SECTION 13 - PERSONNEL MONITORING DEVICES

A. Introduction

The preceding sections discussed many of the instruments and detection principles used in health physics. These are mostly electronic and measure a radiation field at a point and for an instant of time. The rate meters are very useful in survey work. We need the information they provide as an aid toward the evaluation of a potential hazard. We further need devices or methods that will indicate the total amount of radiation to which a person has been exposed. These devices are called dosimeters.

From the start of the Manhattan Project, a need for dosimeters was felt. Because of the large number of people who would come in contact with quantities of radiation, a small, rugged, and inexpensive dosimeter was needed. Studies revealed several features an ideal dosimeter must have. Some of these features are: (1) The response of the unit to equal exposures should be independent of the radiation energy, (2) the dosimeter should cover the range of exposures from less than 260 \( \mu \)C/kg (1 R) to greater than 0.13 C/kg (approximately 500 R), (3) the response should not be produced by agents other than the radiation measured, (4) the device should measure all ionizing radiation, and (5) the unit should be small, light, easy to handle, comfortable to wear, and low in cost. Up to the present, no known dosimeter possesses all these features. Over the years, though, many devices and methods have been studied in an attempt to improve the performance of personnel monitors.

From the outset, one type of device, the film dosimeter, has been used with satisfactory results.\(^1\) Film dosimeters were used in almost all cases in which large numbers of people are involved. Development of solid state and other types of dosimeters has made alternatives to film dosimetry more attractive.\(^2-5\) However, the film dosimeter is still one of the current devices in use for personnel monitoring, although TLD dosimeters have found widespread use (see Section 13.D.1).

B. Photographic Film Dosimetry

It would seem fitting that the very means by which radiation was first detected should also result in a means of measurement. Photographic
film is one of the simplest means of detecting radiation. On the other hand, using film as a dosimeter requires careful attention to many details. Among these are: the type of emulsion, the response of the film, the processing techniques, and the interpretation of the exposure. Despite these factors, the film badge is still currently used. The fact that it is small, rugged, and low in cost enhances its value as a dosimeter. Many treatments in the literature\textsuperscript{6-8} discuss the features of the film technique for dosimetry.

Since the effect of x rays on film was first noted, attempts have been made to relate the response of the film to the amount of exposure. We are, therefore, concerned with such aspects as the nature of the photographic process, the action of the radiation on the film, and the nature of the film response.

1. **Emulsion Properties**

Photographic film most often appears in the form of thin, even layers of the emulsion, spread on a thick support base (see Figure 13.1).

The base substance may be paper, glass, or cellulose. A typical x ray film would have a base about 200 $\mu$m thick and two emulsion layers, each about 12 $\mu$m thick.\textsuperscript{7} The emulsion consists of small silver halide crystals, or grains, embedded in a gelatin matrix. The size of the crystals (most often silver bromide) and their content by weight differ for x ray films and neutron films. The average grain size, which greatly affects the film response, is about 1-2 $\mu$m in diameter in x ray film and about one-fifth that size in neutron film.\textsuperscript{7} The amount of silver bromide in the emulsion ranges from 40 weight percent (w/o) for some common films to 80 w/o for neutron films.\textsuperscript{6} Neutron films also differ from x ray films in that the neutron film emulsion is usually much thicker and often only in a single layer.
Figure 13.1 Cross section through a typical x-ray (photon) film. (Adapted from PERSONNEL DOSIMETRY TECHNIQUES FOR EXTERNAL RADIATION (Symposium), Madrid, OECD/NEA (1963).)

2. **Photographic Effect**

In essence, the theory describing the effect of an exposing agent on a film was first advanced by Gurney and Mott. More recent treatments discuss the modern aspects of this theory.

a. **Latent-Image Formation**

In the Gurney-Mott theory, the energy transferred by the exposing agent causes electrons to be raised into the conduction band of the silver halide crystals. This requires about 5.8 eV per electron. These electrons are trapped at defects in the crystal lattice. The trapping action creates a space charge, which then attracts a silver ion. This silver center traps further electrons and silver ions. When these clusters become large enough, the grain can be developed. These larger silver clumps are referred to as latent-image centers.

The formation of the latent image is enhanced as the number of electrons set free in the grain increases. For charged
particles, the probability of a latent image being formed depends upon AgBr grain size and the specific energy loss of the particle. For photons and neutrons, the grain size and the energy transferred to the secondaries are key factors.

For grains of a given size, the response depends upon how stable the resulting silver clusters are. The stable centers can be developed. During this process, the latent-image centers are reduced to silver by the chemical action of the developer. The silver plates out as a black deposit on the film. The silver forms only at points where a stable latent-image center has been produced. The unchanged silver halide is dissolved from the film by use of sodium thiosulfate (fixer or hypo.)

b. **Film Density**

The final effect is that the film becomes darkened. We can measure the degree of the darkening and relate it to the amount of radiation. If a beam of light (intensity $I_0$) falls on the darkened film, some of this light is transmitted (intensity $I$) and some is absorbed. The opacity $O$ is then

$$O = \frac{I_0}{I}.$$  \hspace{1cm} 13.1

The film density $D$ is defined by

$$D = \log_{10}O = \log_{10}(\frac{I_0}{I}).$$  \hspace{1cm} 13.2

With x-ray film, the density produced on the film is related to the exposure. For fast neutrons, track counting is used to measure the response (Section 13.B.8.a):

3. **Properties of Film Response**

Assume that an x-ray film is exposed to a photon beam. The photon action on that film produces a darkening. The degree of response is
a function of the quantity of radiation. If film is exposed to more radiation, the film response is greater darkening. This can be seen on a curve that relates the film response to the exposure. A common method to present this is to plot the density versus log exposure. This type curve is often referred to as a characteristic curve (see Figure 13.2).

a. Characteristic Curve

The characteristic curve typical of many film types is shown by the solid line in Figure 13.2. It consists of three typical portions: the toe (A), a linear portion (B), and a shoulder (C).

In the toe portion of the curve, the film responds very slowly. That is, the density does not change very much with small changes in the exposure. This portion is of limited value in personnel monitoring since it is not easy to obtain accurate exposure readings. In region (B),

![Graph showing characteristic curve for photon film. (Adapted from PERSONNEL DOSIMETRY TECHNIQUES FOR EXTERNAL RADIATION (Symposium) Madrid, OECD/ENEA (1963)).]
the density change is very rapid for small changes in exposure. This is the region in which the film should be used to measure exposure. The accuracy is best in this region since two nearly equal exposures may produce densities that are well-separated. We are then able to pinpoint exposures better.

The useful range of a film in terms of exposure roughly corresponds to the extent of the linear portion. The contrast of the film is often taken to mean the slope of this straight portion. In general, we cannot have both a wide useful range and high contrast in a single film.

The shoulder portion (C) shows that a saturation density is reached. That is, large changes in the exposure produce little, if any, change in the density. Clearly, this is the least useful region in which to measure exposure.

b. General Features of the Characteristic Curve

The actual characteristic curve obtained is affected by the techniques of development. However, for a given process, the shape of the curve does not depend upon the energy of the photons. Also, if there is no latent-image fading, the shape of the curve is independent of the rate at which exposure is received. This aspect of film response is known as the reciprocity law. This law fails if we are near the maximum density for a given film.

Although the shape will be the same, the location of a curve along the log X axis is a function of the energy of the radiation. For a given film, the curves produced by two different energies may be displaced from each other. The shape of the curve produced by beta is the same as that for X or gamma rays, but the location depends upon beta energy.

c. Latent-Image Fading

The fact that latent-image centers tend to fade with time, limits the time a badge may be worn. Under normal conditions, such as
room temperature or below, and low relative humidity, the fading is slight for x-ray films. Neutron films, because of their fine grains, continue to fade unless protected from humidity. Even with photon films, the humidity seems to be the vital factor in latent-image fading.\textsuperscript{12}

d. \textbf{Sensitivity (Response)}

We can measure the sensitivity of a photon film in terms of the reciprocal of the exposure needed to produce a given density. Films are available in a wide range of sensitivities from a number of companies.\textsuperscript{6}

For most film types, the sensitivity, or response, below 100 keV may be > 30 times that at 600 keV. This is due to increased absorption of photons of low energy in the film over that in air.\textsuperscript{1} For the region above 600 keV, the absorption in air becomes proportional to the absorption in the emulsion so that the response remains fairly constant. This aspect of film response is referred to as \textit{energy dependence}.

e. \textbf{Energy Dependence for Unfiltered Film}

Suppose several films of the same type are given an equal exposure, but the photon energy is varied. If we plot the densities obtained from the films against the photon energy, the solid curve in Figure 13.3 results. This type of curve is obtained for unfiltered film. It shows that for the same exposure, the density produced by photons below 0.3 MeV is much higher, reaches a peak value for a certain energy and then decreases. For the region below 0.3 MeV, the density depends on the energy of the photon. This energy dependence of the film hinders proper interpretation of the film response. In most cases, the exposure is exaggerated so that readings are on the safe side. That is, we read a higher density as a greater exposure. For increased exposure, the density values increase proportionately, but the peak remains at the same value of photon energy. This peak occurs because of the silver halide in the emulsion.
Figure 13.3 Energy dependence in typical photon film, with and without a filter. (Adapted from NBS Handbook 57)

That is, the response curve reflects the absorption of energy in the silver bromide. However, the exposure X reflects the energy absorbed from photons in air. The peak should occur roughly at the energy for which

$$\frac{\mu}{\rho_{AgBr}} = \frac{\mu}{\rho_{air}} = \text{maximum value.}$$

Although the K-absorption edge of silver is at 22 keV, the peak in the response curve occurs at about 45 keV because of the above ratio. The film absorbs a larger fraction of the photons at this energy than at any other which results in the increased darkening.

In some instances, the photon energy is above 0.3 MeV and well known. This presents little, if any, problem in using films. In other cases, we must use film to monitor a wide energy range, which extends below 0.3 MeV. When this is the case, we need a means to correct for the effects below 0.3 MeV.
f. Energy Dependence for Filtered Film

When we place a metal or plastic filter in front of the film, the filter absorbs some of the photons before they reach the film. These filters are thin enough to not greatly affect the photons in the region above 0.3 MeV. They are thick enough, though, to affect those below 0.3 MeV. Filters tend to flatten the response in the region below 0.3 MeV. This is shown by the dotted portion in Figure 13.3. General features produced by the use of a filter are: (1) The peak response is reduced, or flattened; (2) peak location may shift; and (3) the uniform response may extend down to 200 keV, or even below.

An ideal filter would make the response the same no matter what the photon energy. For most combinations of filter and film, we cannot readily obtain uniform response below 30 keV. However, above 200 keV, this is obtainable.

The response of filtered film depends upon: (1) photon energy; (2) filter thickness; (3) the atomic number of the filter; (4) the filter K-absorption edge; and (5) filter area. For these reasons, different filter materials are used. Some common substances used include Cd, Sn, W, Pb, Ag, Cu, and Al. Each produces its own preferential absorption of the softer radiation. The substance used, and its thickness, depend upon the information we are after. For simple applications, a single filter may be all that we desire. When we would like to know something about the energy spectrum, multishield systems are employed. In this case, the density ratios behind filters are compared. Because of the differences in Z number and/or thickness of the filters, the ratios can provide a crude indication of the energy.\(^1,6\)

One of the more common filter substances in use is cadmium. A 1 mm cadmium filter-film pair allows us to measure the exposure to within about ±20% for energies ≥ 100 keV.\(^13\) A single shield composed of many elements has also been reported.\(^14\)

4. Reading and Interpretation

If a film is processed without being exposed, it will show a
slight density. This density is known as the base fog. The value of the base fog is a function of the type of emulsion, film age, the manufacturing processes, and the film storage conditions and development time.

To correct for the base-fog effect, control films are processed with the monitoring films. The control films should be from the same batch as the other films and stored under the same conditions. Then, if all are processed in the same way, the base fog on the control films spotlights extraneous effects as well as normal fog. The base-fog values can then be subtracted from the density readings of the monitoring films to give corrected values.

a. Calibrations Films

Once, the film density is obtained, it must still be related to the exposure. That is, the density must be calibrated against known exposures, since films are not absolute devices. A simple means of attaining this end is to prepare and process a set of calibration films with each batch of film. This accounts for: (1) the variation of response because of energy, and (2) the variation in density because of processing factors.

Films may be calibrated for beta by the use of a thick piece of uranium metal. This acts as a diffuse source of beta incident on the film. The surface dose rate from uranium can be measured with an extrapolation chamber.

b. Interpretation

The interpretation of the readings in terms of the exposure often depends upon the number of filters used in the badge. In some units, this number may be as much as five. Besides the filters, most units have an "open-window" section. That is, part of the film is not covered by a filter. The window section records the response due to a mixture of both hard and soft radiation. The softer radiation affects the window section more than the hard radiation does.
If only hard photons (> 200 keV) are involved, there is no problem, since only the bare film would be needed. For a pure photon field, without regard to spectrum, we can use just a single filter. This filter should be designed to match the response profile of the film used. If the radiation field consists of a mixture of beta and gamma of unknown energy spectra, then we need a multishield device.

For a multifilter badge, the densities behind the filters reflect somewhat the character of the transmitted radiation. This enables us to gain some knowledge of the energies involved from density differences beneath pairs of filters. By proper use of calibration charts, we can then interpret the readings in terms of the indicated spectrum.

The window sections presents more of a problem. Since the response is not at all uniform, detailed spectrum information is needed. However, this is impossible in most cases; therefore, we must use whatever knowledge we can glean from the filtered response. By use of this knowledge, we can partially evaluate the reading in the open-window section. As yet, there is no really satisfactory way of assessing exposure from the window section of the badge. All present methods suffer in that they fail to properly identify the response due to $\beta$.

5. Filter Holders

The film holder is often in the form of a clip-on badge, in which the shields are fastened to the inside surfaces. That is, a shield is both in front of and behind the film when it is inserted into the badge. The number and type of shields used vary greatly throughout the country.

Some badges have been designed to be "tamperproof" by the use of a locking device, which is opened by magnets. Others serve as identification badges as well as film holders. Film dosimeters in the form of wrist badges and/or rings have also been used. Badges with a number of devices to detect a nuclear criticality are also in use. Typically, these contain a number of foils or other detector materials to detect both fast
and thermal neutrons. A high dose γ detector is also included. Not all badges are as elaborate as described. For facilities at which a criticality incident might occur, nearly all have at least an indium foil. This allows for quick sorting of exposed persons following such an incident.

6. **Film Packets**

Many films used for monitoring are similar to medical x-ray film and are contained in dental-size packets. Usually no one film covers the range of exposure needed for personnel monitoring; therefore, most packets contain at least two films. For example, the Kodak type 3 packet contains a double-coated film (high sensitivity) and a single-coated film (low sensitivity). These allow coverage over the range 4 μC/kg (approximately 15 mR) to 0.46 C/kg (approximately 1800 R). Another design, Kodak Type 2, is a single film with a fast emulsion on one side and slow on the other and covering about the same exposure range.

The packet material is often an opaque wrapper of about 0.2-0.3 kg/m² (20-30 mg/cm²) in thickness. This thickness is enough to stop all beta below about 150 keV. For this reason, low-energy beta monitoring is impossible by this method. ²

7. **Electronic Equilibrium Conditions**

The film and its wrapper constitute an equilibrium thickness up to about 0.3 MeV. For photons above 0.3 MeV, the range of secondaries becomes greater than the thickness of film plus wrapper. This results in a loss of electronic equilibrium since we cannot assume that for each electron leaving a small volume, one of about equal energy enters. To maintain electronic equilibrium, the packet must be surrounded by a substance thicker than the range of the secondaries. Many badges employ plastic as the equilibrium layer.

The thickness of the layer needed is a function of the highest photon energy expected. It must be thicker than the range of the highest-energy secondary produced by the photons. This will insure the electron
density measured by the film response is proportional to the photon intensity at some point in the substance. But it also must not be so thick that it greatly attenuates the photon beam, for then the film does not record the maximum exposure, since this occurs at a depth in the layer about equal to the average range of the secondaries. Since the range depends upon this layer substance, the thickness needed is also a function of the material used. A graph of equilibrium thickness versus photon energy is contained in Reference 16.

The preceding pages have pointed out some of the vital factors we must treat in order to use film as a dosimeter. Despite the presence of these pitfalls, a detailed study points out that we can obtain good results with proper care. On the other hand, dosimetry methods other than film have offered a number of attractive features.

Much of what has been already said has dealt with photon films. The next few pages discuss neutron monitoring by film techniques.

8. Neutron Dosimetry

As in the case of instrument design, neutron monitoring by film presents more problems than monitoring for other radiations. The response of film to neutrons depends upon the neutron interactions with the atoms of the emulsion. These interactions may result in charged particles and/or photons being emitted. This occurs when elastic scattering and/or capture take place. As in the case of photon film, one must be concerned with assuring that measurements are made under charged particle equilibrium conditions.

The capture of thermal neutrons in silver and bromine leads to the release of beta and gamma so that neutron response can be read as film density. Also, elastic collisions between fast neutrons and hydrogen in the emulsion and surrounding lead to recoil protons. These protons in turn lose their energy to the grains, which result in the film density.

Neutrons interactions that lead to film density permit quick and easy evaluation of the response. Because photons also produce the same
effect, it is hard to determine only the neutron effect when photons are present. For this reason, fast-neutron monitoring by film is often done by track counting methods.

a. Fast Neutrons

(1) **Track Counting** - Track counting of fast neutron response depends upon the hydrogen in the emulsion and in the surrounding substances. Elastic scattering of fast neutrons with hydrogen produces recoil protons. These protons lose energy to the grains, which are much finer than in x-ray films. The emulsion contains more of these AgBr grains than do photon films. The latent images formed consist of a number of individual grains along the path of the proton. Then, when the film is developed, the track of the proton can be seen by means of a microscope.

In this country, the most preferred track emulsion film is the Kodak Personal Neutron Monitoring, Type A. This type of emulsion is usable in the energy range 0.5 to 14 MeV, in the proper kind of packet. This is the range in which the film response is proportional to the neutron dose. The lower limit of this range results from the nature of the effect. That is, to count as a track, at least three grains must be developed. This requires a proton with energy of about 0.25 MeV. Since, on the average, a neutron transfers about half its energy to a proton in an elastic collision, this sets the lower limit. The upper limit is imposed by the emulsion thickness. That is, the practical limit of the emulsion thickness sets the high-energy end of the proton energy loss that can be detected.

(2) **Sensitivity** - The sensitivity of the Type A film varies, being on the order of one track per 1500 to 3000 incident neutrons. This seems to be a function of the neutron spectrum. The use of these emulsions is also limited by the response to gamma. The response is a fogging effect, which makes it quite difficult to count tracks. Thus, a gamma field that produces an exposure of about 5 mC/kg (approximately 20 roentgens) renders this type of film unreadable for neutrons.
Since thermal neutrons also produce recoil protons when capture occurs in nitrogen, the total response may contain tracks produced by these protons. However, the sensitivity to thermal neutrons is about 25 to 30 times lower than that of fast neutrons. Under normal circumstances, the thermal-neutron effect is small. At any rate, the tracks counted from this source lead to a safety factor in the evaluation of the fast-neutron response. We can also correct for this effect in multishield badges that contain cadmium filters. A 40-mil-cadmium filter (approximately 1 mm) absorbs the thermal flux so that proton-recoil tracks behind this shield should be due only to fast neutrons.

(3) Latent-image Fading - For photon films, the fading is slight and occurs mostly in a short period of time. For track film, the fading is extreme and seems to progress with time. We can protect the film and reduce this effect by sealing the film in humidity-proof envelopes.

(4) Reading and Interpretation - The tracks are often counted by means of a dark-field microscope. In this device, the background of the field of view appears dark, so the tracks are seen as a series of white dots. The method consists of simply counting the number of tracks seen in a field of view. The field in this case is only a small portion of the film.

The number of tracks in any one field is small and varies from field to field. The fields to be viewed during counting should be chosen at random. In this way, the person counting the tracks is less likely to influence the result. The number of fields that must be counted to obtain consistent results is a function of field size. In this country, most counting programs require from 25 to 40 fields for good statistics. For this reason, the counting of a large number of films may be quite tedious.

As for photon film, the use of calibration films that are processed along with the monitoring film allows us to interpret the unknown response. That is, film exposed to a known fluence of fast
neutrons allows us to measure the expected number of tracks in a given number of counted fields. Thus, we can relate the response of a monitoring film to that of the calibration film. The fluence derived can then be evaluated in terms of a dose equivalent based on the curves of Snyder.\textsuperscript{23}

For the range of neutron energy between 0.5 and 14 MeV, the number of proton-recoil tracks remains independent of the neutron energy. This assumes charged particle equilibrium conditions. In view of this, we can evaluate the fast-neutron dose equivalent fairly well, since the quality factor is almost constant in this range. However, for an intermediate spectrum (between thermal and 0.5 MeV), this method fails to give any response. Thus, film dosimetry is not able to cover the entire range of neutron energy desired for health physics operations.

b. Thermal Neutrons

In the discussion of the fast neutron methods, we mentioned that thermal neutrons may also be monitored by density and/or track-counting methods. That is, a shield of cadmium, silver, indium, or rhodium over a photon film may be used for density readings. The capture of thermal neutrons leads to beta and gamma being emitted, which produces the density on film.

For a dense photon field, it is difficult to determine the portion of density due to thermal neutrons. Now, if we have both a high-capture cross-section substance (cadmium) and a low one (tin), it allows estimation of the thermal-neutron response.\textsuperscript{19} The density under the cadmium is caused by both capture gammas and the other photons present. The density under the other substance results mainly from the photons not due to capture.

Although track counting may be used for thermal neutrons, the sensitivity is low for recoill protons from nitrogen. The response may be increased by loading the emulsion with a good thermal-neutron absorber.\textsuperscript{13} Lithium (tritium recoils) and boron (alpha recoils) are two of the common loading substances. These substances may increase the sensitivity by more than an order of magnitude.
In badges that contain either cadmium or rhodium, we can use differential track counting to measure the thermal response. Thus, recoil tracks under these shields are a measure of the fast neutron response. The tracks in an open-window section are a measure of thermal plus fast neutron response. Then, the difference allows us to obtain the thermal response alone.

C. **Pocket Dosimeters**

The pocket dosimeter, often used in conjunction with a film badge or other primary monitor, is a small electroscope, about the size and shape of a fountain pen. This device can be either self-reading or not. In the self-reading type, a small compound microscope allows us to observe the response. In the other type, the response is read on a separate device.

The detection system usually consists of a small quartz-fiber electroscope, which forms a part of the collecting electrode. The instrument case, which is insulated from the fiber system, serves as the other electrode. The collecting volume is small (approximately $2 \times 10^{-6}$ m$^3$) and most often contains air at ambient pressure.

1. **Principle of Operation**

A positive charge may be placed on the electrode and fiber by means of a separate charger. The leakage current must be kept low; for this reason, a magnetic switch is often built into the system. That is, contact between the electrode and the charger cannot be made unless a magnetic field is used.

The fiber is repelled by the electrode since they both acquire a like charge. The image of the fiber can be viewed by means of the microscope. A scale in the eyepiece of the microscope can be calibrated, so that exposure may be measured in terms of image movement. The light for viewing enters through a window either on the side of, or at the end of, the device. By adjusting the voltage on the charger, we can bring the image to zero-scale reading.
When ions are produced in the volume of the chamber, they move to the fiber and electrode. This neutralizes some of the charge on the system, and the fiber moves closer to the electrode. The amount of charge lost depends upon the number of ions formed in the volume. If the agent causing the ionization is radiation, then the movement of the fiber image is a measure of the amount of radiation. For photons, the scale divisions can then be related to the exposure.

2. Exposure Measurement

The system may be viewed as a capacitor of C farads charged to a voltage V. Then, the charge on the system is given by equation 1.16

\[ Q = CV, \text{ in coulombs.} \]

The value of the charge put on the device is a function of the design. A typical value for the capacitance is around 3 pF, and the charging voltage may be 180 volts. In this case, the total charge that would result is then \( Q = (3 \times 10^{-12})(180) = 5.4 \times 10^{-10} \) coulombs.

The ions produced in the chamber volume are then collected by the electrode, and the system loses some of its charge. This results in a drop in the voltage of the system. This voltage change causes the fiber to deflect, and the fiber image moves along the scale in the eyepiece. The exposure can be measured in terms of this voltage change in the system.

The exposure, \( X \), is defined in terms of the charge collected in a volume of air of known mass; that is, adapting equation 4.3,

\[ X = \frac{Q}{m} \]

in which \( Q \) is the coulombs, and \( m \) is in kg. Therefore, for the pocket dosimeter,

\[ X = \frac{Q}{m} = \frac{CAV}{\rho V} \text{ (C/kg);} \]

13.3
where $\Delta V$ is the drop in voltage, $\rho$ is the density of air in kg/m$^3$, and the volume, $\text{Vol}$, of the chamber is in m$^3$. When we replace $\rho$ by its value of 1.293 kg/m$^3$, the result is

$$X = \frac{0.773CAV}{\rho \text{Vol}} \text{ (C/kg)}$$  \hspace{1cm} (13.4)

Since the density of air is a function of both temperature and pressure, a correction term is often needed to account for this variation.

The range of the device is then a function of the parameters in equation 13.4. Suppose we charge a dosimeter of sensitive volume $2 \times 10^{-6}$ m$^3$ and capacitance 3 pF to 180 volts. What will be the voltage change if the device is expected to read an exposure of 26 $\mu$C/kg (approximately 0.1 R) full scale? The required voltage change would be

$$X = \frac{0.773 \ \text{CAV} \ \text{Vol}}{2 \times 10^{-6}} \text{ (C/kg)}$$

$$2.6 \times 10^{-5} \ \text{C/kg} = \frac{0.773 \ (3 \times 10^{-12}) \Delta V}{2 \times 10^{-6}}$$

and

$$\Delta V = \frac{5.20 \times 10^{-11}}{2.32 \times 10^{-12}} = 22.4 \text{ volts}$$

The scale of the device can then be designed so that, for the above voltage change, the fiber image moves from 0 to 26 $\mu$C/kg (0.1 R). The scale is so arranged that when the fiber is fully charged its image is on zero.

3. **Characteristics**

Pocket dosimeters come in many ranges, such as 26 and 52 $\mu$C/kg (200 mR), as well as .26 - 12.9 mC/kg (1-50 R) full scale. The response of a dosimeter is seldom linear, except in the region of the
calibrated scale. For this reason, we should not attempt to estimate readings if the device shows more than a full-scale reading. Also, when reading a dosimeter, we should keep the fiber image vertical. This reduces the geotropic effect, that is, the tendency to give a reading that depends on the orientation of the device.

These devices are subject to discharge when dropped or bumped against an object. Most of these units are put through a "drop" test before they are put into routine use. Since any leakage of charge produces a reading, good insulation of the electrode is needed. When exposed to high-humidity areas, dosimeters may suffer a breakdown of the insulation. The normal leakage rate of a good dosimeter should be less than 3% in a 48 h period. More details concerning the desirable performance specifications for dosimeters may be found in Reference 24.

4. Energy Dependence

Most pocket dosimeters have walls of aluminum, Bakelite, or a plastic substance. The inner surface may then be coated with Aquadag to insure a conducting surface. These devices show a high degree of energy dependence for photons below 300 keV. Above this value, the response can be accurate to within ±10% of the true exposure. Below 300 keV, the error sometimes may be as high as a factor of 2 to 3.

Because of the case thickness used in most of these devices, the β response is often poor. Most of these units are highly directional in their β response and do not respond to β below 1 MeV.

Some of these dosimeters may have an inside coating of $^{10}\text{B}$ so that they can be used as thermal-neutron dosimeters.\(^{25}\)

In many cases, the purpose of the pocket dosimeter is merely to supplement the film badge, not to replace it. For this reason, the device is widely used, although it has several disadvantages. The main feature in its favor is the direct reading capability. Thus, we can check the unit at frequent intervals and get at least a rough idea of the exposure received. This will, at times, allow us to better ration our work time in the radiation field. In addition, when one needs to distribute the exposure in a given operation, the direct reading capability can be invaluable. Also,
in some applications in which radiation pulses are of importance, direct reading capability allows one to get a relative indication of the variation in radiation fields.

D. Solid State Dosimeters

As a result of irradiation, some solid substances undergo changes in some of their physical properties. These changes amount to a storage of energy in some way, and this forms the basis of using these solids for dosimetry. These main features have been studied: optical density changes, radiophotoluminescence, thermoluminescence, and conductivity changes. Not all of these methods are suitable for personnel dosimetry.\textsuperscript{2,5,26}

In studies of optical-density changes, glasses and plastics are most often used. Radiation induces color changes in these substances, and the solid can then absorb light in spectral regions that were transparent to the normal substance. When light of a given wavelength is passed through the solid, the optical density can then be measured on a spectrophotometer. In glasses, the dose range for linear response extends from about 10 to \(10^{4}\) Gy \((10^{3} - 10^{6} \text{ rad})\). This range for plastics is between about \(10^{4}\) and \(10^{7}\) Gy \((10^{6} - 10^{9} \text{ rad})\) for most substances.\textsuperscript{5} The high ranges in this method preclude its use for personnel dosimetry.

Before irradiation, some substances fluoresce when light is passed through them. When these solids are exposed, the result may be a loss of fluorescence.\textsuperscript{27} Anthracene, naphthalene, and other organic solids are among the substances used in this method. This method seems to be better than the color change effect for high-level dosimetry. Since the range for this method is from about \(10^{3}\) to \(10^{6}\) Gy \((10^{5} - 10^{8} \text{ rad})\), it is also not suited for personnel dosimetry.

1. Thermoluminescence

Phosphors that were originally used the most in studies of thermoluminescence include manganese-activated calcium fluoride (CaF\(_{2}\):Mn) and lithium fluoride (LiF).\textsuperscript{28} Other substances, such as
CaSO$_4$:D$_4$, LiB$_4$O$_7$:Mn,Si, CaF$_2$:Dy, and BeO, etc., have also been used.\textsuperscript{5,28-30} In these substances, electrons are moved from their normal places when the solid is irradiated. They migrate about until "trapped" by lattice defects in the solid. At normal temperature, the electrons remain there for quite some time, but are released from the traps by heating. The luminescence appears when the electrons return to their normal positions. This light (blue-green) for LiF, CaF$_2$:Mn can be measured and related to the absorbed dose in the phosphor. This method requires a means of heating the phosphor as well as a system to measure the light output.

a. Lattice Defects or Traps

Solids that have a crystal structure contain many kinds of lattice defects (activator centers, see Figure 10.7). Some of these defects may be: missing atoms or ions, dislocations in the crystal plane structure, interstitials (atoms or ions at interlattice positions), or even the presence of foreign substances (impurities).\textsuperscript{27} The regions about these defects are not always able to maintain a state of neutral charge. The presence of any charge at the activator center attracts unlike charges. If electrons move into these regions and a positive center is there, the electrons are attracted to this charge. Also, positive ions are attracted to those regions in which there is a negative center about the defect. When the charge centers are strong enough, they can even bind the ions that are attracted to them. These stronger centers are referred to as "traps," and the strength of the binding is called the "trap depth." The trap depth depends upon the type of defect (trap); a solid may contain many kinds of traps, each with its own trap depth.

To be of use as a dosimeter, the thermoluminescent (TL) material must be able to retain the trapped electrons at room temperature and must be capable of a strong light output when heated. If the traps are near the edge of the band gap, the number of carriers which can be trapped will be large. This will mean that the material will have good detection sensitivity, but, on the other hand, may exhibit fading.\textsuperscript{31} CaSO$_4$:Mn is
such a material. Its response goes down to 0.2 μGy (20 μrad) but shows fading. LiF and CaF₂:Mn have deeper traps so that fading is less but these are not as sensitive.

Another problem of TL material used for environmental monitoring applications is the presence of radioactive impurities in the solid. This contamination from trace materials can be significant.32

b. Glow Curve

When a solid is exposed to radiation, both electrons and positive ions ("holes") are produced. When some of these are trapped at the defects, they remain bound there as stored energy until they are freed by some means. The energy needed to free these charges is supplied by heating the solid. When the charges are released from the traps, they recombine with unlike charges in other parts of the solid, and light is given off. The light output may be measured by means of a photomultiplier tube.27 A plot of the brightness (relative intensity) versus temperature or time as the solid is heated is called a glow curve (see Figure 13.4). If the heating rate is uniform, both curves are similar. However, the total light emitted as a function of time (area under the glow curve) can be related to the total thermoluminescence.28 The area under the curve as a function of temperature does not have a simple interpretation. As the solid is warmed, the electrons begin to escape from the more shallow traps. When the store of these traps is depleted, the brightness decreases, and this gives rise to the first peak in Figure 13.4. If there are no other type traps in the solid, this would be the only peak. More often, more than one peak shows up. The number of such peaks is a function of the number, as well as the concentration, of different types of traps. The area under a glow peak, called the light sum, is constant for the same solid exposed to a given dose. However, many factors can affect the shape of the glow curve.28 Changes in heating rate produce dramatic effects. For very fast heating, the peak height increases but the time in which light is given off decreases, and the temperature at which the peak occurs shifts to a higher value. For TL dosimetry, one requires a reproducible heating rate, but it need not be uniform.
Following conversion of the light output into current, the readout may be related to dose. Two approaches are used: the peak height is used or the integrated area under the glow curve is used. The peak height method is more dependent on the heating rate and should not be used for loose powder. The area under the glow curve, during the heating time, is directly proportional to the integrated current from the photomultiplier. This latter method is less dependent on the heating rate.

Phosphors which have glow peaks at too low a temperature tend to exhibit fading (loss of the stored energy) with time. If the glow peaks have too high a temperature, infrared radiation will be produced which interferes with the reading. If the glow peaks are ill-defined, then integration becomes difficult with respect to choice of end point. An ideal glow curve would contain a single TL peak at a temperature of about 200°C.

c. Characteristics

The response to γ is linear in the exposure range from about 1 μC/kg (approximately 4 mR) to greater than 0.26 C/kg (approxi-
mately $10^3$ mR); therefore, these phosphors can be used for personnel dosimetry. Above this energy range, some TL materials exhibit a non-linear response. This is called "supralinearity," but the effect can still be accounted for. The response to fast neutrons is low in most of these substances. The thermal neutron response of CaF$_2$:Mn units is about one-fourth that of its $\gamma$ response. The neutron response of LiF is better because of the presence of $^6$Li. That is, natural Li contains about 7.5% $^6$Li. Because of the presence of $^6$Li in LiF, the thermal neutron response is about 1/7 that of the $\gamma$ response on an energy absorbed basis. If we use "almost" pure $^7$Li in the unit, the response to thermal neutrons is negligible. Thus, we can use a pair of Tl chips, one with almost all $^7$Li (called TLD-700 with 99.99% $^7$Li) and one with mostly $^8$Li (called TLD-600 with 95.6% $^6$Li), to arrive at both $\gamma$ and the thermal-neutron doses.\textsuperscript{28} The TLD-700 does not respond to neutrons, so that one can obtain the $\gamma$ contribution from this chip. The TLD-600 responds to both $\gamma$ and thermal neutrons, so the difference in readings between TLD-700 and TLD-600 can be used to estimate the thermal neutron contribution. Normal LiF (available as TLD-100)\textsuperscript{28} is used extensively for photon dosimetry applications. However, this phosphor may also be used in conjunction with TLD-700 to estimate the thermal contribution.

Characteristics of other TL phosphors are discussed in the literature.\textsuperscript{5,28,30}

(1) Energy Dependence - The energy dependence is related to the type of phosphor used. Cameron\textsuperscript{28} reports that LiF is energy-independent in the range 30 keV to 1.33 MeV, within 25%. CaF$_2$:Mn is quite energy-dependent. Because of its high effective atomic number ($Z$), the response per unit exposure is approximately 13 times greater at 40 keV than at $^{60}$Co energy. To combat this effect, filters have been used.\textsuperscript{27} However, the response to soft x rays is then altered because of the attenuation in the filter.

On the other hand, lithium borate with a manganese activator, is relatively energy independent and has an effective $Z$ which
is about equal to air or tissue. Also, BeO, which has an effective Z close to tissue, has a sensitivity comparable to LiF. However, BeO has not found wide acceptance as a TL material.\textsuperscript{33}

(2) **Fading** - These phosphors suffer from fading.\textsuperscript{2} If we use the deeper traps in the solid, the fading is less severe.\textsuperscript{28} When a substance is treated, or doped, with the proper impurity, we can obtain a phosphor with only one kind of trap. For those substances with glow peaks around about 200°C, the fading becomes much less severe. If we measure the main peak in LiF, we find that the stored signal does not fade severely at room temperature.

The LiF units are not affected by atmosphere as are the CaF$_2$:Mn substances, which require careful packaging. However, LiF seems to be more prone to damage effects than CaF$_2$:Mn.\textsuperscript{34} Both substances can be made into sufficiently small units for personnel dosimetry purposes.

(3) **Charged Particle Equilibrium** - As was the case for photographic detectors, the dosimetric information which is obtained must be under conditions of charged particle equilibrium. This requires that the phosphor be covered by a sufficient thickness of material. This thickness is often referred to as the buildup region. Values of the required thickness for photons of various energies can be found in Reference 28. Without this material fronting the TL material, the dose will be somewhat underestimated. Plastics such as Lucite, Teflon or Nylon are often used to supply the buildup layer.

(4) **Applications** - Thermoluminescence was first applied to dosimetry in 1953.\textsuperscript{35} At that time, it was not fully known if the method could be extended to personnel monitoring. Since then, results have shown that the method can be used for this purpose; yet progress has not been spectacular. Nevertheless, TL has been used for $\beta$, $\gamma$ and neutron dosimetry.\textsuperscript{28} Because of the small size of TLD chips, they have been useful in determinations of extremity doses, utilizing finger ring
badges for this purpose. One drawback in the past has been the practice in the U.S. to hold film badges indefinitely for potential recheck. As we have seen, to measure the dose in a TL phosphor, we must remove the electrons from the stored-energy centers. That is, we deplete the traps of the trapped electrons and holes, so that the dosimetric information is then gone. This precludes the option of a recheck. Nevertheless, this is no longer seen as a drawback and increased use of thermoluminescent dosimeters (TLD) is occurring. This has been accelerated in recent years by the availability of automated reading systems.

2. Albedo Dosimeters

An extension of the use of TL absorbers has been in the use of these for neutron dosimetry in albedo dosimeters. The concept albedo refers to reflection from a surface. These devices are designed to detect the thermal neutrons reflected from the body surface when an incident fast neutron fluence interacts with the body. One of the early applications of this method for dosimetry was described by Hoy.

The detection of thermal neutrons is generally based on the reaction

\[ ^{6}\text{Li} + ^{1}\text{n} \rightarrow ^{7}\text{Li}^* \rightarrow ^{4}\text{He} + ^{3}\text{H}. \]

The energetic alpha (4.8 MeV) and the recoil triton lose their energy in the TL material, which is generally LiF. In a typical application, TLD-700 and TLD-600 are used although TLD-100 may be used in place of TLD-600. The \( \gamma \) response of these phosphors are similar. If one uses the pair, say TLD-700 and TLD-600, the response of the TLD-700 will represent only the \( \gamma \) contribution. The TLD-600, with increased \( ^{6}\text{Li} \) content, gives the total \( \gamma \) plus neutron response. By subtracting, one can estimate the contribution due to neutrons. To account for any thermal neutrons which are incident on the body, cadmium (approximately .76 mm thick) or boron-loaded plastic are placed over the phosphor. That is, the desired
response is from the fast neutrons which are incident on the body. When these interact, are thermalized, and reflected from the body, this represents the contribution we wish to measure. If the incident fluence contains thermal neutrons to begin with, their response in the phosphor would introduce an erroneous contribution. The cadmium, or boron-loaded plastic, absorbs the incident thermal neutron fluence so that it does not produce an undesirable response.

a. **Energy Dependence**

The major disadvantage of albedo dosimeters is their severe energy dependence. For this reason, the reading can only be evaluated correctly if the proper calibration factor has been obtained. Two methods of determining these factors are in use.\(^{37}\) The relevant dose equivalent rate can be determined at the particular work place. This can be related to the response of the albedo dosimeter, placed on a phantom (usually a jug of water), at the same location for a measured time interval. By dividing the dosimeter response by the computed dose equivalent, the calibration factor may be determined. The other method was developed by Hankins.\(^{38}\) It consists of using a 0.23 m diameter spherical rem meter and a 0.076 m diameter sphere (covered with .25 mm of Cd). Measurements with each sphere are taken at the relevant location, and the ratio of the readings is determined. The dose equivalent at the location can then be related to the ratio that was obtained with the spheres. Then, for a given measured ratio, the calibration factor can be determined. A plot of these ratios versus the computed calibration factor yields a straight line. So, in order to correctly interpret the albedo response, one must also have evaluated the neutron field at the specified location.

b. **Dosimetric Features**

Albedo dosimeters are quite sensitive and are attractive since the processing may be automated. They overrespond to moderated neutrons and have a poor response to fast neutrons. Because of this, some
facilities employ albedo dosimeters to measure the moderated neutron component and NTA film to read the fast component. Although the response may be difficult to interpret on occasion, a virtue of albedo dosimeters is that a reading will always be obtained when the device is exposed to a significant neutron dose. These systems are capable of detecting about 0.5 mSv (50 mrem) of unmoderated fission neutrons. Albedo response is influenced by high \( \gamma \) fields. Since each phosphor responds comparably to the photon field, one may end up subtracting two large numbers to estimate the neutron contribution. Since there is an error in the measurement of each phosphor, the difference between two large numbers will give a small number with a relatively large error. The response of the albedo dosimeter to neutrons may be improved by adding polyethylene, which moderates the fast neutrons and thereby improves the sensitivity of the device to high-energy neutrons.

3. Radiophotoluminescence

a. General

As a result of the type of center used in the measurement, thermoluminescence results in the loss of the stored information during readout. The radiophotoluminescent (RPL) method is not subject to this feature; therefore, RPL units may be reread. This method has been used with success for silver-activated phosphate glass. Studies with this type glass have revealed that at least two types of stable centers are induced by photon irradiation. One type gives rise to the color effect used in the optical density method. The other type also absorbs light, but will emit an orange fluorescent light when the dose glass is illuminated by ultraviolet light. The intensity of the fluorescence gives a measure of the absorbed dose for the type of radiation used. The light output is measured by a fluorimeter.
b. Characteristics of Silver-activated Glass

In the type glass first used by Schulman, the linear dose range extends from about 0.1 Gy to greater than 10 Gy (10 \(-10^3\) rad). This Schulman glass was often referred to as high-Z glass because the effective atomic number is about 28. The glass was designed for use mainly as a casualty-type dosimeter. In that state of limited sensitivity, the glass was not of use for routine personnel monitoring.

Yokota devised a new low-Z glass as well as a new fluorimeter. The effective Z of this glass was about 16 and was obtained by replacing the KPO₃ in the Schulman glass with LiPO₃. The linear response was retained, and the sensitivity to lower photon doses was greatly increased. The reported γ sensitivity of less than 0.5 mGy (50 mrad) made this type glass of interest in personnel monitoring. Becker and Cheka developed a silver-activated glass utilizing lithium borate, instead of metaphosphate, which had an energy dependence comparable to that of LiF, but which required excessive annealing.

The fast-neutron response is small in RPL devices, being perhaps a few % of the γ response. The thermal-neutron response is greater for the low-Z than the high-Z glass. The magnitude of the response in the glass depends upon the presence of thermal-neutron absorbers such as \(^6\)Li and \(^{10}\)B. We can alter the thermal-neutron sensitivity for the low-Z glass by using pure \(^7\)Li.

One of the main drawbacks of RPL devices is the severe energy dependence of the glass. Because of the presence of the silver, the response peaks near 50 keV, just as it does for film. For the high-Z glass, the response at the peak may be 20-30 times the response at \(^{60}\)Co energy. The peak response may be flattened by the use of metal filters, as is done with film. Silver, tin, aluminum, gold, and cadmium have been used as filters with these glasses. Better response is achieved if these filters are perforated. Yokota describes a number of filter arrangements for decreasing energy dependence.

The glass of either high- or low-Z type is most often used in the form of small cylindrical rods or small blocks. The glass rods are
about 1 mm in OD by 6 mm long. The blocks, such as the Yokota type, are about 8x8x4.7 mm. Fluorimeters, although rather expensive,\textsuperscript{2} are commercially available for reading these devices.

The advances in design, which have improved the performance of this type device, have shown promise of its further use in personnel dosimetry. At present, RPL devices have not received wide acceptance for this purpose in the U.S. However, these are employed as routine dosimeters in Europe and Japan and have achieved good accuracy of dose measurement, stability, and energy and directional independence.\textsuperscript{4,43}

4. Conductivity Methods

Little has been done with the class of solids known as semiconductors in regard to personnel dosimetry. One reason for this is the low sensitivity which precludes dose measurement below about 0.1 Gy (10 rad). However, CdS and Si crystals have been used in clinical dosimetry and other applications.\textsuperscript{16,44}

More frequently, silicon junction detectors have been used for electron and photon dosimetry.\textsuperscript{44} In these applications, either a temporary or permanent change in conductivity is observed.

Silicon p-n junction counters have been applied to fast neutron dosimetry. This method uses the change in forward resistance of the diode due to the damage caused by fast neutrons. Fast neutrons displace silicon atoms from the lattice and thereby change the silicon diode resistance. The change in resistance can then be related to the fast-neutron dose. The unit can be made quite small and is insensitive to $\gamma$ rays. It is not yet suitable for low-level use since its sensitivity is limited to about 0.1 Gy (10 rad).\textsuperscript{16} For neutron energy $> 350$ keV, the diode is relatively energy independent (within $\pm 20\%$ up to 15 MeV).\textsuperscript{16,37} Again, because of the inability to read low doses and the relatively high cost, this method has not been applied to personnel dosimetry. It has been used successfully as a fast neutron dosimeter in nuclear accident applications.
5. **Thermally Stimulated Exoelectron Emission (TSEE)**

The use of thermally stimulated exoelectron emission has not been extensive in the past. Various early studies of the use of this method for dosimetry have not led to wide acceptance. Recent interest in this method has come about because of the ICRP and ICRU recommendations concerning the deep (penetrating) and shallow (superficial) dose equivalents.\(^ {45, 46}\) Many existing personnel dosimeters have filter/detector thicknesses which are unable to adequately measure the superficial dose.\(^ {15}\) However, a recent investigation\(^ {47}\) has indicated that the use of thin films of BeO and utilizing TSEE measurements shows promise.

E. **Track Etch Dosimeters**

The original track recorders which used fissile material had the disadvantage that monitored personnel received a radiation dose from the dosimeter itself.\(^ {3, 48}\) These dosimeters employed a foil of fissionable material as a radiator of recoil particles (fission fragments). A suitable glass (quartz, flint) or dielectric material (mica, Lexan, cellulose nitrate, etc.) was used as the track recorder. Later improvements in the method led to the use of the recoil tracks produced in the material of the recorder itself. Since the recoils consisted mainly of C, O, H and N atoms from the polycarbonate material, the specific energy loss along the track is high. This energy loss could not be supplied by electrons or photons, so the recorders are inherently insensitive to electron and photon radiation.\(^ {31}\) This is an advantage for neutron monitoring, as is the low cost, negligible track fading, and ease of processing.\(^ {37}\) By employing the electrochemical etching technique, the recoil tracks in polycarbonate are increased in size and are made more visible. This enhances the counting of tracks.

Polycarbonate foils do not register tracks from proton recoils, so these devices are relatively insensitive to neutrons below 1 MeV. The response of these dosimeters is approximately proportional to the neutron dose equivalent from about 1 - 20 MeV.\(^ {49}\) Some polymers are unsuitable because cracks or other defects show up as high background track density.
Another plastic recorder, CR-39, has been found to be more sensitive than polycarbonate.\textsuperscript{50} Whereas polycarbonate does not appear to detect recoil protons, CR-39 does. This allows detection of neutrons by CR-39 down to an energy of \( \sim 0.1 \) MeV.

The system makes use of a two-step electrochemical etch process at an elevated temperature.\textsuperscript{51} The foils are put into an etch chamber and placed in an oven which is maintained at a temperature of 60\(^\circ\)C overnight. 60\(^\circ\)C KOH (6.5 N) is added to the chamber and etching is carried out for 5 hours at 3000 V and 60 Hz.\textsuperscript{52} In the 23-minute second step, the voltage is kept at 3000 V but the frequency is changed to 2 kHz. This second step makes the tracks much larger and nearly uniform in size. The enlarged tracks are more easily distinguished from the defects normally found on the foil. This enhances the counting of tracks and also results in an improved track density relative to that obtained without etching. The foils are scanned with an optical bacteria counter and approximately 50\% of the available etched fields are counted.

The sensitivity is about 7500 tracks/m\(^2\) \(\mu\)Sv (7.5 tracks/cm\(^2\) mrem)\textsuperscript{52} and the typical background on a foil is around 80 \(\mu\)Sv (8 mrem). The detection limit for a single foil is \(\sim 100 \mu\)Sv (10 mrem).

There is no fading problem but the foils must be protected from light and high temperatures. Foils are usually stored in the dark and, when in use, must not be exposed to ambient light.

The foils respond to neutrons in the energy range of about 0.1 - 18 MeV. The neutron energy response is relatively flat from 0.08 - 3.5 MeV, but is down by a factor of 3 in the region 13-16 MeV.\textsuperscript{52} This energy dependence is less severe than that for albedo dosimeters. The response of CR-39 should be correct for slightly moderated neutrons coming through shielding as well as for unmoderated neutrons. The linearity of the response extends up to 0.015 Sv (1.5 rem). One drawback of the CR-39 foil system is the highly directional dependence of the response. The response may vary by nearly a factor of five depending upon the angle of incidence of the neutrons.\textsuperscript{52}

The CR-39 dosimetry system is an improvement over albedo dosimeters.
because of the reduced energy dependence and offers less reading problems and fading concerns than NTA film. In addition, since polycarbonate foils do not respond below about 1 MeV, the CR-39 dosimeter offers more capability for monitoring moderated neutron fields. The Department of Energy is supporting the development of the CR-39 dosimetry system for use as a personal neutron dosimeter.

REFERENCES


BIBLIOGRAPHY


QUESTIONS

13.1 What term is given to devices that indicate the total amount of radiation to which a person has been exposed?

13.2 List some of the features desired in a personnel dosimeter.

13.3 What is the most frequently used personnel dosimeter?

13.4 Explain why photographic film is more difficult to use in dosimetry than in radiation detection.

13.5 What is the active material in photographic film?

13.6 What term is given to the underdeveloped image or effect produced by radiation in photographic film?

13.7 Name the chemical used to "fix" the developed photographic film so that it will not change further when exposed to light.

13.8 Explain the difference between film opacity and film density.

13.9 What name is given to the plot of film density versus the logarithm of exposure?

13.10 Why is the linear region of the plot referred to in the previous questions important for measuring exposure?

13.11 The ability of a film to distinguish between two nearly equal exposures is a measure of the film's:

13.12 The effect in which increased exposure of a photographic film causes a decrease in the film's density upon development is known as:

13.13 What law of science indicates that film response for a particular amount of radiation is independent of the rate that the film is exposed?

13.14 Describe the relationship of shape and position of the plot of a characteristic curve in relation to the energy of photons and beta particles.

13.15 List some factors that enhance latent image fading.

13.16 What does the reciprocal of the exposure to produce a given film density define?

13.17 What term is used to indicate that the sensitivity of a film varies with photon energy? What principal technique is used to reduce this effect?
13.18 List the factors which affect the final density of a film.

13.19 What term indicates film density that occurs in unexposed film? How can this effect be corrected.

13.20 What instrument is used to determine film density?

13.21 How is film reading standardized and interpreted?

13.22 List some other purposes that may be served by a film holder other than a device for containing the film.

13.23 Why do film packets for personnel monitoring usually contain two or more films?

13.24 What should determine the equilibrium thickness of the film wrapper and the film holder or film badge?

13.25 What techniques are used in film dosimetry to discriminate between fast neutrons and photons in a mixed field? Between fast and thermal neutrons?

13.26 What term needs correction for a pocket dosimeter reading on

- a) a very humid day?
- b) on a very hot day?

13.27 How can a pocket dosimeter be constructed to measure thermal neutrons?

13.28 Why should a pocket dosimeter be read soon after use?

13.29 What are the energy dependent characteristics of a pocket dosimeter?

13.30 List advantages and disadvantages of the following for use in personnel dosimetry:

- a) thermoluminescence,  b) infrared stimulations
- c) radiophotoluminescence,  d) conductivity methods.

13.31 What is the nuclear reaction that is the basis for the detection of thermal neutrons in albedo dosimeters?

13.32 What are the commonly used materials for track etch detectors?

**PROBLEMS**

13.1 The intensity of a beam of light is reduced to one-third of its original intensity upon passing through a piece of photographic film. Find:
13-41

a) the opacity and  
b) the density of the film.

Answers:  
a) 3  
b) 0.477

13.2 If the net density of a film is 2 for $1.29 \times 10^{-4}$ C/kg, what will be the exposure when the net density is 3.5? Assume that both densities are on the linear portion of the characteristic curve. Assume a slope of 1 per unit log exposure.

Answer: $4.08 \times 10^{-3}$ C/kg

13.3 A pocket dosimeter has a volume of $2.5 \times 10^{-6}$ m$^3$, a capacitance of 150 pF and is charged by a 200 volt potential. If full scale is $1.3 \times 10^{-3}$ C/kg, what will be the voltage change $\Delta V$ when the instrument is discharged to read $7.7 \times 10^{-4}$ C/kg?

Answer: 16.60 volts

13.4 Determine the practicality of a dosimeter identical to the one in the preceding problem except that its capacitance is reduced to 1.5 pF.

13.5 An air equivalent pocket chamber having a capacitance of 75 pF is initially charged to a voltage of 25 V. If the active volume contains $5 \times 10^{-5}$ m$^3$ of air at STP (pressure: 760 mm Hg, temperature 273 K), what photon exposure will drop the chamber voltage to 20 V?

Answer: $5.8 \ \mu$C/kg.

13.6 The exposure measured by a pocket dosimeter is to be corrected for variation of density with pressure and temperature (see equations 13.3 and 13.4). The density at temperature, $T$, can be written as

$$\rho_T = \rho_o \frac{P_T}{P_o T}$$

where $\rho_o (1.293 \ \text{kg/m}^3)$ is the density of air at 760 mm Hg of pressure ($P_o$), and at temperature $T_o=273$ K. Prepare a table of the density correction terms for a range of reasonable pressures and temperatures. Apply these values to the worked example in the text. What conclusions can you draw?