Ionization Chambers

Chapter 12

F.A. Attix, Introduction to Radiological
Physics and Radiation Dosimetry

Outline

- Free-air ion chambers
- Cavity ionization chambers
- Charge and current measurements
- Corrections
- Ion-chamber saturation and ionic recombination
- Ionization energy

Introduction

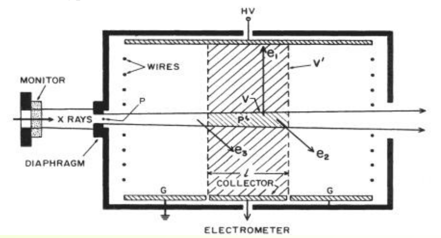
- The ionization chamber is the most widely used type of dosimeter for precise measurements
- They are commercially available in a variety of designs for different applications
- If the ion-collecting gas volume is precisely known the chamber is an absolute dosimeter
- This is not usually practicable outside of national standards laboratories, as there are advantages to working with dosimeters having calibrations traceable to such a laboratory

Free-air ion chamber

- The objective is to measure all the ionization produced by collision interactions in air by the electrons resulting from x-ray interactions in a known air mass, which is related to exposure
- There are different designs of free-air chambers used in standardization laboratories in different countries, some cylindrical and some plane-parallel in geometry
- First consider the plane-parallel type, used at the NBS in calibrating cavity ion chambers for constant x-ray-tube potentials from 50 to 300 kV

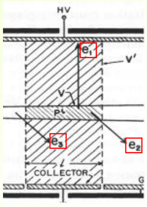
Free-air ion chamber

Typical standard free-air ionization chamber



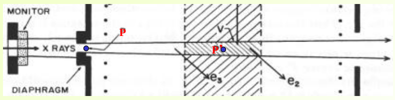
- Main components: Pb shielding box, diaphragm, plates parallel to the beam
- Guard electrodes, and a set of wires provide a uniform electric field
- The ionization for an exposure measurement is produced by electrons originating from volume V; the measured ionization is collected from V`

Free-air ion chamber



- The lateral dimensions of the chamber are great enough to accommodate electrons like e_1, which remain within V' and thus produce all their ionization where it will be collected and measured
- The electrons like e_2, which originate within V, may have paths that carry some of their kinetic energy out of V', but the remaining ionization they produce will go to the grounded guard plate instead of collector plate
- This ionization is replaced by other electrons such as e_3 that originate in the beam outside of volume V
- Volume V` as a whole is in CPE

Free-air ion chamber



- The exposure at the aperture (point *P*) determined by the measurement must be corrected upward by the air attenuation between *P* and the midpoint *P*′ in *V*
- The volume of origin *V* can be replaced by a cylindrical volume $V_c = A_0 l$, where A_0 is the aperture of area, *l* is the path length of photon traversing *V*
- If *Q* (C) is the charge produced in *V*′, the exposure at point *P* is

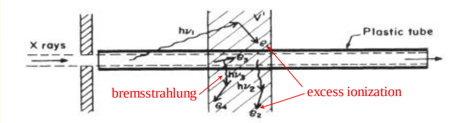
$$X = \frac{Q}{m} e^{\mu x'} = \frac{Q}{l A_0 \rho} e^{\mu x'}$$

where *x*′ is the distance from *P* to *P*′, and μ is the air attenuation coefficient

Free-air ion chamber

- In the preceding treatment μ was taken to be the narrow-beam attenuation coefficient for the x-rays passing through air
- This supposes that scattered photons do not result in measurable ionization in the chamber, which is not strictly the case
- A plastic-tube method was developed to experimentally determine the ionization contribution due to scatter and bremsstrahlung x-rays producing ionization

Free-air ion chamber

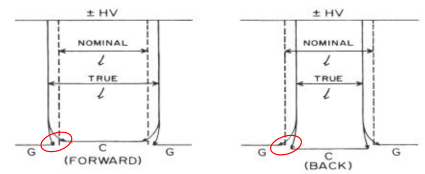


- A tube of nearly air-equivalent material such as Lucite, extending the full length of the ion-chamber enclosure, is positioned inside the chamber so that the x-ray beam passes through it from end to end without striking it
- The plastic is completely coated with conducting graphite, and biased at half of the potential of the HV plate to minimize field distortion
- The ratio of the ionization measured with and without the tube gives the fraction f_s (~0.003 for a chamber of 50x20x20 cm^3) of the total ionization that is contributed by scattered and bremsstrahlung x rays

Electric field distortion in parallel-plate chamber

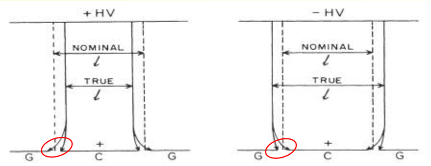
- Parallel-plate free-air chambers must have a uniform electric field between the plates, to assure that the dimensions of the ion-collection volume *V*′ and the length of the volume *V* are accurately known
- In addition to the graded-potential guard wires:
  a. all the plates must be parallel to each other and to the beam axis, which must be perpendicular to the front and back boundaries of the volume *V*′,
  b. the collector and guard plates must be coplanar, and
  c. the collector has to be kept at the same electrical potential as the guards (usually at ground)

Electric field distortion in parallel-plate chamber



Effect of collector (*C*) misalignment with guards (*G*); condition *b* is not satisfied

Electric field distortion in parallel-plate chamber

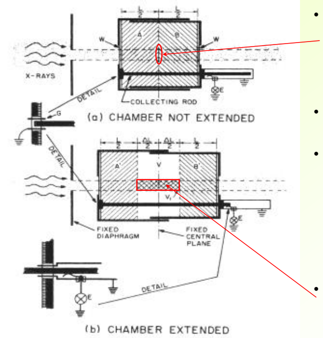


Effect of collector plate surface potential being higher (~ +1 V) than guard plates; condition *c* is not satisfied

Novel free-air chamber designs

- **Variable-length free-air chamber** consists of two telescoping cylinders with the x-ray beam passing along their axis through holes at the centers of the two flat ends
- The ions formed throughout the chamber are collected on an off-center telescoping metal rod, correcting for ion recombination as necessary
- The chamber shell is operated at high potential (e.g., ±5000 V) and is enclosed in a Pb-lined box to keep out scattered x rays

Novel free-air chamber designs



- When the chamber is collapsed, electrons originating in the x-ray beam where it crosses the fixed central plane cannot reach the walls in any direction
- Ionization measurement Q_1 is made in the collapsed condition
- The chamber volume is expanded by a length ΔL (as much as 2-fold), while keeping the chamber midplane and the defining aperture fixed relative to the x-ray source; a second measurement Q_2 is then made
- The difference Q_1-Q_2 is due to electrons originating in V_1

Novel free-air chamber designs

- If A_0 is the aperture area, the exposure at the aperture

$$X = \frac{Q_2 - Q_1}{\rho A_0 \, \Delta L} e^{\mu x'} \left(1 + f_s + f_e\right) \qquad \text{(C/kg)}$$

- Parameters:
  - x' is the distance from the aperture to the central plane of the chamber
  - f_s is a correction factor due to excess charge (produced by scattered and bremsstrahlung x-rays)
  - f_e is the fraction lost due to electrons being stopped by the collecting rod, or inadequate chamber dimensions

Novel free-air chamber designs

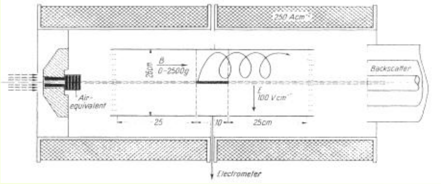
- The advantages of variable-length design over conventional:
  1. There is no dependence of the measurement upon CPE. Since the electrons originating in V_1 cannot escape from the ion-collecting volume, there is no need for replacement of lost electrons
  2. There is no need for electric-field uniformity, plate alignment, or maintenance of the collector at ground potential
  3. The air mass can be defined more accurately, depending only on the length of the collecting volume ΔL

Novel free-air chamber designs

- Free-air chambers are practical mainly with x-rays generated at energies between 10 and 300 keV
- At **higher energies** the range of the secondary electrons in air becomes so great that the size of the chamber becomes prohibitively large (e.g., 1m^3 volume between plates for 500 keV)
- Joyet suggested employing a longitudinal magnetic field in a conventional free-air chamber to bend electron paths into spirals and thus prevent their striking the walls even for x-rays of up to 50 MeV

Novel free-air chamber designs

Parallel-plate free-air chamber with magnetic field and solid air-equivalent filters



- As photons are increased in energy, the secondary electrons produced in Compton and pair-production become more forward directed
- The maximum side-directed (90°) component of the secondary-electron energy resulting from 50-MeV photons is only about 3 MeV
- It is not really a free-air chamber: to produce CPE in the collecting volume need a thick layer of solid "air-equivalent" material upstream to build up an equilibrium population of electrons passing through the ion-collecting region

Cavity ionization chambers

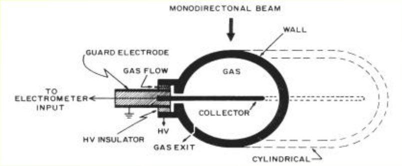
- Cavity ionization chambers basically consist of a solid envelope surrounding a gas- (usually air-) filled cavity in which an electric field is established to collect the ions formed by radiation
- They offer the following advantages:
  1. They can be made *very compact*, even for high-energy use, since the range of the secondary electrons in the solid wall material is only ~10^{-3} as great as in atmospheric air
  2. They can measure *multidirectional radiation fields*, while free-air chambers require nearly monodirectional beams aligned to pass perpendicularly through the aperture
  3. Through the application of cavity theory, the absorbed dose can be determined *in any material* of which the cavity wall is made

Cavity ionization chambers

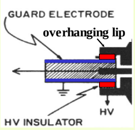
4. Cavity chambers are capable of great variety in design, to permit dose measurements of *charged particles and neutrons, as well as photons*. Free-air chambers are designed exclusively for x rays, mainly below 300 keV, and are not suited for modification for other kinds of radiation
5. Gas cavities can be designed to be thin and flat to measure the dose at the surface of a phantom and its variation as a function of depth, or can be made very small to function as a probe to sample to *dose at various points in a medium* under irradiation
6. Collected charge can be measured *in real time* by connecting the chamber to an electrometer, or the chamber can be operated without cables if it is a condenser-type cavity chamber

Thimble-type chambers

- Spherical or cylindrical chambers having gas volumes of 0.1 – 3 cm^3 are the most common forms of cavity ion chambers
- Conventionally such “thimble” chambers are irradiated at right angles to the stem axis in monodirectional beams
- The high voltage (HV), usually ±200-500V, is applied to the chamber wall, with the collector connected to the electrometer input at or near ground potential



Fully guarded chambers



The insulator arrangement exemplifies a *fully guarded* ion chamber, where electric current leaking through (or across the surface of) the HV insulator is intercepted by a grounded guard electrode (“guard ring”) that extends completely through the insulator assembly in the stem

- It prevents leakage current from reaching the collector
- The inner insulator separating the collector from the guard electrode has no potential difference across it - no leakage
- The insulator-and-guard assembly is covered by an overhanging lip of the chamber wall helping to avoid instabilities caused by charge collection on the insulator surfaces
- Without this lip the ions from a fraction of the chamber volume would be delivered to the guard electrode instead of the collector

Chamber wall thickness

- For dose measurements in fields of *photons or neutrons* under CPE or TCPE conditions, thimble chamber walls should be made
  a) thick enough to keep out of the cavity any charged particles that originate outside of the wall, and simultaneously
  b) thin enough to provide at the cavity an equilibrium charged-particle fluence and spectrum that is fully characteristic of the photon or neutron interactions taking place in the wall material
- Cavity theory together with CPE or TCPE condition is used to find the dose in the medium of interest
- For measurements of the absorbed dose in a *charged-particle* field, the volume must be small, and the chamber wall must be thin, relative to the range of the incident particles

Chamber wall material

- Since air is a medium for the definition of exposure and is a convenient ion-chamber gas, chamber wall is often made of “air-equivalent” materials
- Air equivalence of the wall requires
  - the matching of its mean mass energy-absorption coefficient to that of air for the photon spectrum present
  - the corresponding matching of the mean mass collision stopping powers for the secondary-electron spectrum
- Both conditions can be satisfied if Compton is the dominant interaction

Chamber wall material

- If photoelectric effect is the dominant interaction, its Z-dependence is much stronger than that of mass-collision stopping power; the second requirement is disregarded
- Chamber-wall air equivalence with respect to photons is provided by the *effective atomic number Z*; for PE effect

$$\bar{Z} = \sqrt[m]{a_1 Z_1^m + a_2 Z_2^m + \cdots}$$

where

$$a_1 = \left(f_1 Z_1 / A_1 \right) / \sum_i \left(f_i Z_i / A_i \right)$$

is the fraction of the electrons in the mixture that belong to atoms of atomic number Z_1, and so on; f_1 is the weight fraction of that element present; and $m \sim 3.5$

- On this basis $\bar{Z}_{air} \approx 7.8$

Chamber wall material

- For dosimetry in *charged-particle* beams, the mean mass collision stopping power, derived by use of elemental weight fractions as weighting factors, is the most relevant quantity to be matched between the gas, wall, and reference media
- The average charged-particle energy obtained from

$$\bar{T} = \frac{1}{\Phi} \int_0^{T_{\max}} \Phi_T T \; dT$$

is adequate to represent the charged-particle spectrum for this purpose

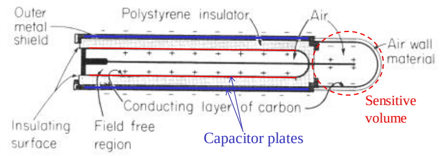
Chamber wall material

- In a thimble chamber wall serves as an electrode
- Various plastics employed as ion-chamber wall materials are generally insulators; hence application of a conducting layer on the inside surface is needed
- Some special materials (A-150 tissue-equivalent plastic) are made volumetrically conducting by incorporation of graphite during manufacture
- The ion-collecting rod in a chamber should be made of the same material as the wall if possible, as cavity theories do not deal with inhomogeneous wall media; however, small surface area of the rod often relaxes this requirement

Insulators

- Materials typically used for electrical insulation in ion-chambers are polystyrene, polyethylene, and teflon; other common plastics, such as PMMA, nylon, and mylar, are also acceptable in most cases
- The main concern is to avoid leakage currents
  - Most observed leakage is a surface phenomenon that is minimal for clean, polished surfaces and worsens with dirt and/or humidity
  - Volumetric leakage materializes through radiation-induced changes at the atomic level due to a combination of electric field and radiation, especially at high doses
  - Charged-particle beams incident on a thick insulator will build up charge wherever the particles stop at the ends of their paths; this condition can persist for hours, distorting the dose distribution in subsequent photon or electron irradiations

Condenser-type chambers



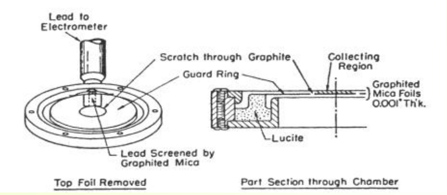
- A thimble chamber (sensitive volume on the right) operating without external connections while being irradiated
- The chamber electrodes are connected in parallel with a capacitor, built into the stem of the chamber
- The reading is obtained as a difference between potentials before and after irradiation: $\Delta Q = Q_1 - Q_2 = C(P_1 - P_2)$

Flat cavity chambers

- Flat cavity chambers have several advantages:

1. Thin foils or plastic membranes used for one or both walls cause min attenuation or scattering of incident electrons or soft x-rays
2. The gas layer can be as thin as ≈ 0.5 mm, allowing sampling with good resolution, especially in regions of high dose gradients
3. The thickness of the gas layer can be made variable, allowing extrapolation of the ionization per unit gas-layer thickness to 0
   - This in effect removes the influence of perturbation due to the presence of a finite cavity in a phantom
4. The dose at the surface of a phantom can be measured by extrapolation, and the buildup vs. depth can be observed by adding thin sheets of phantom medium over the entrance foil

Flat cavity chambers



- Ionization chamber for dosimetry of fast-electron beams
- The guard electrode serves primarily to provide a uniform electric field
- The radius of the collecting volume is defined by the collecting-electrode radius plus the half-width of the insulating scratch or groove around it

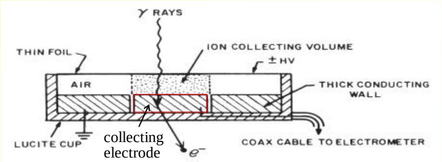
Flat cavity chambers

- Guarded flat chambers can be viewed as plane capacitors having a capacitance proportional to the area of the collecting volume, and inversely proportional to the plate separation
- A simple measurement of the chamber's capacitance can provide a check on the mechanical determination of the collecting volume:

$$C=\frac{\Delta Q}{\Delta P}=8.85\times10^{-14}\frac{a}{s}$$

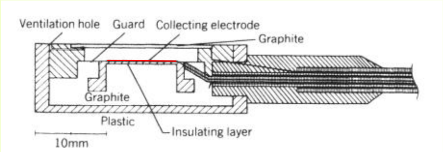
where the numerical constant has units of F/cm

Flat cavity chambers



- Commercially available flat chambers are commonly designed with a thin foil entrance wall, but a thick conducting back wall comprising both the collecting and the guard electrodes
- When placed in γ-ray beam , Compton electrons are knocked out of the back electrode, leading to *measured current difference at opposite polarities*; the true ion current may be obtained as the average of the currents at ±HV
- The effect is most pronounced for a small plate separation and a thin front wall

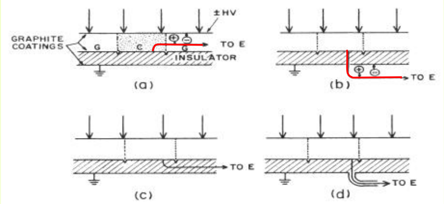
Flat cavity chambers



The collecting electrode is < 0.1 mm thick and is mounted on a thin insulating layer

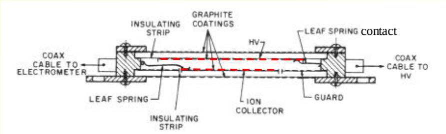
- To avoid polarity-difference effect can use a design where a thin foil collector is supported by (but insulated from) a thicker wall
- Few charged particles can start or be stopped within such a thin collector

Flat cavity chambers



- *Extracameral ionization* collected from air spaces outside of the designated collecting volume, may arise from faulty design of any type of ion chamber, but is more likely to affect flat chambers
- Bare wire in (a) and (b) presents a problem due to local air ionization contributing to the total collected current

Transmission monitor chamber

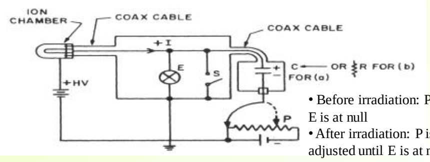


- Used to monitor radiation beam output (for example, in linac)
- HV electrode should be larger in diameter than the ion collector, which in turn should cover the whole beam area
- The collector electrode can be split into quadrants to monitor beam uniformity

Charge and current measurements

- The typical order of magnitude of charge or current to be measured from ionization chambers can be estimated from the fact that an exposure of 1 R generates a charge of ≈3×10^{-10} C in 1 cm^3 of room-temperature air at a pressure of 1 atm
- In most practical cases, ion currents are very small, in the range 10^{-6} to 10^{-14} A, their measurement requires careful technique and appropriate instrumentation
- Conducting a measurement with an ionization chamber requires a high-voltage power supply and an electrometer

Charge and current measurements



- Before irradiation: P=0, E is at null
- After irradiation: P is adjusted until E is at null

Classical null method for measurement of

(*a*) *charge* with an electrometer (E). Potential *P* is supplied by a standard potentiometer, *S* is the input shorting switch, and *C* the known capacitance upon which charge *Q* is collected by the potential *P*, where $Q = CP$ when *E* is at null

(*b*) *current* with an electrometer. Known high-megaohm resistor *R* replaces capacitor *C* in the circuit. The ionization current *I* passes through *R*, thus generating a potential drop *IR* that is equal to the potential *P* when *E* is at null

Atmospheric corrections: air density

- The charge or current collected from an ion chamber in a given field of radiation depends on the mass and type of gas in the chamber
- If, as is most often the case, the chamber volume is open to the ambient atmosphere and is allowed to reach temperature equilibrium with its surrounding, the air density inside can be calculated from

$$\rho = \rho_{0,760}\left[\frac{273}{273+T(^{\circ}\mathrm{C})}\cdot\frac{P-0.3783P_w}{760}\right]$$

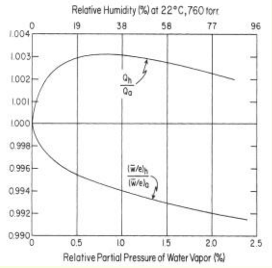
Atmospheric corrections: air density

- The barometric pressure *P*, temperature *T*, and water-vapor pressure P_w all should be measured by suitable instruments located in the same room as the ion chamber
- *T* should be measured to within ±0.2°C at a location near the chamber, allowing adequate time for temperature equilibrium after the chamber is placed in position
- *P* should be measured to within ±0.5 torr
- P_w should be determined within about ±1.3 torr, through a measurement of RH within ±7%

Atmospheric corrections: effect of humidity

- In practical ionization measurements the presence of humidity in the air is often ignored because of the extra nuisance it involves, and because the effect of humidity on $\bar{W}/e$ is such that it works in opposition to the density change when correcting the observed ionization to the value that would result if the chamber contained dry air at 22°C, 760 torr
- For dry air exposed to x-rays or other low-LET radiation the value of $(\bar{W}/e)_a = 33.97$ J/C

Atmospheric corrections: effect of humidity



- For humid air $(\bar{W}/e)_h$ is less, the ratio is a non-linear with P_w
- ρ and m of gas in the chamber under constant V-T-P decrease with increasing humidity
- These opposite trends result in almost flat ionization ratio Q_h/Q_a of 1.0028 ± 0.0003 over the range 15-75% RH

Atmospheric correction of an exposure-calibrated ion chamber

- The calibration of ion chambers in terms of x- and γ-ray exposure is provided by standardization laboratories
- The *exposure calibration factor* of a chamber for a specified quality of *x* or γ radiation is given as

$$N_X = \frac{X}{M}$$

in which *X* is the free-space exposure at the point occupied by the center of the chamber, and *M* is the charge collected from the chamber as a result of that exposure, normalized to 22°C and 760 torr

Atmospheric correction of an exposure-calibrated ion chamber

- *M* is normalized to 760 torr and 22°C by the calibrating laboratory through application of the equation

$$M = M'\left(\frac{760}{P}\cdot\frac{273+T\left({}^{\circ}\mathrm{C}\right)}{273+22}\right)$$

where *M´* is the charge measured under the existing calibration conditions, and *M* is the corrected value to be divided into the exposure *X* to give the calibration factor N_X

Relationship of ionization to absorbed dose in an ion chamber

- The ionization *Q* produced in any gas is related to the absorbed dose *D* in the gas by

$$D = \frac{Q}{\rho V}\cdot\frac{\overline{W}}{e}$$

where each quantity refers to the gas under the actual conditions of the measurement

- If humid air occupies the chamber, then *Q* is the charge produced in the chamber, and ρ is the density of the humid air

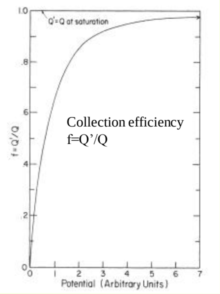
Relationship of ionization to absorbed dose in an ion chamber

- *V* may usually be assumed to be independent of humidity; but for some wall materials (Nylon, A150 plastic) storage under humid conditions causes swelling
  - *V* is not an immediate function of the ambient humidity at the time of the measurement, however
- $\overline{W}/e$ is the value appropriate for the air at the existing humidity level
- *D* is the corresponding absorbed dose in the humid air

Ion-chamber saturation and ionic recombination

- The absorbed dose deposited in a gas by ionizing radiation is proportional to the charge *Q produced* in the gas
- In practice the charge *Q´* that is *collected* by the biased electrode in the chamber and measured by the electrometer is less than *Q*, due to recombination of positive and negative ions within the gas
- An ion chamber is said to be *saturated* to the degree that such ionic recombination is absent

Ion-chamber saturation and ionic recombination



- Increasing the ion-collecting potential applied to the chamber generally reduces recombination and asymptotically approaches saturation
- 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 to ionize the next atom they encounter in the gas

Types of recombination

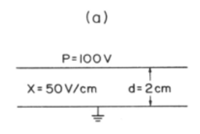
- *Initial or columnar* recombination: occurs when ions formed in the same charged-particle track meet and recombine; generally independent of dose or dose rate
  - is most likely for densely ionized (high-LET particles) tracks
  - may be important for electron tracks in high-pressure gases (>> 1 atm), with low collecting fields (<100 V/cm)
- *General or volume* recombination: ions from different tracks encounter each other on their way to the collecting electrodes; it is dose-rate-dependent

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, O_2, air, SF_6, Freon 12, and other gases containing even small amounts of O_2, H_2O, NH_3, HCl, SiF_4, or the halogens
- It is much easier to saturate an ion chamber containing a non-electronegative gas since the drift velocity of a free electron is ~10^3 time higher than that of a negative ion

Electric field strength vs. chamber geometry

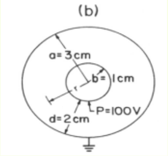
1. Neglecting edge effects, plane-parallel chambers have uniform field strength throughout the chamber volume. For an applied potential *P*, and a distance between the plates *d*:



$$\mathrm{E}(x) = P/d$$

Electric field strength vs. chamber geometry

2. Cylindrical chamber geometry can be characterized in terms of the radius of the outer electrode *a*; the radius of the inner electrode *b*; the field strength E(*r*) at radius *r*; and the applied potential *P*



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

Electric field strength vs. chamber geometry

3. Spherical geometry the field at radius *r* is given by

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

- 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

Theory of volume recombination for constant dose rate

- The theory is developed for electronegative gases
- 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 $f \geq 0.7$
- Parameter ξ depends on the chamber geometry

Theory of volume recombination for constant dose rate

- For plane-parallel chambers

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

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

d = plate separation (cm), $q = Q/vt$ (esu/cm^3 s),

P = applied potential (V),

α = recombination coefficient (cm^3/s),

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

k_1 and k_2= mobilities of positive and negative ions (cm^2/Vs),

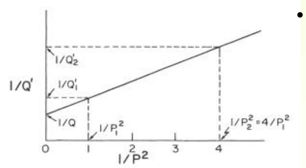
v = volume of ion chamber (cm^3), and

t = irradiation duration, assumed > the ion-transit time of ~1 ms

Theory of volume recombination for constant dose rate

- The equation for f reduces to

$$\frac{1}{Q'} = \frac{1}{Q} + \frac{c}{P^2}$$



- Measuring $1/Q'$ at several values of P and extrapolating to $1/P^2 = 0$ can find a correction for general recombination

Theory of volume recombination for constant dose rate

- For cylindrical chambers:

$$\xi_{\text{cyl}} = m\frac{\left[(a-b)K_{\text{cyl}}\right]^2\sqrt{q}}{P} \qquad K_{\text{cyl}} = \left\{\frac{(a/b)+1}{(a/b)-1} \cdot \frac{\ln(a/b)}{2}\right\}^{1/2}$$

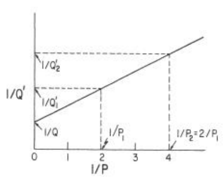
- For spherical chambers

$$\xi_{\text{sph}} = m\frac{\left[(a-b)K_{\text{sph}}\right]^2\sqrt{q}}{P} \qquad K_{\text{sph}} = \left\{\frac{1}{3}\left(\frac{a}{b}+1+\frac{b}{a}\right)\right\}^{1/2}$$

Initial (columnar) recombination

- In case volume recombination is negligible and only initial recombination remains (significant for high-LET particles), theory predicts for an electronegative gas that (here c' is a constant and P is the applied potential)

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



- Extrapolation to 1/P = 0 yields 1/Q
- Charge Q can be determined for initial recombination with either pulsed or continuous radiation, or for general recombination with pulsed radiation only

Pulsed radiation

- The pulses are assumed to be short compared to the ion transit time (~ 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 in expression for ξ
- If pulses are very long compared to the transit time, continuous radiation theory applies

Pulsed radiation

- Collected fraction for short pulses

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

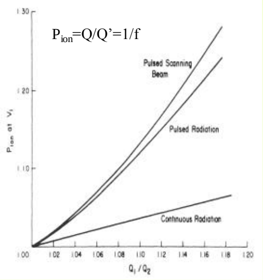
where

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

in which ρ is the initial charge density of positive or negative ions created by a pulse of radiation (esu/cm^3), 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



- Measuring the charges collected at two values of applied potential can yield an accurate value *f* for pulsed radiation
- The AAPM protocol TG-21 has provided a graph of $P_{ion}=1/f$ 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 $P_2 = P_1/2$

Ionization, excitation, and W

- Charged particles depositing energy in a medium produce both ionizations and excitations of atoms
- The energy going into excitation decreases the ionization efficiency of a charged particle
- The mean energy spent by a charged particle of initial energy T_0 in producing each ion pair is higher than the ionization potential of an atom. It is defined as:

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

where $\overline{N}$ is the expectation value of the number of ion pairs produced by a particle stopping in the medium

Ionization, excitation, and W

- In general *W* cannot be calculated for a gas
- In calculations for an electron stopping in He, *W* = 41.8 eV, (vs. 41.3 eV obtained experimentally)
- Three components are included in the energy imparted as absorbed dose: ionization E_i, excitation E_{ex}, and sub-excitation E_{se}

E_i	62% of W	Direct energy deposition
E_{ex}	20% of W	Direct energy deposition, less effect than E_i
E_{se}	18% of W	No biological effect, goes into gas heating

Ionization, excitation, and W

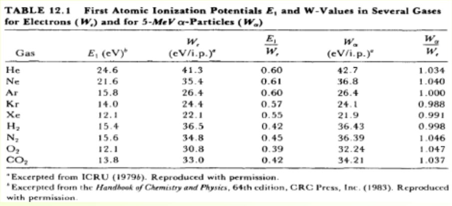


TABLE 12.1 First Atomic Ionization Potentials E_1 and W-Values in Several Gases for Electrons (W_e) and for 5-*MeV* α-Particles (W_α)

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 (1979*b*). Reproduced with permission.

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

- Measured W_e (for electrons) and W_α (for α-particles)
- The ionization efficiency is lower in the molecular gases, which have more excitation modes than the noble gases
- Values for α-particles are close to those for electrons

Summary

- Free-air and cavity ionization chambers
- Measurements of small charges and currents require sensitive equipment and care
- Chamber gas mass has to be known with high accuracy: chamber design, electric field distribution, corrections for P,T,V
- Collection efficiency corrections for ionic recombinations (continuous and pulsed radiation)
- Ionization energy