Chapter 9
Measurement of Radiation: Instrumentation and Techniques

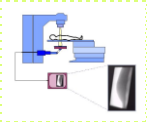
Radiation Dosimetry I

Text: H.E Johns and J.R. Cunningham, The physics of radiology, 4th ed.

http://www.utoledo.edu/med/depts/radther

Measurement of radiation

- Ionization chambers
  - Efficiency of ion collection
  - Practical considerations
- Solid state detectors
- Thermoluminescent dosimetry
- Chemical dosimetry
- Calorimetry



Charge collection in ion chamber

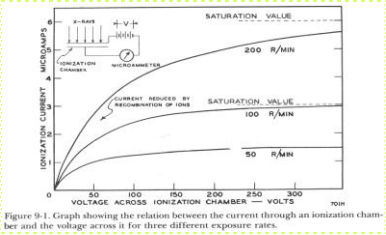


Figure 9-1. Graph showing the relation between the current through an ionization chamber and the voltage across it for three different exposure rates.

- Ion pairs produced by radiation can recombine before reaching the electrodes
- Measured current reaches its saturation value when all charges are collected

Charge collection in ion chamber

- Positive (negative) ions move to towards the negative (positive) electrode
- Mobility k_+ (k_-)
  - Ion velocity is proportional to the electric field
    $$v_+ = k_+ \varepsilon$$
  - Depends on type of gas; in air $k_- \approx k_+ \approx 1.8\ cm^2/(s \cdot V)$
- Typical values for parallel plate ion chamber
  - For voltage of 300V, and electrodes 2 cm apart:

  velocity v=270 cm/s, time to cross the chamber t=7.41 ms – long enough to meet another ion and recombine

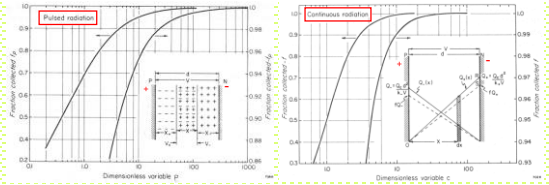
Charge collection in ion chamber

- Once recombined the ion cannot be collected
- Recombination coefficient α
  - For charge concentrations Q_+, Q_- charge lost to recombination per unit volume in time t:
    $$\frac{\alpha}{e} Q_+ Q_- t$$
  - Typical values for air $\alpha = 1.6 \times 10^{-6}\ cm^3 s^{-1}$; charge concentration ~pC/cm^3 to nC/cm^3
  - Time-dependent process, distribution of charges changes with time

Charge collection in ion chamber

- Charge concentration change in time is described through differential equation (for $Q_+ = Q_-$)
  $$dQ = -\frac{\alpha}{e} Q^2 dt$$
- Charge concentration at time *t*: $Q = \dfrac{Q_0}{1 + \dfrac{\alpha}{e} Q_0 t}$
- The description is further complicated by spatial charge distribution (pulsed vs. continuous radiation)

Pulsed vs. continuous radiation



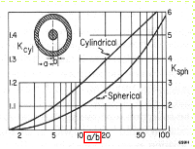
- Fraction of charge collected in a parallel plate chamber

$$f_p = p\ln\left(1+\frac{1}{p}\right) \qquad f_p = \frac{1}{1+1/c^2}$$

$$p = 0.306\times10^{-12}\frac{V}{d^2 Q_0} \qquad c = 1.219\times10^{-6}\frac{V}{d^2\sqrt{Q_c}}$$

Spherical and cylindrical chambers

- Most practical ionization chambers are either cylindrical or spherical
- Electrical field varies with the distance from the central electrode (~1/r)
- Use the equivalent gap length:
  - $d=K_{cyl}(a-b)$ for cylindrical
  - $d=K_{sph}(a-b)$ for spherical
- Use K_{cyl} and K_{sph} depend on ratio of a/b



Types of ionization chambers

- Free-air chamber
  - Parallel plate design , very large
  - Require mono-directional beam
  - Photons only, mainly below 300 keV
- Cavity chamber
  - Can be made very compact (typical range of secondary electrons in solids is ~10^{-3} of that in air)
  - Can measure multi-directional beams
  - Can be used for photons, charged particles and neutrons
  - Cavity can have different geometries: thimble, flat

Practical ionization chamber

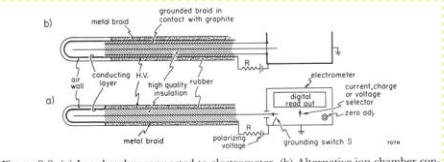
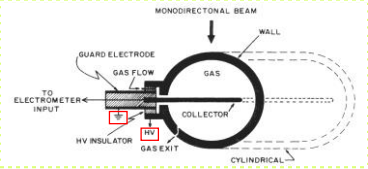


Figure 9-8. (a) Ion chamber connected to electrometer. (b) Alternative ion chamber configuration with guarded construction to minimize leakage.

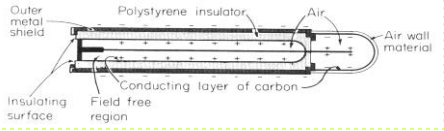
- Cavity ionization chambers consist of a solid envelope surrounding a gas-filled cavity where an electric field is established to collect the ions produced by radiation
- Require signal readout device (electrometer)
- Proper electrical shielding is essential

Fully guarded chambers



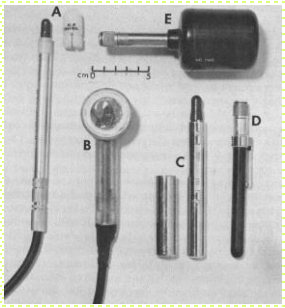
- The high voltage (±200-500 V) is applied to the chamber wall
- In a *fully guarded* ion chamber electric current leaking through the HV insulator is intercepted by a grounded guard electrode ("guard ring") that extends through the insulator assembly in the stem; this current cannot reach the collector and affect the measured charge
- The collector is connected to the electrometer input at or near ground potential; thus little leakage occurs here

Condenser type chambers



- Operates without external connections while being irradiated
- The chamber electrodes are connected in parallel with a capacitor, built into the stem of the chamber
- Ions are produced in both of the air compartments, but are collected only in the chamber, reducing the voltage and charge of the capacitor
- Charge collected during irradiation: $Q=C(V_0-V_f)$ is proportional to exposure

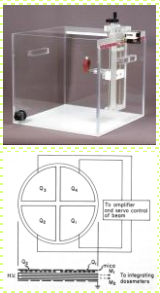
Types of cavity ion chambers



- (a) Farmer ion chamber with Co-60 cap
- (b) Thin walled chamber
- (c) Victoreen condenser chamber with electrode cover
- (d) Pencil ion chamber for personnel protection
- (e) Large volume sensitive chamber for measurement of low levels of radiation

Types of measurements performed with ion chambers

- Absolute dosimetry
- Buildup measurements
- Beam profile measurements
- Dose to personnel
- Stray radiation measurements
- Linac output monitors



Correction for distance: inverse square law

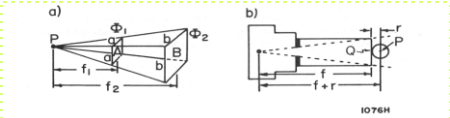


Figure 9-13. (a) Diagram to illustrate the *inverse square law*. (b) Diagram to illustrate the method for correcting the measured exposure at P to the exposure at the end of the treatment applicator.

- Photon fluence changes with the distance from the source

$$\Phi_A = \Phi_B \frac{f_2^2}{f_1^2}$$

- Need to correct for distance if the detector cannot be placed exactly at the distance of interest

Example 1

- During routine quality assurance (QA) checks, the optical distance indicator (ODI) is found to read 100 cm when the distance is actually 101.5 cm. If uncorrected, the effect on the dose at dmax for a field apparently set up at 100 cm would be:

A. An overdose of 3%.
B. An overdose of 1.5%.
C. An overdose of 1 %.
D. An underdose of 1.5%.
E. An underdose of 3%.

Patient will be further than expected, therefore underdose

$$\Phi_A = \Phi_B \frac{f_2^2}{f_1^2}$$

$$\frac{f_2^2}{f_1^2} = \frac{101.5^2}{100^2} = 1.03$$

Solid state detectors

- In a gas-filled chambers the ionization is produced by the secondary electrons originating in the wall of the detector
- Solid detectors offer high detection efficiency and more direct relationship between the radiation field evaluated and the signal produced
- Compactness, fast signal collection, possibility of spectroscopic measurements
  - Semiconductor diode detectors
  - Scintillators

Solid state detectors

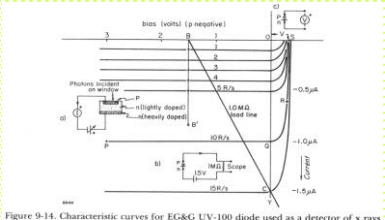
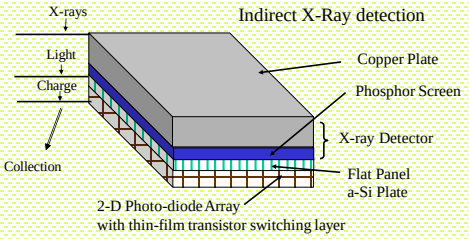


Figure 9-14. Characteristic curves for EG&G UV-100 diode used as a detector of x rays generated at 100 kV. (a) Schematic representation of diode used in the bias mode with p negative. (b) Diode used with a 1 MΩ load resistor giving operation along line BC. (c) Diode used on open circuit along line OS.

- Si diode can be used in photovoltaic mode or under external reverse bias

Solid state detectors: EPID



- Electronic portal imaging device
- Indirect x-ray detection: light produced by the interaction of x-ray in the scintillator is converted to charge by the a-Si photodiode

Thermoluminescent dosimetry

- In some crystalline materials radiation creates excited states that become "frozen"; these states can be converted to light after heating
- The amount of emitted light is proportional to the absorbed dose
- Can be made into any shape
- Wide dose range - from 10^{-3} to 10^{3} Gy

Thermoluminescent dosimetry

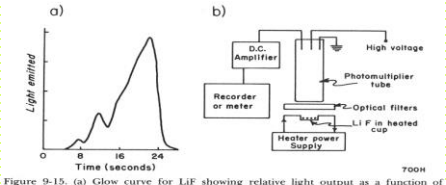


Figure 9-15. (a) Glow curve for LiF showing relative light output as a function of heating time. (b) Schematic diagram showing apparatus for measuring light output from a thermoluminescent material.

- The different peaks in this diagram correspond to different "trapped" energy levels
- The area under the whole glow curve can be used to measure dose

Chemical dosimetry

- The energy absorbed from radiation may produce a chemical change in the absorbing medium, and the amount of this may be used to measure dose
- Fricke dosimeter: under irradiation an acidic aqueous solution of ferrous sulphate oxidazes to ferric sulphate in the amount proportional to the absorbed energy:

$$D = \frac{\Delta M}{G\rho}$$

- The amount of produced ferric sulphate ions ΔM can be readily measured by transmission of UV (305 nm) light through the solution; ρ is the density of ferrous sulphate, G is radiation chemical yield

Film dosimetry

- When radiation strikes a film very small crystals of silver bromide become more susceptible to chemical change and form a *latent image*
- When the film is developed, the crystals that have been altered by the radiation are reduced to small grains of metallic silver
- The film is then *fixed* by selectively dissolving the unaffected silver bromide, but not the metallic silver
- Areas that have been exposed to x rays appear dark
- Optical density $OD=\log_{10}(I_0/I_T)$ is determined when film is placed over uniformly illuminated light box
- For high energy radiations, films are useful in obtaining a quick quantitative pattern of a radiation distribution

Film dosimetry

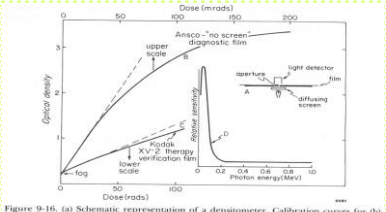


Figure 9-16. (a) Schematic representation of a densitometer. Calibration curves for (b) fast and (c) slow films showing optical density as a function of exposure. (d) Sensitivity as a function of photon energy, due to Ehrlich (E5).

- A careful calibration of density versus exposure over the range of interest must be made for each batch of film used and each development protocol
- Silver (Z = 47) absorbs radiation < 150 keV very strongly by the photoelectric process, so in the range from 0 to 150 keV the response is very energy-dependent

Example 2

- Two x-ray films, each with optical density of 1.5, are placed on top of one another. The fraction of incident light transmitted through the "sandwich" is

A. 0.03
B. 0.015
C. 0.001
D. 0.0225
E. None of the above

$$OD = \log_{10}\frac{I_0}{I_T} \Rightarrow I_T = I_0 10^{-OD}$$

$$I_{T2} = I_{T1}10^{-OD_2} = I_0 10^{-OD_1}10^{-OD_2} = I_0 10^{-(OD_1+OD_2)}$$

$$\frac{I_{T2}}{I_0} = 10^{-3} = 0.001$$

Example 3

- To store images with 256 shades of gray, each pixel in the image will require:

A. 1 byte
B. 6 bytes
C. 8 bytes
D. 1 bit
E. 6 bits

$$256 = 2^n,$$

$$n = \frac{\ln 256}{\ln 2} = 8$$

$$256 = 2^8, \text{or } 8\,\text{bits} = 1\,\text{byte}$$

Example 4

- Ten 1024x1024 digital images with 64 shades of gray are to be transmitted at the rate of 1.049×10^5 bits/s. The images can be transmitted in approximately _____.

A. 10 s
B. 30 s
C. 1 min
D. 10 min
E. 1 h

64=2^6 which means 6 bits are needed to encode
No. of bits transmitted N=1024x1024 x 6 x10
$= 6.29 \times 10^7$ bits
t=N/rate= $6.29 \times 10^7 / 1.049 \times 10^5$ bits/s = 599 seconds or ~10 minutes

Calorimetry

- Direct measurement of absorbed dose
- 1 Gy in water produces $\Delta T = 2.39 \times 10^{-4}$ C
- The temperature change can be measured using thermistor: semiconductor material changing its resistance by ~5% per ^oC
- Typically a thermistor with resistance of 10^3-10^5 Ohms are used

Calorimetry

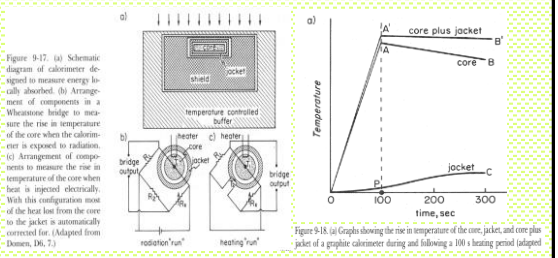


Figure 9-17. (a) Schematic diagram of calorimeter designed to measure energy locally absorbed. (b) Arrangement of components in a Wheatstone bridge to measure the rise in temperature of the core when the calorimeter is exposed to radiation. (c) Arrangement of components to measure the rise in temperature of the core when heat is injected electrically. With this configuration most of the heat lost from the core to the jacket is automatically corrected for. (Adapted from Domen, D6, 7.)

Figure 9-18. (a) Graphs showing the rise in temperature of the core, jacket, and core plus jacket of a graphite calorimeter during and following a 100 s heating period (adapted

- Calorimeters may be used to measure locally absorbed energy
- Temperature rise due to radiation energy absorption is compared to that of direct heat absorption: $E_{ab} = E_h(\Delta T_r/\Delta T_h)$

Calorimetry

TABLE 9-2
Temperature Diffusivity

Material	ρ-Density g/cm³	c-Specific Heat $Jg^{-1}°C^{-1}$	k-Thermal Conductivity $Jcm^{-1}s^{-1}°C^{-1}$	Temperature Diffusivity $k/\rho c$ [cm^2/s]
Carbon	2.25	.71	2	1.25*
Copper	8.96	.38	4.0	1.16
Water	1.00	4.2	6.1×10^{-3}	1.4×10^{-3}
A-150 (TEP)	1.13	1.7	1.3×10^{-3}	68×10^{-6}*

- Long-term temperature drift is typically a problem due to thermal gradients and imperfect thermal insulation
- Temperature diffusivity defines the ability of a material to dissipate thermal gradients (the larger the value, the faster temperature gradients disappear)