Chapter 4: Radiation Monitoring Instruments

Set of 107 slides based on the chapter authored by
G. Rajan, J. Izewska
of the IAEA publication:
Review of Radiation Oncology Physics:
A Handbook for Teachers and Students

Objective:

To familiarize the student with instruments used for monitoring the exposure from external radiation.

IAEA
International Atomic Energy Agency

Slide set prepared in 2006
by G.H. Hartmann (Heidelberg, DKFZ)
Comments to S. Vatnitsky:
dosimetry@iaea.org

CHAPTER 4. TABLE OF CONTENTS

IAEA

4.1 INTRODUCTION

Radiation exposure to humans can be broadly classified as:

- internal exposure
- external exposure

This chapter only deals with monitoring of external exposures.

IAEA

4.1 INTRODUCTION

The aim of external exposure monitoring is the measurement of:

- Radiation levels in and around **work areas** (needs an area monitor)
- Levels around **radiation therapy equipment** or **source containers** (needs an area monitor)
- Dose equivalents received by **individuals working with radiation** (needs a personal monitor).

IAEA

4.1 INTRODUCTION

The results of external exposure monitoring is used:

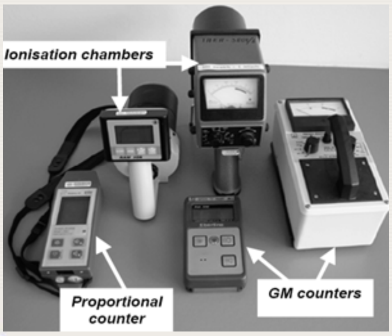
- to **assess** workplace conditions and individual exposures;
- to **ensure** acceptably safe and satisfactory radiological conditions in the workplace;
- to **keep records** of monitoring over a long period of time, for the purposes of regulation or as good practice.

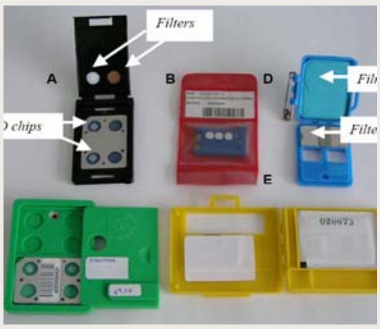
4.1 INTRODUCTION

Radiation monitoring instruments are distinguished into:

Area survey meters (or area monitors)

Personal dosimeters (or individual dosimeters)





4.2 OPERATIONAL QUANTITIES FOR RADIATION MONITORING

All these instruments must be calibrated in terms of appropriate quantities for radiation protection.

Two issues must be addressed:

- Which quantities are **used** in radiation protection?
- Which quantities are in particular **appropriate** for
  - area monitoring ?
  - individual monitoring ?

4.2 OPERATIONAL QUANTITIES FOR RADIATION MONITORING

4.2.1 Dosimetric quantities for radiation protection

- 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).
- Details of dosimetric quantities for radiation protection can be found in Chapter 16.

4.2 OPERATIONAL QUANTITIES FOR RADIATION MONITORING

4.2.1 Dosimetric quantities for radiation protection

Brief introduction of radiation protection quantities:

- The absorbed dose is the basic physical dosimetry quantity.
- However, it is not entirely satisfactory for radiation protection purposes because the effectiveness in damaging human tissue differs for **different types of ionizing radiation**.
- To account additionally also for **biological effects** of radiation upon tissues, specific quantities were introduced in radiation protection.

IAEA

4.2 OPERATIONAL QUANTITIES FOR RADIATION MONITORING

4.2.1 Dosimetric quantities for radiation protection

The basic quantity in radiation protection is the

equivalent dose *H*

Its definition requires two steps:

- the assessment of the **organ dose D_T**
- the introduction of **radiation-weighting factors** to account for the biological effectiveness of the given radiation in inducing health effects

IAEA

4.2 OPERATIONAL QUANTITIES FOR RADIATION MONITORING
4.2.1 Dosimetric quantities for radiation protection

1. Step: Definition of **Organ dose D_T**

The organ dose is defined as the mean absorbed dose D_T ("physical" dose) in a **specified tissue or organ T** of the human body given by

$$D_T = \frac{1}{m_T} \int_{m_T} D \, dm = \frac{\varepsilon_T}{m_T}$$

where

- m_T is the mass of the organ or tissue under consideration
- ε_T is the total energy imparted by radiation to that tissue or organ.

4.2 OPERATIONAL QUANTITIES FOR RADIATION MONITORING
4.2.1 Dosimetric quantities for radiation protection

2. Step: Introduction of **radiation-weighting factors**

The organ dose is multiplied by a radiation-weighting factor w_R to account for the **biological** effectiveness of the given radiation in inducing health effects.

$$H_T = w_R \cdot D_{T,R}$$

where $D_{T,R}$ is the absorbed dose delivered by radiation type R averaged over a tissue or organ T.

The resulting quantity is called the **equivalent dose H_T**
Unit: J/kg or sievert (Sv)

4.2 OPERATIONAL QUANTITIES FOR RADIATION MONITORING
4.2.1 Dosimetric quantities for radiation protection

Example of radiation-weighting factors:

- for x rays, γ rays and electrons: $w_R = 1$
- for protons: $w_R = 5$
- for α particles: $w_R = 20$
- for neutrons, w_R depends on the neutron energy: w_R ranges from 5 to20

IAEA

4.2 OPERATIONAL QUANTITIES FOR RADIATION MONITORING
4.2.1 Dosimetric quantities for radiation protection

- The equivalent dose *H* is not directly measurable.
- There are no laboratory standards to obtain traceable calibration for the radiation monitors using this quantity.

→ **Operational quantities** have been introduced that can be used for practical measurements and serve as a substitute for the quantity equivalent dose *H.*

IAEA

4.2 OPERATIONAL QUANTITIES FOR RADIATION MONITORING

4.2.1 Appropriate quantities for radiation monitoring

The concept of **operational quantities** is:

- They are based on dose equivalent **at a point in the human body** (or in a phantom).
- They relate to the **type and energy of the radiation** existing at that point.
- They can therefore be **calculated** on the basis of the **fluence** at that point.

IAEA Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 4.2.1 Slide 8

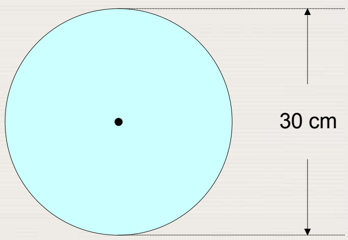
4.2 OPERATIONAL QUANTITIES FOR RADIATION MONITORING

4.2.2 Appropriate quantities for area monitoring

- It is desirable to assess the quantity of equivalent dose in a phantom approximating the human body.
- The phantom selected for this purpose is the so-called **ICRU sphere**.
- The **ICRU sphere**, 30cm in diameter, is a tissue-equivalent sphere.

Composition:

Oxygen	76.2%
Carbon	11.1%
Hydrogen	10.1%
Nitrogen	2.6%.



IAEA Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 4.2.2 Slide 1

4.2 OPERATIONAL QUANTITIES FOR RADIATION MONITORING

4.2.2 Appropriate quantities for area monitoring

- For area monitoring, two **operational quantities** have been introduced, based on the ICRU sphere.
- These two quantities additionally refer
  - to **weakly penetrating** radiation, or
  - to **strongly penetrating** radiation
- In practice, the term 'weakly penetrating' radiation usually applies to
  - photons below 15 keV, and
  - to beta rays.

IAEA Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 4.2.2 Slide 2

4.2 OPERATIONAL QUANTITIES FOR RADIATION MONITORING

4.2.2 Appropriate quantities for area monitoring

The two **operational quantities** introduced for area monitoring are:

- the **ambient dose equivalent** $H^*(d)$
- the **directional dose equivalent** $H'(d)$

where d refers to a certain depth in the ICRU sphere

IAEA Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 4.2.2 Slide 3

4.2 OPERATIONAL QUANTITIES FOR RADIATION MONITORING

4.2.3 Ambient dose equivalent

ambient dose equivalent H*(*d*)

- Definition:
  It is the dose equivalent that would be produced by the corresponding aligned and expanded field in the ICRU sphere at a depth *d* on the radius opposing the direction of the aligned field.

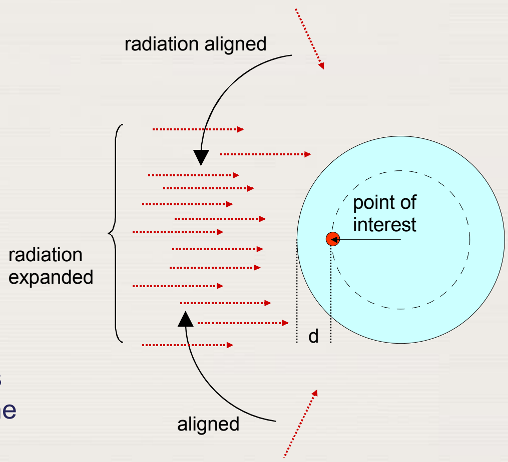
- Unit: sievert (SV)

4.2 OPERATIONAL QUANTITIES FOR RADIATION MONITORING

4.2.3 Ambient dose equivalent

- **Expanded field:**
  The fluence and its directional and energy distribution have the same values throughout the volume of interest as in the actual field at the point of interest.

- **Aligned field:**
  The fluence and its energy distribution are the same as in the expanded field, but the fluence is unidirectional.



4.2 OPERATIONAL QUANTITIES FOR RADIATION MONITORING

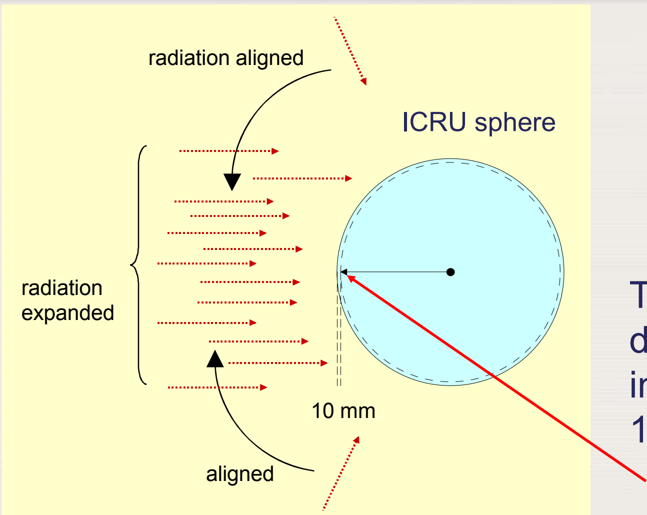
4.2.3 Ambient dose equivalent

Weakly and strongly penetrating radiation

- The relevant depth in the ICRU sphere for strongly penetrating radiation is *d* = 10 mm.
- The relevant depths in the ICRU sphere for weakly penetrating radiation are:
  - *d* = 3.0 mm used for skin
  - *d* = 0.07 mm used for eye lens

4.2 OPERATIONAL QUANTITIES FOR RADIATION MONITORING

4.2.3 Ambient dose equivalent



The ambient dose equivalent in a depth of 10 mm:

H*(10mm)

4.2 OPERATIONAL QUANTITIES FOR RADIATION MONITORING

4.2.4 Directional dose equivalent

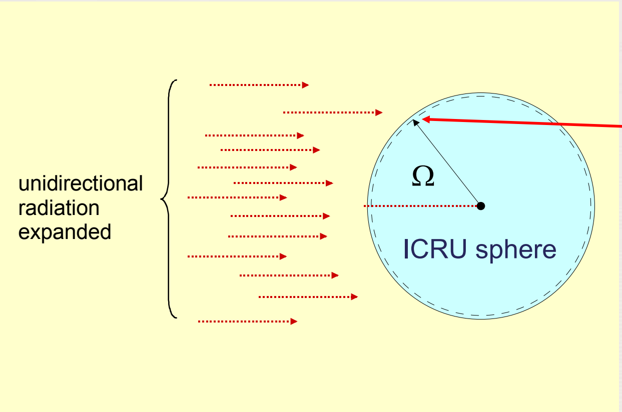
directional dose equivalent H'(*d*,Ω)

- ❑ Definition:
  It is the dose equivalent that would be produced by the corresponding expanded field in the ICRU sphere at a depth *d* on a radius in a specified direction Ω.

- ❑ Unit: sievert (SV)

4.2 OPERATIONAL QUANTITIES FOR RADIATION MONITORING

4.2.4 Directional dose equivalent



The ambient dose equivalent H'(0.07mm,Ω)

4.2 OPERATIONAL QUANTITIES FOR RADIATION MONITORING

4.2.5 Appropriate quantities for radiation monitoring

- The **operational quantity** for individual monitoring is the

  personal dose equivalent $H_p(d)$

- It is the equivalent dose in soft tissue below a specified point on the body at an appropriate depth *d*.

- The relevant depth for strongly penetrating radiation is d = 10 mm.

- The relevant depth for weakly penetrating radiation is:
  - d = 3.0 mm used for skin
  - d = 0.07 mm used for eye lens

IAEA

4.2 OPERATIONAL QUANTITIES FOR RADIATION MONITORING

4.2.6 Summary of operational quantities

	weakly penetrating radiation	strongly penetrating radiation
Area monitoring	$H^*(0.07), H^*(3)$ $H'(0.07,\Omega), H'(3,\Omega)$	$H^*(10)$ $H'(10,\Omega)$
Individual monitoring	$H_p(0.07), H_p(3)$	$H_p(10)$

IAEA

4.2 OPERATIONAL QUANTITIES FOR RADIATION MONITORING

4.2.6 Summary of operational quantities

Area monitoring	H*(d) and H'(d) are measured with survey meters of which the reading is linked to the equivalent dose in the ICRU sphere.
Individual monitoring	$H_p(d)$ is measured with a dosimeter which is worn at the surface of the body and covered with the appropriate layer of a tissue-equivalent material.

IAEA

4.3 AREA SURVEY METERS

Radiation instruments used as survey monitors can be distinguished into two groups of detectors:

Gas filled detectors:

- ionization chambers
- proportional counters
- Geiger-Mueller (GM) counters

Solid state detectors:

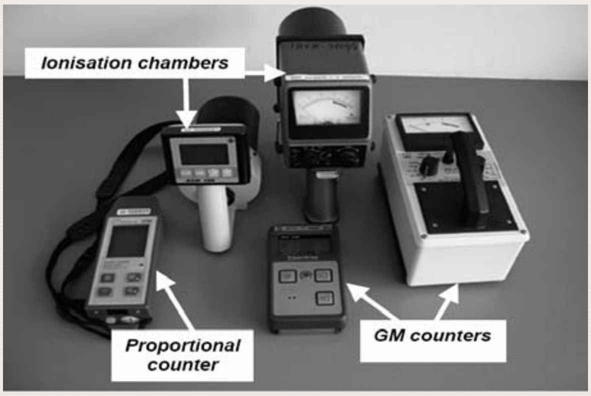
- scintillator
- semiconductor detectors).

IAEA

4.3 AREA SURVEY METERS

Properties of gas-filled detectors:

- ❑ Survey meters come in different shapes and sizes depending upon the specific application.



IAEA

4.3 AREA SURVEY METERS

Properties of gas-filled detectors:

- ❑ Noble gases are generally used in these detectors.

Reason:

- The limit of the dose rate that can be monitored should be as high as possible:
  ⇨ a high charge-collection time is required!
- A high charge-collection time results from a high mobility of charge carriers.
- The charge carriers are electrons and negative ions.
- The mobility of negative ions is about three orders of magnitude smaller than that of electrons.
- Noble gases are non-electronegative gases in which negative ion formation by electron attachment is avoided.

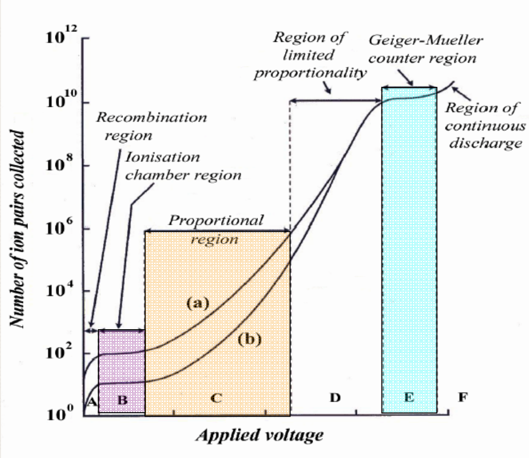
IAEA

4.3 AREA SURVEY METERS

Properties of gas-filled detectors:

Depending upon the voltage applied the detector can operate in one of three regions:

- ionization region B
- proportional region C
- Geiger-Müller (GM) region E

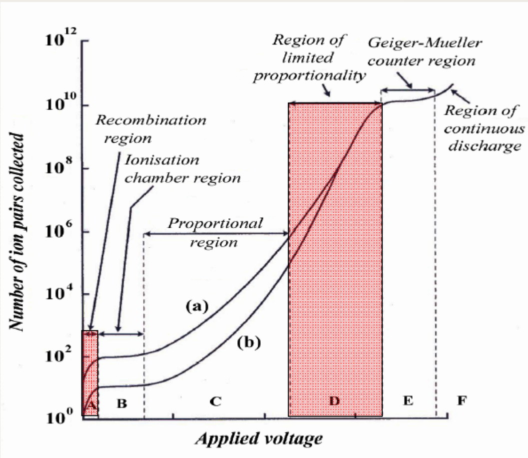


4.3 AREA SURVEY METERS

Properties of gas-filled detectors:

Regions not used for survey meters:

- Region A (recombination)
- Region D (limited proportionality in the "signal versus applied voltage")



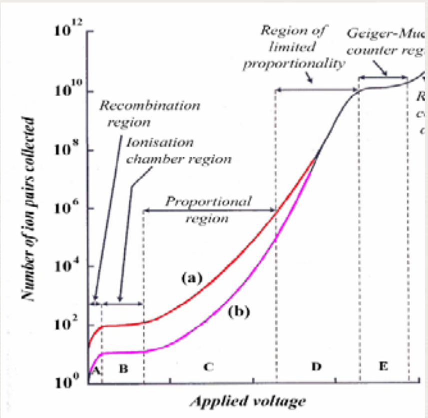
4.3 AREA SURVEY METERS

Properties of gas-filled detectors:

- Because of their high sensitivity, the tubes of GM-based gamma monitors are smaller in size compared to ionization chamber-type detectors.
- 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 time required by the detector to regain its normal state after registering a pulse, ‘pulse’ detectors will saturate at high intensity radiation fields. Ionization chambers, operating in the current mode, are more suitable for higher dose rate measurements.

4.3 AREA SURVEY METERS
4.3.1 Ionization chambers

- In the ionization 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:



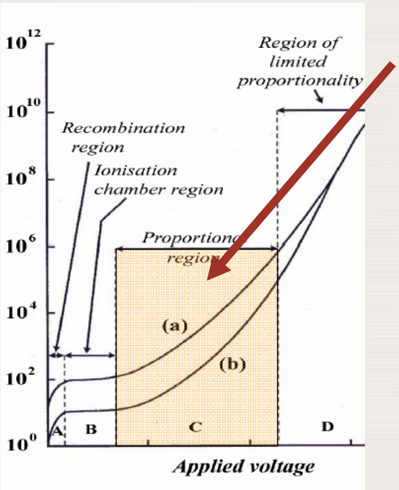
— for 1 MeV beta particles

— for 100 keV beta particles

4.3 AREA SURVEY METERS
4.3.1 Ionization chambers

- 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.
- 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.

4.3 AREA SURVEY METERS
4.3.2 Proportional counters



At a sufficiently high voltage, a charge multiplication occurs (= proportional region).

This occurs when the primary ions gain sufficient energy between successive collisions, in particular in the neighborhood of the thin central electrode.

The amplification is about 10^3-fold to 10^4-fold.

4.3 AREA SURVEY METERS

4.3.2 Proportional counters

Proportional counters are more sensitive than ionization chambers.

Proportional counters 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 AREA SURVEY METERS

4.3.3 Neutron area survey meters

- ❑ Neutron area levels are normally associated with a photon background.
- ❑ ⇨ Neutron area survey meters require a discrimination against the photon background.

4.3 AREA SURVEY METERS
4.3.3 Neutron area survey meters

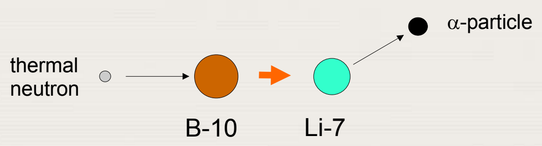
A mixed neutron-photon radiation field has:

Neutrons which produce secondary particles (reaction products with high LET)	**Photons** which produce secondary electrons (with low LET)

- Because of the LET differences, the particle discrimination function of gas -filled detectors can be used.
- A high efficiency of discrimination is obtained when the gas-filled detector is operating in the proportional region.

4.3 AREA SURVEY METERS
4.3.3 Neutron area survey meters

- **Thermal neutrons can be detected very efficiently:**
- A thermal neutron interacts with boron-10 nucleus causing an (n,α) reaction.



- The alpha particles can be detected easily by their ionizing interactions.
- Therefore, thermal neutron detectors usually
  - have a coating of a boron compound on the inside of the wall or
  - the counter is filled with BF^3 gas.

4.3 AREA SURVEY METERS
4.3.3 Neutron area survey meters

To detect also **fast neutrons,** the counter is surrounded by a **moderator** made of hydrogenous material.

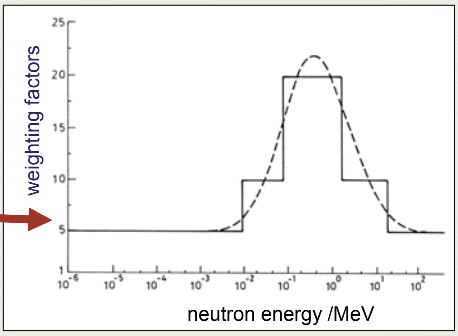
The fast neutrons interacting with the moderator get thermalized.

Subsequently they are detected by the BF^3 counter placed inside the moderator.

The whole assembly is now a fast neutron counter.

4.3 AREA SURVEY METERS
4.3.3 Neutron area survey meters

- Filter compensation is required to reduce the over-response to thermal neutrons so that the response follows the weighting factors w_R. (broken line, solid line is a useful approximation)

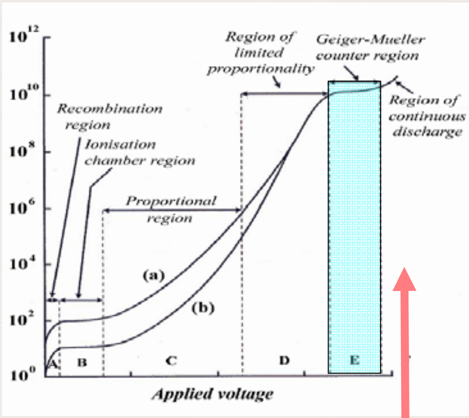


- The output is approximately proportional to the dose equivalent in soft tissue over a wide range (10 decades) of neutron energy spectra.
- Other neutron detectors work on the same principles.

4.3 AREA SURVEY METERS
4.3.4 GM counters

In the GM region the discharge spreads throughout the volume of the detector.

➡ The pulse height becomes independent of the primary ionization or the energy of the interacting particles.



Gas-filled detectors cannot be operated at voltages beyond this region because they continuously discharge.

IAEA

4.3 AREA SURVEY METERS
4.3.4 GM counters

- ❑ Because of the large charge amplification (9 to 10 orders of magnitude), GM survey meters are widely used at very low radiation levels.

- ❑ 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 ionization chambers are used for more precise measurements.

IAEA

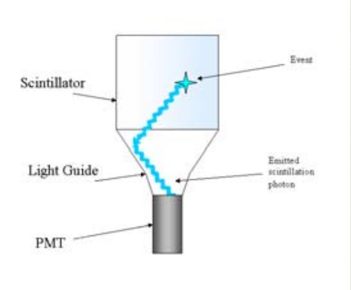
4.3 AREA SURVEY METERS
4.3.4 GM counters

Disadvantage of GM counters:

- 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 paralyzed in a very high radiation field and yield a zero reading.
- Therefore ionization chambers should be used in areas where radiation rates are high.

4.3 AREA SURVEY METERS
4.3.5 Scintillator detector

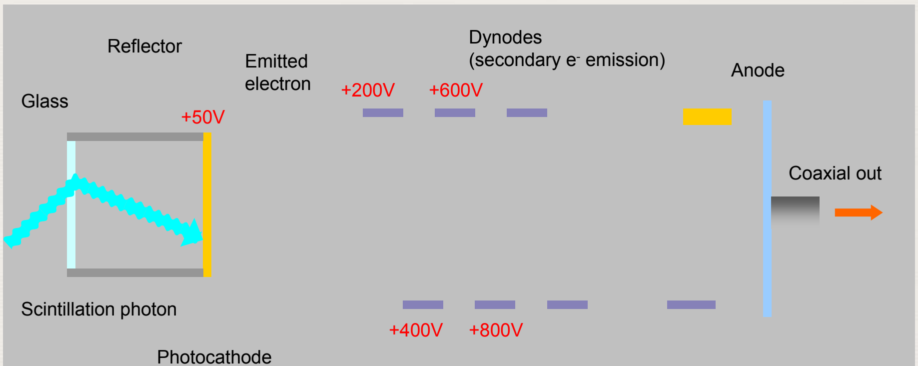
- Detectors based on scintillation (light emission) are known as scintillation detectors and belong to the class of solid-state detectors.
- Certain organic and inorganic crystals contain activator atoms and emit scintillations (light) upon absorption of radiation.



- High atomic number phosphors are mostly used for the measurement of gamma rays, while the plastic scintillators are mostly used with beta particles.

4.3 AREA SURVEY METERS
4.3.5 Scintillator detector

A photomultiplier tube is optically coupled to the scintillator to convert the light pulse into an electric pulse.



Other survey meters use photodiodes.

4.3 AREA SURVEY METERS
4.3.6 Semiconductor detector

- ❑ Semiconductors detectors belong to the class of solid-state detectors.
- ❑ They act like solid-state ionization chambers on exposure to radiation.
- ❑ The sensitivity of solid state detectors is about 10^4 times higher than that of gas-filled detectors because:
  - the average energy required to produce an ion pair is one order less
  - the material density is typically 3 orders more compared to gases

4.3 AREA SURVEY METERS
4.3.6 Semiconductor detector

- The high sensitivity of semiconductor detectors helps in miniaturizing radiation-monitoring instruments.
- Example:
  A commercial electronic pocket dosimeter based on a semiconductor detector

4.3 AREA SURVEY METERS
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.

4.3 AREA SURVEY METERS

4.3.7 Commonly available features of area survey meters

- 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 AREA SURVEY METERS

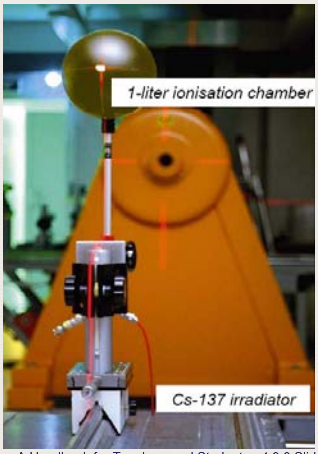
4.3.8 Calibration of survey meters

- As any other measuring instrument, protection level area survey meters have to be calibrated against a reference instrument that is traceable to a National Standards Laboratory.
- However, the equivalent dose *H* and also the operational quantities for area monitoring based on the ICRU sphere are not directly measurable.
- Therefore, the following two-step concept is used:
  - (1) measurement of basic radiation quantities
  - (2) determination of equivalent dose by using theoretical conversion coefficients

4.3 AREA SURVEY METERS
4.3.8 Calibration of survey meters

- Step 1: Measurement of basic radiation quantities:

Example:
In a reference photon field of Cs-137, the air-kerma in air is measured using a reference instrument for gamma radiation, that is a large volume ionization chamber.



4.3 AREA SURVEY METERS
4.3.8 Calibration of survey meters

- Step 1: Determination of the air-kerma in air :

$$(K_{air})_{air} = M_R \cdot N_R$$

where
- $(K_{air})_{air}$ is the air-kerma in air
- M_R is the reading of the reference instrument corrected for influence quantities
- 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

4.3 AREA SURVEY METERS

4.3.8 Calibration of survey meters

- Step 2: Determination of equivalent dose by using conversion coefficients *h*

$$H = h \cdot (K_{air})_{air}$$

4.3 AREA SURVEY METERS

4.3.8 Calibration of survey meters

Example:
The value of the conversion coefficient

$$h_{H^*(10)} = [H^*(10)/(K_{air})_{air}]$$

is **theoretically** available by a calculation.

Using the data for the calibration beam quality in the calculation, a reference instrument reading in terms of air-kerma in air can be converted to *H**(10) by:

$$H^*(10) = h_{H^*(10)} \cdot (K_{air})_{air}$$

4.3 AREA SURVEY METERS
4.3.9 Properties of area survey meters: *Sensitivity*

- **Sensitivity**
  Sensitivity S is defined as the inverse of the calibration factor N:

$$S = \frac{1}{N}$$

- A high sensitivity is required to monitor low levels of radiation.
- **Scintillation-based systems** are even more sensitive than GM counters because of higher gamma conversion efficiency and the dynode amplification.

4.3 AREA SURVEY METERS
4.3.9 Propreties of area survey meters: *Sensitivity*

- **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.

A commercial contamination monitor

4.3 AREA SURVEY METERS
4.3.9 Properties of area survey meters: *Sensitivity*

- Sensitivity of **ionization chamber based survey meters** can be adjusted by using :
  - decade resistances
  - detector of larger volume
  - detector gas under high pressure

- A wide range of dose equivalent rates can be covered:

1 μSv/h → **1 Sv/h**

4.3 AREA SURVEY METERS
4.3.9 Proprieties of area survey meters: *Sensitivity*

- **GM-based systems** would saturate beyond a few thousand counts per second because of finite resolving time.
- However, low dead time counters or dead time correction circuits enable these detectors to operate also at higher intensity radiation fields.

4.3 AREA SURVEY METERS

4.3.9 Properties of area survey meters: *Energy dependence*

- Survey meters are normally calibrated at one or more beam qualities.
- However, they are often used in situations where the radiation field is complex or unknown.
- ⇨ The requirement on survey meters is:
  They should have a low energy dependence over a wide energy range.
- They should have a low energy dependence in particular with respect to the operational quantities.

IAEA

4.3 AREA SURVEY METERS

4.3.9 Properties of area survey meters: *Energy dependence*

Low energy dependence with respect to the operational quantities.

- The energy dependence is driven the calibration factor $N_{H^*(10)}$
- Example:

$$H^*(10) = N_{H^*(10)} \cdot M$$

with

$$N_{H^*(10)} = h_{H^*(10)} \cdot N$$

IAEA

4.3 AREA SURVEY METERS

4.3.9 Properties of area survey meters: *Energy dependence*

From

$$H^*(10) = N_{H^*(10)} \cdot M$$

it follows:

$$N_{H^*(10)} = \frac{H^*(10)}{M} = \frac{H^*(10)}{(K_{air})_{air}} \cdot \frac{(K_{air})_{air}}{M}$$

- Conclusion:
  $H^*(10)/(K_{air})_{air}$ as well as $(K_{air})_{air}/M$ should have a flat energy dependence.

4.3 AREA SURVEY METERS

4.3.9 Properties of area survey meters: *Directional dependence*

- The **directional response** of the instrument can be studied by rotating the survey monitor about its vertical axis,.

- A survey monitor usually exhibits isotropic response as required for measuring ambient dose equivalent.

- For that a response within ±60° to ±80° with respect to the reference direction of calibration is required.

- A survey monitor typically has a much better response for higher photon energies (> 80 keV).

4.3 AREA SURVEY METERS

4.3.9 Properties of area survey meters: *Dose equivalent range*

- Survey meters may cover a **dose equivalent range** from:

  1 nSv/h — **1 Sv/h**

  but the typical range in use is:

  1 μSv/h — **1 Sv/h**

4.3 AREA SURVEY METERS

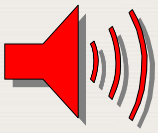
4.3.9 Properties of area survey meters: *Response time*

- 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.

4.3 AREA SURVEY METERS
4.3.9 Properties of area survey meters: *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 due to **saturation**.

Danger:



- Some survey meters, especially the older models, may read 'zero' on overload. Such survey meters should not be used for monitoring.

IAEA

Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 4.3.2 Slide 11

4.3 AREA SURVEY METERS
4.3.9 Properties of area survey meters: *Overload characteristics*

- In particular GM survey meters are not suitable for use in **pulsed fields** due to the possible overload effect.

- Ionisation chamber-based survey meters should be used instead.

IAEA

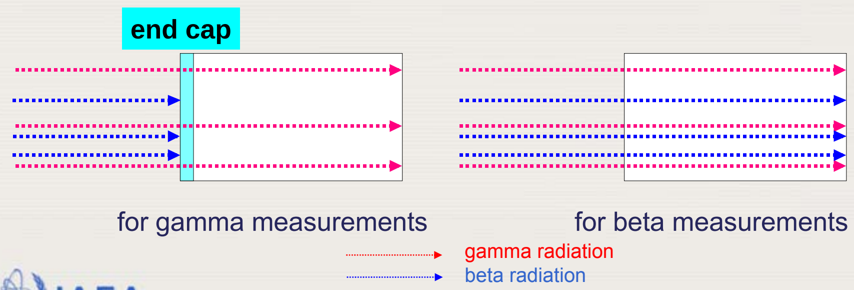
Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 4.3.2 Slide 12

4.3 AREA SURVEY METERS
4.3.9 Properties of area survey meters: *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.

4.3 AREA SURVEY METERS
4.3.9 Properties of area survey meters: *Discrimination capacity*

- 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.



4.3 AREA SURVEY METERS

4.3.9 Properties of area survey meters: *Uncertainties*

- The standards laboratory provides the uncertainty associated with the calibration factor of the survey monitor.
- **Type *A* uncertainty:**
  Subsequent measurements at the user provide a type *A* uncertainty.
- **Type B 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.

IAEA

4.3 AREA SURVEY METERS

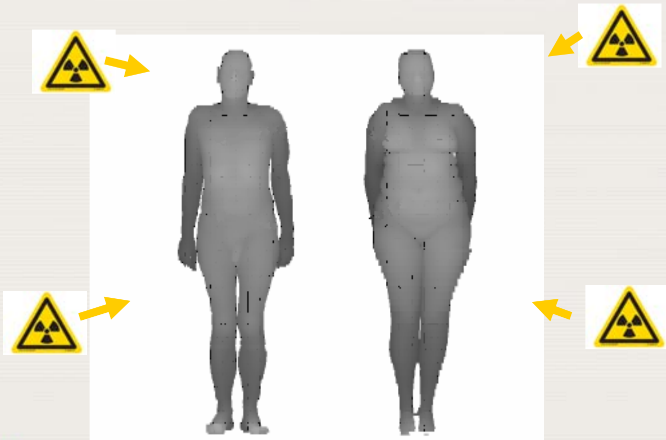
4.3.9 Properties of area survey meters: *Uncertainties*

- 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 standards laboratory conditions

IAEA

4.4 INDIVIDUAL MONITORING

Individual monitoring is the measurement of radiation doses received by individuals working with radiation.



4.4 INDIVIDUAL MONITORING

Individual monitoring is used for those who regularly work in controlled areas or those who work full time in supervised areas:

- to have their doses monitored on a regular basis;
- to verify the effectiveness of radiation control practices in the workplace;
- for detecting changes in radiation levels in the workplace;
- to provide information in case of accidental exposures.

4.4 INDIVIDUAL MONITORING

The most widely used individual monitoring systems are based on:

TLD dosimetry

Film dosimetry

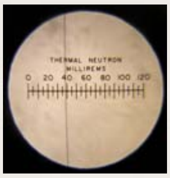
4.4 INDIVIDUAL MONITORING

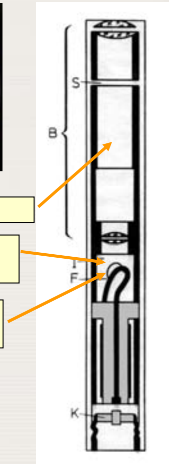
Other measuring techniques used for individual monitoring systems:

- ❑ Radiophotoluminesce (RPL)
- ❑ Optically simulated luminescence (OSL)
- ❑ In case of fast neutron doses:
  - Albedo dosimeter
  - nuclear track emulsion

4.4 INDIVIDUAL MONITORING

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**.



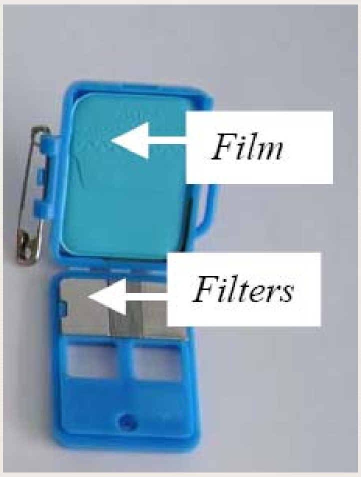


Setup of a simple pocked dosimeter

4.4 INDIVIDUAL MONITORING

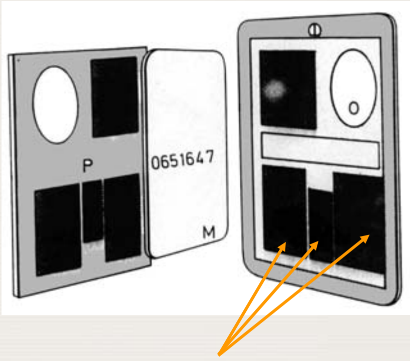
4.4.1 Film badge

- A film badge is a special emulsion photographic film in a light-tight wrapper enclosed in a case or holder with windows with appropriate filters.
- The badge holder creates a distinctive pattern on the film indicating the type and energy of the radiation received.



4.4 INDIVIDUAL MONITORING
4.4.1 Film badge

- The film is a non-tissue equivalent radiation detector.
- The film has **not** the response of a tissue-equivalent material.
- **A filter system is therefore required to adjust the energy response.**
- One filter is adequate for photons of energy above 100 keV.
- A **multiple filter system** is used for lower energy photons.



4.4 INDIVIDUAL MONITORING
4.4.1 Film badge

Evaluation: Cumulative doses from beta, x, gamma, and thermal neutron radiation are evaluated by:

- Production of **calibration films;** (exposed to known doses of well defined radiation of different types);
- Measuring the **optical density** of the film under different filters;
- **Comparing** the optical density with the calibration films.

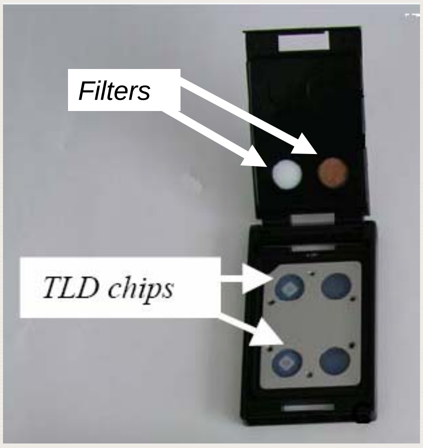
4.4 INDIVIDUAL MONITORING
4.4.1 Film badge

A film can also serve as a **monitor of neutron doses**.

- **Thermal neutrons:**
  A cadmium window absorbs thermal neutrons and the resulting gamma radiation blackens the film below this window as an indication of the neutron dose.
- **Fast neutrons:**
  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.

4.4 INDIVIDUAL MONITORING
4.4.2 Thermoluminescent dosimetry (TLD) badge

- A TLD badge 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
  - CaSO4:Dy
  - CaF2:Mn.



4.4 INDIVIDUAL MONITORING

4.4.2 Thermoluminescent dosimetry (TLD) badge

- If the TLD material incorporates atoms with a high Z, it is **not tissue equivalent**. Then a filter system similar to film badges must be provided to achieve the required energy response.
- TLD badges using low Z phosphors do not require such complex filter systems.
- The TLD signal exhibits fading, but this effect is less significant than with films.

IAEA

4.4 INDIVIDUAL MONITORING

4.4.2 Thermoluminescent dosimetry (TLD) badge

- Because of the small size of TLDs, they 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.

finger ring dosimeter

IAEA

4.4 INDIVIDUAL MONITORING
4.4.2 Thermoluminescent dosimetry (TLD) badge

A TLD can also serve as a monitor for neutrons

Techniques:

- Using the body as a moderator to thermalize neutrons (similarly to albedo dosimeters)
- Using LiF enriched with lithium-6 for enhanced thermal neutron sensitivity due to the (n,α) reaction of thermal neutrons in lithium-6.

IAEA

4.4 INDIVIDUAL MONITORING
4.4.3 Radiophotoluminescent (RPL) glass dosimetry systems

A radiophotoluminescent glass block is positioned in the center of a holder.

To determine the dose, the glass block is removed from the holder and exposed to ultraviolet radiation in a reader.

The result is that the glass emits light, the intensity of which is proportional to the radiation exposure.

The reader measures the intensity of the emitted light and converts this into personal dose equivalent.

A personnel RPL dosimeter (1950s-1960s)

IAEA

The physics of a RPL glass dosimeter:

- The material used is silver activated phosphate glass.
- When silver activated phosphate glass is exposed to radiation, stable luminescence centers are created in silver ions, denoted as Ag° and Ag^{++}.
- This luminescence centers emit light upon excitation. The readout technique uses pulsed ultraviolet laser excitation.
- A photomultiplier tube registers the orange fluorescence emitted by the glass.

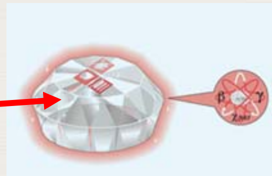
Advantages of RPL glass systems:

- The RPL signal is not erased during the readout, thus the dosimeter can be re-analysed 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 $H_p(10)$.
- The RPL signal exhibits very low fading and is not sensitive to the environmental temperature making it convenient in individual monitoring.

4.4 INDIVIDUAL MONITORING

4.4.4 Optically stimulated luminescence (OSL) systems

- ❑ Optically stimulated luminescence is now commercially available also for measuring personal doses.
- ❑ OSL dosimeters contain a thin layer of aluminum oxide (Al203:C).



- ❑ During analysis the aluminum oxide is stimulated with selected frequencies of laser light producing luminescence proportional to radiation exposure.

4.4 INDIVIDUAL MONITORING

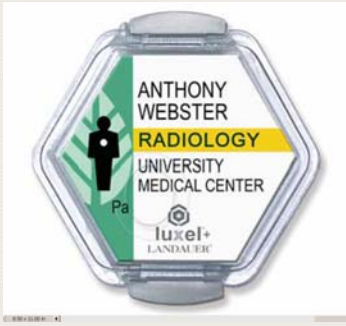
4.4.4 Optically stimulated luminescence (OSL) systems

- ❑ Commercially available badges are integrated, self contained packets that come preloaded, incorporating an Al203 strip sandwiched within a filter pack that is heat-sealed.
- ❑ Special filter patterns provide qualitative information about conditions during exposure.

4.4 INDIVIDUAL MONITORING

4.4.4 Optically stimulated luminescence (OSL) systems

- 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.



IAEA Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 4.4.4 Slide 3

4.4 INDIVIDUAL MONITORING

4.4.4 Optically stimulated luminescence (OSL) systems

- The dosimeters can be used in a wide dose range up to 10 Sv.
- Photon Energy range is from 5 keV to 40 MeV.
- OSL dosimeters can be re-analysed several times without loosing the sensitivity and may be used for up to one year.

IAEA Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 4.4.4 Slide 4

4.4 INDIVIDUAL MONITORING
4.4.5 Direct reading personal monitors

- ❑ In addition to passive dosimetry badges, direct reading personal dosimeters are widely used:
  - to provide direct read-out of the dose at any time,
  - for tracking the doses received in day-to-day activities
  - in special operations (e.g., source loading survey, handling of any radiation incidents or emergencies).

IAEA

4.4 INDIVIDUAL MONITORING
4.4.5 Direct reading personal monitors

Direct reading personal dosimeters fall into two categories:

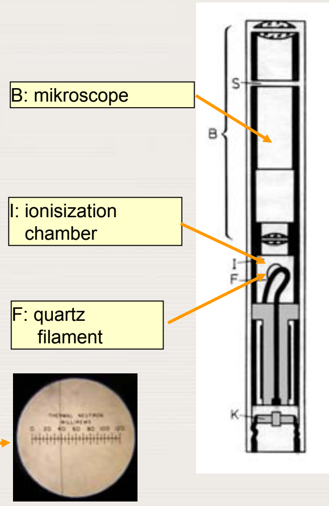
- ❑ Self-reading pocket dosimeters

- ❑ Electronic personal dosimeters.

IAEA

4.4 INDIVIDUAL MONITORING
4.4.5 Direct reading personal monitors

- ❑ Self-reading pocket dosimeter resembles a pen and consists of an ionization chamber that acts as a capacitor.
- ❑ The capacitor is fully charged. The quartz filament is pushed away (similar to the old charge meter in physics) and reads zero before use.
- ❑ On exposure to radiation the ionization 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.



IAEA

4.4 INDIVIDUAL MONITORING
4.4.5 Direct reading personal monitors

- ❑ 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 now available with the measurement range down to 30 keV photon energy.

IAEA

4.4 INDIVIDUAL MONITORING
4.4.5 Direct reading personal monitors

- The modern EPDs are calibrated in the personal dose equivalent, i.e., in terms of $H_p(10)$ or $H_p(0.07)$ for 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.

IAEA

4.4 INDIVIDUAL MONITORING
4.4.6 Calibration

- 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:
  - **slab phantom** to represent human torso,
  - **pillar phantom** for wrist or ankle dosimeters
  - **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.

IAEA

4.4 INDIVIDUAL MONITORING
4.4.6 Calibration

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

(1) Air-kerma in air is measured in a reference field, using a reference ionisation chamber, calibrated by a standards laboratory.

(2) Values for:

$$\left(\frac{H_p(d)}{(K_{air})_{air}}\right)_{slab} = h_{kHp}$$

are theoretically available.
Using these data for the calibration beam quality, a reference instrument reading can be converted to $[H_p(d)]_{slab}$.

(3) The dosimeter badge is then placed at the calibration point on a phantom and its reading M is determined.

$N_{Hp} = H_p(d)/M$ gives the calibration in terms.

IAEA Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 4.4.6 Slide 2

4.4 INDIVIDUAL MONITORING
4.4.6 Calibration

Calibration of personal dosimeters on a PMMA slab phantom using a standard cesium-137 gamma ray beam. The ratio between H_p(d) and the reading of the dosimeters is determined giving the calibration factor.

IAEA Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 4.4.6 Slide 3

4.4 INDIVIDUAL MONITORING

4.4.7 Properties of personal monitors: *Sensitivity*

- Dosimeters based on:
  - Film
  - TLD badges

  can measure the dose equivalent as low as 0.1 mSv and can go up to 10 Sv.
- Dosimeters based on:
  - optically stimulated luminescence
  - radiophotoluminescence

  are more sensitive with the lower detection limit of 10-30 μSv.

IAEA

4.4 INDIVIDUAL MONITORING

4.4.7 Properties of personal monitors: *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. CaSO4: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.

IAEA

4.4 INDIVIDUAL MONITORING

4.4.7 Properties of personal monitors: *Energy dependence*

- 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.

IAEA

4.4 INDIVIDUAL MONITORING

4.4.7 Properties of personal monitors: *Uncertainties*

- ICRP has stated that, it is 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 100% 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.

IAEA

4.4 INDIVIDUAL MONITORING

4.4.7 Properties of personal monitors: *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).
- film and TLD dosimeters:

  1oo μSv — **10 Sv**
- OSL and RPL dosimeters:

  1o μSv — **10 Sv**
- self-reading pocket dosimeters:

  5o μSv — **0.2 Sv**
- Electronic personal dosimeters:

  0.1 μSv — **10 Sv**

4.4 INDIVIDUAL MONITORING

4.4.7 Properties of personal monitors: *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 quantity H'(10,Ω).
- The directional dependence must be evaluated and the appropriate corrections derived.

4.4 INDIVIDUAL MONITORING

4.4.7 Properties of personal monitors: *Discrimination capacity*

- 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.