Brian L. Justus, et. al.. "Dosimetry Measurement."

Dosimetry Measurement

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Radiation dosimetry is a field of radiation detection devoted to the quantitative measurement of the physical changes that occur in matter upon exposure to ionizing radiation. Radiation dosimetry is performed on a routine basis to ensure the occupational safety of workers when there exists a risk of radiation exposure. Such routine personal dosimetry is used to monitor and limit the long-term occupational exposure to workers and to assist with the assessment of the dose received in the event of an accidental exposure. Some occupations that have an associated risk of radiation exposure include medical personnel performing clinical X-ray diagnostic and radiotherapy procedures, and military and civilian personnel involved in power plant maintenance and operation. Radiation dosimetry is also an important tool in a wide range of environmental monitoring and industrial processing applications. The scope of this chapter is limited to discussion of the most widely used and commercially available technologies for dosimetry of ionizing radiation for personal protection; however, it should be recognized that many of the same technologies are used with equal effectiveness for other dosimetry applications.

69.1 Radiation Dosimetry Quantities and Units

The goal of radiation dosimetry is to quantify the amount of energy that is deposited in matter upon interaction with ionizing radiation. Ionizing radiations fall into three categories: charged particles such as beta and alpha particles, neutral particles such as neutrons, and electromagnetic radiation such as gamma rays and X-rays. The mechanism and the efficiency of the energy deposition depends on the type and the energy of the radiation as well as on the composition of the absorbing material. In particular, the biological consequences to living tissue following radiation exposure are quite dependent on the type of radiation. In order to provide a useful measure of the biological damage that might be expected to occur upon energy deposition in tissue, a system of units and standards has been developed that takes into account the differing biological effectiveness of different types of radiation. Over the years, these units and standards have undergone extensive revision and this process is still evolving. However, the units and standards in current use have been defined in detail in recent reports [1,2] published by the

TABLE 69.1 Radiation Weighting Factors for Various Types of Radiation

Type of Radiation	Quality Factor
Photons, all energies	1
Electrons and muons, all energies	1
Neutrons, <10 keV	5
Neutrons, 10 keV to 100 keV	10
Neutrons, >100 keV to 2 MeV	20
Neutrons, >2 MeV to 20 MeV	10
Neutrons, >20 MeV	5
Protons, other than recoil protons, >2 MeV	5
Alpha particles, fission fragments and heavy nuclei	20

From Reference 1.

International Commission on Radiation Units and Measurements (ICRU) and the International Commission on Radiological Protection (ICRP) and are the subject of a recent review article [3]. A brief summary of the fundamental units is provided below.

The quantity of primary interest in radiation dosimetry is the amount of energy that is absorbed per unit mass. The amount of energy imparted to a volume of matter is the difference between the sum of the energies of all the charged and uncharged particles entering the volume and the sum of the energies of all of the charged and uncharged particles leaving the volume, plus any change in the rest mass of the matter. The mean energy imparted per unit mass is defined as the absorbed dose, *D*, expressed in (SI) units as J kg^{-1}. The special name for the unit of absorbed dose is the gray (Gy). If the mass exposed to radiation is at a point in tissue, knowledge of the amount of absorbed dose alone is not sufficient to judge the biological effectiveness of the charged particles producing the absorbed dose. A quality factor, Q, is used to weight the absorbed dose to provide an estimate of the relative hazard of different energies and types of ionizing radiation. Q is a dimensionless factor that converts absorbed dose to dose equivalent, H, at a point in tissue. The dose equivalent has the same (SI) units, J kg^{-1}, as the absorbed dose, but the special name for the unit of dose equivalent is the sievert (Sv). If the amount of absorbed dose received on average over a specific tissue or organ is of interest, the quality factor is called the radiation weighting factor, w_R [1]. Table 69.1 lists values of w_R for various types and energies of radiation. The equivalent dose, H_T, in a tissue or organ is defined as the average absorbed dose in the given organ due to a particular type of radiation and is scaled by w_R. Thus, the total equivalent dose in a specific organ, T, due to exposure by each radiation type, R, is given by:

$$H_T = \sum_R w_R D_{T,R} \tag{69.1}$$

The equivalent dose also uses the special unit of sievert. For example, if an organ is exposed to neutrons of energy less than 10 keV, and receives an absorbed dose of 10 Gy (10 J kg^{-1}), the equivalent dose is determined, using Table 69.1 and Equation 69.1, to be 50 Sv (50 J kg^{-1}). Since the biological effectiveness of the exposure also depends on the specific organs targeted, dimensionless tissue weighting factors, w_T, have been defined that reflect the probability of damage resulting from a given equivalent dose. The effective dose, E, for an exposed individual is then the sum of the weighted equivalent doses for all tissues and is given by the expression:

$$E = \sum_T w_T H_T \tag{69.2}$$

The effective dose also uses the special unit of sievert. It should be pointed out that despite the adoption of nomenclature and definitions for equivalent dose and effective dose, for all practical purposes the quantities measured and reported for dosimetry applications are the dose equivalents defined in terms of the quality factor, Q. A further quantity for reporting purposes is the personal dose equivalent, $H_p(d)$, the dose equivalent in soft tissue, at an appropriate depth, d, below a specified point in the body. For weakly penetrating radiation, such as beta particles, a depth of 0.07 mm, or $H_p(0.07)$ is used. Eye doses are reported for 3 mm depth ($H_p(3)$) and deep doses are reported for 10 mm depth ($H_p(10)$). The personal dose equivalent is typically measured with a dosimeter that is covered with the appropriate thickness of tissue equivalent material. The dosimeter is worn on the surface of the body and is calibrated in a phantom. A phantom is a medium, such as poly(methyl methacrylate), that mimics the attenuating characteristics of the human body.

Another unit for absorbed dose, found in older publications and in current use in the United States, is the rad. One rad equals 100 erg g^{-1}. Similarly, another unit for dose equivalent is the rem. To convert from this system to the international standard (SI) units, the following conversions are used: 1 Gy = 100 rad and 1 Sv = 100 rem.

When an ionization chamber is exposed to X-ray or gamma ray photons, the amount of ionization produced in the air inside the chamber is called the exposure, X. The (SI) unit of exposure is C kg^{-1} and the special unit is called the roentgen, R. Originally, R was defined as the amount of X-ray or gamma radiation that produces 1 esu of charge of either sign in 0.001293 g of air (the mass of 1 cm^3 of air at STP). The conversion from R to C kg^{-1} is $1\ R = 2.58 \times 10^{-4}\ C\ kg^{-1}$. When air is exposed to radiation, the average energy required to form an ion pair is 33.97 J C^{-1}. For an exposure of 1 R, the absorbed dose in air is $8.77 \times 10^{-3}\ J\ kg^{-1}$.

69.2 Thermoluminescence Dosimetry

Thermoluminescence dosimetry is perhaps the most widely used and cost-effective technique for radiation dosimetry. It is for many organizations the technique of choice for routine monitoring of occupational radiation exposure. Thermoluminescence dosimetry is also widely used in medicine to determine patient exposure as a result of X-ray diagnostic procedures and cancer radiotherapy treatments. The dose ranges of interest for these applications can be roughly defined as 0.1 to 1 mGy for personal dosimetry applications, 1 to 100 mGy for clinical X-ray diagnostics, and 1 to 10 Gy for medical radiotherapy applications. Thermoluminescence dosimeter (TLD) phosphors are commercially available that exhibit a linear dose response and are capable of accurately measuring the absorbed dose for all the applications and doses mentioned above. The radiation-sensitive element of a TLD is a small quantity, typically less than 100 mg, of an inorganic crystal doped with metal impurities, called activators. The activators provide the crystal with the energy storage capacity as well as the luminescent properties that are required for the crystal to function as a thermoluminescent phosphor upon exposure to ionizing radiation. The details of the energy storage and thermoluminescence mechanisms, despite intense research over many decades, are not well understood. Complex, long-range, many-body interactions between activator sites and their immediate environment may be involved. Despite this mechanistic uncertainty, the thermoluminescence phenomenon has been used reliably by following well-established heuristic procedures and by referring to a simple and intuitive model. This model assumes that the activators provide point defects, known as traps and luminescence centers, in the crystal lattice. Upon exposure to ionizing radiation, electrons and holes are captured in metastable states at the trap centers by local potential minima until such time that the electrons and holes are thermally stimulated to overcome the electric potential. The electrons and holes can then recombine, with the emission of photons, at the luminescence centers. It is apparent from this model that thermoluminescence dosimetry is a passive, integrating technique. Further, the technique shows no dose rate dependence and for most applications the TLD phosphors can be reused many times.

A comprehensive review of the properties and applications of a wide range of TLD phosphors has been published recently [4]. The characteristics of the phosphors that are of most interest for dosimetry applications include the sensitivity and the dynamic range of the TL response, the response to different types of radiation over a broad energy spectrum, the fading characteristics, reusability, and the reproducibility of the response. The TL response of the phosphor to ionizing radiation is indicated by measurement

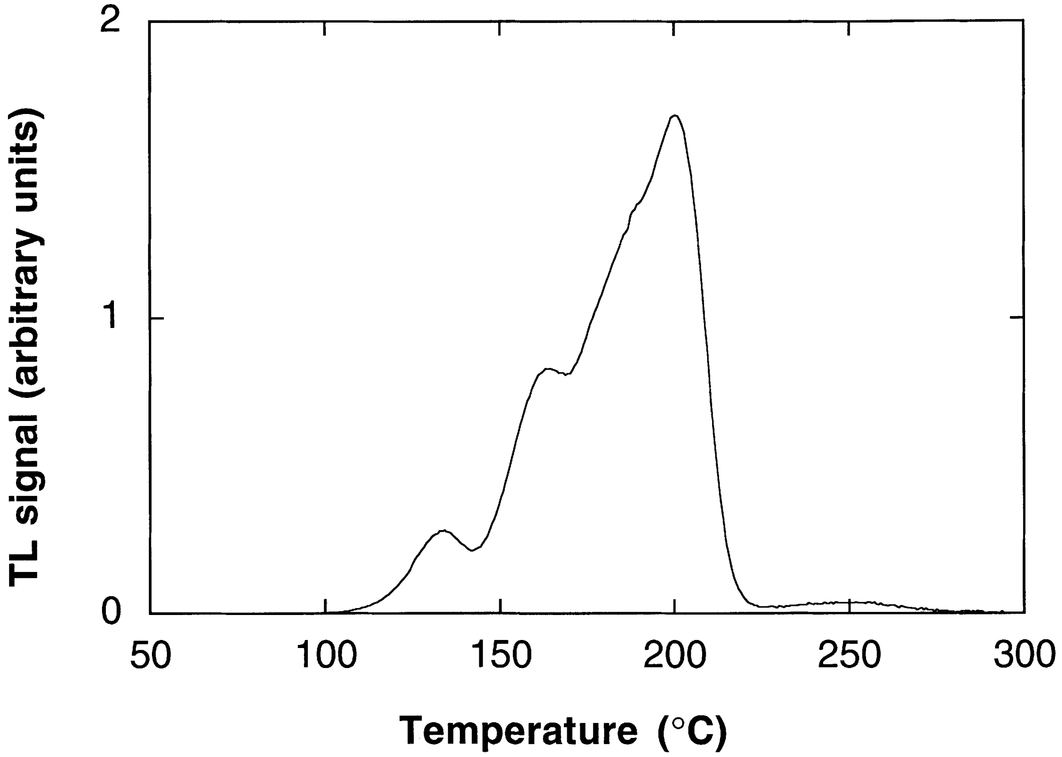

FIGURE 69.1 Thermoluminescence glow curve of LiF phosphor activated with trace amounts of Mg^{2+} and Ti^{4+} (TLD-100). The phosphor was exposed to a 2-Gy dose of ^{60}Co gamma rays and the glow curve was read using a Harshaw 2000 A/B TLD reader.

of the glow curve. A glow curve is a plot of the TL intensity vs. temperature, measured as the phosphor is heated. A representative glow curve of a commercially available LiF TLD is shown in Figure 69.1. The glow curve usually exhibits one or more glow peaks that correspond to the release and recombination of electron and hole traps of differing trap depth and stability. Thermoluminescence dosimetry is best accomplished using phosphors having glow peaks in the range 200°C to 250°C. Peaks in this temperature range are necessary to provide room-temperature trap storage times of several months. Although all traps fade with time, rapid fading of the stored information occurs from traps having glow peak temperatures below 200°C, effectively precluding practical dosimetry. Glow peaks having temperatures greater than 250°C require quite high temperatures (>300°C) to release all the filled traps. In this case, blackbody radiation from the hot phosphor and other ancillary hot matter within the sample readout chamber (sample planchet, hot gas) interferes with and can easily overwhelm the TL signal due to actual trap recombination. The response of TLD phosphors as a function of absorbed dose must be carefully calibrated for all doses of interest. This is necessary because the response deviates from linear above a threshold dose, different for each phosphor, and, ultimately, the TL signal saturates and the phosphors suffer irreversible damage at very high doses. The TL response per absorbed dose as a function of energy, for low-LET electromagnetic radiation (gamma ray and X-ray), is generally fairly uniform. The efficiency for higher LET radiation can vary and should be calibrated as a function of energy. Since personal dosimetry applications require the measurement of doses absorbed by human tissue, tissue equivalent TLDs (effective atomic number closely matches that of tissue) are attractive because the energy dependence of the TL response closely matches that of tissue.

The most commonly used TLD phosphors are lithium fluoride (LiF), calcium fluoride (CaF_2), lithium borate ($Li_2B_4O_7$), calcium sulfate ($CaSO_4$), and aluminum oxide (Al_2O_3) activated with trace quantities

FIGURE 69.2 Thermoluminescence dosimeter body badge. A standard TLD badge contains three LiF phosphor chips. A fourth chip and a fast neutron track-etch foil can be added if required. (Courtesy of Landauer, Inc.)

of transition metal or rare earth metal ions. TLD phosphors are available in a variety of forms, including powders, compressed chips, Teflon-impregnated disks, single crystals, extruded rods and thin films. TLD phosphors have been developed that respond primarily to gamma- and *X*-radiation, while others have been developed that, in addition, respond strongly to thermal neutrons. Unfortunately, there are no TLD phosphors having neutron sensitivity without gamma sensitivity. Therefore, in a mixed field of neutrons and gamma rays, TLDs are used in pairs, with one TLD having primarily gamma-ray sensitivity and the other having gamma-ray and thermal neutron sensitivity. The difference in the TL signal between the two TLDs of such a pair is assumed to represent the thermal neutron dose. Neutron sensitivity is enhanced, for example, in LiF phosphors by incorporating a high concentration of ^{6}Li since ^{6}Li has a much higher thermal neutron cross-section than ^{7}Li (TLD-600 contains 96% ^{6}LiF while TLD-700 has essentially no ^{6}Li). The manufacturers of TLDs exert considerable effort to maintain the uniformity of their products from batch to batch, a task of some difficulty since the characteristics of phosphors are a sensitive function of not only the composition but also the details of the manufacturing process. Thus, the properties of TLD phosphors of similar composition can vary considerably, and both the manufacturers of phosphors as well as the dosimetry service industries typically test and sort chips into groups based on their measured parameters. A representative commercially available TLD badge is shown in Figure 69.2. This standard badge contains three LiF TLDs and is capable of measuring gamma- and X-ray doses from 0.1 mGy to 10 Gy and energetic beta radiation doses from 0.4 mGy to 10 Gy. These badges are typically returned to the manufacturer on a monthly or quarterly basis for readout.

The actual practice of thermoluminescence dosimetry requires some care to achieve accurate and reproducible results. For example, TLD-100 traditionally has been a very widely used phosphor, due to its tissue equivalence, that can yield accurate and fairly sensitive dose information. However, the energetics of the trap population in TLD-100, as well as the trap dynamics and intertrap communication with time, are extremely complex phenomena. Reproducible dosimetry requires that the sensitivity remain unchanged after each use. This is accomplished by careful adherence to a detailed protocol that may include a pre-irradiation anneal (for example, 400°C for 1 h followed by 80°C for 10 to 24 h), a post-irradiation anneal to 125°C, and finally heating to readout the TL signal. It is common for individual TLD users to develop their own unique protocols for annealing and reading TLD chips. Excellent dose reproducibility (<5%) can be expected with care by following a well-defined protocol and using a set of individually calibrated TLD chips on a single, well-maintained TLD reader.

TLD instrumentation is commercially available from a number of suppliers. The choice of instrumentation depends largely on the form of the dosimeter phosphor chosen (compressed chip, Teflon disk, etc.), the desired sensitivity, and the degree of automation desired. The key element in any TLD reader is the heating method. The heating method should provide for controlled, reproducible heating and, if speed of processing is important, rapid cooling. Contact heating of the TLD on a planchet through which an electric current flows is a widely used heating technique. Because the surface of the TLD is not perfectly smooth, more uniform heating can be performed using noncontact methods, such as heating with a stream of hot gas or heating with infrared light. Laser heating is another noncontact method that permits rapid heating (>1000°C s^{-1}) using small quantities of TLD phosphor, yet permits very high signal-to-noise ratios [5]. Regardless of the heating method, blackbody radiation from the metal planchet and/or the TLD chip must be attenuated by colored glass and dielectric coated optical filters. The signal-to-noise ratio is also improved by the elimination of spurious TL signals that arise due to static charges or contamination on the surface of the TLD. Spurious TL signals are reduced by purging the sample compartment with a low flow of inert gas, such as dry nitrogen. Light detection is typically accomplished with a photomultiplier tube, using either a DC or photon counting mode of operation. The glow curve is collected using any of the heating methods described, and the TL signal can be reported as either a glow peak height or as the integrated area of a glow peak.

The conventional TLD technology described above requires bulk heating of the TLD to high temperatures (400°C to 600°C) in order to read the stored dose information. Once the TLD has been read, the dose information is permanently erased. If any malfunction in the equipment occurs during readout, the data cannot be recovered. Alternative TLD technologies have been developed that do not completely erase the dose information and permit additional, successive readouts of the absorbed dose. This characteristic can eliminate accidental loss of dose information and can also provide, if desired, an archival record of exposure. Two such dosimeters, utilizing laser readout methods, are commercially available. These dosimeters function based on optical phenomena known as phototransferred thermoluminescence (PTTL) [6] and radiophotoluminescence (RPL) [7]. A commercial dosimeter (Landauer, Inc.) based on the phenomenon of PTTL is also known as a cooled optically stimulated luminescence (COSL) dosimeter. In preparation for readout of the dose information, the dosimeter is first cooled to liquid nitrogen temperature. It is then irradiated with ultraviolet laser light to phototransfer electrons from deep traps to shallow traps. The thermoluminescence that results from the release of electrons from these very shallow traps, as the dosimeter is allowed to warm to room temperature, provides a very sensitive measure of the absorbed dose. Since it is not necessary to heat the dosimeter to high temperatures, the trapped charges are not fully annealed and the process can be repeated several times. A commercial RPL dosimeter, also known as the flat glass dosimeter (Toshiba Glass Co., Ltd.) uses a silver-activated phosphate glass that is read out by a pulsed ultraviolet laser. The manufacturer employs a special luminescence analysis protocol since the glass exhibits a prompt luminescence even in the absence of ionizing radiation exposure. RPL dosimeters are nevertheless capable of performing sensitive and reproducible dose measurements. New optical dosimetry technologies, based on the phenomenon of room-temperature optically stimulated luminescence (OSL), are being developed [8,9] and promise to provide both superior sensitivity and multiple readout capability.

Companies that provide TLD and other personal dosimetry products and services are listed in Table 69.2. This list is not intended to be comprehensive, nor is it intended to represent an endorsement by the U.S. government.

69.3 Ionization Chamber Dosimeters

Ionization chamber-based radiation dosimeters are among the most widely used and the most accurate instruments available for determining radiation exposure and absorbed dose. The operational principle of the ionization chamber is based on the formation and the collection of ion pairs that result from the interaction of energetic charged particles that pass through gases contained in a well-defined volume and electric field. Several types of ionization chambers are available, including real-time radiation field monitors, and integrating devices that accumulate dose information for extended periods of time. Real-time devices monitor the radiation-induced currents while integrating devices record changes in a static electric field. A wide array of ionization chambers, intended for applications in medical physics, equipment calibration, and personal dosimetry, are available. Small volume (<1 mL), precision ionization chambers are used by medical physicists for radiotherapy applications. These chambers are generally tissue or air equivalent and while very accurate, have low sensitivity. Larger volume (<1000 mL) ionization chambers are used for applications such as field standardization and diagnostic X-ray machine calibration that require high sensitivity in addition to excellent accuracy. For personal dosimetry applications, compact integrating ionization chambers, about the size of a ballpoint pen, termed “pocket chambers” are used. Some pocket chamber dosimeters provide a method for direct visual readout based on the electrostatic deflection of a charged quartz fiber relative to a calibrated scale. Initially, the dosimeter is fully charged, representing the zero dose setting. Exposure to a radiation source causes a loss of charge on the fiber and spring tension causes the fiber to partially return to its uncharged position. A lens system incorporated into the dosimeter in conjunction with a scale can be used to determine the absorbed dose. A commercially available direct-reading dosimeter is illustrated schematically in Figure 69.3. These instruments can measure gamma and X-ray doses from a fraction of a milligray up to several gray. Greater accuracy is possible using indirect readout, pocket chambers that utilize precision electrometers to measure the change in the potential between the cathode and anode following exposure to radiation. These dosimeters are particularly useful for measuring low-level (<mGy) exposures. Another type of ionization chamber, used primarily for radon detection, utilizes the voltage drop across an electret element to determine radiation dose (Rad-Elec, Inc.). An electret is an electrically poled insulator material, such as Teflon, that retains surface charges for long periods of time. Ion pairs produced by radiation exposure are separated and collected, resulting in a net decrease in the electret charge. Changes in the electret voltage can then be calibrated in terms of radiation exposure.

69.4 Film Dosimetry

Photographic films have been used for many years for radiography and personal dosimetry applications. However, due to the greater convenience, superior sensitivity, faster turnaround, and reusability of TLD personal dosimeters, film emulsion personal dosimeters have in many cases been displaced by TLD dosimeters. A notable example of this trend is the dosimetry program of the United States Navy, which has turned exclusively to TLD dosimeters. Despite this, film remains useful for specific applications that require analysis of an image or a charged particle track and they remain the most convenient dosimetry method available if a permanent record of the exposure is desired. Radiographic films are sensitive to a variety of radiation sources, including photons (X-ray and gamma ray), charged particles (electrons, protons, and alpha particles), and neutrons (slow and fast). A major problem associated with the use of radiographic films for dosimetry purposes is that the energy response is not at all flat. A number of approaches have been used to flatten the response, including, for example, the incorporation of a

TABLE 69.2 Vendors of Personal Dosimetry Products and Services

Vendor	Product or Service
Bicron NE 6801 Cochran Road Solon, OH 44139 Tel: (216) 248-7400	TLD phosphors, TLD readers
Panasonic Industrial Comp. Applied Technologies Group 2 Panasonic Way/7E-4 Secaucus, NJ 07094 Tel: (201) 348-5339	TLD phosphors, optically heated TLD readers, electronic dosimeters
Landauer, Inc. 2 Science Road Glenwood, IL 60425-1568 Tel: (708) 755-7000	TLD, film, track-etch services, COSL dosimeter
ICN Dosimetry Service P.O. Box 19536 Irvine, CA 92713 Tel: (714) 545-0100	TLD, film services
Eberline Dosimetry Service 5635 Jefferson St, NE Albuquerque, NM 87109-3412 Tel: (505) 345-9931	TLD readers, TLD service
Dosimeter Corporation of America 5 Eastmans Road Parsippany, NJ 07054 Tel: (800) 322-8258	Pocket dosimeters, electronic dosimeters
Toshiba Glass Co., Ltd. 3583-5 Kawashira Yoshida-Cho Haibara-Gun Shizuoka-Ken Japan Tel: 0548-32-1217	RPL glass dosimeter
Siemens Environmental Systems Limited Sopers Lane, Poole, Dorset, BH17 7ER United Kingdom Tel: 44 1202 782779	Electronic dosimeter
SAIC Commercial Products 4161 Campus Point Court San Diego, CA 92121 Tel: (619) 458-3846	Electronic dosimeters
RADOS Technology, Inc. 6460 Dobbin Road Columbia, MD 21045 Tel: (410) 740-1440	TLD dosimeters, electronic dosimeters
SE International, Inc. 436 Farm Road Summertown, TN 38483-0039 Tel: (615) 964-3561	Pocket dosimeters

TABLE 69.2 (continued) Vendors of Personal Dosimetry Products and Services

Vendor	Product or Service
Bubble Technology Industries Hwy. 17, Chalk River Ontario, Canada, K0J 1J0 Tel: (613) 589-2456	Bubble dosimeters
Apfel Enterprises 25 Science Park New Haven, CT 06511 Tel: (203) 786-5599	Bubble dosimeters

scintillator dye such as *p*-terphenyl in the emulsion [10]. This approach has the effect of flattening the response curve dramatically between 0.1 MeV and 1.0 MeV, as well as increasing the sensitivity of the film. More commonly, in a manner similar to that used in multiple chip TLD badges, a series of metal filters, applied to different portions of the film, is used to provide energy discrimination. The film is then analyzed according to the sensitivity of each film segment for a particular radiation energy range. Figure 69.4 is a photograph of a commercially available film dosimeter badge that incorporates six absorbing filters to discriminate beta-, gamma-, and X-radiation. The dose range that can be measured is 0.1 mGy to 5 Gy for gamma- and X-radiation and 0.4 mGy to 10 Gy for energetic beta particles. Radiographic films consist of a thin layer of gelatin, approximately 10 µm to 20 µm thick, containing silver halide microcrystals, coated onto a polymer or glass substrate. Exposure to a source of radiation sensitizes the microcrystallites, creating a latent image that darkens visibly following development of the film. The radiation dose is determined by measuring the extent of the darkening with a densitometer. The densitometer measures the optical density (OD) of the film by comparing the transmission, T, of light through the exposed film with the transmission, T_0, of an identical film that has not been exposed to radiation. The optical density is a logarithmic function, $\mathrm{OD} = \log(T_0/T)$, and can be measured accurately for values up to approximately 3. Developed film typically has a background OD of about 0.1 due to scattered light. Undeveloped film is quite sensitive to environmental factors such as light, temperature and, in particular, moisture and must be carefully protected while in use. Film dosimeters are available that can also perform thermal and fast neutron dosimetry. The response of film to thermal neutrons is enhanced by the use of a film-converter such as a 0.5 to 1 mm thick Cd foil. The foil absorbs thermal neutrons, yielding gamma rays that interact with the emulsion. Nuclear track emulsions are films that are used for dosimetry of fast neutrons in a manner quite similar to the track-etch detectors described in the next section. Nuclear track emulsions are generally much thicker than radiographic film emulsions and contain higher concentrations of silver halide microcrystals. Recoil protons transfer energy to the microcrystallites in the emulsion, creating latent images of the tracks of the protons. The range of charged particles in the emulsion is generally quite small, compared to photons, so that practically all of the energy is deposited in the film along the tracks. Nuclear track emulsions are no longer widely used due largely to the extremely high threshold, ~0.7 MeV, required for track visualization. Fast neutron dosimetry with film badges is most often accomplished by using a track-etch detector in conjunction with the radiographic film emulsion.

69.5 Track-Etch Dosimetry

Solid-state track detectors exploit the damage that occurs in dielectric materials upon exposure to ionizing charged particles. Energy is deposited in the material along a track defined by the trajectory of the ionizing particle. The damage is manifested as pits that develop on the surface of the material upon etching by chemical and electrochemical techniques. The pits are clearly evident using a simple optical microscope and the track density can be estimated using either manual or automated pit counting methods. The

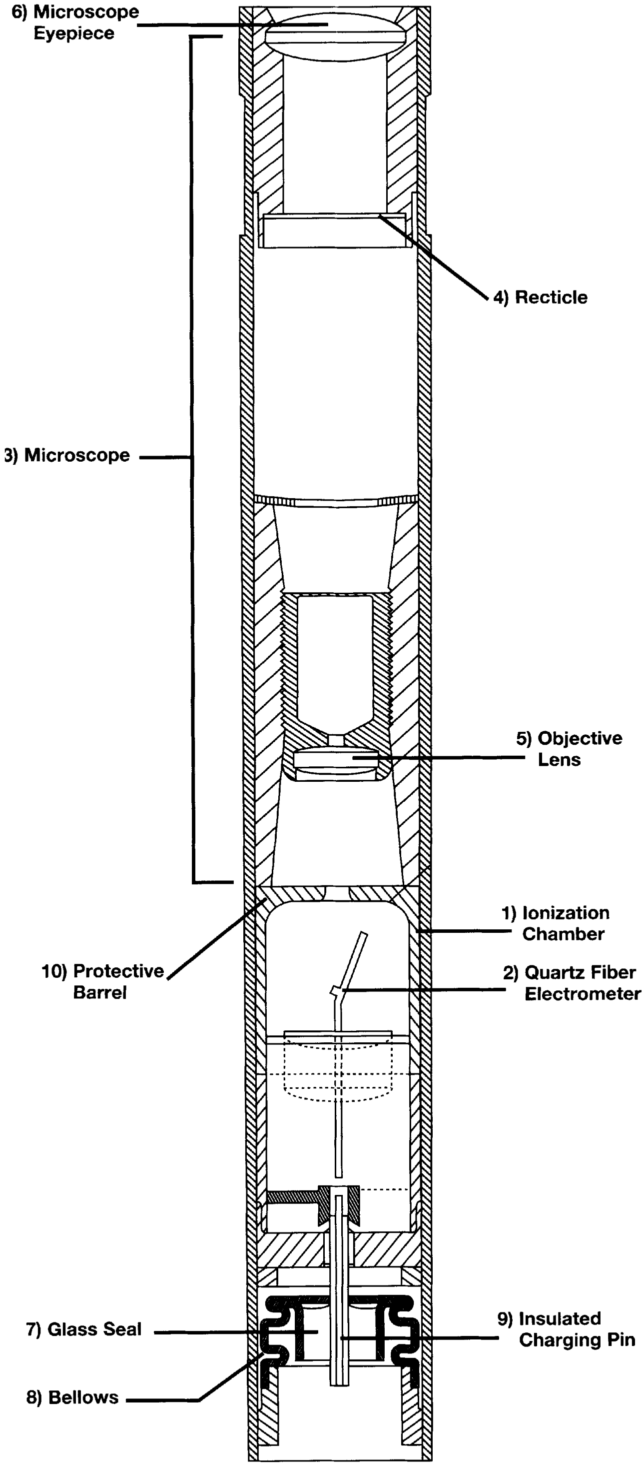

FIGURE 69.3 Schematic of direct reading pocket ionization chamber. The radiation dose is determined by measuring the deflection of a movable quartz fiber electrode. The deflection of the fiber is determined optically by projecting the image of the fiber onto a reticle using a microscope objective. (Courtesy of Dosimeter Corp. of America.)

FIGURE 69.4 Film badge for personal dosimetry. (Courtesy of Landauer, Inc.)

track density is a direct measure of the radiation dose (for many particles, there is one track formed per particle), and track-etch detectors are very effective and sensitive dosimeters. At present the most important track-etch dosimetry applications utilize organic polymer films for alpha track detection (radon monitoring) and fast neutron personal dosimetry. The principal attractive features of track-etch detectors are their extreme simplicity and low cost, good sensitivity, near tissue equivalence, small size, passive operation, and insensitivity to fast electrons and gamma rays. Track-etch detection is a favorite dosimetry technique of graduate students worldwide because of its simplicity; however, commercially available track-etch detectors are manufactured with extreme care to provide users with uniform polymer films and reproducible dose response.

Alpha Track Dosimetry

Commonly used solid-state track detectors that possess sensitivity suitable for alpha particle dosimetry include plastics such as cellulose nitrate, polycarbonate, and polyallyl diglycol carbonate [11]. Since track-etch detection is a surface phenomenon, care must be exercised to avoid scratching the surface of the polymer film, as any surface imperfections can result in false positive signals. The surfaces of the polymer film should also be protected from soiling since dust, dirt, grease, water, or any other foreign material can attenuate the alpha particles and prevent track registration in the detector. Polymer track-etch detectors do not fade significantly at room temperature; however, if the temperature is elevated such that the polymer softens, then the track damage can be annealed and etching will not yield a pit. Typically, radon track dosimeters are allowed to accumulate the alpha dose due to radon and its daughters for extended periods (up to a year) before being returned to the manufacturer for determination of the track density and the corresponding alpha particle activity. Dosimetry of other radioisotopes that emit alpha particles can also be performed; however, the response of the detector is dependent on the isotope detected. For example, alpha track detectors have been used for monitoring plutonium and americium contamination in soil and provide a convenient and cost-effective radiation survey method for decontamination and decommissioning activities [12].

Fast Neutron Track Dosimetry

The performance of polymer track-etch detectors used for personal dosimetry of fast neutrons is typically enhanced by the use of adjacent layers of a hydrogen-rich polymer, known as a proton radiator [13]. Fast neutron dosimetry is made possible by the neutron-proton elastic scattering process that occurs in the track-etch detector and the radiator. The recoil protons produced by this process are responsible for generating the damage tracks in the polymer film and thus provide an indirect measurement of the neutron flux. Although the polymers used for track-etch detection of neutrons, such as CR-39, contain hydrogen and provide for neutron-proton elastic scattering, the use of a proton radiator, such as polyethylene (having a much higher concentration of hydrogen), significantly improves the performance of the dosimeter [14]. The energy spectrum of the protons that leave the radiator and reach the detector depends on both the neutron energy and the thickness of the radiator. In addition, the total number of protons emitted depends on the neutron energy and the radiator thickness. When the thickness of the radiator equals the range of the most energetic proton emitted, then the condition of protonic equilibrium is met. Under this condition, the greatest number of protons are emitted and the detector has the greatest sensitivity. However, at protonic equilibrium, the sensitivity also displays the greatest variation in the energy response. A flatter energy response can be obtained using thinner radiators that avoid the condition of protonic equilibrium. This is obtained, however, at the expense of the sensitivity. Track-etch detection can be used for dosimetry of fast neutrons at nuclear power plants, particle accelerators and due to exposure from unmoderated isotope sources such as californium-252 and americium-241 beryllium.

69.6 Bubble Dosimetry

Another method for fast neutron personal dosimetry is bubble detection. Bubble dosimeters are manufactured using a clear, elastic polymer gel as a host matrix, supporting a dispersion of nanometer-scale superheated droplets of a liquid, such as Freon. Neutrons incident on the polymer gel generate recoil protons in an elastic scattering process, followed by deposition of the proton energy along a track, in a process similar to that described in the discussion of track-etch detectors. However, in the track-etch detectors, the tracks must be visualized by a separate etching procedure. The charged particles in a bubble dosimeter deposit their energy directly into the superheated droplets, causing the droplets to effectively explode into much larger gas bubbles. This process, which can be readily heard, is immediate, generating bubbles that can easily be seen by the naked eye, provided the bubble diameter exceeds a critical diameter required in order for the bubble to persist stably in the gel. The fast neutron dose is determined by counting the total number of bubbles generated. Bubble counting can be performed manually, by visual inspection of the dosimeter, or by automated means. Commercial bubble dosimeters are available that use either optical or acoustic automated counting techniques. Dosimeters have been developed using droplet materials that have differing energy thresholds, thereby providing the dosimeters with limited spectroscopic capabilities. Bubble dosimeters have been developed that are compensated to provide a temperature-independent response. Fast neutron bubble dosimeters have several advantages in common with track-etch detectors, including good sensitivity, near tissue equivalence, passive operation, small size, and insensitivity to thermal neutrons and gamma radiation. Additional advantages include immediate bubble visualization (no need for a separate track developing step), limited reusability, sensitivity adjustability, a flat dose response over a wide energy range, utilization of the entire volume of the dosimeter, and angular response superior to that of track-etch detectors. Bubble dosimeters are more

FIGURE 69.5 Bubble dosimeters for personal dosimetry of fast neutrons. The dosimeter on the left is shown before exposure to fast neutrons. For comparison, a dosimeter exposed to fast neutrons is shown on the right. Bubbles are clearly evident throughout the volume of the dosimeter. (Courtesy of Siemens Medical Systems, Inc.)

expensive than track-etch dosimeters and are best utilized when the energy of the neutron field is known. Figure 69.5 is a photograph of commercially available bubble dosimeters, before and after exposure to neutrons. A comprehensive review of bubble dosimeters, including new developments, has been published recently [15].

69.7 Electronic Personal Dosimeters

All of the personal dosimeters discussed to this point are passive devices that require no external power source. The radiation dose is determined upon completion of the sampling period by subjecting the dosimeter to a separate processing step. The nature of the processing depends on the dosimeter, but examples include heating of a TLD, chemical etching of a foil, development of an emulsion, or simply

FIGURE 69.6 Electronic personal dosimeter. (Courtesy of Siemens Medical Systems, Inc.)

counting bubbles. The electronic personal dosimeter (EPD), by contrast, is an active device that uses silicon diode detector technology to provide real-time measurements of radiation dose. The EPD has gained popularity in recent years and has mounted a serious challenge to thermoluminescence dosimetry as the preferred official dosimeter of record. EPDs can provide extremely sensitive real-time measurements of both the total dose and the dose rate. In addition, the EPD can be designed to provide an audible alarm if the total dose or dose rate exceed user defined settings. While the quality and characteristics of EPDs from different manufacturers can vary significantly, some EPDs offer accurate dose measurements over a wide range of doses, dose rates and energies, and perform on a par with TLD dosimeters. A commercially available EPD is shown in Figure 69.6. This unit uses three silicon diodes to provide deep and shallow dose information for a wide range of gamma, beta, and X-radiation energies. EPDs typically have a display for manual readout of dose data, but can be used with an automated reader for convenient archiving of data and for rezeroing the dosimeter for repeat use. Personal dosimeters are envisioned that would combine active and passive technologies, providing the accuracy and convenience of real time dose monitoring in addition to the reliability of passive, cumulative dose measurements.

Defining Terms

Radiation dosimetry: The quantitative measurement of the physical changes that occur in matter upon exposure to ionizing radiation.

Absorbed dose (D): The mean energy absorbed per unit mass.

Dose equivalent (H): The mean energy absorbed per unit mass, scaled with a quality factor, Q, that provides an estimate of the relative biological hazard of the radiation.

Equivalent dose (H_T): The mean absorbed dose in an organ, T, scaled by a radiation weighting factor, w_R.

Effective dose (E): The total mean absorbed dose for an exposed individual. Obtained by summing the equivalent doses for all tissues, each scaled by a tissue weighting factor, w_T.

Personal dose equivalent $H_P(d)$: The dose equivalent in soft tissue at a depth, d, below a specified point in the body. Commonly reported as shallow dose (d = 3 mm) and deep dose (d = 10 mm).

References

1. ICRP Publication 60, Ann. ICRP 21(1-3), 1990 *Recommendations of the International Commission on Radiological Protection*, Oxford: Pergamon Press; International Commission on Radiological Protection, 1991.
2. ICRU Report 51, *Quantities and Units in Radiation Protection Dosimetry*, Washington, D.C.: International Commission on Radiation Units and Measurements, 1993.
3. W. K. Sinclair, The Present System of Quantities and Units for Radiation Protection, *Health Physics*, 70, 781-786, 1996.
4. S. W. S. McKeever, M. Moscovitch, and P. D. Townsend, *Thermoluminescence Dosimetry Materials: Properties and Uses*. Ashford, England: Nuclear Technology Publ., 1995.
5. P. Braunlich, Present State and Future of TLD Laser Heating, *Radiation Protection Dosimetry,* 34, 345-351, 1990.
6. S. D. Miller and P. A. Eschbach, Optimized Readout System for Cooled Optically Stimulated Luminescence, *Radiation Effects and Defects in Solids*, 119-121, 15-20, 1991.
7. E. Piesch, B. Burgkhardt, and M. Vilgis, Progress in Phosphate Glass Dosimetry: Experiences and Routine Monitoring with a Modern Dosimetry System, *Radiation Protection Dosimetry,* 47, 409-414, 1993.
8. S. W. S. McKeever, M. S. Akselrod, and B. G. Markey, Pulsed Optically Stimulated Luminescence Dosimetry using α-Al_2O_3:C, *Radiation Protection Dosimetry,* 65, 267-272, 1996.
9. B. L. Justus, S. Rychnovsky, M. A. Miller, K. J. Pawlovich, and A. L. Huston, Optically Stimulated Luminescence Radiation Dosimetry using Doped Silica Glass, *Radiation Protection Dosimetry,* 74, 151-154, 1997.
10. R. A. Dudley, Dosimetry with Photographic Emulsions, in Frank H. Attix and William C. Roesch (eds.) *Radiation Dosimetry, Vol. II.* New York: Academic Press, 1966.
11. G. Espinosa, R. B. Gammage, and K. E. Meyer, Response of Different Polyallyl Di-Glycol Carbonate Materials to Alpha Particles, *Radiation Meas.*, 26, 173-177, 1996.
12. K. E. Meyer, R. B. Gammage, C. S. Dudney, S. Reed-Walker, P. Kotrappa, R. V. Wheeler, and M. Salasky, Field Measurements of Plutonium and Americium Contamination in Soils at the Nevada Test Site using Passive Alpha Detectors, *Radioactivity and Radiochemistry*, 5, 26-41, 1994.
13. J. L. Decossas, J. C. Vareille, J. P. Moliton, and J. L. Teyssier, Theoretical Study and Calculation of the Response of a Fast Neutron Dosemeter Based on Track Detection, *Radiation Protection Dosimetry,* 5, 163-170, 1984.
14. S. Sadaka, L. Makovicka, J. C. Vareille, J. L. Decossas, and J. L. Teyssier, Study of a Polyethylene and CR 39 Fast Neutron Dosemeter II: Dosimetric Efficiency of the Device, *Radiation Protection Dosimetry,* 16, 281-287, 1986.
15. H. Ing, R. A. Noulty, and T. D. McLean, Bubble Detectors — A Maturing Technology, *Radiation Measurements*, 27, 1-11, 1997.

Further Infomation

F. H. Attix, *Introduction to Radiological Physics and Radiation Dosimetry*. New York: John Wiley & Sons, 1986.

K. Becker, Dosimetric Applications of Track Etching, in Frank H. Attix (ed.) *Topics in Radiation Dosimetry, Supplement* 1. New York: Academic Press, 1972.

J. W. Boag, Ionization Chambers, in Frank H. Attix and William C. Roesch (eds.) *Radiation Dosimetry, Vol. II*. New York: Academic Press, 1966.

G. Shani, *Radiation Dosimetry Instrumentation and Methods*. Boca Raton, FL: CRC Press, 1991.

K. R. Kase, B. E. Bjarngard, and F. H. Attix (eds.) *The Dosimetry of Ionizing Radiation, Vol. III*. New York: Academic Press, 1990.

G. F. Knoll, *Radiation Detection and Measurement*. New York: John Wiley & Sons, 1989.
