]

Dependence of W on Type of Radiation

- The table above also lists W_α -values obtained with 5-MeV α -particles
- These values tend to be approximately equal to, or 3-5% greater than, the low-LET values W_e
- For most non-noble gases $W_\alpha > W_e$ by a few percent
- Few W_p -values for protons have been obtained, and those are generally thought to be less reliable than the W_α -values
 - Consequently, where W_p is not reliably known for a gas, W_α is usually substituted

W for Gas Mixtures

- Approximately,

$$\left(\frac{1}{W}\right)_{\text{mix}} \cong \sum_i \left(\frac{P_i}{P} \cdot \frac{1}{W_i}\right)$$

where P_i is the partial pressure of the i th gas species, and P is the total pressure of the mixture

- Hence P_i/P is the fractional number of molecules of each type present
- A more accurate mixing formula, including empirical weighting factors, is described in the ICRU report mentioned earlier

“ W ” in Semiconductors

- When a gas is condensed to a solid, the discrete energy levels of the isolated atoms broaden into conduction and valence energy bands in the solid
- The energy gap E_g between valence and conduction bands is typically ~ 1 eV in semiconductors vs. ionization potentials of >10 eV in gases

“ W ” in Semiconductors (cont.)

- Similarly to the situation in a gas, though, the energy spent by a charged particle is divided between electron-hole pairs (corresponding to ion pairs in a gas), phonon production (like excitation in a gas), and subexcitation electrons
- The “ W ” value in Si at 300 K is 3.62 eV for α 's and 3.68 for electrons, and in Ge at 77 K it is 2.97 eV for both