Dosimetry by Pulse-Mode Detectors

Chapter 15

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

Outline

- Problem statement
- Geiger-Muller counters
- Proportional counters
- Scintillators
- Semiconductor detectors
- Summary

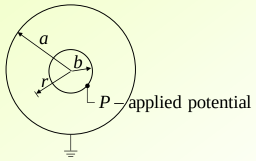
Introduction

- Integrating dosimeters provide measurements of the full energy imparted to matter by radiation: TLD's, film, chemical, and calorimetric dosimeters
- Pulse-mode detectors: gas proportional counters, Geiger-Muller counters, scintillators, and semiconductor detectors
- The objective is to discuss
  - the characteristics of these devices that make them useful for dosimetry
  - how their output signals can be interpreted in relation to the absorbed dose

Gas multiplication

- An ionization chamber operated at an applied potential great enough to cause *gas multiplication*
- Free electrons from ionizing events can derive enough kinetic energy from the applied electric field, within a distance equal to the electrons' mean free path σ_e, to ionize other gas molecules with which they collide
- A single electron can give rise to an "avalanche"
- At atmospheric pressure the minimum field strength required is ~ 10^3 V/mm

Cylindrical counter



- Electrical field strength is not uniform:

$$X(r) = P / r \ln(a/b)$$

- The maximum occurs at the surface of the inner electrode

$$X(b) = P / b \ln(a/b)$$

Gas multiplication

- The central wire must serve as the *anode*, so that the free electrons produced by radiation in the counter gas travel toward the thin high-field sheath around the wire
- For gas multiplication to occur, at a pressure p (atm), and applied potential P, the field strength $\mathrm{E}(r)$ must satisfy

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

- The radius r_s of the outer boundary of the amplifying sheath region is

$$r_s = \frac{P}{pK \ln(a/b)}$$

Gain factor

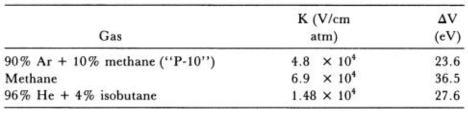
- The gain factor **G** is the number of electrons that arrive at the wire anode per electron released by ionizing radiation in the gas volume
- For cylindrical geometry

$$\mathrm{G} \cong \exp\left\{ \frac{0.693P}{\Delta V \ln(a/b)} \ln \frac{P}{Kpb \ln(a/b)} \right\}$$

- ΔV is the average potential difference (eV) through which an electron moves between successive ionizing events; K *is* the minimum value of the electric field strength per atmosphere of gas pressure; p is the gas pressure in atmospheres

Gain factor

Characteristics of typical proportional-counting gases



Gas	K (V/cm atm)	ΔV (eV)
90% Ar + 10% methane ("P-10")	4.8×10^4	23.6
Methane	6.9×10^4	36.5
96% He + 4% isobutane	1.48×10^4	27.6

- A cylindrical proportional counter with a = 1 cm, $b = 10^{-3}$ cm, P=1000 V, containing P-10 gas at 1 atm would have G~100
- Reducing the gas pressure to 0.5 atm would increase G~2000
- Substitution of the He-isobutane mixture at 1 atm would provide an even higher G ~ 4000
- The upper G limit *for proportional* gas multiplication is ~ 10^4

Gain factor

- For a chamber operating with a fixed gain G, the total charge collected Q at the wire during a given exposure to ionizing radiation will be just GxQ if the device had been operated as a saturated ion chamber
- An ion chamber operating with G > 1 is called an *amplifying ion chamber.* Its advantages over a simple ion chamber are:
  - greater sensitivity, since the charge collected is G-fold larger
  - the gas-filled cavity comes closer to satisfying the B-G conditions if reduced pressure is employed

Proportional counters

- Amplifying ion chambers with its output measured in terms of numbers and amplitudes of *individual pulses*, instead of the charge collected
- An "ionizing event" includes all of the ionization produced in the counter gas by the passage of a single charged particle and its δ-rays
- At least half of positive ions and electrons originate within the amplifying sheath (typically, 1-2 μm from the central electrode)

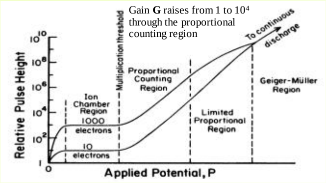
Proportional counters

- All ionized particles are produced almost simultaneously and move "in unison", giving rise to a sharply defined fast-rising electrical pulse
- The height of the electrical pulse is proportional to the number of electrons in the associated avalanche, which in turn is proportional to the number of ion pairs created in the original ionizing event
- Thus the size (i.e., height) of the electrical pulse is *proportional* to the energy imparted to the gas in the initial event, provided that *W/e* is constant (there is a small LET dependence)

Proportional counters

- Free electrons reach the anode wire within ~1 μs
- Measured electrical pulse, however, is primarily due to the much slower motion of positive ions away from the central wire
- If only gross pulse counting is required proportional counters can operate with pulse resolving times of about 1 μs
- If pulse heights are to be measured also, the average interval between pulses should be greater, approaching the transit times for the positive ions (~100 μs) for greatest accuracy

Pulse-height analysis



Gain **G** raises from 1 to 10^4 through the proportional counting region

- Pulse height from a detector depends on the applied potential
- Two curves represent initial ionizing events releasing 10 and 10^3 electrons

- The ion-chamber region: almost complete collection of charge
- Proportional counting starts after the gas-multiplication threshold
- Limited proportionality region: space-charge effects limited
- G-M region: initiating events of different sizes produce equal pulses

Pulse-height analysis

- Employ multi-channel analyzer to obtain a differential distribution of counts per channel vs. channel number
- To facilitate the calibration of the pulse height *h* in terms of absorbed dose to the counter gas, some proportional counters are equipped with a small α-particle source
- The expectation value of the dose contributed to the gas by each α-particle can be written as

$$\overline{D}_\alpha = \frac{1}{m}\left(\frac{dT}{\rho dx}\rho\Delta x\right)$$

m – mass of gas; *ρ* – gas density; d*T*/*ρ*d*x* – mass collision stopping power of the gas for α-particle

Pulse-height analysis

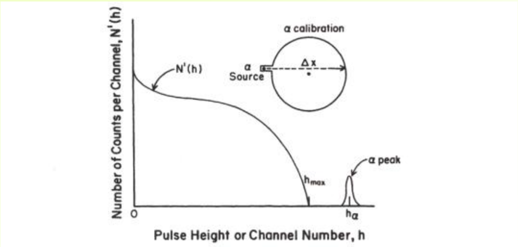


FIGURE 15.2. Differential distribution of counts per pulse-height channel vs. channel number for a proportional counter, as measured by a pulse-height analyzer. A built-in α-particle source is used to calibrate the channel number *h* in terms of absorbed dose to the counter gas. Assuming a constant $\overline{W}/e$ value for all events, the channel number is proportional to the absorbed dose contributed to the gas by each event. Thus the dose to the gas that is represented by a count in channel *h* is $\boxed{D(h) = (h/h_\alpha)\overline{D}_\alpha.}$

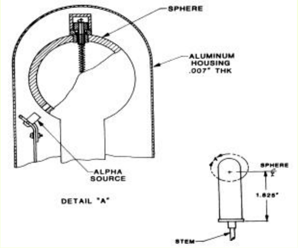
Pulse-height analysis

- The total dose in the gas can be found by summing all the counts, each weighted by its pulse height *h* expressed as

$$D_g = \sum_{h=0}^{h_{\max}} N'(h)\frac{h}{h_\alpha}\overline{D}_\alpha = \sum_{h=0}^{h_{\max}} N'(h)D(h)$$

- Such a proportional counter can be used as an absolute dosimeter

Proportional counter: example



13-mm-I.D. tissue-equivalent proportional counter

- Rossi counters usually made with spherical walls of tissue-equivalent plastic, and are operated while flowing a tissue-equivalent counting gas through at reduced pressure, typically ~ 10^{-2} atm
- Adjustment of the gas pressure allows simulation of biological target objects such as individual cells, in terms of the energy lost by a charged particle in crossing it

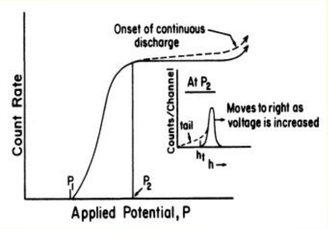
Proportional counters

- Proportional counters of various designs are also used for many applications in which pulse-height analysis is not used
- The main advantages of proportional counters over G-M counters in this connection are
  a) their short pulse length (~1 μs) with practically no additional dead time, accommodating high count rates, and
  b) the capability of discriminating by simple means against counting small pulses that might result, for example, from background noise, or γ-ray interactions in a mixed γ + neutron field

Geiger-Muller counters

- As the voltage applied to a gas counting tube is increased, the pulse height begins to saturate, gradually reaching the G-M region of operation
- For any voltage in that region all the gas-amplified pulses come out approximately the same, regardless of the size of the initiating event
- If the resulting pulse size is larger than the counter-circuit threshold h_t, then the pulses will be counted. As a result, one would expect to see a step function in the count-rate-vs.-voltage curve where the pulse height begins to exceed h_t

Geiger-Muller counters



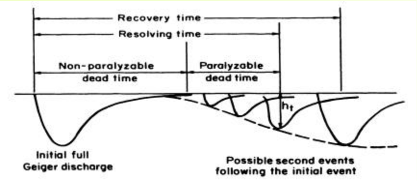
The counting plateau in a G-M tube. The solid curve is an "ideal" G-M plateau that would be seen for a narrow distribution of pulse heights. The dashed curve has a residual slope within the G-M region because of the presence of a low-amplitude "tail" on the pulse-height distribution (inset).

- The step is S-shaped, due to the Gaussian distribution of the pulse sizes produced in the counter even under ideal G-M conditions
- A small-pulse "tail" on the Gaussian distribution of pulse heights is mostly produced by the ionizing events that occur during the period before the G-M tube recovered from the preceding discharge

Geiger-Muller counters

- Immediately after a discharge the positive space charge so weakens the electric field near the wire that gas multiplication cannot occur
- Thus the tube does not respond to radiation at all until the positive-ion cloud starts arriving at the cathode and the electric field strength gradually builds up again
- As that takes place, the tube becomes capable of responding to an ionizing event with a discharge of less than full size

Geiger-Muller counters: dead time



- The *true dead time* is the time from the start of the preceding pulse until the tube recovers starting to generate minimum-sized pulses
- The *recovery time* is the time until a full-sized pulse is possible
- The minimum time between detectable pulses will be less than the recovery time. This is the *pulse resolving time*, but is more commonly referred to as the "dead time"

Geiger-Muller counters: dead time

- If an ionizing event occurs during the true dead time, it causes no electron avalanche and hence has no effect on the tube
  - This is called *nonparalyzable* dead-time behavior
- If an ionizing event occurs after the end of the true dead time, but before the resulting pulse is large enough to be counted (i.e., > h_t), not only will that event go uncounted but a new dead-time period will begin
  - This is called *paralyzable* dead-time behavior

Geiger-Muller counters

- Since G-M counters are only *triggered by* ionizing events, producing discharge pulses of more or less the same size regardless of the initiating event, the observed output has little information about the dose to the counter gas
- They are used in some dosimetry applications due to several advantages:
  - Require little if any further amplification, with pulses of 1-10V
  - Inexpensive and versatile in their construction and geometry
- They are often used in radiation survey meters to measure x-and γ-ray fields in radiation-protection applications
- When equipped with a thin (~1 mg/cm^2) window they can also be used to detect β-rays

Geiger-Muller counters

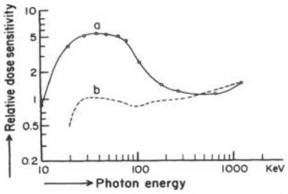


FIGURE 15.6. Typical energy-dependence curves of the response relative to tissue dose for survey meters containing G–M tubes of the following types: (*a*) uncompensated, and (*b*) compensated with metallic filters to produce flatter response. (Kiefer et al., 1969. Reproduced with permission from R. Maushart and Academic Press.)

- Most G-M tubes are constructed of materials that are higher in atomic number than tissue or air, and exhibit strong photoelectric-effect response below ~ 100 keV
- Enclosing the G-M tube in a suitable high-Z filter tends to flatten the overresponse at low energies; can be used as an approximate dose-rate or exposure-rate meter

Scintillation dosimetry

- Many transparent substances, including certain solids, liquids, and gases, scintillate (emit visible light) in response to ionizing radiation
- The light emitted can be converted into an electrical signal and amplified using photomultiplier (PM) tube
- Very fast decay times, down to ~ 10^{-9} s, make organic liquid and plastic scintillators excellent choices for coincidence measurements with good time-resolution
- Versatile in volume shape and size
- Used in spectroscopic applications due to lower cost and the greater convenience of room temperature operation (compared to semiconductor detectors)

Scintillation dosimetry

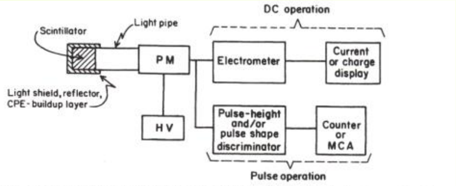


FIGURE 15.7. General schematic design for a scintillation detector for dosimetry applications. A light pipe optically couples the scintillator to the photomultiplier tube. The scintillator is otherwise enclosed in an optically opaque and internally reflective envelope that may also filter out short-range radiation and may additionally serve as a CPE buildup layer for indirectly ionizing radiation.

Scintillation dosimetry

- Only a very small part of the energy imparted to a scintillator appears as light; the rest is dissipated as heat. Typically ~ 1 keV of energy is spent in the scintillator for the release of one electron from the PM tube's photocathode
- The light generated in a scintillator by a given imparted energy depends on the linear energy transfer (LET) of the charged particles delivering the energy
- For dosimetry of γ-rays or electrons, either the PM-tube output should be measured as an electric current or the pulse-heights must be analyzed and calibrated in terms of dose. Simple counting of pulses without regard to their size is not a measure of the dose in a scintillator

Scintillation dosimetry

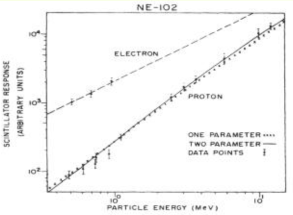


FIGURE 15.8. Light output vs. particle energy for electrons and protons stopped in the plastic scintillator NE-102. The light output is proportional to electron energy, but not to proton energy. Curves are based on Birks's theory (1964) that dense ionization tracks create damaged molecules, which lower the scintillation efficiency. (Craun and Smith, 1970. Reproduced with permission from North-Holland Physics Publishing.)

- In typical organic scintillators increasing the particle LET decreases the light output for a given energy imparted
- The light response from electrons that spend their full track length in the scintillator is proportional to their starting energy above ~125 keV

Scintillation dosimetry

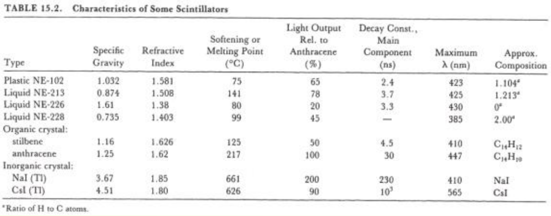


TABLE 15.2. Characteristics of Some Scintillators

Type	Specific Gravity	Refractive Index	Softening or Melting Point (°C)	Light Output Rel. to Anthracene (%)	Decay Const., Main Component (ns)	Maximum λ (nm)	Approx. Composition
Plastic NE-102	1.032	1.581	75	65	2.4	423	1.104^a
Liquid NE-213	0.874	1.508	141	78	3.7	425	1.213^a
Liquid NE-226	1.61	1.38	80	20	3.3	430	0^a
Liquid NE-228	0.735	1.403	99	45	—	385	2.00^a
Organic crystal:							
stilbene	1.16	1.626	125	50	4.5	410	$C_{14}H_{12}$
anthracene	1.25	1.62	217	100	30	447	$C_{14}H_{10}$
Inorganic crystal:							
NaI (Tl)	3.67	1.85	661	200	230	410	NaI
CsI (Tl)	4.51	1.80	626	90	10^3	565	CsI

[a] Ratio of H to C atoms.

- For dosimetry applications where soft tissue is the dose-relevant material, organic plastics, liquids, and crystals are the most useful because they are made mostly of the low-Z elements C and H. Thus they do not overrespond to photons through the photoelectric effect
- The hydrogen content makes the *(n, p)* elastic-scattering interaction the main process for fast-neutron dose deposition, as it is in tissue

Scintillation dosimetry

Scintillators are often used as a more sensitive substitute for an ionization chamber in a γ-ray survey meters

- For plastic scintillators the average energy spent by an electron per light photon produced is ~ 60 eV; *W* in a gases is ~30 eV
- For good optical coupling ~1/3 of the photons reach the PM-tube photocathode; typical photocathode efficiency is ~ 15%, and tube gain ~ 10^6. Thus for equal masses of chamber gas and plastic scintillator, the output current for the latter is $3x10^4$ greater
- Assuming 1g/cm^3 for the scintillator and 0.001g/cm^3 for the gas in the ion chamber, equal volumes would favor the scintillator by a factor of $3x10^7$ - comparable in sensitivity to a G-M tube of the same size
- However, the plastic scintillator has an output current for electrons (with E> 125 keV) that is proportional to the absorbed dose in the plastic medium, which approximates tissue

Scintillation dosimetry

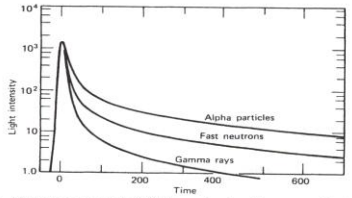


FIGURE 15.9. **Time dependence of scintillation pulses in stilbene, normalized to equal heights at time zero, when excited by radiations of different LET. The curve labeled "neutrons" represents the protons generated by (*n*, *p*) interactions. (Bollinger and Thomas, 1961. Reproduced with permission from L. M. Bollinger and The American Institute of Physics.)**

- In some materials, notably stilbene and NE-213 liquid scintillator, a sizable longer-time-constant component exists that is LET-dependent. Particles with denser tracks thus have a more pronounced component of longer decay time constant

Scintillation dosimetry

- Electronic discrimination can be provided to count pulses of differing lengths separately, making it possible to apply different dose calibrations to the pulse heights for radiations having different LETs
- Since the efficiency of scintillators decreases with increasing LET, this technique allows that defect to be compensated for. This is especially useful for dosimetry in combined neutron-γ-ray fields
- Combinations of two different scintillators coupled to the same PM tube, called "phoswiches" are useful for some dosimetry situations. The scintillators are chosen to have different decay times so pulse-shape discrimination can be applied to separate the signals. For example, one thin scintillator can be used to stop a relatively non-penetrating component of radiation (e.g. β-rays), while a thicker scintillator behind the first interacts more strongly with more penetrating γ-rays

Semiconductor detectors

- Si and Ge detectors are used mainly for spectrometry in applications where highest energy resolution is required
- Semiconductor detectors have characteristics that make them attractive as dosimeters, for measuring either dose or dose rate, as a substitute for an ion chamber
- Can serve as a solid-state analogue of a proportional counter, since the ionization produced by a charged particle in traversing the detector sensitive volume is
  - –proportional to the energy spent
  - –independent of LET for particles lighter than α's
- Semiconductor detectors may be employed as neutron dosimeters by measuring the resulting radiation damage

Semiconductor detectors

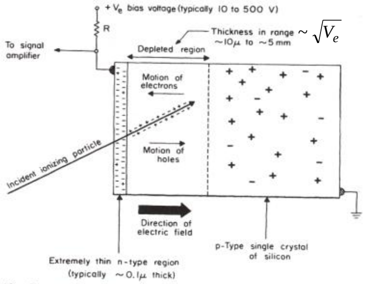


FIGURE 15.10. **Reverse-biased *p*–*n* junction detector (Miller, 1961. Reproduced with permission from the Brookhaven National Laboratory. Drawing made available by courtesy of J. F. Fowler, 1966.)**

Semiconductor detectors

- The mean energy spent per electron-hole pair
  - –in Si at 300 K is 3.62 eV for α's and 3.68 for electrons
  - –in Ge at 77 K it is 2.97 eV for both

  leading to ~ 10 times as much ionization is formed in semiconductor detectors as in ion chambers for the same energy expenditure
- Electrons have mobilities of 1350 cm/s per V/cm in Si and 3900 in Ge, at 300 K. Hole mobilities are 480 cm/s per V/cm in Si and 1900 in Ge, at 300 K, producing a voltage-pulse rise times ~ 10^{-7} - 10^{-8} s

Semiconductor detectors

- Si diode detectors with reverse bias applied offer great sensitivity and response time
- There is an advantage in operating without external bias due to the DC leakage current decreasing more rapidly than the radiation-induced current with as the bias voltage is reduced to zero. Since this leakage current is strongly temperature-dependent, minimizing its magnitude is advantageous
- The residual zero-bias radiation-induced current results from alteration of charge-carrier concentrations, giving rise to a potential difference between the electrodes.
- The measurement of the radiocurrent is done with a low-impedance circuit such as an operational amplifier

Semiconductor detectors

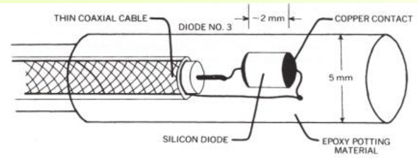


FIGURE 15.11*a*. Design of unbiased silicon *p–n* junction (Gager et al., 1977. Reproduced with permission from L. D. Gager and the American Institute of Physics.)

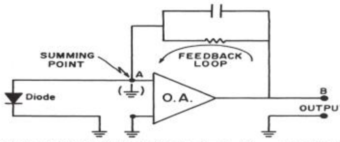


FIGURE 15.11*b*. Operation of unbiased silicon *p–n* junction (Gager et al., 1977. Reproduced with permission from L. D. Gager and The American Institute of Physics.)

Semiconductor detectors

- The ranges of dose rate measured in radiotherapy applications (0.03-3 Gy/min) produce adequate output currents from an unbiased silicon diode detector with a typical sensitivity of ~2×10^{-11} A per R/min (a commercial device by Nuclear Associates, with volume of 0.2 mm^3)
- The Si detector has a strong energy-dependent response; a high-*Z* filter surrounding the detector helps flatten the energy dependence per roentgen or per tissue rad
- Comparison of depth-dose measurements of linac x-ray beams taken with this detector and with a Farmer ion chamber demonstrated good agreement between the two, with a better signal-to-noise ratio in Si detector

Semiconductor detectors

- The most common types of semiconductor detectors are the lithium-drifted type, prepared by diffusing Li^+ ions into high-purity Si or Ge crystals
- Drifted regions up to ~ 2 cm in thickness can be achieved, and the entire intrinsic volume acts as the dosimeter's sensitive volume. Changing the applied potential varies the electric field strength, but doesn't change its depth
- Ge(Li) detectors are preferred over Si(Li) for x- or γ-ray spectrometry >50 keV, or energy-fluence measurements, because of the higher *Z* (32) and a greater photoelectric cross section
- Si(Li) detectors are preferred for lower-energy x rays and for β-ray dosimetry due to their much lower backscattering. Detectors with areas ~ 15 cm^2 are available

Semiconductor detectors

- The density of Si is ~ 2.3 g/cm^3, or about 1800 times that of air (Ge is 5.3 g/cm^3, 4100 times)
- Considering the ionization energy *W* difference, a Si(Li) detector will produce about 18,000 times as much charge as an ion chamber of the same volume, in the same x-ray field, at energies where the photoelectric effect is unimportant (> 100 keV)
- Disadvantage: Ge(Li) and Si(Li) detectors must be maintained at low (liquid nitrogen) temperature

Summary

- Proportional counters: rely on gas multiplication; collected charge is proportional to the number of original electrons
- Geiger-Muller counters: rely on gas multiplication; all pulses have the same amplitude
- Scintillators: convert kinetic energy of charged particles into detectable light within a short time
- Semiconductor detectors: electron-hole pairs are created along the path of charged particle (reverse biased, or with no external bias)