

# Integrating Dosimeters

## Chapter 14

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

### Outline

- Thermo-luminescence dosimetry
- Photographic dosimetry
- Chemical dosimetry
- Calorimetric dosimetry

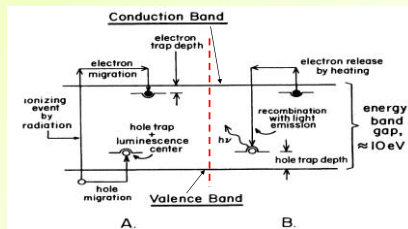
### Introduction

- Two ways to register signal produced in response to radiation: integrating (current) mode and pulse mode
- In integrating dosimetry the signal is proportional to the dose deposited over a period of time
- No information on spectrum or time-resolved signal due to individual quanta
- Energy deposition results in measurable changes within a dosimeter material (chemical, structural, etc.)

### Thermo-luminescence dosimetry

- The sensitive volume of a TLD consists of a small mass (~1-100 mg) of crystalline dielectric material containing suitable *activators* to make it perform as a thermoluminescent phosphor
- The activators provide two kinds of *centers*:
  - *Traps* for the electrons and “holes”, which can capture and hold the charge carriers in an electrical potential well for usefully long periods of time
  - *Luminescence centers*, located at either the electron traps or the hole traps, which emit light when the electrons and holes are permitted to recombine at such a center

### Thermo-luminescence dosimetry

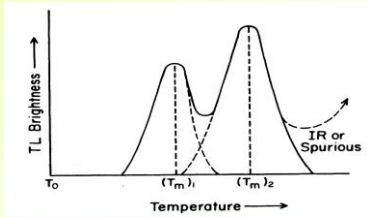


- Energy-level diagram of the TL process:  
(A) ionization by radiation, and trapping of electrons and holes;  
(B) heating to release electrons, allowing luminescence production

### Thermo-luminescence dosimetry

- At the temperature during irradiation traps should be deep enough (in terms of potential energy) to prevent the escape of the electron or hole for extended periods of time, until deliberate heating releases either or both of them
- Upon heating the electron enters the conduction band and migrates to a hole trap, which acts as a luminescence center
- Recombination is accompanied by the release of a light photon

## Thermo-luminescence dosimetry

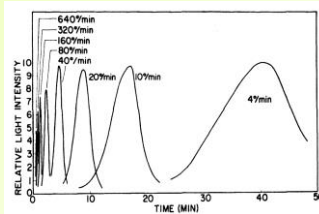


- A TL glow curve vs. temperature that results from the gradual heating of an irradiated thermoluminescent phosphor that contains two trap depths
- At higher temperatures IR signal from heating or spurious TL emission may interfere

## Thermo-luminescence dosimetry

- $T_m$  depends on heating rate, increasing gradually with  $q$ ; for the same values of  $\alpha$  and  $E$ 
  - $T_m = 248^\circ\text{C}$  for  $q = 5\text{ K/s}$
  - $T_m = 263^\circ\text{C}$  for  $q = 10\text{ K/s}$
- At higher temperatures the light-emission efficiency may decrease by a process called *thermal quenching* (higher probability for recombination to occur without emission of a photon)
- Thus at higher heating rates some loss of total light output may be noticed

## Thermo-luminescence dosimetry



- The time to reach the glow peak is nearly inversely proportional to the heating rate
- Varying the heating rate leaves total light output constant, preserving the area of glow curves in terms of brightness vs. time

- Glow curves vs. time obtained with a  $\text{CaF}_2\text{:Mn}$  TL dosimeter at eight linear heating rates, from 4 to 640  $^\circ\text{C}/\text{min}$
- The dose to the phosphor was adjusted to be inversely proportional to the heating rate in each case

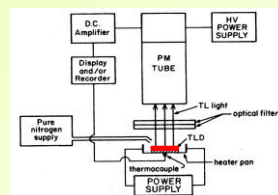
## Thermo-luminescence dosimetry

- The *light sum* rather than the height of the glow peak should be used as a measure of the absorbed dose, since it is less dependent on fluctuations in the heating rate
- The peak height may be used if the heating rate is very stable; this may be advantageous in measuring small doses for which the upper limb of the glow curve rises due to IR and spurious effects

## Thermo-luminescence dosimetry

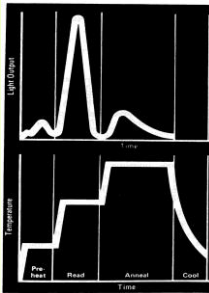
- Only a small part of the energy deposited as absorbed dose in a TLD phosphor is emitted as light when the substance is heated, the rest goes into non-radiative recombinations
- The ratio (TL light energy emitted per unit mass)/(absorbed dose) is called the *intrinsic TL efficiency*
- Examples: 0.039% in  $\text{LiF}$  (TLD-100), 0.44% in  $\text{CaF}_2\text{:Mn}$ , and 1.2% in  $\text{CaSO}_4\text{:Mn}$
- TLDs must be used under reproducible conditions to obtain consistent results

## Thermo-luminescence dosimetry



- TLD reader is the instrument used to heat a TLD phosphor, and measure the resulting TL light emitted
- The TLD phosphor is placed in the heater pan and heated while the emitted light is measured with a photomultiplier
- Heating-program reproducibility is vital in achieving reproducible TL dosimetry
- Constant light sensitivity is also essential, so that a given TLD light output always gives the same reading

## Thermo-luminescence dosimetry



- One typical scheme is to heat the phosphor rapidly through the unstable-trap region, ignoring light emission until some preset temperature is reached
- Then the phosphor is either heated linearly or abruptly raised to a temperature sufficient to exhaust the glow peak of dosimetric interest, while measuring the emitted-light sum, which is displayed as a charge or dose reading
- Finally, the phosphor may be heated further (annealed) to release any remaining charge from deeper traps, while ignoring any additional light emission

## Thermo-luminescence dosimetry

Phosphor	LiF: Mg, Ti	CaF <sub>2</sub> : Mn	Li <sub>2</sub> BeO <sub>3</sub> : Mn	Cs <sub>2</sub> SO <sub>4</sub> : Mn
Density (g/cm <sup>3</sup> )	2.64	3.18	2.3	2.61
Effective atomic number	8.2	16.3	7.4	15.3
TL emission spectra (nm):				
Range	350-600	440-600	550-630	650-660
Maximum at	400	500	665	500
Temperature of main TL glow peak at 40°C/min (°C)	215	290	180	180
Approximate relative TL output for <sup>60</sup> Co	1.0	≈3	≈0.3	≈70
Energy response without added filter (30 keV/Co)	1.25	≈13	≈0.9	≈10
Useful range	mR-10 <sup>3</sup> R	mR-3 × 10 <sup>3</sup> R	mR-10 <sup>3</sup> R	μR-10 <sup>3</sup> R
Fading	Small, <5% (12 wk)	≈10% in first month	~10% in first month	50-60% in first 24 h

- TLD phosphors consist of a host crystalline material containing one or more activators (traps, luminescence centers, or both)
- Amounts of activators range from a few parts per million up to several percent in different phosphors
- The host crystal almost entirely determines the radiation interactions
- LIF is often preferred due to its Z close to that of tissue

## Advantages of TLDs

- For the most widely used, LiF (TLD-100):
  - Wide useful dose range*, from a few mrad to ~10<sup>3</sup> rad linearly; 10<sup>3</sup>-10<sup>4</sup> rad of supralinear response vs. dose
  - Dose-rate independence*, 0-10<sup>11</sup> rad/s
  - Small size; passive energy storage*: can be used as dose probes with little disturbance of the radiation field; can be made thin enough to approach B-G conditions at high energies, but TCPE is achieved due to their condensed state
  - Commercial availability*: both TLDs and readers
  - Reusability*: employing appropriate annealing procedures, and checking for possible alteration in radiation sensitivity, TLD phosphors can be reused many times until they become permanently damaged by radiation, heat or environment. Thus it is feasible to calibrate individual dosimeters.

## Advantages of TLDs

- Readout convenience*: TLD readout is fairly rapid (< 30 s) and requires no wet chemistry.
- Economy*: reusability usually reduces cost per reading
- Availability of different types with different sensitivities to thermal neutrons*
- Automation compatibility*: for large personnel-monitoring operations automatic readers are available
- Accuracy and precision*: reading reproducibility of 1-2% can be achieved with care. Comparable accuracy may be obtained through individual calibration and averaging of several dosimeters in a cluster, since their volume is small.

## Disadvantages of TLDs

- Lack of uniformity*: different dosimeters made from a given batch of phosphors show a distribution of sensitivities; different batches of phosphor have different average sensitivities. Individual dosimeter calibration, or at least batch calibration, is necessary
- Storage instability*: TLD sensitivity can vary with time before irradiation, as a result, for example, of gradual room-temperature migration of trapping centers in the crystals. Controlled annealing of the TLDs can usually restore them to some reference condition
- Fading*: irradiated dosimeters do not permanently retain 100% of their trapped charge carriers, resulting in a gradual loss of the latent TLD signal. This must be corrected for, especially in applications (e.g., personnel monitoring) that involve long time delays
- Light sensitivity*: TLDs show some sensitivity to light, causing accelerated "fading", or leakage of filled traps, or ionization and the filling of traps, giving spurious TL readings

## Disadvantages of TLDs

- Spurious TL*: scraping or chipping of TLD crystals or surface contamination by dirt or humidity also can cause spurious TL readings. The presence of an oxygen-free inert gas during readout suppresses these signals
- "Memory" of radiation and thermal history*: the sensitivity can change after receiving a large dose of radiation and undergoing readout. Additional annealing may be necessary to restore the original sensitivity. For large doses it may be more economical to throw away the phosphor after a single use
- Reader instability*: TLD readings depend on the light sensitivity of the reader as well as on the heating rate of the phosphor. Thus reader constancy is difficult to maintain over long time periods.
- Loss of a reading*: the measurement of light out of a TLD erases the stored information. Unless special provision is made (e.g., a spare TLD), there is no second chance at getting a reading. Reader malfunction can lose a reading

## Photographic dosimetry

- Photographic emulsion consists of microscopic grains of silver bromide (AgBr), dispersed in a gelatin layer on either one or both sides of a supporting film
- Incident charged particles produce ion pairs in or near the grains, and their effect is to convert  $\text{Ag}^+$  ions to Ag atoms
- Ag atoms on a grain (containing typically  $10^{10}$   $\text{Ag}^+$  ions) constitute a *latent image* developable by a chemical process
- In that process all of the  $\text{Ag}^+$  ions are converted to Ag atoms and the bromine is removed, leaving behind an opaque microscopic grain of silver
- The presence of this elemental silver may be detected optically and quantitatively related to the absorbed dose

## Photographic dosimetry

- In x-ray emulsions the radiation effect is measured by a densitometer in terms of the *light opacity* of the film
- Opacity* is defined as  $I_0/I$ , where  $I_0$  is the light intensity in the absence of the film, and  $I$  is transmitted through the film
- The *optical density* (OD) is defined as  $\log_{10}(I_0/I)$
- If  $a$  is the average area ( $\text{cm}^2/\text{grain}$ ) obscured by a single developed grain of silver, and  $n$  is the number of developed grains per  $\text{cm}^2$  of film, then  $I_0/I \cong e^{an}$

$$\text{and } \text{OD} = \log_{10}\left(\frac{I_0}{I}\right) = an \log_{10} e = 0.4343an$$

as long as  $n \ll N$ , where  $N$  is the number of AgBr grains per unit area ( $\text{cm}^2$ ) in the unexposed film

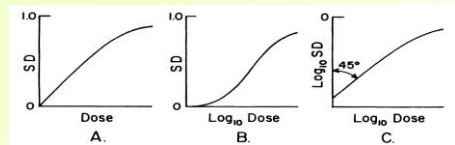
## Photographic dosimetry

- Film-density measurements are sometimes expressed in terms of the *standard density* (SD), defined as:

$$\text{SD} = \frac{(\text{OD}) - (\text{OD})_f}{(\text{OD})_m - (\text{OD})_f}$$

where (OD) is the optical density of the exposed film,  $(\text{OD})_f$  is that of the unexposed film, and  $(\text{OD})_m$  is the maximum optical density measured if all the grains are developed

## Photographic dosimetry



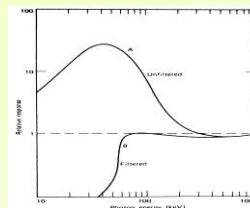
- Three common types of plots of film dosimeter response:
  - (A) standard density (SD) vs. dose ( $D$ ) in tissue or water;
  - (B) SD vs.  $\log_{10} D$ , is called the "H and D" curve; its slope, called *contrast*, measures the ability of the film to distinguish between two nearly equal exposures by OD difference
  - (C)  $\log_{10}$  SD vs.  $\log_{10} D$
- Graphs like A and C are most useful for dosimetry, since they are linear at low doses for the case where the single-hit response dominates (usual case)

## Practical exposure range for x-ray film

Film	Responsive Range	Approx. Saturation Exposure
PPL	0.25 – 5 cGy	10 cGy
XTL	1 – 15 cGy	30 cGy
XV-2	5 – 100 cGy	200 cGy
EDR2	25 – 400 cGy	700 cGy

- Useful ranges of some Kodak films for radiation therapy dosimetry applications

## Photographic dosimetry: x-ray energy dependence



- Photoelectric effect in the AgBr grains causes the film to absorb x-ray energy 10-50 times more readily for  $h\nu < 0.1$  MeV than does tissue or air
- This over-response can be compensated with high-Z filter

Relative response per unit of x-ray exposure, normalized to a typical film-badge dosimeter with and without a compensating filter allows the badge to yield spectral information, if different metal foils are used over different areas of the badge

## Advantages of photographic dosimetry

- a. Spatial resolution
- b. Reading permanence
- c. Commercial availability
- d. Geometry
- e. Linearity vs. dose
- f. Dose-rate independence

## Disadvantages of photographic dosimetry

- a. Wet chemical processing
- b. Energy dependence for x-rays
- c. Sensitivity to hostile environments
- d. Double-valued response functions
- e. "Blindness" to low-energy neutrons

## Radiochromic dosimeters

- Offer very high spatial resolution and relatively low spectral sensitivity variation
- Insensitive to visible light, hence ease of handling and preparation in room light
- Films color directly and do not require chemical processing: a color change (colorless to blue, red, green, etc.) indicates exposure to radiation
- Image formation occurs as a dye-forming or a polymerization process
- TG-63 protocol on radiochromic film dosimetry

## Chemical dosimetry

- In chemical dosimetry, the dose is determined from quantitative chemical change in an appropriate medium, which may be liquid, solid, or gaseous
- Aqueous liquid systems, especially the Fricke dosimeters, are most relevant to the measurement of dose in tissue
- Radiation interacts mainly with water molecules, producing free radicals  $\text{H}^\cdot$  and  $\text{OH}^\cdot$ , and molecular products ( $\text{H}_2$  and  $\text{H}_2\text{O}_2$ )
- Primary products are produced in  $\leq 10^{-10}$  s heterogeneously; by  $10^{-6}$  s after the initial interaction, the spatial distribution of these primary products homogenizes due to diffusion, simultaneous with their chemical interactions with the solutes present

## Chemical dosimetry

- The yield of the measured product is expressed as a *G-value*, or more recently in terms of the *radiation chemical yield*,  $G(X)$ , for the product  $X$
- The *G-value* is the number of chemical entities (e.g., molecules) produced, destroyed, or changed by the expenditure of 100 eV of radiation energy
- $G(X)$  is expressed in units of moles/J,  $G(X) = G \times 1.037 \times 10^{-7}$
- $G(X)$  is usually  $\sim 10^{-6} - 10^{-7}$  moles/J in aqueous chemical dosimeters, a dose of 10 Gy then requires measurement of  $\sim 10^{-5} - 10^{-6}$  M solutions of the product with acceptable accuracy
- Not suitable for measurement of small doses

## Cavity-theory considerations for chemical dosimetry

- It is impractical to make irradiation vessels small enough to behave as B-G cavities
- Their diameters are made  $>$  than the range of secondary charged particles, so that wall effects become negligible and CPE or TCPE is achieved in the dosimeter solution itself
- Alternatively, for photon or neutron irradiations wall matching to the solution in the irradiation vessel in terms of atomic numbers minimizes cavity wall effects
- For electron beams, wall matching is controlled by stopping-power and electron-scattering consideration



## Cavity-theory considerations for chemical dosimetry

Material	$\mu_{en}/\rho$ (cm <sup>2</sup> /g)	$(dT/\rho dx)_c$ (MeV cm <sup>2</sup> /g)	$[(\mu_{en}/\rho)/(dT/\rho dx)_c]$ (MeV <sup>-1</sup> )
Water	0.0296	2.355	0.0126
Vycor (SiO <sub>2</sub> )	0.0266	1.961	0.0136
Lucite	0.0288	2.292	0.0126
Polystyrene	0.0288	2.305	0.0125

- Burlin theory predicts that if the ratio  $[(\mu_{en}/\rho)/(dT/\rho dx)_c]$  is the same for the wall and the cavity materials, cavity size no longer affects the dose in the cavity
- For <sup>60</sup>Co γ-rays polystyrene or Lucite provide the best choice
- For electron beams, SiO<sub>2</sub> irradiation vessels should be avoided

## Calculation of absorbed dose

- The average absorbed dose in the dosimeter solution is given by

$$\bar{D} = \frac{\Delta M}{\rho G(X)}$$

- where  $\Delta M$  (mole/liter) is the change in molar concentration of product X due to the irradiation, and  $\rho$  (g/cm<sup>3</sup> or kg/liter) is the solution density
- This assumes that  $G(X)$  (mole/J) applies to the production of X throughout the molar range  $\Delta M$

## The Fricke ferrous sulfate dosimeter

- The measured ratio of the transmitted light intensities through the irradiated and unirradiated samples  $I/I_0 = 10^{-A(OD)}$  can be related to the corresponding increase in optical density  $\Delta(OD) = \epsilon l \Delta M$
- Substituting for  $\Delta M$  the average absorbed dose

$$\bar{D} = \frac{\Delta(OD)}{\epsilon l G(\text{Fe}^{3+}) \rho}$$

## The Fricke ferrous sulfate dosimeter

- For  $\epsilon = 2187$  liter/mole cm at 304 nm and 25°C;  $l = 1$  cm;  $G(\text{Fe}^{3+}) = 1.607 \times 10^{-6}$  mole/J for low-LET radiations such as <sup>60</sup>Co γ rays;  $\rho = 1.024$  kg/liter for standard Fricke solution at 25 °C

$$\bar{D} = 278 \Delta(OD) \text{ Gy}$$

- Thus the normal dose range of the Fricke dosimeter (40 – 400 Gy) corresponds to  $\Delta(OD)$  values of  $\approx 0.14$  to 1.4 for a 1-cm spectrophotometer cell at 304 nm

## The Fricke ferrous sulfate dosimeter

- The solution must be *air-saturated* during irradiation for the  $\text{Fe}^{2+} \rightarrow \text{Fe}^{3+}$  oxidation reaction to proceed with the expected  $G$  value; stirring the sample or bubbling air through it during irradiation may be necessary
- The system is dose-rate-independent up to  $2 \times 10^6$  Gy/s
- The upper limit of the Fricke system can be extended to 4000 Gy
- The lower dose-range limit can be reduced to  $\approx 4$  Gy by increasing the photometric light pathlength to 10cm

## Other chemical dosimeters

- A variety of other chemical dosimeters have been described
- Most are limited to dose ranges still higher than the upper limit of the extended Fricke system ( $> 4 \times 10^3$  Gy)
- One especially versatile dosimeter is the radiochromic dye-cyanide system, which is commercially available in some forms

## Advantages of aqueous chemical dosimeters

1. Aqueous solutions have an effective  $Z$ , density, and  $\mu_{en}/\rho$  close to those of water: application of cavity theory is simplified
2. Liquid dosimeters can be irradiated in a container similar in shape and volume to the object being studied
3. Easy to achieve a large-size dosimeter in the Burlin-theory sense, but the B-G conditions are difficult to satisfy
4. Absolute dosimetry is possible, at least for the Fricke system
5. Dose ranges within the limits  $10^{-10}$ – $10^{10}$  rad
6. Linear response vs. dose is found in some chemical dosimeters over limited but useful ranges

## Disadvantages of aqueous chemical dosimeters

1. Lack of storage stability prevents commercial availability, requiring careful wet chemistry in the user's laboratory, a pronounced disadvantage
2. Useful dose ranges tend to be too high for personnel monitoring or small-source measurement
3. Individual systems usually show some degree of dose-rate and LET dependence, as well as dependence on the temperature of the solution during irradiation and during the readout procedure

## Calorimetric dosimetry

- The measurement of the temperature rise in calorimetric dosimeters comes closest of any method to providing a direct measurement of the full energy imparted to matter by radiation
- Only relatively small corrections for thermal leakage and for chemical reactions are necessary
- While in principle any kind of thermometer can be used in a calorimeter, the temperature change is so small that in practice only *thermocouples* and *thermistors* are sufficiently sensitive

## Calorimetric dosimetry

- The temperature increase per unit of absorbed dose to the material in the calorimeter's sensitive volume depends on its *thermal capacity*,  $h$ , usually expressed in cal/g °C or J/kg °C
- The amount of energy required to raise 1 g of water 1 °C (=1 cal) depends upon the temperature of the water to which it refers
  - it is usually assumed 15 °C in thermal-capacity (or specific-heat) tables; hence 1 cal = 4.185 J, and 1 cal/g °C = 4185 J/kg °C

## Calorimetric dosimetry

- For a sensitive volume containing a material of thermal capacity  $h$  (J/kg °C), mass  $m$  (kg), and thermal defect  $\delta$ , and that absorbs  $E$  joules of energy, the temperature increase is given by

$$\Delta T = \frac{E(1-\delta)}{hm} = \frac{\bar{D}(1-\delta)}{h} \quad (^\circ\text{C})$$

where  $\bar{D}$  is the average absorbed dose (Gy)

- The *thermal defect*  $\delta$  is the fraction of  $E$  that does not appear as heat, due to competing chemical reactions, if any

## Calorimetric dosimetry

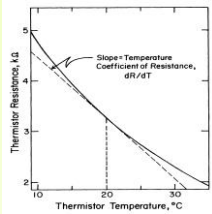
Thermal capacity of several calorimetric materials

Material (at $\approx 20^\circ\text{C}$ )	$h$ (cal g <sup>-1</sup> °C <sup>-1</sup> ) <sup>a</sup>	$h$ (J kg <sup>-1</sup> °C <sup>-1</sup> )
Aluminum	.214	896
Mercury	.03325	139.2
Copper	.0921	385.4
Graphite	.17	$7.1 \times 10^2$
Gold (at 18°C)	.0312	130.6
Silicon (at 25°C)	.1706	714
Water	.999	4181

<sup>a</sup>The calorie is referred to water at 15°C

- In Al a dose of 1 Gy causes a temperature increase of  $1.12 \times 10^{-3}$  °C
- To measure this temperature rise with 1 % precision requires a thermometer capable of detecting temperature changes  $\sim 10$   $\mu^\circ\text{C}$

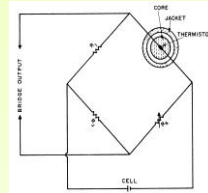
## Calorimetric dosimetry: thermistors



- Thermistors can be obtained in small sizes comparable to thermocouples
- They are semiconductors made of metallic oxides
- They exhibit negative temperature coefficients of the order of several percent per °C at room temperatures, increasing in negative coefficient with decreasing temperature

A typical resistance-vs.-temperature curve for a thermistor. The slope  $dR/dT$  at 20 °C, shown by the dashed line, is  $\approx -120 \Omega/^\circ\text{C}$  or  $-3.7\%/^\circ\text{C}$

## Calorimetric dosimetry: thermistors



- The resistance of a thermistor at room temperature is typically  $10^3 - 10^5 \Omega$ , which can be measured with great precision by a Wheatstone bridge
- The bridge null detector must be sensitive enough so that the power dissipated in the thermistor is negligible compared to the radiation heating

A Wheatstone bridge circuit for measuring the resistance of a thermistor in the sensitive volume (or "core") of a calorimetric dosimeter. When  $R_x$  is set to produce a null current reading,  $R_x/R_3 = R_1/R_2$ , from which  $R_x$  can be determined

## Absorbed-dose calorimeter

- If the thermal capacity and thermal defect of the core material are known, then the calorimeter can be operated adiabatically, without energy calibration, providing that the thermal leakage is negligible
- The average absorbed dose in the core is found from

$$\bar{D} = \frac{h\Delta T}{1-\delta}$$

- The mass of the core is not needed

## Advantages of calorimetric dosimeters

1. They can be made absolute
2. The measurement of temperature rise is the most direct measurement of the energy involved in the absorbed dose
3. Almost any absorbing material, solid or liquid, can be employed in the calorimeter sensitive volume
4. Inherently dose-rate-independent under adiabatic conditions. No saturation effects at high dose rates as other dosimeters
5. Calorimeters add up the energy contributions in the sensitive volume from different types of radiations (e.g., neutrons and  $\gamma$  rays) with weighting factors of unity
5. Calorimeters have no LET dependence
6. Calorimeters are relatively stable against radiation damage

## Disadvantages of calorimetric dosimeters

1. Temperature rises to be measured are typically very small, limiting calorimetry to relatively large doses
2. Thermal insulation, and instrumentation for thermal control and measurement, often make the calorimeter apparatus bulky and difficult to transport and set up. This limits their use for calibration of other dosimeters
3. For low dose rates, thermal leakage in and out of the calorimetric sensitive volume limits the accuracy and precision
4. Some materials (e.g., tissue-equivalent plastic) undergo radiation-induced endothermic or exothermic reactions resulting in thermal defect (e.g., in A150-type TE plastic about 4% of the absorbed dose goes to an endothermic reaction)

## Summary

- Main types of integrating dosimeters:
  - Thermo-luminescence
  - Photographic
  - Chemical
  - Calorimetric



## 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

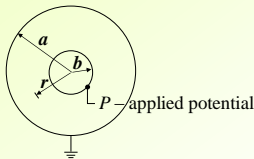
## Introduction

- Pulse-mode detectors record the charge from individual event interaction; usually more desirable for getting information on amplitude and timing of individual pulses
- Major types: 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  $\sigma_e$  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  $\sim 10^3$  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  $E(r)$  must satisfy

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

- 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

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

- $\Delta V$  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)	$\Delta V$ (eV)
90% Ar + 10% methane ("P-10")	$4.8 \times 10^4$	23.6
Methane	$6.9 \times 10^4$	36.5
96% He + 4% isobutane	$1.48 \times 10^4$	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  $G \sim 100$
- Reducing the gas pressure to 0.5 atm would increase  $G \sim 2000$
- Substitution of the He-isobutane mixture at 1 atm would provide an even higher  $G \sim 4000$
- The upper G limit for *proportional* gas multiplication is  $\sim 10^4$

## 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  $G \times Q$  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  $\delta$ -rays
- At least half of positive ions and electrons originate within the amplifying sheath (typically, 1-2  $\mu\text{m}$  from the central electrode)

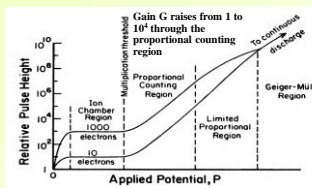
## Proportional counters

- 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  $\sim 1$   $\mu\text{s}$
- 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  $\mu\text{s}$
- If pulse heights are to be measured also, the average interval between pulses should be greater, approaching the transit times for the positive ions ( $\sim 100$   $\mu\text{s}$ ) for greatest accuracy

## Pulse-height analysis



- 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  $\alpha$ -particle source
- The expectation value of the dose contributed to the gas by each  $\alpha$ -particle can be written as

$$\bar{D}_\alpha = \frac{1}{m} \left( \frac{dT}{\rho dx} \rho \Delta x \right) \quad \begin{array}{l} m - \text{mass of gas; } \rho - \text{gas} \\ \text{density; } dT/\rho dx - \text{mass} \\ \text{collision stopping power of} \\ \text{the gas for } \alpha\text{-particle} \end{array}$$

## Pulse-height analysis

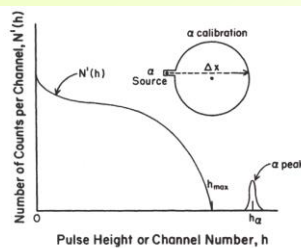


FIGURE 15.2. Differential distribution of counts per pulse-height channel vs. channel number for a proportional counter, as measured by a pulse-height analyzer. A built-in  $\alpha$ -particle source is used to calibrate the channel number  $h$  in terms of absorbed dose to the counter gas. Assuming a constant  $W/e$  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  $D(h) = (h/h_\alpha)D_\alpha$ .

## 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

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

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

## 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 are
  - a) their short pulse length ( $\sim 1 \mu\text{s}$ ) 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  $\gamma$ -ray interactions in a mixed  $\gamma$  + neutron field

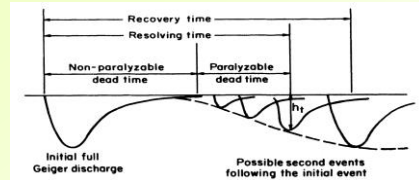
## Geiger-Muller counters

- 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

- 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

- 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  $\gamma$ -ray fields in radiation-protection applications
- When equipped with a thin ( $\sim 1 \text{ mg/cm}^2$ ) window they can also be used to detect  $\beta$ -rays

## 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  $\sim 10^{-9}$  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

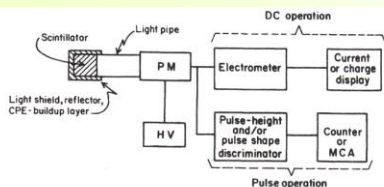


FIGURE 15.7. General schematic design for a scintillation detector for dosimetry applications. A light pipe optically couples the scintillator to the photomultiplier tube. The scintillator is otherwise enclosed in an optically opaque and internally reflective envelope that may also filter out short-range 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  $\sim 1 \text{ keV}$  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  $\gamma$ -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

## Scintillation dosimetry

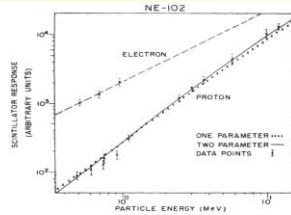


FIGURE 15.8. Light output vs. particle energy for electrons and protons stopped in the plastic scintillator NE-102. The light output is proportional to electron energy, but not to proton energy. Curves are based on Birks's theory (1964) that dense ionization tracks create damaged molecules, which lower 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  $\sim 125$  keV

## Scintillation dosimetry

TABLE 15.2. Characteristics of Some Scintillators

Type	Specific Gravity	Refractive Index	Softening or Melting Point ( $^{\circ}\text{C}$ )	Light Output Rel. to Anthracene (%)	Decay Const., Main Component (ns)	Maximum $\lambda$ (nm)	Approx. Composition
Plastic NE-102	1.032	1.581	75	65	2.4	423	1.104 <sup>a</sup>
Liquid NE-213	0.874	1.508	141	78	3.7	425	1.213 <sup>a</sup>
Liquid NE-226	1.51	1.39	90	20	3.3	430	0 <sup>a</sup>
Liquid NE-228	0.735	1.403	99	43	—	385	2.00 <sup>a</sup>
Organic crystal:							
stilbene	1.16	1.626	125	30	4.5	410	C <sub>14</sub> H <sub>12</sub>
anthracene	1.25	1.62	217	100	30	447	C <sub>14</sub> H <sub>10</sub>
Inorganic crystal:							
NaI (Tl)	3.67	1.85	661	200	230	410	NaI
CaI (Tl)	4.51	1.80	626	90	10 <sup>3</sup>	565	CaI

<sup>a</sup>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  $\gamma$ -ray survey meters

- For plastic scintillators the average energy spent by an electron per light photon produced is  $\sim 60$  eV;  $W$  in a gases is  $\sim 30$  eV
- For good optical coupling  $\sim 1/3$  of the photons reach the PM-tube photocathode; typical photocathode efficiency is  $\sim 15\%$ , and tube gain  $\sim 10^6$ . Thus for equal masses of chamber gas and plastic scintillator, the output current for the latter is  $3 \times 10^4$  greater
- Assuming  $1\text{g/cm}^3$  for the scintillator and  $0.001\text{g/cm}^3$  for the gas in the ion chamber, equal volumes would favor the scintillator by a factor of  $3 \times 10^7$  - 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

- 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- $\gamma$ -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.  $\beta$ -rays), while a thicker scintillator behind the first interacts more strongly with more penetrating  $\gamma$ -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  $\alpha$ 's
- Semiconductor detectors may be employed as neutron dosimeters by measuring the resulting radiation damage

## Semiconductor detectors

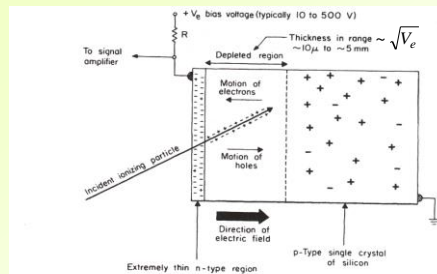


FIGURE 15.10. Reverse-biased  $p$ - $n$  junction detector (Miller, 1961. Reproduced with permission from the Brookhaven National Laboratory. Drawing made available by courtesy of J. F. Fowler, 1966.)



## Semiconductor detectors

- The mean energy spent per electron-hole pair
  - in Si at 300 K is 3.62 eV for  $\alpha$ 's and 3.68 for electrons
  - in Ge at 77 K it is 2.97 eV for bothleading to  $\sim 10$  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  $\sim 10^{-7} - 10^{-8}$  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

## Semiconductor detectors

- The most common types of semiconductor detectors are the lithium-drifted type, prepared by diffusing  $\text{Li}^+$  ions into high-purity Si or Ge crystals
- Drifted regions up to  $\sim 2$  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  $\gamma$ -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  $\beta$ -ray dosimetry due to their much lower backscattering

## Semiconductor detectors

- The density of Si is  $\sim 2.3$  g/cm<sup>3</sup>, or about 1800 times that of air (Ge is 5.3 g/cm<sup>3</sup>, 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)