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

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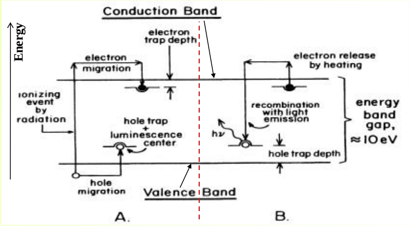
Thermo-luminescence dosimetry



- 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

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Thermo-luminescence dosimetry

- The simple kinetics for the escape of such trapped charge carriers at a temperature T(K) were first described by Randall and Wilkins using the equation

$$p = \frac{1}{\tau} = \alpha e^{-E/kT}$$

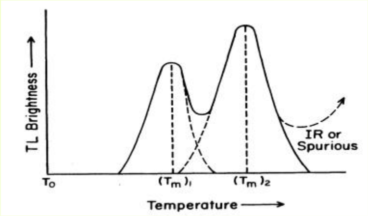
Here p is the probability of escape per unit time (s^{-1}), τ is the mean lifetime in the trap, α is called the *frequency factor*, E is the energy depth of the trap (eV), and k is Boltzman's constant

- On the assumption of constant values for E, and α, increasing T causes p to increase and τ to decrease

Thermo-luminescence dosimetry

- If the temperature T is increased linearly vs. time, an increase in the rate of escape of trapped electrons will occur, reaching a maximum at some temperature T_m followed by a decrease as the supply of trapped electrons is gradually exhausted
- A corresponding peak in TL brightness will also be observed at T_m ,this is called a *glow peak*
- The presence of more than one trap depth E gives rise to plural glow peaks, which may be unresolved or only partially resolved within the *glow curve*

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

- The value of T_m is related to the linear heating rate q (K/s) by the relation from R-W theory:

$$\frac{E}{kT_m^2} = \frac{\alpha}{q} e^{-E/kT_m}$$

- Assuming α = 109/s and q = 1 K/s, can estimate

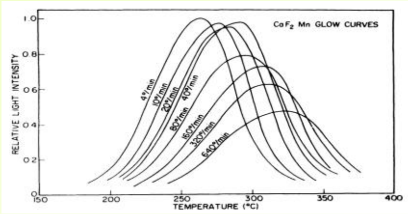
$$T_m = (489 \text{ K/eV})\ E$$

hence T_m = 216 °C for E = 1 eV

Thermo-luminescence dosimetry

- T_m depends on heating rate, increasing gradually with q; for the same values of α and E
  - – T_m = 248 °C for q = 5 K/s
  - – T_m = 263°C for q = 10 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



- Position of the glow peak T_m increases with the heating rate q
- For $q \leq 40$ °C/min the glow curve areas are approximately constant
- The onset of thermal quenching is observed at T_m =290°C

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

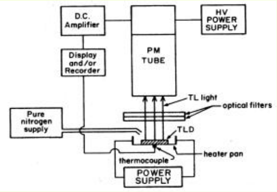
Thermo-luminescence dosimetry

- The usefulness of a given *phosphor trap* (and its associated TL glow peak) depends on its independence on ambient conditions
- If the traps are not stable at room temperature before irradiation, changes in radiation sensitivity and glow-curve shape will be observed
- In general TL phosphors give best performance as dosimeters if they receive uniform, reproducible, and optimal (depending on the phosphor) heat treatment before and after use
- For example, LiF (TLD-100) phosphor requires special annealing (e.g., 400 °C for 1 h, quick cooling, then 80 °C for 24h) to minimize sensitivity drift

Thermo-luminescence dosimetry

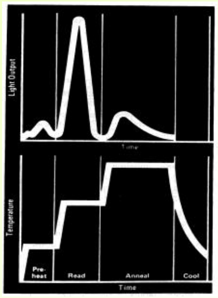
- Only a small part of the energy deposited as absorbed dose in a TLD phosphor is emitted as light when the substance is heated, the rest goes into non-radiative recombinations
- The ratio (TL light energy emitted per unit mass)/(absorbed dose) is called the *intrinsic TL efficiency*
- This has been measured as 0.039% in LiF (TLD-100), 0.44% in CaF_2:Mn, and 1.2% in $CaSO_4$:Mn
- TLDs must be used under reproducible conditions to obtain consistent results, considering that such a small fraction of the absorbed dose energy is relied upon as a measure of the entire dose

Thermo-luminescence dosimetry



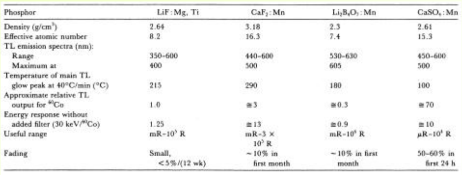
- TLD reader is the instrument used to heat a TLD phosphor, and measure the resulting TL light emitted
- The TLD phosphor is placed in the heater pan and heated while the emitted light is measured with a photomultiplier
- Heating-program reproducibility is vital in achieving reproducible TL dosimetry
- 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_2 : Mn	$Li_2B_4O_7$: Mn	$CaSO_4$: Mn
Density (g/cm^3)	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	530–630	450–600
Maximum at	400	500	605	500
Temperature of main TL glow peak at 40°C/min (°C)	215	290	180	100
Approximate relative TL output for ^{60}Co	1.0	≅3	≅0.3	≅70
Energy response without added filter (30 keV/^{60}Co)	1.25	≅13	≅0.9	≅10
Useful range	mR–10^5 R	mR–3 × 10^5 R	mR–10^6 R	μR–10^4 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

Thermo-luminescence dosimetry

- The most common forms of TLD:
  1. Bulk granulated, sieved to 75-150- μm grain size
  2. Compressed pellets or "chips", usually 3.2 mm^2 by 0.9 mm thick
  3. A Teflon matrix containing 5% or 50% by weight of <40-μm grain-size TLD powder
  4. A TLD pellet fastened on an ohmic heating element in an inert-gas-filled glass bulb
  5. Single-crystal plates, cleaved from a larger crystal
  6. Powder enclosed in plastic tubing that can be heated
- Forms 3 and 4 are preferred

Calibration of TLDs

- Most TL phosphors have some threshold dose level below which the TL light output per unit mass is proportional to the absorbed dose to the phosphor, provided that:
  - a) the LET of the radiation remains low or practically constant
  - b) the phosphor sensitivity is kept constant by using reproducible annealing procedures
- A ^{60}Co γ-ray calibration in terms of average phosphor dose in the TL dosimeter can then be used as an approximate calibration for all low-LET radiations

Calibration of TLDs

- The ^{60}Co calibration (under TCPE conditions) gives the TL reading per unit of average phosphor dose
- If the chip area presented to the beam is A (m^2), its mass is m (kg), and the ^{60}Co γ-ray calibration factor is $k_{\mathrm{Co}} = (\bar{D}_{\mathrm{TLD}}/r)_{\mathrm{Co}}$ [Gy/(scale division)], where r is the TLD reading, then the energy fluence of a stopped beam is

$$\Psi = \frac{k_{\mathrm{Co}}\, rm}{A} \qquad (\mathrm{J/m^2})$$

Calibration of TLDs

- For a free-space ^{60}Co γ-ray exposure X (C/kg) at the point to be occupied by the center of the TLD in its capsule, the average absorbed dose in the TLD, under TCPE

$$\bar{D}_{\mathrm{TLD}} = 33.97 a \beta X \left[\frac{(\mu_{\mathrm{en}}/\rho)_{\mathrm{TLD}}}{(\mu_{\mathrm{en}}/\rho)_{\mathrm{air}}} \right]_{\mathrm{Co}}$$

where a is a correction for broad-beam γ-ray attenuation in the capsule wall plus the half thickness of the TLD

- For a LiF TLD chip in a Teflon capsule 2.8 mm thick (for TCPE) the average dose calculated from this equation is

$$\bar{D}_{\mathrm{LiF}} = 31.1X \qquad (\mathrm{Gy})$$

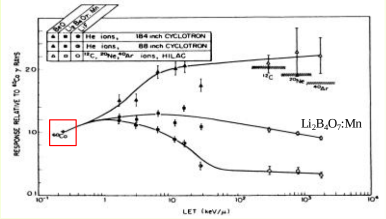
Calibration of TLDs

- For all low-LET radiations, the average absorbed dose in the TLD can then be obtained from the observed TLD reading r by

$$\bar{D}_{\mathrm{TLD}} = k_{\mathrm{Co}} r$$

- For higher-LET radiations than ^{60}Co γ-rays, TLDs typically show some variation in efficiency, and consequently a reciprocal change in the low-LET calibration factor k_{Co}

LET dependence for TLDs



- LET response of BeO, $Li_2B_4O_7$:Mn, and LiF. The curves give values of $k_{\mathrm{Co}}/k_{\mathrm{LET}}$ as a function of LET in water, in keV/μm
- LET dependence is different for different phosphors, with lithium borate coming closest to constancy

Advantages of TLDs

- For the most widely used, LiF (TLD-100):
  - a. *Wide useful dose range*, from a few mrad to ~10^3 rad linearly; 10^3-10^4 rad of supralinear response vs. dose
  - b. *Dose-rate independence*, 0-10^{11} rad/s
  - c. *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
  - d. *Commercial availability:* both TLDs and readers
  - e. *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

f. *Readout convenience:* TLD readout is fairly rapid (< 30 s) and requires no wet chemistry.

g. *Economy:* reusability usually reduces cost per reading

h. *Availability of different types with different sensitivities to thermal neutrons*

i. *Automation compatibility:* for large personnel-monitoring operations automatic readers are available

j. *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

a. *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

b. *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

c. *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

d. *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

d. *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

e. *"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

g. *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.

h. *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 Ag^+ ions to Ag atoms
- Ag atoms on a grain (containing typically 10^{10} Ag^+ ions) constitute a *latent image* developable by a chemical process
- In that process all of the 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

- Chemical processing usually comprises three steps:
  1. *Developing*: the developer molecules reduce the Ag^+ ions to Ag atoms in all grains, whether ionized or not. Those having a latent image are reduced much more rapidly, and the developing process can then be terminated
  2. *Stop Bath:* immersion of the emulsion in a dilute acetic acid "stop bath" terminates development quickly. This is necessary for quantitative photographic dosimetry
  3. *Hypo:* sodium thiosulfate ("hypo") solution is used to dissolve out the remaining undeveloped grains of AgBr. The film is finally washed in pure water and air-dried

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 (cm^2/grain) obscured by a single developed grain of silver, and n is the number of developed grains per cm^2 of film, then $I_0 / I \cong e^{an}$

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

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

Photographic dosimetry

- The following assumptions lead to a simple dosimetric model:
  - a. Incoming x-rays give rise to a secondary-electron fluence of Φ (*e*/cm^2) passing perpendicularly through the film
  - b. A single electron hit renders a grain developable
  - c. All grains have the same projected area *a*, which does not to change during development (the target area for electron hits is the same as the light-stopping area)

Photographic dosimetry

- For the fraction of grains struck and made developable

$$\frac{n}{N} \cong a\Phi \qquad \text{or} \qquad \mathrm{OD} = 0.4343a^2 N\Phi$$

- For a small fluence Φ (i.e., where $n << N$), the OD~Φ (and consequently also to the dose) in the emulsion
- The OD is also proportional to the emulsion thickness, since $N \propto$ thickness

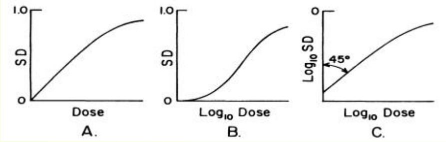
Photographic dosimetry

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

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

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

Photographic dosimetry



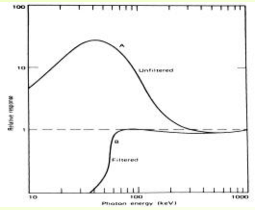
- Three common types of plots of film dosimeter response:
  - (*A*) standard density (SD) vs. dose (*D*) in tissue or water;
  - (*B*) SD vs. $\log_{10} D$, is called the “H and D” curve; its slope, called *contrast*, measures the ability of the film to distinguish between two nearly equal exposures 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 ^{60}Co γ-rays, for 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 the most common and generally the most relevant to the measurement of dose in tissue or other biological material

Chemical dosimetry

- Aqueous dosimeters usually consist of dilute solutions, therefore radiation interacts mainly with water molecules, producing free radicals H and OH, and molecular products such as H_2 and H_2O_2
- These chemically active primary products are produced in $\leq 10^{-10}$ s heterogeneously (close to the charged particle tracks)
- By 10^{-6} s after the initial interaction, the spatial distribution of these primary products tends to homogenize 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
- This requires sensitive detection methods and rules out the measurement of small doses

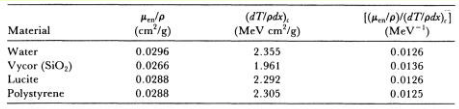
Chemical dosimetry

- To minimize errors due to chemical interference by impurities storage or irradiation vessels have to be thoroughly cleaned by washing and rinsing in distilled water, heat cleaning at 550°C or irradiation under $10^3 – 10^4$ Gy
- Typical storage or irradiation vessels are made of fused silica (Vycor) or plastics (polystyrene or Lucite) that are closer matched to the atomic number of the solution

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	μ_{en}/ρ (cm^2/g)	$(dT/\rho dx)_c$ (MeV cm^2/g)	$[(\mu_{en}/\rho)/(dT/\rho dx)_c]$ (MeV^{-1})
Water	0.0296	2.355	0.0126
Vycor (SiO_2)	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 ^{60}Co γ-rays polystyrene or Lucite provide the best choice
- For electron beams, SiO_2 irradiation vessels should be avoided

Attenuation in vessel walls of chemical dosimeter

- For SiO_2, $\rho \approx 2.2$ g/cm^3, hence an attenuation correction is called for when such a vessel is immersed in a water phantom
- For plastics the effect can be neglected for a thin-walled vessel is immersed in a phantom :
  - Polystyrene has a density ≈ 1.04 g/cm^3, close to that of water
  - For Lucite $\rho \approx 1.18$ g/cm^3; even in this case a 1-mm vessel wall immersed in a water phantom would only attenuate a photon beam by ≈ 0.04% more than the water it displaces

Calculation of absorbed dose

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

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

  where ΔM (mole/liter) is the change in molar concentration of product X due to the irradiation, and ρ (g/cm^3 or kg/liter) is the solution density
- This assumes that $G(X)$ (mole/J) applies to the production of X throughout the molar range ΔM

The Fricke ferrous sulfate dosimeter

- The chemical dosimeter of choice for most applications calling for a linear dose range from 40 to 400 Gy
- Suitable special procedures are available for extending this range to ≈ 4 Gy or upward to 4×10^3 Gy
- The standard Fricke dosimeter solution is composed of 0.001 *M* $FeSO_4$ or $Fe(NH_4)_2(SO_4)_2$ and 0.8 *N* H_2SO_4, prepared from high-purity reagents and triple-distilled water
- The solution needs to be stored in the dark in a refrigerator
- For optimal results fresh solution should be prepared just before use

The Fricke ferrous sulfate dosimeter

- Under irradiation solutions of ferrous sulfate ($FeSO_4$) oxidize to ferric sulfate $Fe_2(SO_4)_3$, producing ferric ions Fe^{3+}
- Measurement of the produced amount of ferric ion can be done by chemical titration of the irradiated and unirradiated samples to obtain ΔM of Fe^{3+}
- Usually absorption spectroscopy is used instead as a more convenient and sensitive method, which requires only a small sample (~ 1 cm^3)
  - An absorption cell of l=1-cm pathlength is used, at a wavelength of 304 nm
  - Constant-temperature chamber is required to minimize temperature variations in the molar extinction coefficient ε for Fe^{3+}

The Fricke ferrous sulfate dosimeter

- The measured ratio of the transmitted light intensities through the irradiated and unirradiated samples $I/I_0=10^{-\Delta(OD)}$ can be related to the corresponding change in molar concentration

$$\Delta(\text{OD}) = \varepsilon l \ \Delta M$$

- Substituting for ΔM the average absorbed dose

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

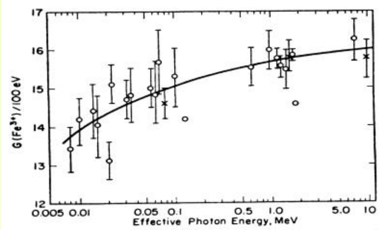
The Fricke ferrous sulfate dosimeter

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

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

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

The Fricke ferrous sulfate dosimeter



- The approximate variation of G value for ferric ion Fe^{3+} production as a function of photon energy
- The best value for ^{60}Co γ-rays is G=15.5 molecules per 100 eV, or G(X)=1.607x10^{-6} mole/J

The Fricke ferrous sulfate dosimeter

- The solution must be *air-saturated* during irradiation for the $Fe^{2+} \rightarrow Fe^{3+}$ 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 2×10^6 Gy/s
- The upper limit of the Fricke system can be extended to 4000 Gy by raising the ferrous sulfate content from to 0.05 M, and bubbling oxygen through the solution
- The lower dose-range limit can be reduced to ≈ 4 Gy by increasing the photometric light pathlength to 10cm

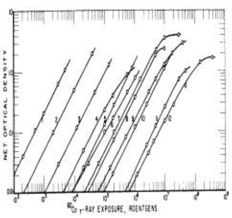
Other chemical dosimeters

- 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 × 10^3 Gy)
- One especially versatile dosimeter is the radiochromic dye-cyanide system, which is commercially available in some forms

Advantages and disadvantages of aqueous chemical dosimeters

1. Dilute aqueous solutions have an effective *Z*, density, and μ_{en}/ρ that are close to those of water for photon energies over the entire range of practical interest, simplifying application of cavity theory. This is especially advantageous with electron beams, where the spectrum is not well known
2. Liquid dosimeters can be irradiated in a container similar in shape and volume to the object being studied. For example, the average dose in an organ located within a phantom can be measured

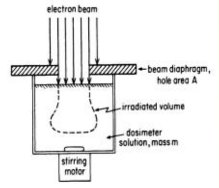
Advantages and disadvantages of aqueous chemical dosimeters



Typical optical-density response curves of various dye-type dosimeters exposed to ^{60}Co γ-rays

3. It is relatively 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. Different chemical dosimeters can be used to cover various dose ranges within the limits 10–10^{10} rad
6. Linear response vs. dose is found in some chemical dosimeters over limited but useful ranges

Advantages and disadvantages of aqueous chemical dosimeters



Energy-fluence measurement by a liquid chemical dosimeter

7. Liquid dosimeters can be used to measure the energy fluence of relatively nonpenetrating beams (e.g., electron beams), as shown in the diagram:

   If $\overline{D}$ is the average dose (Gy) in the *m* kilograms of dosimeter solution, then the energy spent is $m\overline{D}$ and the electron energy fluence $\Psi = m\overline{D}/A$ (J/m^2) at the collimator of area *A* (m^2)

Advantages and disadvantages of aqueous chemical dosimeters

8. Lack of storage stability prevents commercial availability, requiring careful wet chemistry in the user's laboratory, a pronounced disadvantage
9. Useful dose ranges tend to be too high for personnel monitoring or small-source measurement
10. 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 δ, and that absorbs E joules of energy, the temperature increase is given by

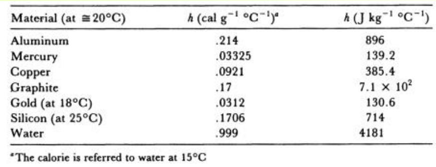
$$\Delta T = \frac{E(1-\delta)}{hm} = \frac{\bar{D}(1-\delta)}{h} \quad (^{\circ}\mathrm{C})$$

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

- The *thermal defect* δ 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 ≅20°C)	h (cal g^{-1} °C^{-1})[a]	h (J kg^{-1} °C^{-1})
Aluminum	.214	896
Mercury	.03325	139.2
Copper	.0921	385.4
Graphite	.17	7.1×10^2
Gold (at 18°C)	.0312	130.6
Silicon (at 25°C)	.1706	714
Water	.999	4181

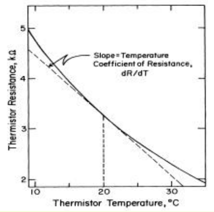
[a] The calorie is referred to water at 15°C

- In Al a dose of 1 Gy causes a temperature increase of 1.12×10^{-3} °C
- To measure this temperature rise with 1 % precision requires a thermometer capable of detecting temperature changes ~10 μ°C

Calorimetric dosimetry: thermocouples

- Thermocouples typically have temperature coefficients of 40 – 70 μV/°C
- A temperature change of 10 μ°C per 1 Gy would then give a potential change of (4 – 7) × 10^{-10} V
- This is too small to detect with available instruments, therefore thermocouples are generally found to be most useful in calorimeters where large doses (> 10 Gy) are given, usually in a short enough time period for thermal leakage to be negligible (i.e., under *adiabatic conditions*)

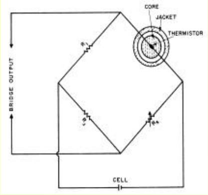
Calorimetric dosimetry: thermistors



- 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 ≈-120 Ω/°C or –3.7%/°C

Calorimetric dosimetry: thermistors



- The resistance of a thermistor at room temperature is typically 10^3 – 10^5 Ω, 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

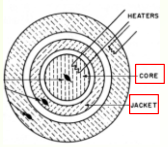
A Wheatstone bridge circuit for measuring the resistance of a thermistor in the sensitive volume (or "core") of a calorimetric dosimeter. When R_x is set to produce a null current reading, $R_c/R_x = R_1/R_J$, from which R_c can be determined

Calorimeter design

- Three general types of radiometric calorimeter designs, depending on the quantity to be measured:
  - – absorbed dose in a reference medium
  - – energy fluence in a radiation beam
  - – power output of a radioactive source

Absorbed-dose calorimeter

- The calorimeter must have a sensitive volume that is small compared to the penetrating ability of the radiation and is thermally insulated from its surroundings
- The sensitive volume (often called the *core*) is made of a thermally conductive material identical to, or simulating, a medium of dosimetric interest (e.g., graphite, tissue-equivalent plastic, or silicon), and contains a temperature sensor of negligible mass, usually a thermistor
- The core is surrounded by a shell (“jacket” or “mantle”) of the same material to provide charged-particle as well as thermal equilibrium



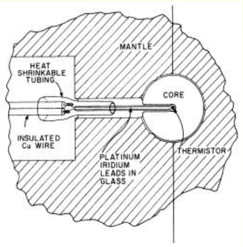
Absorbed-dose calorimeter

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

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

- The mass of the core need not be known

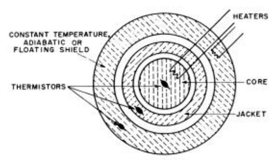
Absorbed-dose calorimeter



An absolute adiabatic silicon calorimetric dosimeter for measuring the absorbed dose to silicon from intense single pulses of penetrating x-rays

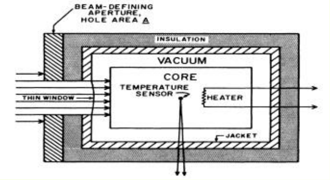
- The core is a pea-sized sphere of high-purity silicon of known thermal capacity, enclosed in an equilibrium-thickness shell of the same material, insulated from the surrounding air by a shell of styrofoam
- The core, containing a very small calibrated thermistor, is centered in a spherical void by four conical points of silicon projecting from the inside of the shell

Absorbed-dose calorimeter



- The conventional practice has been to design an ohmic heater into the core of a known mass
- The thermal capacity *h* of the core can then be determined by supplying electrical energy *E* through heaters and measuring the resulting ΔT in the core
- Dosimetry by means of such an apparatus is generally complicated and time-consuming; simplifications are possible if the jacket have the same mass and is made of the same material as the core, and that their two thermistors are virtually identical with respect to dR/dT as well as resistance
- Some modifications to a Wheatstone bridge allow the small amount ΔR_x necessary to balance the bridge to be expressed as $\Delta R_x = \Delta R_J + \Delta R_c$

Energy-fluence calorimeters



- An energy-fluence calorimeter contains a core, usually a cylindrical piece of dense material such as lead or gold, large enough to stop an incident beam of radiation
- The core is suspended by nylon strings in an insulated vacuum chamber, sometimes adjacent to a twin core that serves as a control to determine thermal leakage

Energy-fluence calorimeters

- Because of the size of the core, more than one thermistor may be necessary to sample the temperature adequately, and the heater should be designed to distribute the heat uniformly
- The high-*Z* core may require a significant backscattering correction
- *h* can be determined through electrical calibration
- The energy fluence of the radiation beam passing through the aperture of area *A* is given (neglecting δ) by

$$\Psi = \frac{E}{A} = \frac{\Delta T\ hm}{A}$$

Calorimeters for measuring power output of a radioactive source

- It has a cup-shaped core into which a radioactive source can be inserted for measurement
- The walls of the core are made thick enough to stop all the radiation to be measured from escaping
- Electrical calibration can be used to determine h
- Then the power output (W) is given by

$$P = \frac{dE}{dt} = hm\frac{\Delta T}{\Delta t}$$

where temperature rise ΔT (°C) occurs in the core of mass m (kg) during the time interval Δt (s), and δ has been neglected

Advantages of calorimetric dosimeters

1. They can be made absolute, either intrinsically or by means of electrical-heating calibration
2. The measurement of temperature rise comes closest of any dosimetric technique to being a direct measurement of the energy involved in the absorbed dose. Only relatively small exothermic or endothermic chemical reactions, and thermal leakage, must be corrected for, if needed
3. Almost any absorbing material, solid or liquid, can be employed in the calorimeter sensitive volume, as long as it is thermally conductive and has a known thermal defect
4. Calorimeters are inherently dose-rate-independent under adiabatic conditions. They are best used at high dose rates, where other dosimeters show saturation effects

Advantages of calorimetric dosimeters

5. Calorimeters add up the energy contributions in the sensitive volume from different types of radiations (e.g., neutrons and γ rays) with weighting factors of unity, neglecting differences in thermal defect
6. Calorimeters have no LET dependence (neglecting minor differences in thermal defect, if any), since ionic recombination is irrelevant to the temperature rise
7. Calorimeters are relatively stable against radiation damage at high doses; the thermistor (if used as the temperature sensor) is usually the limiting factor in this respect

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. In A150-type TE plastic about 4% of the absorbed dose goes to an endothermic reaction instead of heat

Summary

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