CHAPTER 4.

RADIATION MONITORING INSTRUMENTS

GOVINDA RAJAN
Medical Physics and Safety Section,
Bhabha Atomic Research Center,
Mumbai, Maharashtra, India

JOANNA IZEWSKA
Dosimetry and Medical Radiation Physics Section
Department of Nuclear Sciences and Applications
International Atomic Energy Agency
Vienna, Austria

4.1. INTRODUCTION

Radiation exposure to humans can be broadly classified as internal and external exposures. In radiation therapy sealed sources are used almost exclusively and they are unlikely to cause internal exposure. This chapter deals with monitoring of external exposures.

- External exposure monitoring refers to measuring:
  - Radiation levels in and around work areas;
  - Levels around radiation therapy equipment or source containers;
  - Dose equivalents received by individuals working with radiation.
- Radiation monitoring is carried out:
  - To assess workplace conditions and individual exposures;
  - To ensure acceptably safe and satisfactory radiological conditions in the workplace; and
  - To keep records of monitoring, over a long period of time, for the purposes of regulation or as good practice.
- Radiation monitoring instruments are used both for area monitoring and for individual monitoring. The instruments used for measuring radiation levels are referred to as *area survey meters* (or area monitors) and the instruments used for recording the dose equivalents received by individuals working with radiation are referred to as *personal dosimeters* (or individual dosimeters). All instruments must be calibrated in terms of appropriate quantities used in radiation protection.

4.2. OPERATIONAL QUANTITIES FOR RADIATION MONITORING

Recommendations regarding dosimetric quantities and units in radiation protection dosimetry are set forth by the International Commission on Radiation Units and Measurements (ICRU). The recommendations on the practical application of these quantities in radiation protection are established by the International Commission on Radiological Protection (ICRP).

- The operational quantities are defined for practical measurements both for area and individual monitoring.

- In radiation protection the radiation is characterized as either *weakly* or *strongly penetrating* depending on which dose equivalent is closer to its limiting value. In practice, the term 'weakly penetrating' radiation usually applies to photons below 15 keV and for beta rays.

- For the purpose of area monitoring *ambient dose equivalent* $H^*(d)$ and the *directional dose equivalent* $H'(d,\Omega)$ are defined. They link the external radiation field to the effective dose equivalent in the ICRU sphere phantom (see Chapter 16), at the depth d, on a radius in a specified direction Ω.

- For strongly penetrating radiation the depth d = 10 mm is used; the ambient dose equivalent is denoted $H^*(10)$ and the directional dose equivalent $H'(10, \Omega)$. For weakly penetrating radiation the ambient and directional dose equivalents in the skin at $d = 0.07$ mm, $H^*(0.07)$ and $H'(0.07,\Omega)$ are relevant, and in the lens of the eye at $d = 3$ mm, $H^*(3)$ and $H'(3,\Omega)$, are relevant.

- For individual monitoring the *personal dose equivalent* $H_p(d)$ is defined. $H_p(d)$ is the dose equivalent in soft tissue below a specified point on the body at a depth d (see also Chapter 16).

- For strongly penetrating radiation the depth d = 10 mm is used and the personal dose equivalent is denoted $H_p(10)$. For weakly penetrating radiation the personal dose equivalent in the skin at $d = 0.07$ mm, $H_p(0.07)$, and in the lens of the eye at $d = 3$ mm, $H_p(3)$, are used.

- $H_p(d)$ can be measured with a dosimeter which is worn at the surface of the body and covered with the appropriate layer of a tissue-equivalent material.

4.3. AREA SURVEY METERS

- Radiation instruments used as survey monitors are either gas filled detectors or solid state detectors (*e.g.*, scintillator or semiconductor detectors).

- Depending upon the design of the gas filled detector and the voltage applied between the two electrodes, the detector can operate in one of three regions shown in Fig. 4.1, *i.e.*, the ionisation region B, proportional region C, or Geiger-Müller (GM) region E.

- Regions of recombination and of limited proportionality in the "signal versus applied voltage" plot (regions A and D in Fig. 4.1) are not used for survey meters.

- The gas-filled detector is usually cylindrical in shape, with an outer wall and a central electrode well insulated from each other. The wall is usually made of tissue-equivalent material for ionisation chamber detectors and of brass or copper for other types of detectors.

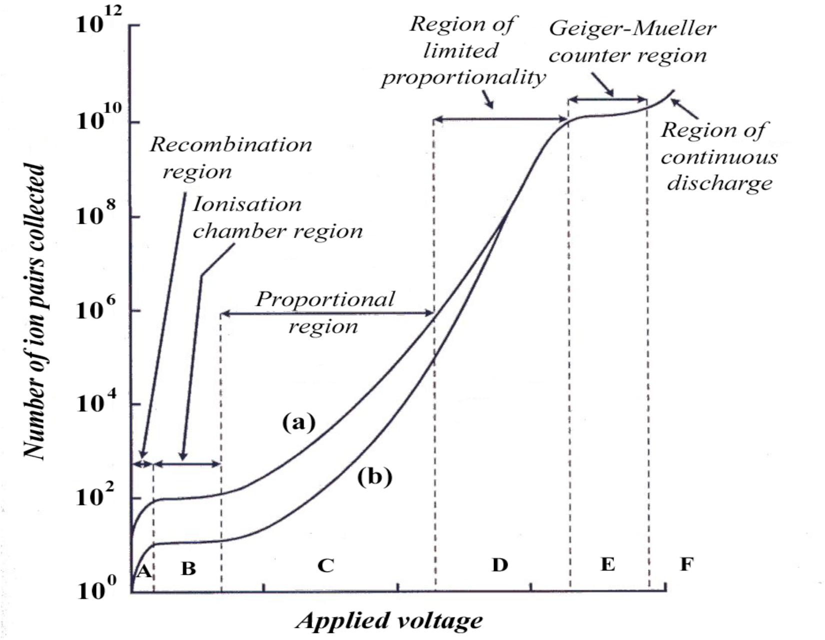

FIG. 4.1. Various regions of operation of gas-filled detector: region A represents the recombination region; region B the ionisation region; region C the proportionality region; region D the region of limited proportionality; and region E the Geiger-Müller region. Curve (a) is for 1 MeV beta particles; curve (b) for 100 keV beta particles.

- Survey meters come in different shapes and sizes depending upon the specific application (see Fig. 4.2).

- The gas is usually a non-electronegative gas in order to avoid negative ion formation by electron attachment that would increase the collection time in the detector, thus limiting the dose rate that can be monitored. The increase in charge-collection time results from the relatively slow mobility of ions that is about three orders of magnitude smaller than that of electrons. Noble gases are generally used in these detectors.

- Beta-gamma survey meters have a thin end-window to register weakly penetrating radiation. The gamma efficiency of these detectors is only a few percent (as determined by the wall absorption), while the beta response is near 100% for beta particles entering the detector.

- Because of their high sensitivity, the tubes of GM-based gamma monitors are smaller in size compared to ionisation chamber-type detectors.

- Depending upon the electronics used, the detectors can operate in a ‘pulse’ mode or in the ‘mean level’ or current mode. The proportional and GM counters are normally operated in the pulse mode.

- Because of the finite resolving time (the time required by the detector to regain its normal state after registering a pulse) these detectors will saturate at high intensity radiation fields. Ionisation chambers, operating in the current mode, are more suitable for higher dose rate measurements.

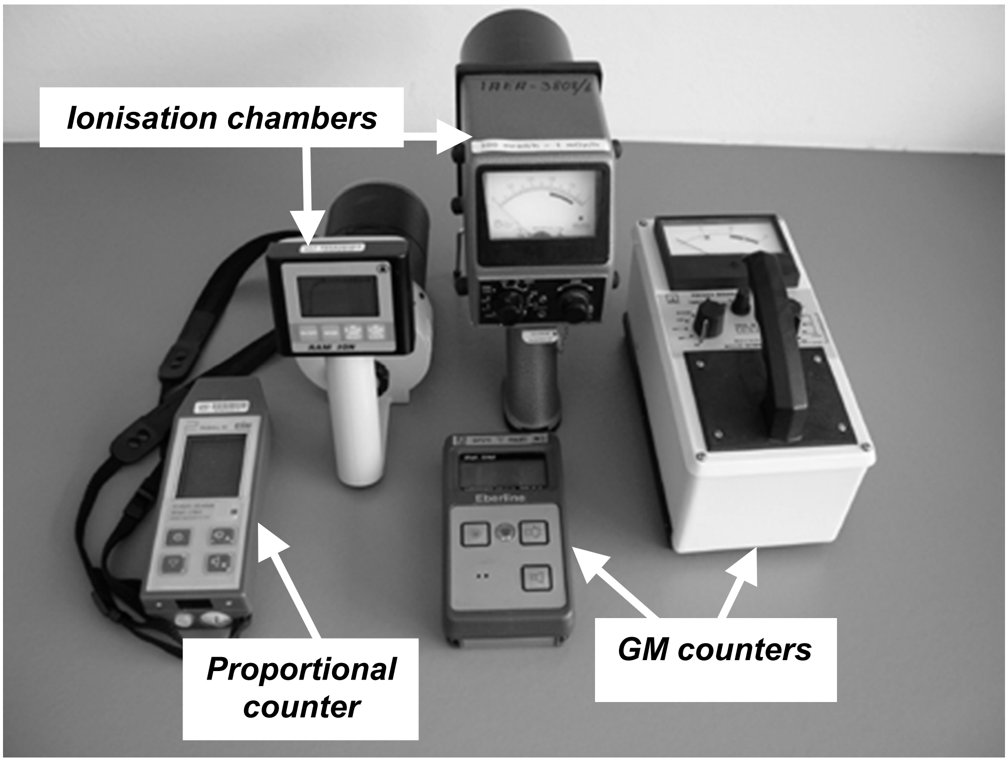

FIG. 4.2. Area survey meters commonly used for radiation protection level measurements: ionisation chambers, a proportional counter, GM counters.

4.3.1. Ionisation chambers

- In the ionisation region the number of primary ions of either sign collected is proportional to the energy deposited by the charged particle tracks in the detector volume.

- Because of the linear energy transfer (LET) differences, the particle discrimination function can be used (see Fig. 4.1).

- Build-up caps are required to improve detection efficiency when measuring high-energy photon radiation, and they should be removed when measuring lower energy photons (10 - 100 keV) and beta particles.

4.3.2. Proportional counters

- In the proportional region there is an amplification of the primary ion signal due to ionisation by collision between ions and gas molecules (charge multiplication). This occurs when, between successive collisions, the primary ions gain sufficient energy, in the neighborhood of the thin central electrode, to cause further ionisation in the detector. The amplification is about 10^3-fold to 10^4-fold.

- Proportional counters are more sensitive than ionisation chambers and they are suitable for measurements in low intensity radiation fields. The amount of charge collected from each interaction is proportional to the amount of energy deposited in the gas of the counter by the interaction.

4.3.3. Neutron area survey meters

- Neutron area survey meters operate in the proportional region so that the photon background can be easily discriminated against.

- Thermal neutron detectors usually have a coating of a boron compound on the inside of the wall or else the counter is filled with the BF_3 gas.

- A thermal neutron interacts with boron-10 nucleus causing an (n,α) reaction and the alpha particles can be detected easily by their ionizing interactions.

- To detect fast neutrons the same counter is surrounded by a moderator made of hydrogenous material (Fig. 4.3). The whole assembly is then a fast neutron counter. The fast neutrons interacting with the moderator get thermalized and are subsequently detected by the BF_3 counter placed inside the moderator.

- Filter compensation is applied to reduce thermal range over-response so that the response follows the ICRP radiation weighting factors w_R (see chapter 16). The output is approximately proportional to the dose equivalent in soft tissue over a wide range (10 decades) of neutron energy spectra.

- Other neutron detectors (*e.g.*, those based on helium-3) also function on the same principles.

FIG. 4.3. Neutron dose equivalent rate meter with a thermalizing polyethylene sphere with a diameter of 20 cm.

4.3.4. GM counters

- In the GM region the discharge spreads throughout the volume of the detector and the pulse height becomes independent of the primary ionisation or the energy of the interacting particles. In the GM counter detector the gas multiplication spreads along the entire length of the anode. Gas-filled detectors cannot be operated at voltages beyond the GM region because they continuously discharge.

- Because of the large charge amplification (9 to 10 orders of magnitude), GM survey meters are widely used at very low radiation levels (*e.g.*, in areas of public occupancy around the radiotherapy treatment rooms).

- GM counters exhibit strong energy dependence at low photon energies and are not suitable for the use in pulsed radiation fields. They are considered ‘indicators’ of radiation, whereas ionisation chambers are used for more precise measurements.

- GM detectors suffer from very long dead-times, ranging from tens to hundreds of ms. For this reason, GM counters are not used when accurate measurements are required of count rates of more than a few 100 counts per second. A portable GM survey meter may become paralysed in a very high radiation field and yield a zero reading. Therefore ionisation chambers should be used in areas where radiation rates are high.

4.3.5. Scintillator detectors

- Detectors based on scintillation (light emission) are known as scintillation detectors and belong to the class of solid-state detectors. Certain organic and inorganic crystals contain activator atoms and emit scintillations upon absorption of radiation. High atomic number phosphors are mostly used for the measurement of gamma rays, while the plastic scintillators are mostly used with beta particles.

- Scintillating phosphors include solid organic materials like anthracene, stilbene and plastic scintillators as well as thallium-activated inorganic phosphors, such as NaI(Tl) or CsI(Tl).

- A photomultiplier tube (PMT) is optically coupled to the scintillator to convert the light pulse into an electric pulse. Some survey meters use photodiodes in place of photomultiplier tubes.

4.3.6. Semiconductor detectors

- Bulk conductivity detectors are formed from intrinsic semiconductors of very high bulk resistivity (*e.g.*, CdS or CdSe). They act like solid-state ionisation chambers on exposure to radiation and, like the scintillation detectors, belong to the class of solid-state detectors.

- Extrinsic (*i.e.*, doped with trace quantities of impurities such as phosphorus or lithium) semiconductors, like silicon or germanium, are used to form junction detectors. They too act as solid-state ionisation chambers on an application of a reverse bias to the detectors and exposure to radiation.

- The sensitivity of solid state detectors is about 10^4 times higher than that of gas-filled detectors due to the average energy required to produce an ion pair (being one order less) and the material density (typically 3 orders more) compared to gases. This helps in miniaturizing solid-state radiation-monitoring instruments.

4.3.7. Commonly available features of area survey meters

- "Low battery" visual indication.
- Auto zeroing, auto ranging, auto back-illumination facilities.
- Variable response time and memory to store the data values.
- Option for both the 'rate' and the 'integrate' modes of operation.
- Analog or digital display, marked in conventional (exposure/air-kerma) or recent "ambient dose equivalent" or "personal dose equivalent" units.
- Audio indication of radiation levels (through the 'chirp' rate).
- Re-settable / non-re-settable alarm facility with adjustable alarm levels.
- Visual indication of radiation with flashing LEDs.

4.3.8. Calibration of survey meters

- Protection level area survey meters have to be calibrated against a reference instrument that is traceable (directly or indirectly) to a National Standards Laboratory.

- A reference instrument for gamma radiation is generally an ionisation chamber (Fig. 4.4) with a measuring assembly. Reference instruments do not indicate directly the dose equivalent H required for calibration of radiation protection monitoring instruments. Rather, they measure basic radiation quantities, such as the *air-kerma in air* for photon radiation, and the dose equivalent H is then determined by using appropriate conversion coefficients h:

$$H = h \cdot N_{\mathrm{R}} \cdot M_{\mathrm{R}} \,, \tag{4.1}$$

where

N_{R} is the calibration factor (*e.g.*, in terms of *air-kerma in air* or *air-kerma rate in air*) of the reference chamber under the reference conditions and
M_{R} is the reading of the reference instrument corrected for influence quantities.

- A reference instrument is calibrated free-in-air for the range of reference radiation qualities (defined by ISO). The same reference qualities should be used for the calibration of radiation protection monitoring instruments.

- Typically, calibration of survey meters in terms of the ambient dose equivalent $H^*(10)$ involves three steps:

  - *Air-kerma in air* is measured in a reference field, using a reference standard.

  - The values of the conversion coefficient $h_{H^*} = [H^*(10)/(K_{\mathrm{air}})_{\mathrm{air}}]$ are theoretically available. Using these data for the calibration beam quality, a reference instrument reading can be converted to $H^*(10)$.

- The survey monitor being calibrated is then placed at the calibration point and its reading M is determined. The calibration factor in terms of the ambient dose equivalent, N_{H^*}, for the survey monitor is determined from the equation: $N_{H^*} = H^*(10)/M$.

4.3.9. Properties of survey meters

- ***Sensitivity***

  - Sensitivity S is the inverse of the calibration factor N.
  - Using decade resistances, detector of larger volume, or detector gas under high pressure a wide range of dose equivalent rates can be covered with ionisation chamber based survey meters, *e.g.*, 1 μSv/h to 1 Sv/h.
  - Because of finite resolving time, GM-based systems would saturate beyond a few thousand counts per second. Low dead time counters or dead time correction circuits enable these detectors to operate at higher intensity radiation fields.
  - Scintillation-based systems are more sensitive than GM counters because of higher gamma conversion efficiency and the dynode amplification.
  - Scintillation-based systems are generally used for survey at very low radiation levels (*e.g.*, contamination monitoring, lost source detection survey, etc.). However, they can also be used at higher radiation levels, since their resolving time is quite low (a few μsec or lower) compared to GM counters.

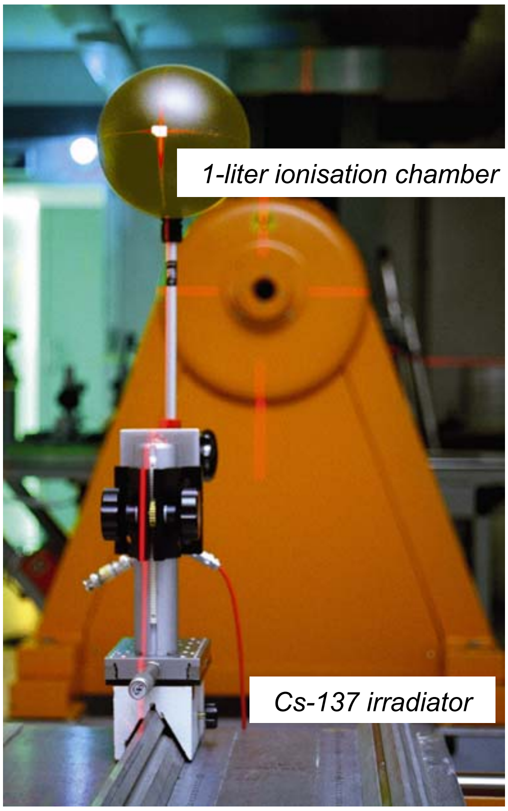

FIG. 4.4. Reference ionisation chamber used for the calibration of area survey meters in a Cs-137 gamma beam.

- ***Energy dependence***

  - Survey meters are calibrated at one or more beam qualities, but are often used in situations where the radiation field is complex or unknown. So these survey meters should have low energy dependence over a wide energy range.
  - In the past, survey meters were designed to exhibit a flat energy response that follows exposure or *air-kerma in air*.
  - For measuring the dose equivalent
    $N_{H^*}=[H^*(10)/M]= [H^*(10)/(K_{\text{air}})_{\text{air}}]/[(K_{\text{air}})_{\text{air}}/\text{M}]$
    their response with energy shall vary as the quantity $[H^*(10)/(K_{\text{air}})_{\text{air}}]$.
  - GM counters exhibit strong energy dependence for low energy photons (<80 keV).

- ***Directional dependence***

  - By rotating the survey monitor about its vertical axis, the directional response of the instrument can be studied.
  - A survey monitor usually exhibits isotropic response as required for measuring ambient dose equivalent, within ±60° to ±80° with respect to the reference direction of calibration and typically has much better response for higher photon energies (> 80 keV).

- ***Dose equivalent range***

  - Survey meters may cover a range from nSv/h to Sv/h but the typical range in use is μSv/h to mSv/h.

- ***Response time***

  - Response time of the survey monitor is defined as the *RC* time constant of the measuring circuit, where *R* is the decade resistor used and *C* the capacitance of the circuit.
  - Low dose equivalent ranges would have high *R* and hence high *RC* values and so the indicator movement would be sluggish.
  - It takes at least 3 to 5 time-constants for the monitor reading to stabilize.

- ***Overload characteristics***

  - The survey meters must be subjected to dose rates of about 10 times the maximum scale range to ensure that the meter reads full scale rather than near zero on saturation.
  - Some survey meters, especially the older models, may read 'zero' on overload (*i.e.*, when the dose equivalent rate exceeds the scale range). Such survey meters should not be used for monitoring, since the worker may wrongly assume that there is no radiation in an area where the radiation field is actually very high.
  - GM survey meters are not suitable for use in pulsed fields due to the possible overload effect and ionisation chamber-based survey meters should be used instead.

- ***Long term stability***

    - The survey meters have to be calibrated in a standards dosimetry laboratory with the frequency prescribed by the regulatory requirements of the country, typically once every three years.
    - The survey meters also need calibration immediately after repairs or immediately on detecting any sudden change in response.
    - The long term stability of the survey meters must be checked at regular intervals using a long half-life source in a reproducible geometry.

- ***Discrimination between different types of radiation***

    - End-window GM counters have a removable buildup cap to discriminate beta from gamma rays.
    - For beta measurements the end cap must be removed to allow beta particles to enter the sensitive volume.

- ***Uncertainties in the area survey measurements***

    - The standards laboratory provides, along with the survey monitor calibration, the uncertainty associated with the calibration factor.
    - Subsequent measurements at the user department provide a type *A* uncertainty. The uncertainties due to energy dependence and angular dependence of the detector, the variation in the user field conditions compared to calibration conditions, etc., contribute to type *B* uncertainties. These two types of uncertainties are added in quadrature to get the combined uncertainty associated with the survey meter measurements.
    - The combined uncertainty is multiplied by the coverage factor of $k = 2$ or $k = 3$ to correspond to the confidence limits of 95% or 99%, respectively.
    - Typically the uncertainty of the measurements with area monitors is within 30% under the standard laboratory conditions.

4.4. INDIVIDUAL MONITORING

Individual monitoring is the measurement of radiation doses received by individuals working with radiation. Individuals who regularly work in *controlled areas* or those who work full time in *supervised areas* (see chapter 16 for the definitions) should wear personal dosimeters to have their doses monitored on a regular basis. Individual monitoring is also used to verify the effectiveness of radiation control practices in the workplace. It is useful for detecting changes in radiation levels in the workplace and to provide information in case of accidental exposures.

- The most widely used individual monitoring systems are based on TLD or film dosimetry, although other techniques, such as radiophotoluminesce and optically simulated luminescence, are in use in some countries.

- Albedo dosimeters and nuclear track emulsions are used for monitoring fast neutron doses.

- Self-reading pocket dosimeters and electronic personal dosimeters are direct reading dosimeters and show both the instantaneous dose rate and the accumulated dose at any point in time.

- As explained in Section 4.1.2, the operational quantity for individual monitoring of external exposure is the personal dose equivalent H_p(d) with the recommended depth d = 10 mm for strongly penetrating radiation and d = 0.07 mm for weakly penetrating radiation. Personal dosimeters are calibrated in these quantities.

4.4.1. Film badge

- A special emulsion photographic film in a light-tight wrapper enclosed in a case or holder with windows, with appropriate filters, is known as a film badge (see Fig. 4.5).

- The badge holder creates a distinctive pattern on the film indicating the type and energy of the radiation received. While one filter is adequate for photons of energy above 100 keV, the use of a multiple filter system is necessary for lower energy photons.

- As the film is non-tissue equivalent, a filter system has to be used to flatten the energy response, especially at lower photon beam qualities, to approximate the response of a tissue-equivalent material.

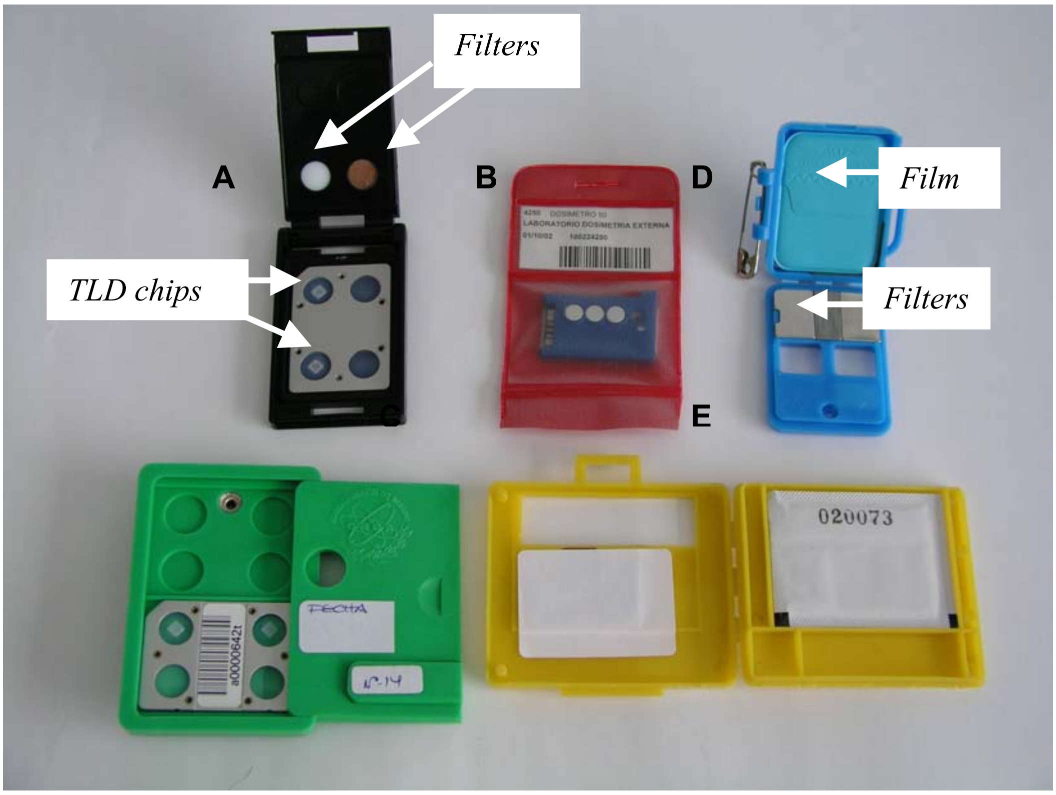

FIG. 4.5. Personal dosimeters: Examples of TLD badges (A, B, C) and film badges (D, E).

- Cumulative doses from beta, *x*, gamma, and thermal neutron radiation are evaluated by measuring the film optical densities under different filters, and then comparing the results with calibration films that have been exposed to known doses of well defined radiation of different types.

- The film can also serve as a monitor for thermal neutrons. The cadmium window absorbs thermal neutrons and the resulting gamma radiation blackens the film below this window as an indication of the neutron dose.

- For fast neutrons monitoring, nuclear track emulsions are used. The neutrons interact with hydrogen nuclei in the emulsion and surrounding materials, producing recoil protons by elastic collisions. These particles create a latent image, which leads to darkening of the film along their tracks after processing.

- Films are adversely affected by many external agents, such as heat, liquids, excessive humidity, etc. The latent image on undeveloped film fades with time, limiting possible wearing periods to three months in ideal conditions.

4.4.2. Thermoluminescent dosimetry (TLD) badge

- A TLD badge (see Fig. 4.5.) consists of a set of TLD chips enclosed in a plastic holder with filters. The most frequently used TLD materials (also referred to as phosphors) are LiF:Ti,Mg, $CaSO_4$:Dy and CaF_2:Mn. Different badge designs (TLD materials, filters) are in use in different countries.

- The doses of beta, *x* and gamma radiation registered by the TLD are evaluated by measuring the TLD output under different filters and then comparing the results with calibration curves established for the calibration TLD badge that has been exposed to known doses under well defined conditions.

- The TLD badges that use high atomic number *Z* TLD materials are not tissue equivalent and, like film, they too require filters to match their energy response to that of tissue. TLD badges using low *Z* phosphors do not require such complex filter systems.

- The TLD signal exhibits fading, but the problem is less significant than that for films.

- The TLD badges currently used for beta monitoring have a relatively high threshold for beta particles (about 50 keV) because of the thickness of the detector and its cover.

- TLDs are convenient for monitoring doses to parts of the body (*e.g*., eyes, arm or wrist, or fingers) using special type of dosimeters, including extremity dosimeters.

- Various techniques have been used for neutron monitoring such as using the body as a moderator to thermalize neutrons (similarly to albedo dosimeters) or using LiF enriched with lithium-6 for enhanced thermal neutron sensitivity due to the (n,α) reaction of thermal neutrons in lithium-6.

4.4.3. Radiophotoluminescent (RPL) glass dosimetry systems

- Radiophotoluminescent (RPL) glass dosimeters are the accumulation-type solid-state dosimeters based on the radiophotoluminecence phenomenon to measure the radiation dose. The material used is silver activated phosphate glass. The dosimeters come in the shape of small glass rods.

- When silver activated phosphate glass is exposed to radiation, stable luminescence centres are created in silver ions, Ag^{o} and Ag^{++}. The readout technique uses pulsed ultraviolet laser excitation. A photomultiplier tube (PMT) registers the orange fluorescence emitted by the glass.

- RPL signal is not erased during the readout, thus the dosimeter can be reanalysed several times, and the measured data reproduced. Accumulation of the dose is also possible that may be used for registration of the lifetime dose.

- Commercially available RPL dosimeters typically cover the dose range of 30 μSv to 10 Sv. They have a flat energy response within 12 keV to 8 MeV for $H_p(10)$.

- RPL signal exhibits very low fading and is not sensitive to the environmental temperature making it convenient in individual monitoring.

4.4.4. Optically stimulated luminescence (OSL) systems

- Optically stimulated luminescence is now commercially available for measuring personal doses. OSL dosimeters contain a thin layer of aluminum oxide (Al_20_3:C). During analysis the aluminum oxide is stimulated with selected frequencies of laser light producing luminescence proportional to radiation exposure.

- Commercially available badges are integrated, self contained packets that come preloaded, incorporating an Al_20_3 strip sandwiched within a filter pack that is heat-sealed. Special filter patterns provide qualitative information about conditions during exposure.

- OSL dosimeters are highly sensitive*; e.g.*, the Luxel® system can be used down to 10 μSv with a precision of ±10 μSv. This high sensitivity is particularly suitable for individual monitoring in low-radiation environments. The dosimeters can be used in a wide dose range up to 10 Sv. in photon beams from 5 keV to 40 MeV.

- OSL dosimeters can be reanalysed several times without loosing the sensitivity and may be used for up to one year.

4.4.5. Direct reading personal monitors

In addition to passive dosimetry badges, direct reading personal dosimeters are widely used:

(i) to provide direct read-out of the dose at any time,
(ii) for tracking the doses received in day-to-day activities
(iii) in special operations (*e.g.*, source loading survey, handling of any radiation incidents or emergencies).

Direct reading personal dosimeters fall into two categories: (1) Self-reading pocket dosimeters and (2) Electronic personal dosimeters (EPD).

Self-reading pocket dosimeter resembles a pen and consists of an ionisation chamber that acts as a capacitor. The capacitor is fully charged and reads zero before use. On exposure to radiation for an interval of time the ionisation produced in the chamber discharges the capacitor and the exposure (or air-kerma) is directly proportional to the discharge that can be directly read against light through a built-in eyepiece. However, the use of pocket dosimeters has declined in recent years because of their poor useful range, charge leakage problems, and poor sensitivity compared to electronic personal dosimeters.

Electronic personal dosimeters based on miniature GM counters or silicon detectors are available with the measurement range down to 30 keV photon energy.

- The modern EPDs are calibrated in the personal dose equivalent, *i.e*., in terms of $H_p(10)$ or $H_p(0.07)$ for both photons and beta radiation. EPD provides instantaneous display of accumulated dose equivalent at any time.
- EPDs have auto-ranging facilities and give visual and audio indication (flashing or chirping frequency proportional to dose equivalent rate), so that the changes in radiation field can be recognized immediately.
- EPDs are very useful at the emergency situations for immediate readout of the doses received.

4.4.6. Calibration

Personal dosimeters should be calibrated in terms of operational quantities for individual monitoring of external exposure, *i.e*., the personal dose equivalent $H_p(d)$ with the recommended depth d = 10 mm for strongly penetrating radiation and d = 0.07 mm for weakly penetrating radiation (see Section 4.1.2).

- For calibration, the dosimeters should be irradiated on standardized phantoms that provide approximation of the backscatter conditions of the human body. Three types of phantoms are recommended that cover the needs of calibration of the whole body dosimeters, wrist or ankle dosimeters and finger dosimeters. These are: slab phantom to represent human torso, pillar phantom for wrist or ankle dosimeters and rod phantom for finger dosimeters. The standard phantoms are composed of ICRU tissue. The International Standards Organization (ISO) recommends special water phantoms (referred to as ISO slab phantoms), although in practice PMMA phantoms are used with the appropriate corrections.

- Calibration of personal dosimeters in terms of H_p(d) involves three steps:

  (1) *Air-kerma in air* $(K_{\mathrm{air}})_{\mathrm{air}}$ is measured in a reference field, using a reference ionisation chamber, calibrated by a standards laboratory.
  (2) $[H_p(d)/(K_{\mathrm{air}})_{\mathrm{air}}]_{\mathrm{slab}} = h_{\mathrm{kHp}}$ values are theoretically available. Using these data for the calibration beam quality, a reference instrument reading can be converted to $[H_p(d)]_{\mathrm{slab}}$.
  (3) The dosimeter badge being calibrated is then placed at the calibration point on a phantom and its reading M is determined. $N_{\mathrm{Hp}} = H_p(d)/M$ gives the calibration factor in terms of the personal dose equivalent for the dosimeter badge.

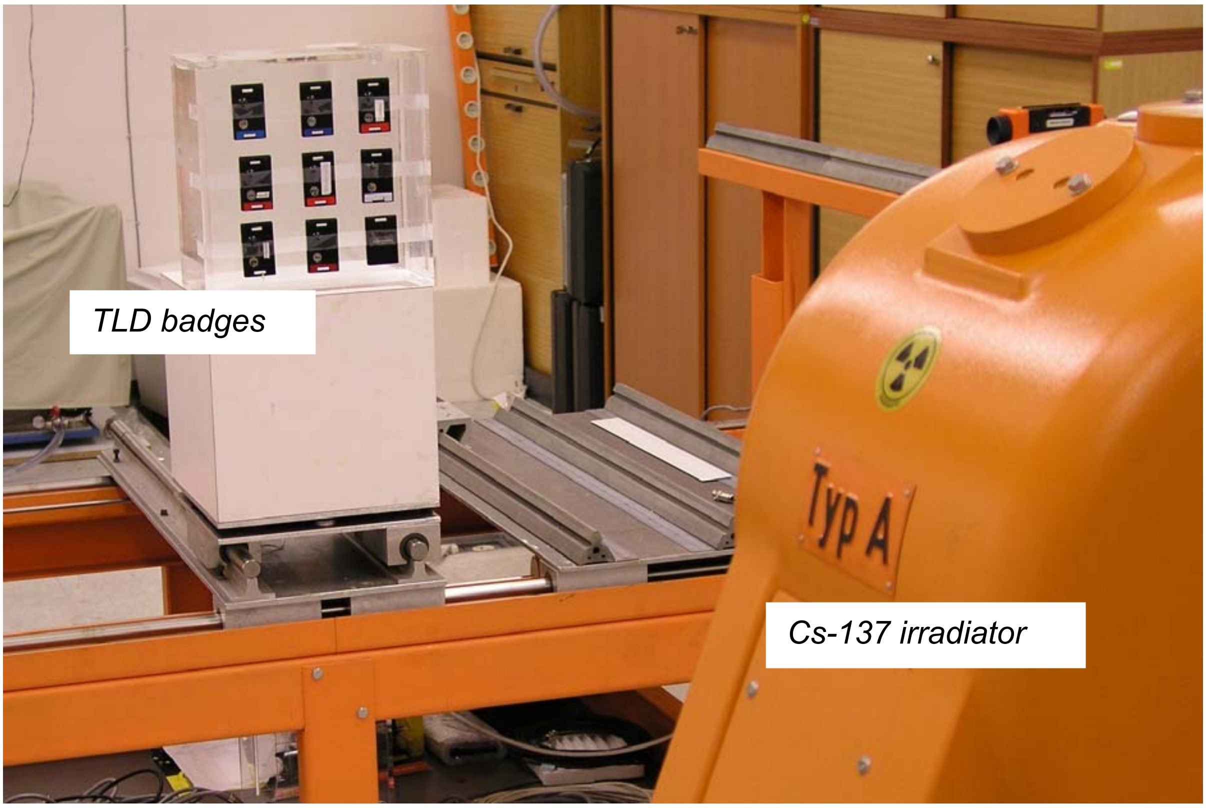

FIG. 4.6. Calibration of personal dosimeters on a PMMA slab phantom using a standard cesium-137 gamma ray beam.

4.4.7. Properties of personal monitors

- ***Sensitivity***
  - The film and TLD badges can measure the dose equivalent as low as 0.1 mSv and can go up to 10 Sv; OSL and RPL dosimeters are more sensitive with the lower detection limit of 10-30 μSv.
  - Personal dosimeters are generally linear in the dose range of interest in radiation protection.

- ***Energy dependence***
  - The film exhibits a strong energy dependence and is empirically designed to reduce its energy response to within ±20%.
  - LiF TLD is nearly tissue-equivalent and exhibits good energy dependence characteristics. $CaSO_4$:Dy shows significant energy dependence and its energy response is reduced by empirical adjustments in the badge design.
  - Commercially available RPL dosimeters (*e.g.*, Asahi-PTW) have flat energy response from 12 keV to 8 MeV.
  - Commercially available OSL dosimeters (*e.g.*, Landauer) have flat energy response from 5 keV to 40 MeV.

- For direct reading pocket dosimeters the energy dependence is within ±20% over the range from 40 keV to 2 MeV.
- For EPDs containing energy-compensated detectors, energy dependence is within ±20% over the energy range from 30 keV to 1.3 MeV.
- The energy response values quoted above can vary in energy range and in the degree of flatness depending on the individual monitor material and construction details.

- ***Uncertainties in personal monitoring measurements***

  - ICRP has stated that, in practice, it is usually possible to achieve an uncertainty of about 10% at the 95% confidence level (k=2) for measurements of radiation fields in laboratory conditions. However, in the work place, where the energy spectrum and orientation of the radiation field are generally not well known, the uncertainties in a measurement made with an individual dosimeter will be significantly greater and may be a factor of 1 for photons and still greater for neutrons and electrons.
  - The uncertainty in the measurements with EPD is about 10% for low dose rates (2 mSv/h) and increases to 20% for higher dose rates (<100 mSv/h) in laboratory conditions.

- ***Dose equivalent range***

  - Personal monitors must have as wide a dose range as possible so that they can cover both the radiation protection and accidental situations (typically from 10 μSv to about 10 Sv).
  - The dose range normally covered by film and TLD dosimeters is from about 100 μSv to 10 Sv and by the OSL and RPL dosimeters 10 μSv to 10 Sv.
  - The self-reading pocket dosimeters can measure down to about 50 μSv and the upper dose limit of the available pocket dosimeters is around 200 mSv.
  - Electronic personal dosimeters measure in the range from 0.1 μSv to10 Sv.

- ***Directional dependence***

  - According to the ICRU, the individual dosimeter must be iso-directional, *i.e.*, its angular response relative to normal incidence must vary as the ICRU directional dose equivalent equivalent quantity $H'(10,\Omega)$. (see section 4.1.2).
  - The directional dependence must be evaluated and the appropriate corrections derived.

- ***Discrimination between different types of radiation***

  - Film dosimeters can identify and estimate the doses of x rays, gamma rays, beta particles and thermal neutrons.
  - TLD, OSL and RPL dosimeters generally identify and estimate doses of *x* rays, gamma and beta radiation.

BIBLIOGRAPHY

ATTIX, F.H., “Introduction to radiological physics and radiation dosimetry”, Wiley, New York, New York, U.S.A. (1986).

INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA), “Calibration of radiation protection monitoring instruments”, Safety Reports Series No 16, IAEA, Vienna, Austria (2000).

INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA), “International basic safety standards for protection against ionizing radiation and for the safety of radiation sources”, Safety Standards Series. 115, IAEA, Vienna, Austria (1996).

INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION (ICRP), “Conversion coefficients for use in radiological protection against external radiation: Adopted by the ICRP and ICRU in September 1995”, ICRP Publication 78, ICRP, Oxford, United Kingdom (1997).

INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, (ICRU), “Determination of dose equivalents resulting from external radiation sources”, ICRU Report 43, ICRU, Bethesda, Maryland, U.S.A. (1988).

INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, (ICRU), “Measurement of dose equivalents from external photon and electron radiations”, ICRU Report 47, ICRU, Bethesda, Maryland, U.S.A. (1992).

INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, (ICRU), “Quantities and units in radiation protection dosimetry”, ICRU Report 51, ICRU, Bethesda, Maryland, U.S.A. (1993).

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO), “X and Gamma Reference Radiations for Calibrating Dosemeters and Dose Ratemeters and for Determining their Response as a Function of Energy”, International Standard ISO 4037. See also High Rate Series of Filtered X-Radiations, International Standard ISO 4037-1979/Addendum 1(1983); Low Rate Series of Filtered X-Radiations, International Standard ISO 4037-1979/Amendment 1-1983 (E), ISO, Geneva, Switzerland (1979).

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO), “Reference beta radiations for calibrating dosimeters and dose rate meters and for determining their response as a function of beta radiation energy”, International Standard ISO 6980, ISO, Geneva, Switzerland (1984).

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO), “Dosimetry of the reference radiation fields used for determining the response of protection level dosimeters and dose-rate meters at photon energies between 4 and 9 MeV”, Draft International Standard ISO/DP 9991, ISO, Geneva, Switzerland (1988).

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO), “Dosimetry of X and Gamma Reference Radiations for Radiation Protection over the Energy Range from 9 keV to 1.3 MeV”, International Standard ISO/DIS 8963, ISO, Geneva, Switzerland (1988).

KNOLL, G. F., “Radiation detection and measurement”, Wiley, New York, New York, U.S.A. (1979).

NRPB-GS 5, “New radiation quantities recommended by ICRU for practical use in radiation protection: their implementation in the United Kingdom”, NRPB, Didcot, United Kingdom (1986).

NRPB document, “Dose quantities for protection against external radiations”, NRPB **4**, No, 3, NRPB, Didcot, United Kingdom (1993).