PRACTICAL RADIATION TECHNICAL MANUAL

WORKPLACE MONITORING FOR RADIATION AND CONTAMINATION

IAEA
International Atomic Energy Agency

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INTERNATIONAL ATOMIC ENERGY AGENCY
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FOREWORD

Occupational exposure to ionizing radiation can occur in a range of industries, such as mining and milling; medical institutions; educational and research establishments; and nuclear fuel facilities. Adequate radiation protection of workers is essential for the safe and acceptable use of radiation, radioactive materials and nuclear energy.

Guidance on meeting the requirements for occupational protection in accordance with the Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (IAEA Safety Series No. 115) is provided in three interrelated Safety Guides (IAEA Safety Standards Series No. RS-G-1.1, 1.2 and 1.3) covering the general aspects of occupational radiation protection as well as the assessment of occupational exposure. These Safety Guides are in turn supplemented by Safety Reports providing practical information and technical details for a wide range of purposes, from methods for assessing intakes of radionuclides to optimization of radiation protection in the control of occupational exposure.

Occupationally exposed workers need to have a basic awareness and understanding of the risks posed by exposure to radiation and the measures for managing these risks. To address this need, two series of publications, the Practical Radiation Safety Manuals (PRSMs) and the Practical Radiation Technical Manuals (PRTMs) were initiated in the 1990s. The PRSMs cover different fields of application and are aimed primarily at persons handling radiation sources on a daily basis. The PRTMs complement this series and describe a method or an issue related to different fields of application, primarily aiming at assisting persons who have a responsibility to provide the necessary education and training locally in the workplace.

The value of these two series of publications was confirmed by a group of experts, including representatives of the International Labour Organization, in 2000. The need for training the workers, to enable them to take part in decisions and their implementation in the workplace, was emphasized by the

International Conference on Occupational Radiation Protection, held in Geneva, Switzerland in 2002.

This Practical Radiation Technical Manual, which incorporates revisions drawn up in 2002, was originally developed following recommendations of an Advisory Group Meeting on Radiation Protection Technical Guides, held from 23 to 27 April 1990, in Vienna, Austria. The format and contents of the draft were agreed by a committee of experts comprising Deping Li (China), A.V. Bilbao (Cuba), P. Bory (France), F.E. Stieve (Federal Republic of Germany), G.J. Koteles (Hungary), Mr. S. Venkatesan (India), M.S. Sohrabi (Iran), S.K. Wanguru (Kenya), R. Wheelton (United Kingdom), C. Jones (USA), V. Kozlov (USSR), G. Severuikhin (USSR), H.G. Menzel and D. Teunen (representing CEC), G.H. Coppee (representing ILO) and R.V. Griffith (IAEA). Major contributions were made by Mr. R. Wheelton, United Kingdom, who also contributed to the present revision, undertaken by the Radiation Monitoring and Protection Services Section, IAEA.

CONTENTS

IAEA PRACTICAL RADIATION TECHNICAL MANUAL

WORKPLACE MONITORING FOR RADIATION AND CONTAMINATION

This Practical Radiation Technical Manual is one of a series which has been designed to provide guidance on radiological protection for employers, Radiation Protection Officers, managers and other technically competent persons who have a responsibility to ensure the safety of employees working with ionizing radiation. The Manual may be used together with the appropriate IAEA Practical Radiation Safety Manuals to provide adequate training, instruction or information for all employees engaged in work with ionizing radiations.

Introduction

Ionizing radiations cannot be seen, felt or sensed by the human body in any way but excessive exposure to them may have adverse health effects. Radiation measuring instruments are needed in order to detect the presence of such radiations and avoid excessive exposure. The use of appropriate and efficient instruments enables exposures to be controlled and the doses received to be kept as low as reasonably achievable.

This Manual explains the basic terminology associated with such measuring instruments and describes the principal types, their construction and typical applications in the workplace.

It is important to ensure not only that monitoring is carried out where there is a potential radiation exposure but also that the monitoring instrument is appropriate to the task and that the user places correct interpretations on the results obtained.

The Manual will be of most benefit if it forms part of more comprehensive training or is supplemented by the advice of a qualified expert in radiation protection. Some of the instrument tests and calibrations described in this Manual require the services of a qualified expert.

1. TYPES OF RADIATION MEASURING INSTRUMENTS

Radiation measuring instruments are needed to detect and quantify two types of exposure: external exposure to penetrating radiations emitted by sources outside the human body; and internal exposure which is associated with radioactive materials which are in a form capable of entering and interacting with the human body.

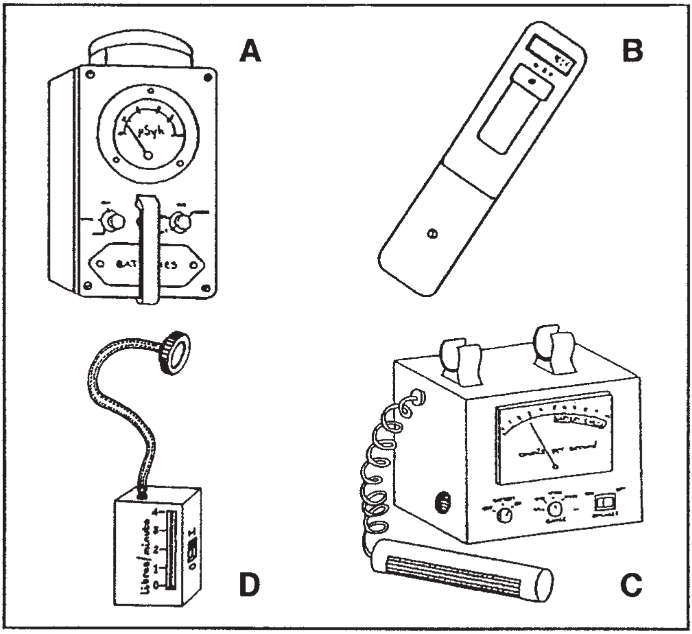
Four basic types of radiation measuring instrument may be used in the workplace:

(A) Dose rate meters used to measure the external exposure.

(B) Dosimeters which indicate the cumulative external exposure.

(C) Surface contamination meters which indicate the potential internal exposure when a radioactive substance is distributed over a surface.

(D) Airborne contamination meters and gas monitors which indicate the internal exposure when a radioactive substance is distributed within an atmosphere.



Workplace radiation monitoring instruments.

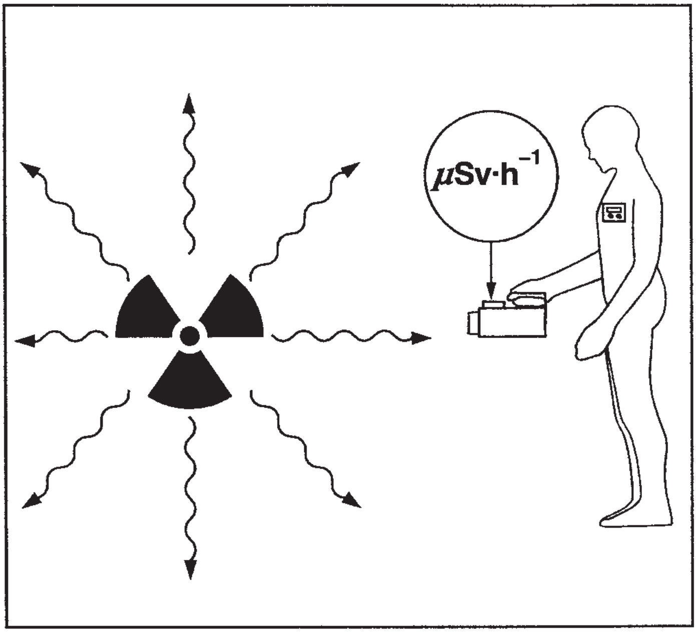
Instrument types include:
dose rate meters, dosimeters, surface contamination meters,
and airborne contamination meters and gas monitors.

2. DOSE RATE METERS

A dose rate meter absorbs energy from penetrating radiation. A suitable and efficient instrument which is matched to the specific task should be capable of providing direct readings of the dose equivalent rate in microsieverts per hour (μSv/h or $\mu Sv \cdot h^{-1}$). A smaller number of instruments indicate the absorbed dose rate in micrograys per hour ($\mu Gy \cdot h^{-1}$). These usually respond only to X, gamma and/or beta radiations. Specialized instruments are necessary to measure neutron dose equivalent rates.

Older units of dose rate — millirem per hour (mrem/h), millirad per hour (mrad/h) and milliroentgen per hour (mR/h) — are still displayed on some instruments (10 $\mu Sv \cdot h^{-1}$ is equivalent to 1 mrem/h).

Dose rate meters may not be able to provide an accurate response to rapidly changing or pulsed radiation fields. Integrating dose rate meters and dosimeters are more appropriate in such circumstances.



A dose rate meter measures external hazards in units of dose equivalent rate.

Dose rate meters provide direct measurements of external exposure.

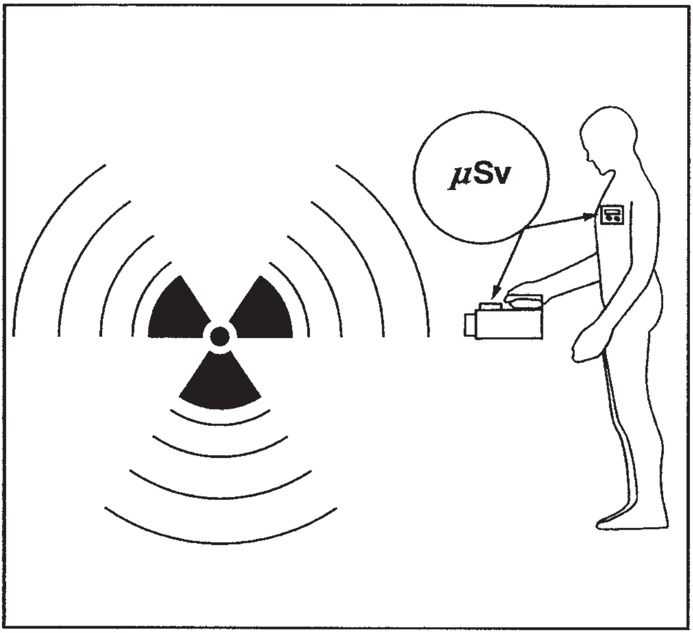
3. DOSIMETERS

A dosimeter measures the cumulative energy absorbed as a consequence of exposure to ionizing radiation.

Personal dosimeters must be worn by radiation workers to measure their radiation exposure. Passive dosimeters routinely monitor cumulative doses resulting from an external exposure. Active dosimeters provide an immediate reading of the dose in microsieverts (μSv) and may also provide an immediate alarm signal when the measured dose approaches a value pre-set by the manufacturer or user.

Integrating dose rate meters and dosimeters are used to assess an external exposure which is rapidly changing, for example: (a) a task of short duration has to be carried out in the presence of high dose rates; (b) the source (e.g., an X ray machine) emits radiation pulses of short duration.

Further information on dosimeters is provided in the Practical Radiation Technical Manual on Individual Monitoring.



Personal dosimeters and integrating dose rate meters measure the dose equivalent due to an external hazard that is rapidly changing.

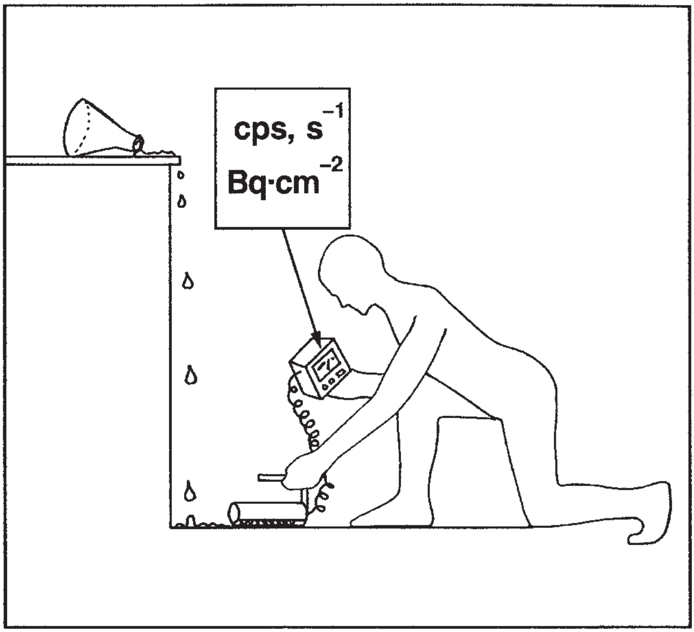
Dosimeters provide a measurement of cumulative exposure to radiation.

4. SURFACE CONTAMINATION METERS

Surface contamination meters are used to detect the presence of radioactive substances on accessible surfaces.

Even low concentrations of such substances may present a potential internal exposure. However, each instrument will have detection efficiencies ranging from zero to 30% (at best) for different radionuclides. Measurements must be made using a calibrated instrument with the best available, predetermined detection efficiency for the contaminant. The measurements, in counts per second (cps or s^{-1}), then need to be converted to becquerels per square centimetre (Bq cm^{-2}).

Some surface contamination meters are programmable. The user sets the instrument's likely response to the radionuclide in use and obtains a direct measurement of surface contamination (in Bq cm^{-2}).



A surface contamination meter indicates the internal hazard.

Surface contamination meters are used to detect and measure radioactive substances on surfaces.

5. AIRBORNE CONTAMINATION METERS AND GAS MONITORS

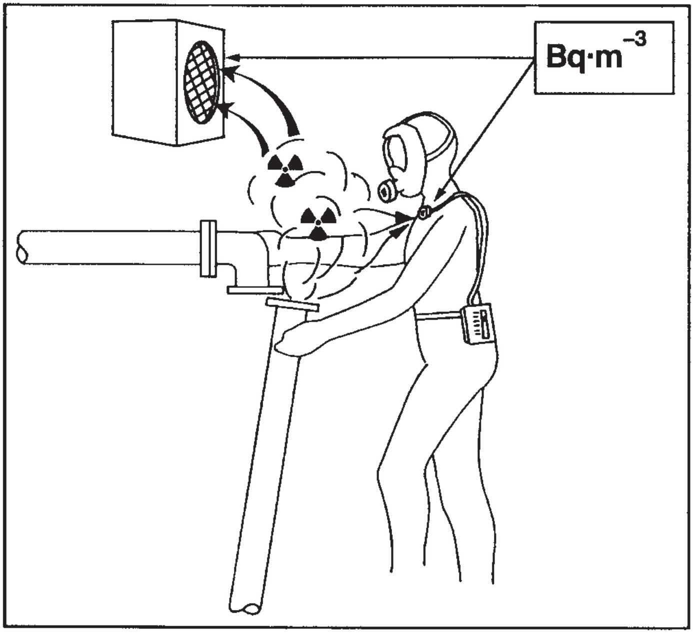
Airborne contamination meters are used to detect radioactive aerosols which may be present within the atmosphere. These may be dispersion aerosols (dusts), condensation aerosols (smoke) or liquid aerosols (mists). The instruments used normally draw potentially contaminated air at a constant rate through a filter. The instrument may then be capable of detecting the accumulated radioactive material on the filter or the filter may need to be assessed elsewhere.

Gas monitors contain a radiation detector and continuously sample the air directly to measure the presence of radioactive gases.

The contaminant must be identified in order to determine the activity concentration in becquerels per cubic metre ($Bq \cdot m^{-3}$).

Airborne contamination meters and gas monitors may be used to assess airborne contamination in the workplace. Personal air samplers (PAS) are used to monitor the often more significant hazard within the breathing zone of an individual worker. These instruments are often passive devices which do not provide immediate results. They only provide retrospective assessments of the working conditions but may also provide estimates of intakes.

Instruments that are capable of detecting the radionuclide may be used as active devices to provide an alarm signal when the airborne radioactivity concentration reaches a pre-set value.



Personal and static samplers and gas monitors are used to monitor airborne contamination.

Airborne contamination meters are used to detect and measure particulate radioactivity in the atmosphere.

Gas monitors are used to detect and measure radioactive gases in the atmosphere.

6. BASIC INSTRUMENT COMPONENTS

Commercially available radiation detection instruments are often described and procured on the basis of their essential components. The key components are:

(A) *The detector.* The detector contains a medium which absorbs radiation energy and converts it into a signal. Electrical charge usually forms the signal. Common detectors include:

Gas filled detectors;
Ionization chambers;
Proportional counters;
Geiger-Müller counters;
Scintillation counters;
Solid state detectors.

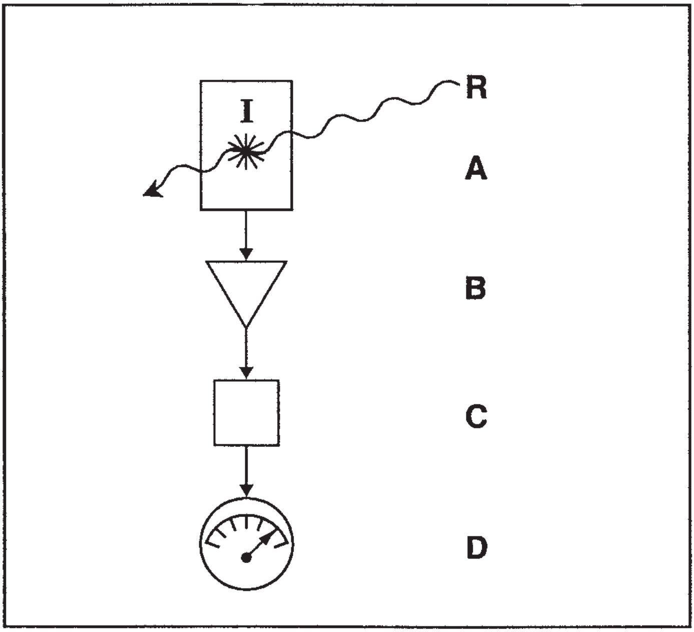
(B) *The amplifier.* The signals from a detector may need to be electronically amplified.

(C) *The processor.* According to the type of instrument, the processor may be a device to measure the size or number of signals produced by the detector. It may also translate the quantity measured into appropriate radiological units.

(D) *The display.* The measurement is presented either in a digital format or as an analogue display showing a pointer on a graduated scale.

(R) *The radiation.* Ionizing radiations (alpha or beta particles, gamma or X rays, or neutrons) which enter the detector need to be absorbed to be detected.

(I) *Ionization.* The process in which the detector medium absorbs radiation energy.



Radiation monitoring instrument components.

All types of instruments are constructed using basic instrument components.

7. IONIZATION CHAMBERS AS GAS FILLED DETECTORS

Ionization chambers, like proportional counters and Geiger-Müller counters, are gas filled detectors. The essential components of these detectors are:

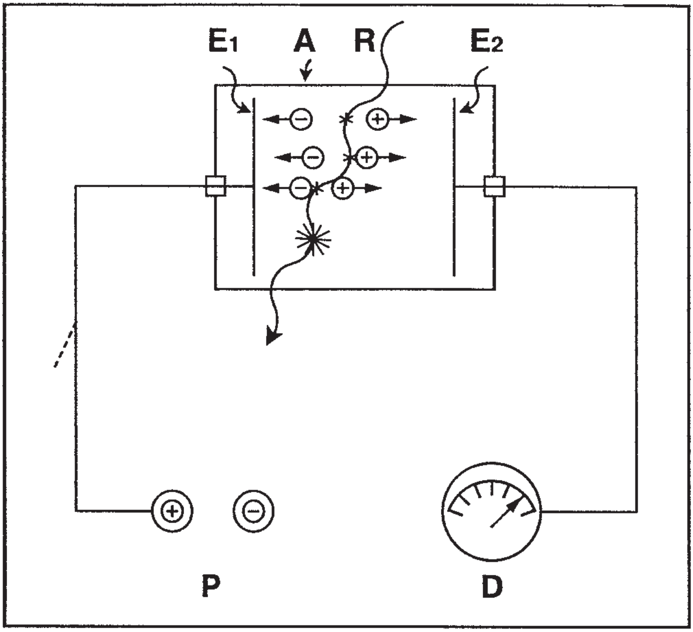
A — a container or detector wall which encloses the gas. The material used strongly influences the instrument's performance and use.

$E_{1,2}$ — electrodes (a positive anode and a negative cathode) physically separated and across which a fixed potential difference (voltage) is maintained.

P — a power supply (battery).

D — a display.

Ionization counters can operate with different gas fillings and gas pressures but often air is used at atmospheric pressure and temperature. When the gas absorbs radiation energy and is ionized, the number of ions created is proportional to the energy absorbed. The ions move under the influence of the electrode potential difference and are collected by the electrodes to form a small electrical current which can be measured by the processor.



Principal components of an ionization chamber.

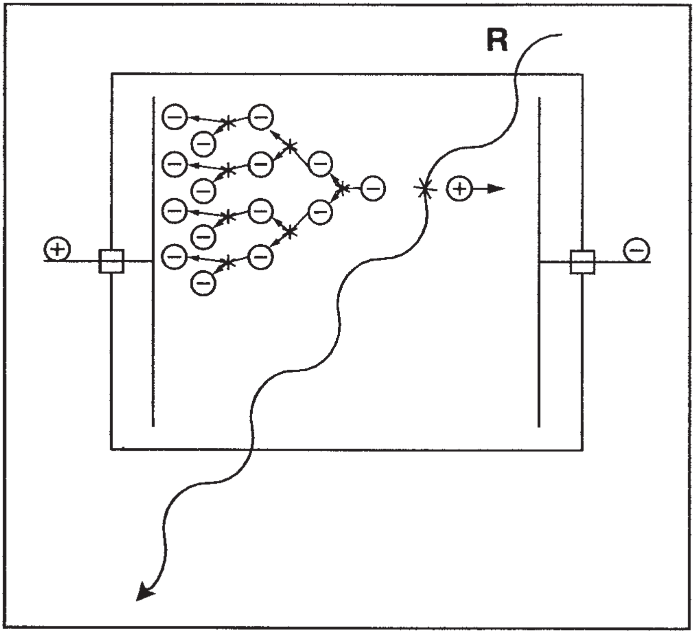
Ionization chambers, proportional counters and Geiger-Müller counters are gas filled detectors operating on the fact that radiation causes ionization in the gas filling.

8. PROPORTIONAL COUNTERS AND GAS AMPLIFICATION

Proportional counters typically contain a mixture of inert and organic gas fillings, but other fillings may be used to form special detectors. For example, incorporating boron trifluoride (BF_3) allows the detection of neutrons (see Section 19).

The detectors may operate at elevated gas pressures to provide higher detection efficiencies for X, gamma and beta radiations. The high voltages applied also increase their sensitivity to low dose rates.

The higher voltages cause the ions, which are created by ionizing radiations, to accelerate as they approach the electrodes. The fast moving negative ions ⊖ in turn cause further ionization. This is called gas amplification. The number of ions collected by the electrode will be proportional to the number produced by the radiation. The detector's output is a pulse of charge when the ions are collected on the electrode. The size of this pulse is proportional to the energy absorbed by the detector.



Gas amplification occurs in both proportional and Geiger-Müller counters.

Proportional counters and Geiger-Müller counters use gas amplification to increase detector outputs over the primary ionizations.

9. GEIGER-MÜLLER COUNTERS AND DETECTOR OUTPUT

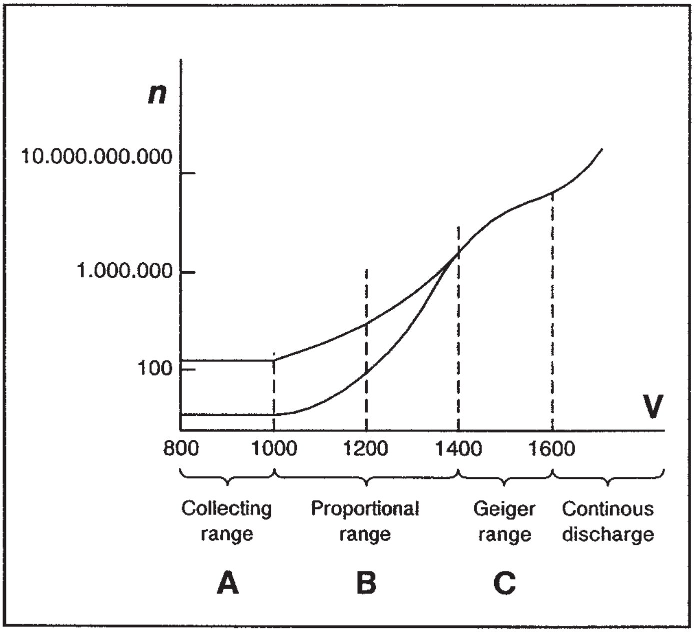
Geiger-Müller counters (also called GM and Geigers) contain a low pressure inert gas and traces of an organic or halogen gas called the quenching agent.

The potential difference between a GM's electrodes is high and sufficient to cause an almost complete ionization of the detector gas from the gas amplification of a single primary ionization. A momentary reduction of the voltage then allows the detector's recovery.

The graph illustrates the relative response of gas filled detectors to a single ionizing particle. The number of ions collected (*n*) is plotted against the detector voltage (V). The detector regions are indicated.

A — ionization chambers. Above a minimum voltage the few primary ions do not recombine and are collected.
B — proportional counters. The detector's response increases with increasing ionization.
C — Geiger-Müller counters. The avalanche of ions collected is independent of the primary ionization.

A GM's output differs from that of other gas filled detectors. Pulses of electrical charge result at a count rate which is related to the radiation fluence (particle intensity) and independent of the energy absorbed in the detector.



Typical outputs of gas filled detectors in response to single primary ionizations from different types of radiation.

Gas filled detectors need to operate at the appropriate voltages in order to function properly.

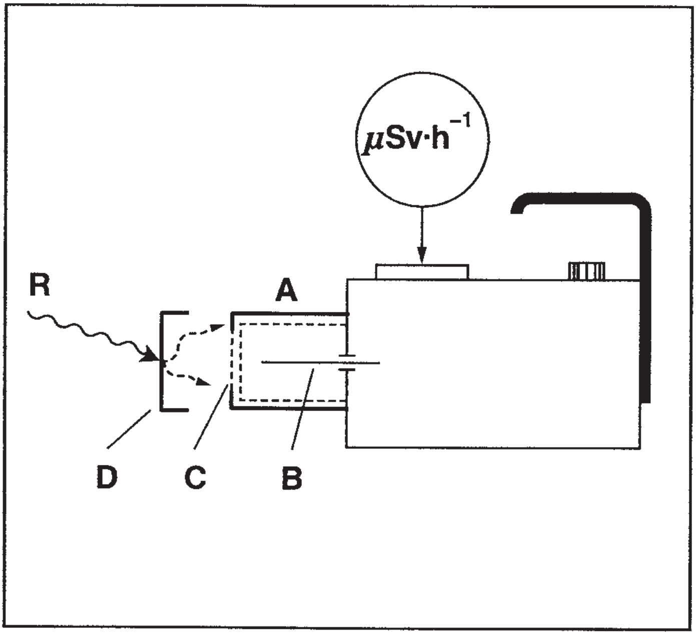
10. PRACTICAL IONIZATION CHAMBER INSTRUMENTS

Ionization chambers are used to manufacture accurate dose rate meters as well as integrating dose rate meters. A typical construction is illustrated:

A — the cylindrical detector wall serves as the cathode (negative electrode) and is normally made of air-equivalent, carbon coated plastic or aluminium.
B — the axial anode (positive electrode).
C — beta window made of thin foil (3–7 $mg \cdot cm^{-2}$).
D — protective buildup cap (200–300 $mg \cdot cm^{-3}$) made of toughened plastic or aluminium.

The buildup cap is used to improve the detection efficiency when measuring high energy photon radiations. It is removed when measuring dose rates due to low energy photons (10 to 100 keV) and beta radiations.

Detector volumes of a few hundred cubic centimetres are needed to measure exposures in nanocoulombs per hour ($nC \cdot h^{-1}$). The processor converts these units to the appropriate radiation dose rates from about 10 $\mu Sv \cdot h^{-1}$. Ambient variations of temperature, humidity and air pressure will affect the detector and should be corrected as appropriate. Detectors may be screened against extraneous radiofrequency interference.



A dose rate meter.

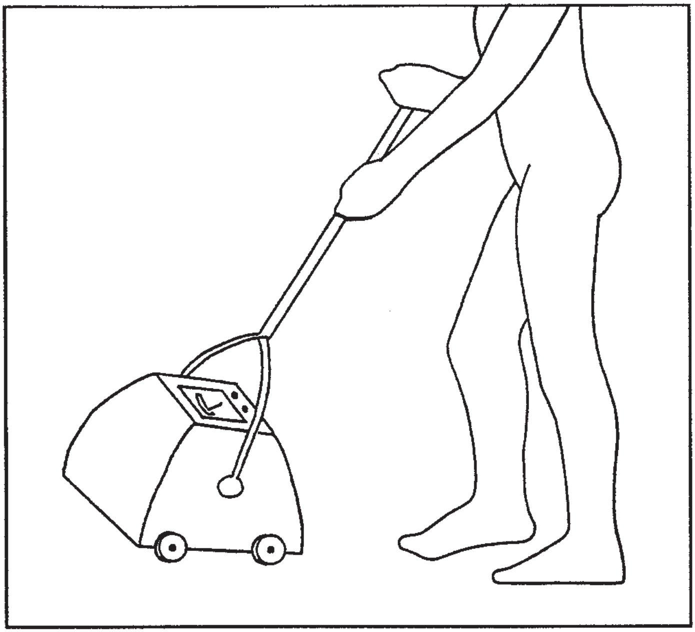
Practical ionization chambers provide accurate measurement of dose rate.

11. PRACTICAL PROPORTIONAL COUNTERS

Portable dose and dose rate meters which incorporate proportional counters are uncommon in the workplace. Although proportional counters capable of measuring low dose rates are smaller than equivalent ionization chambers, their need for a highly stable power and gas supplies and other technical requirements disadvantage them. The proportional counter's superior features are best used in the form of surface contamination meters which may contain detectors as large as 1500 cm^2.

Compared with Geiger counters, proportional counters have a better response to low energy photons and a sensitivity to beta radiations. However, Geiger instruments are less costly for measuring dose rates due to penetrating radiations.

Proportional counters are of most use in the laboratory. The detector's applications include spectrometry, neutron detection, discrimination between ionizing particles (e.g., electrons and protons) and absolute measurements of the activity of beta emitters.



A large area proportional counter incorporated in a floor contamination meter.

Proportional counters are used to measure dose rate, airborne radioactivity and surface contamination.

12. PRACTICAL GEIGER-MÜLLER COUNTERS

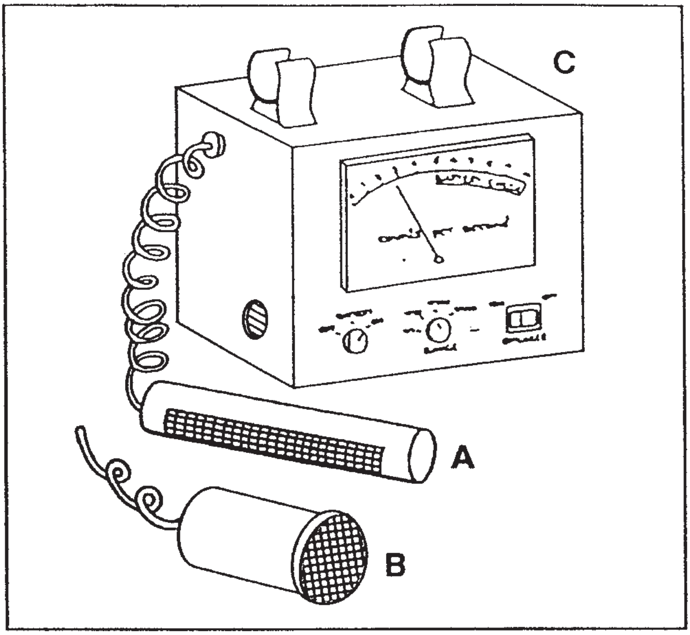
Geiger-Müller counters are mass produced in a range of shapes, sizes, sensitivities and detection geometries. The detector requires only a moderately stable voltage, a simple amplifier and other inexpensive components, including a ratemeter (C), to construct a useful instrument.

Common forms include:

(A) *The Geiger tube.* A cylindrical tube (often of glass about 30 $mg\cdot cm^{-2}$ thick) contains a tubular cathode and an axial wire anode. As a side window detector, the tube is enclosed within a metal shield which has a shutter. The shield protects the tube and provides a means to discriminate between penetrating and non-penetrating radiations.

(B) *The end window Geiger tube.* A cylindrical thin metal body forms the cathode which is sealed at one end by a thin window of about 2 $mg\cdot cm^{-2}$. Alpha, beta and photon radiations are detected through the window but with poor detection efficiencies.

The pulsed output of Geiger counters is often to form an audible indication of the detected count rate. Such instruments rapidly respond to varying dose rates. The less sophisticated Geiger counters can be 'saturated' by an exceptionally high dose rate. In this potentially hazardous situation, these instruments become paralysed and cease to function. Special circuits may ensure that a full scale reading is maintained under these circumstances.



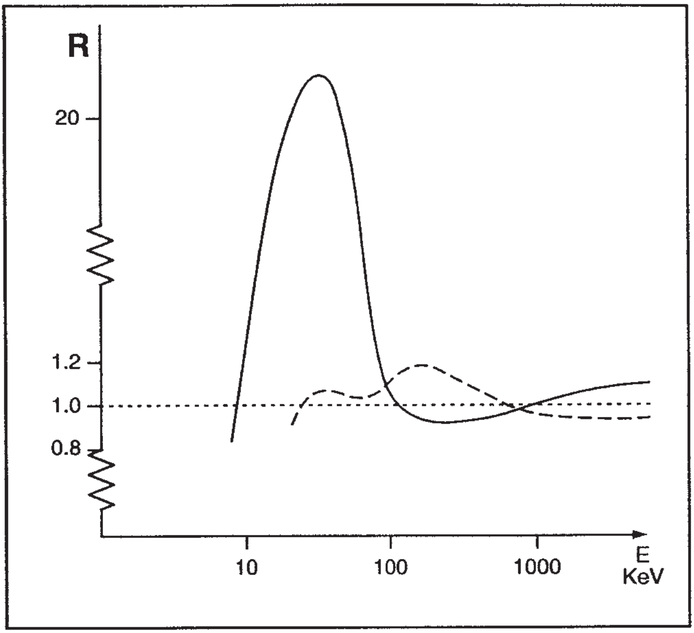
Geiger counter probes and a ratemeter — useful as search instruments and surface contamination meters.

Geiger-Müller counters are the most commonly commercially used instruments to measure dose rate, dose and surface contamination.

13. COMPENSATED GEIGER DOSE RATE METERS

The Geiger counter has a high sensitivity but is very dependent upon the energy of photon radiations. The graph illustrates the relative response (*R*) of a typical Geiger counter plotted against photon energy (*E*). At about 60 keV the response, shown by the solid line in the figure, reaches a maximum which may be thirty times higher than the detector's response at other radiation energies.

In order to more accurately measure dose rates, a normalized response at 1.0 is required, as represented by the dotted line. The detector's poor energy response may be corrected by adding a compensation sheath. Thin layers of metal are constructed around the Geiger tube to attenuate the lower photon energies, where the fluence per unit dose rate is high, to a higher degree than the higher energies. The modified or compensated response, shown as a dashed line on the graph, may be independent of energy within ± 20% over the range 50 keV to 1.25 MeV. Compensation sheaths also influence an instrument's directional (polar) response and prevent beta and very low energy photon radiations from reaching the Geiger tube.



Energy response characteristics typical of Geiger counters and compensated Geiger counters.

Geiger-Müller counters can be compensated to provide a uniform response as dose rate meters.

14. SCINTILLATION COUNTERS

The essential components of a scintillation counter are:

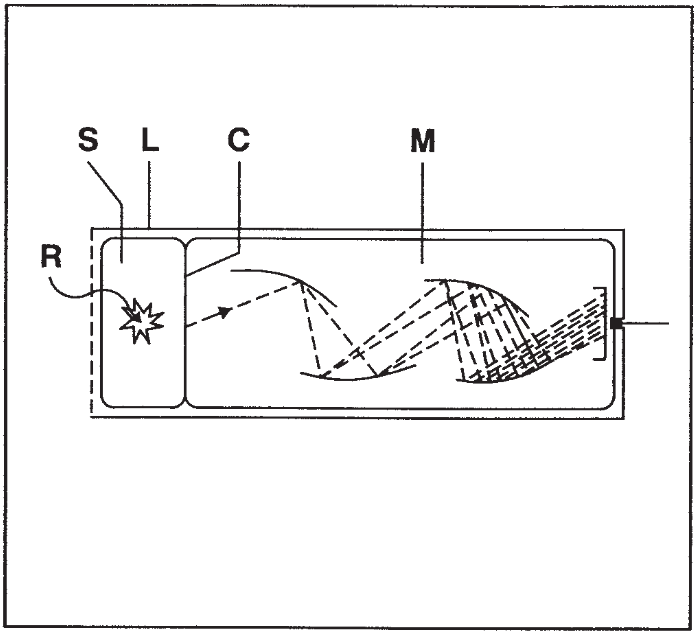
S — scintillator. A substance (a phosphor) contained within an opaque material. Ionizing radiations interact with the scintillator, which almost immediately converts some of the absorbed energy into a flash of light.

L — light guide transfers the scintillation to the photocathode (C) of the photomultiplier (M).

C — photocathode is a translucent, light sensitive coating of material (e.g., antimony-caesium) on the photomultiplier window. When it absorbs light it emits a proportionate number of electrons.

M — photomultiplier tube contains electrodes called dynodes. A successively in-creased potential difference (about 2000 V overall) draws electrons to each dynode in turn. The number of electrons increases at each dynode. The number of electrons is amplified by about one million.

Phosphors include solid organic materials such as anthracene and stilbene, liquid solutions of organic materials (liquid scintillants), solid solutions of organic materials (plastic scintillants) and activated inorganic crystals such as sodium iodide and caesium iodide which are activated by trace quantities of thalium (NaI(Tl) and CsI(Tl)).



Principal components of a scintillation counter.

Scintillation counters contain a phosphor and a photomultiplier.

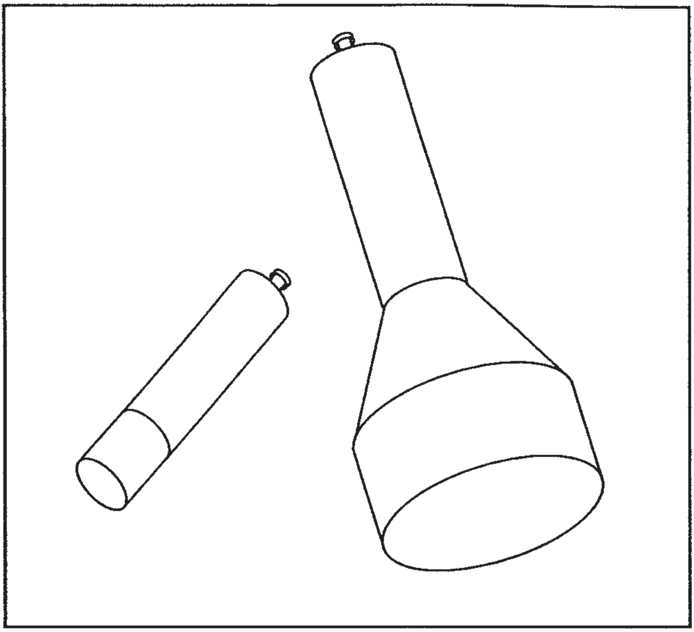
15. PRACTICAL BULK SCINTILLATION COUNTER INSTRUMENTS

The very wide range of phosphors in a multitude of sizes, geometries and sensitivities can be combined with photomultipliers ranging from 6 to 300 mm in diameter to manufacture a large variety of scintillation counter instruments.

Plastic and inorganic phosphors with densities close to 1000 times greater than those of gas filled detectors form gamma and X ray detectors of very high sensitivity. Crystals of up to 40 cm in diameter and 40 cm in thickness exist but crystals of a diameter between 1 cm and 7.5 cm and of a thickness between 1 cm and 7.5 cm are regularly used. For radiation that is incident perpendicular to a 2.5 cm thick NaI(Tl) crystal, the detection efficiency is about 37% for 1 MeV photons, rising to almost 100% at energies below 200 keV.

For detectors of sufficient size, the scintillations will be proportional to the energy of the incident photons, allowing them to be used for gamma spectrometry. The scintillation rate is proportional to the radiation fluence and not the dose rate, but scintillation dose rate meters, that operate over limited energy ranges, can indicate low and high dose rates even at low photon energies. However, the photomultiplier's demand for a stable voltage supply and high component costs make these instruments comparatively expensive. Their bulk, weight and vulnerability to shock also limit their usefulness. However, portable instruments are now available which provide spectrometry as well as dosimetry.

Lithium iodide activated by europium (LiI(Eu)) and silver activated zinc sulphide (ZnS(Ag)) in a boron loaded plastic scintillator are used for neutron detection.



Penetrating radiation scintillation counter probes.

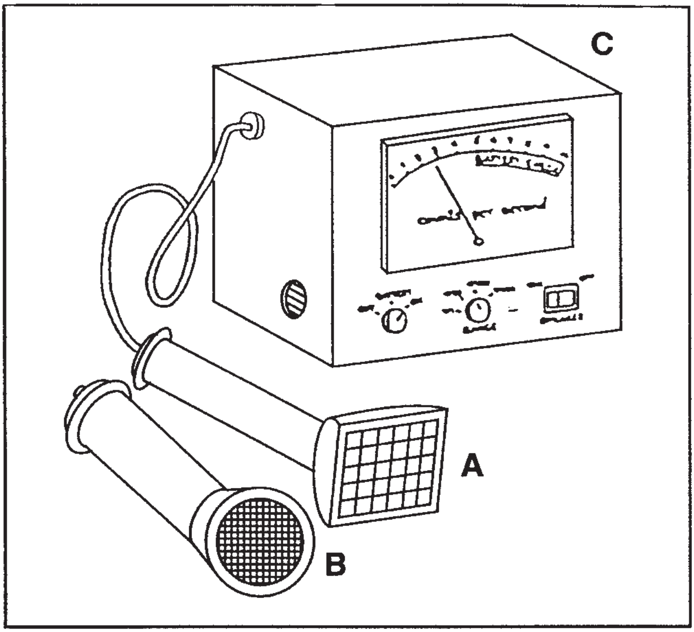
Scintillation counter instruments can be designed to be highly sensitive to gamma and neutron radiations.

16. PRACTICAL SCINTILLATION COUNTER CONTAMINATION MONITORS

Highly sensitive surface contamination probes incorporate a range of phosphor arrangements. In addition to the gamma phosphors described, other examples include: zinc sulphide (ZnS(Ag)) powder coatings (5–10 $mg \cdot cm^{-2}$) on glass or plastic substrates or coated directly onto the photomultiplier window for detecting alpha and other heavy particles; caesium iodide (CsI(Tl)) that is thinly machined (0.25 mm) and that may be bent into various shapes; and plastic phosphors in thin sheets or powders fixed to a glass base for beta detection.

Probes (A and B in the figure) and their associated ratemeters (C) tend not to be robust. Photomultipliers are sensitive to shock damage and are affected by localized magnetic fields. Even minor damage to the thin foil through which radiation enters the detector allows ambient light to enter and swamp the photomultiplier. Cables connecting ratemeters and probes are also a common problem.

Very low energy beta emitters (for example ^3H) can be dissolved in liquid phosphors in order to be detected.



Non-penetrating radiation scintillation counter probes and ratemeter.

Scintillation counter instruments can be designed to be highly sensitive to alpha and beta radiations.

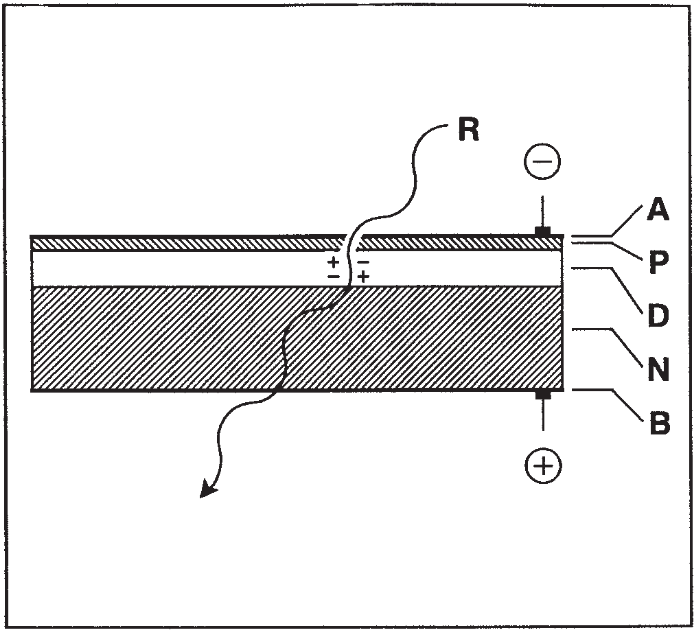
17. SOLID STATE DETECTORS

Solid state detectors utilize semiconductor materials. Intrinsic semiconductors are of very high purity and extrinsic semiconductors are formed by adding trace quantities (impurities) such as phosphorus (P) and lithium (Li) to materials such as germanium (Ge) and silicon (Si). There are two groups of detectors: junction detectors and bulk conductivity detectors.

Junction detectors are of either the diffused junction or the surface barrier type: an impurity is either diffused into, or spontaneously oxidized onto, a prepared surface of intrinsic material to change a layer of ‘p-type’ semiconductor from or to ‘n-type’. When a voltage (reverse bias) is applied to the surface barrier detector, as shown, it behaves like a solid ionization chamber.

A — very thin metal (gold) electrode.
P — thin layer of p-type semiconductor.
D — depletion region, 3–10 mm thick formed by the voltage, is free of charge in the absence of ionizing radiations.
N — n-type semiconductor.
B — thin metal electrode which provides a positive potential at the n-type semiconductor.

Bulk conductivity detectors are formed from intrinsic semiconductors of very high bulk resistivity (for example CdS and CdSe). They also operate like ionization counters but with a higher density than gases and a ten-fold greater ionization per unit absorbed dose. Further amplification by the detector creates outputs of about one microampere at 10 $mSv \cdot h^{-1}$.



Principles of surface barrier solid state counter —
shown enlarged and in section.

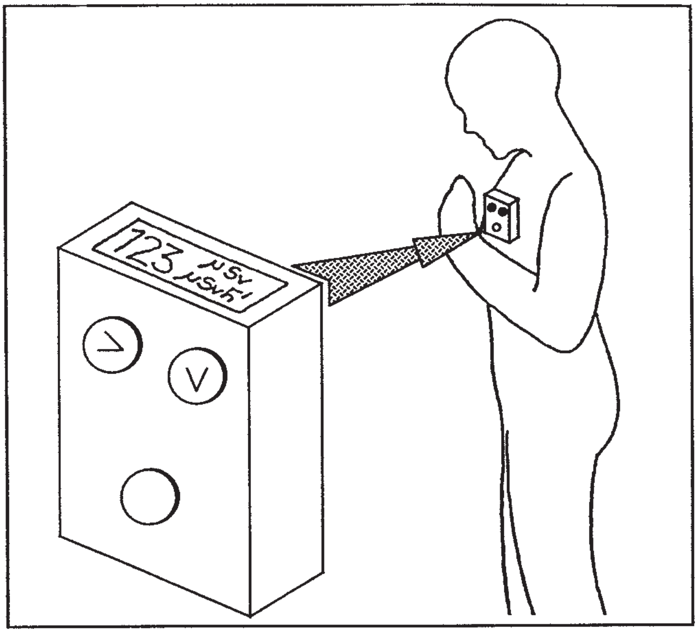
Solid state counters contain semiconductor devices.

18. PRACTICAL SOLID STATE DETECTORS

The main applications for semiconductor detectors are in the laboratory for the spectrometry of both heavy charged (alpha) particle and gamma radiations. However, energy compensated PIN diodes and special photodiodes are under development as pocket electronic (active) dosimeters.

Specially combined thin and thick detectors provide the means to identify charged particles. These are used to monitor for plutonium in air, discriminating against alpha particles arising from natural radioactivity, and for monitoring for radon daughter products in air. Their small physical size and insensitivity to gamma radiation have found novel applications: inside nuclear fuel flasks monitoring for alpha contamination and checking sealed radium sources for leakage.

Bulk conductivity detectors can measure high dose rates but with minute-long response times. A Ge(Li) detector operated at –170°C is capable of a very high gamma resolution of 0.5%. The temperature dependence and high cost add to their impracticality.



A miniature, personal, electronic, integrating dose rate meter.

Solid state counters are used in special applications, some of which are still under development.

19. NEUTRON DETECTION

As chargeless particles, neutrons are detected only by their interactions with atomic nuclei. Detector nuclei may react to neutrons in three specific ways: some disintegrate, emitting secondary ionizing radiations; others recoil and cause ionization; and certain nuclei are activated.

The interaction of thermal neutrons with boron-10 (^{10}B) is used as the basis for a number of detectors. A ^{10}B nucleus which absorbs a thermal neutron undergoes a neutron-alpha (n,α) reaction, emitting an alpha particle and forming ^{7}Li. Similarly, after an (n,α) reaction ^{6}Li forms ^{3}He. Detectors also employ the neutron-proton (n,p) reaction of ^{3}He and (n,fission) reactions utilizing fissionable materials. The neutron-gamma (n,γ) reactions in cadmium and rhodium are used by photographic detectors.

The interaction of fast neutrons in hydrogenous materials produces recoil protons which are readily detected in photographic emulsion, gas filled, scintillation and solid state detectors.

Radioactivity is induced in indium, gold and sulphur as a function of the neutron dose. Suitably calibrated detectors may be used to measure the activity.

$$^{10}B + {}^{1}n \longrightarrow {}^{7}Li + {}^{4}He\ (\alpha)$$

$$^{6}Li + {}^{1}n \longrightarrow {}^{3}He + {}^{4}He\ (\alpha)$$

$$^{3}He + {}^{1}n \longrightarrow {}^{3}H + {}^{1}H\ (p)$$

Nuclear interactions used in the detection of neutrons.

Neutrons are detected by interaction with certain target nuclei.

20. PRACTICAL NEUTRON MONITORING INSTRUMENTS

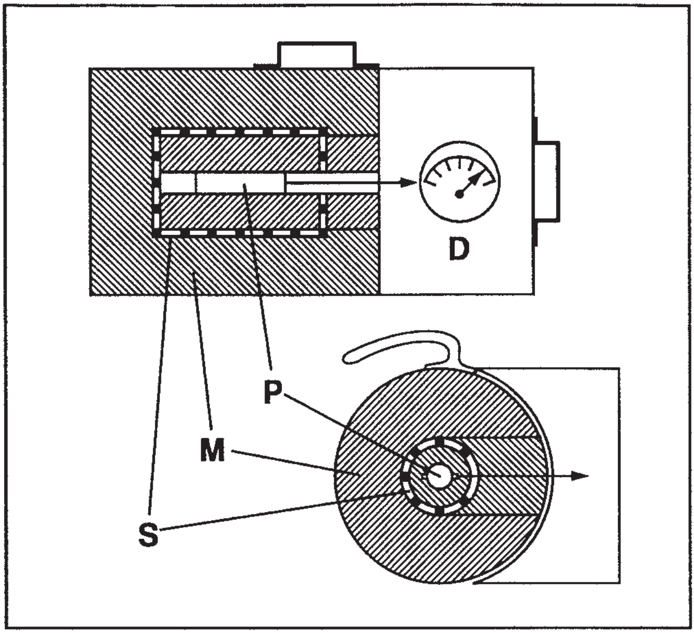
Air filled ionization chambers with thin internal coatings of boron are effective but proportional counters which contain either boron trifluoride (BF_3) or helium-3 (^3He) gas form more sensitive detectors. A typical instrument construction is shown:

D — display.
P — proportional counter incorporating BF_3 or ^3He.
M — cylindrical or spherical polyethylene moderator to thermalize incident fast neutrons for detection.
S — perforated cadmium or boron plastic sheath which modifies the energy response according to neutron quality factors to enable the direct measurement of dose equivalent rates.

Gas filled proton recoil detectors are lined with polythene and may also incorporate ethylene gas.

Scintillation detectors for thermal neutrons may incorporate such phosphors as LiI(Eu) or ZnS(Ag) mounted on a boron loaded plastic. Fast neutrons may be detected directly using organic scintillators or ZnS(Ag) in clear plastic; or they may be moderated and then detected using a boron loaded plastic and ZnS(Ag) phosphor.

Semiconductor detectors utilize (n,α), (n,p) or recoil proton reactions but unpreventable recoil reactions damage the semiconductor.



Longitudinal and transverse section of a typical neutron monitoring instrument.

Neutron dose rate meters are specially constructed instruments.

21. TESTING DOSE RATE METERS

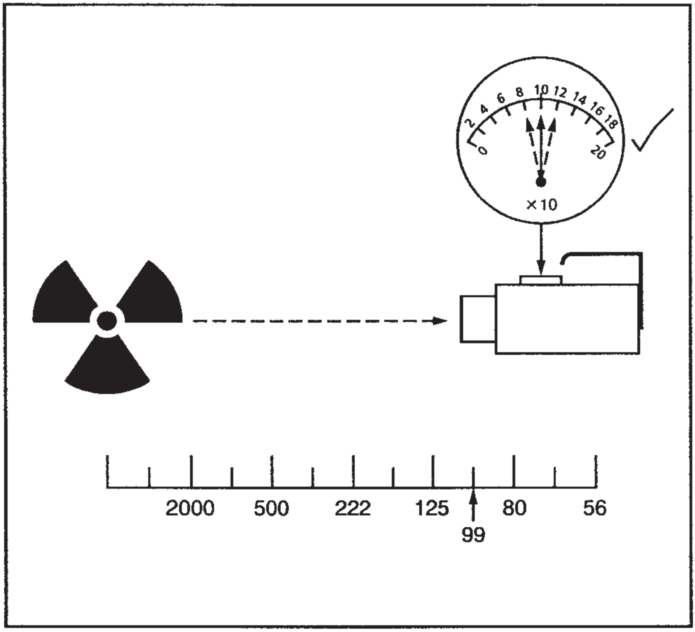
Most dose rate meters are ‘type tested’ by manufacturers and independent laboratories. The results may be found in the technical literature. In addition to the instrument’s description, its directional and energy response as well as accuracy may be reported over the appropriate dose rate and energy ranges.

Each instrument must be tested before first use, at regular intervals (annually) and after any repair which may have affected the instrument’s performance. These tests are conducted by qualified experts using calibrated radiation sources. The objectives are:

(i) To check that the instrument operates efficiently and to its specification. In addition to its radiation response, the instrument’s electrical and mechanical features may also be tested.

(ii) To reveal the magnitude of any likely errors in the instrument’s measurements. The user may accept ± 20% errors but should correct known errors which fall outside these limits. Errors in excess of ± 50% suggest that the instrument is unsuitable for the intended purpose. The linearity of response, interrange differences and overload protection may also be investigated.

The user of a dose rate meter should keep a certificate relating to the last formal test or calibration and should carry out routine checks on the instrument. Some instruments have installed check sources but the regular measurement of a known dose rate serves the purpose. The battery condition should be checked each time the instrument is used.



Calibrated sources and the inverse square law are applied to the testing of dose rate meters.

Dose rate meters must be formally tested and calibrated at appropriate intervals.

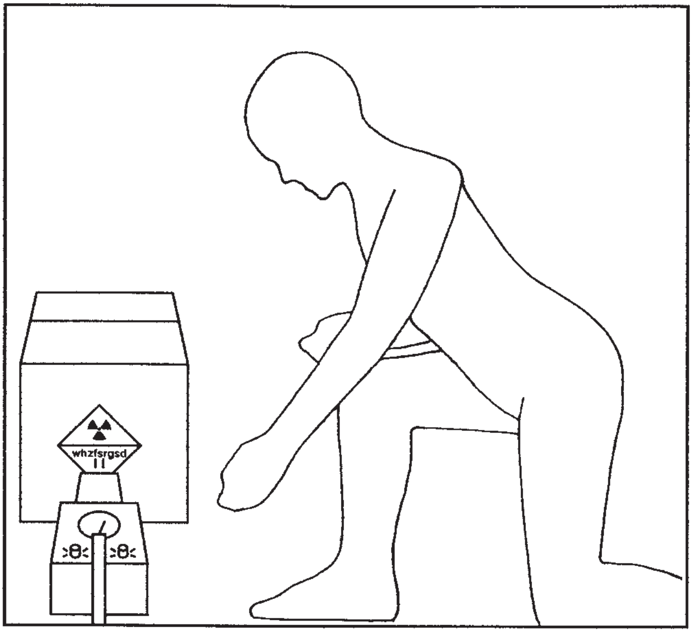
22. USE OF DOSE RATE METERS

The dose rate meter used should be suitable for the application. An incorrect choice can lead to inaccurate or even erroneous assessments of the external hazard.

The use of ionization chambers can result in narrow beams of radiation being underevaluated and even undetected because of their slow response. Any measurement requires the beam to exceed the detector's size. As 'search instruments' faster responding, end window Geigers and scintillation counters are better used.

A buildup cap may be used as a 'discriminator' to shield an ionization counter and provide a rough indication of the type and energy of incident radiation. The technique is useful to identify bremsstrahlung arising from beta radiation applications. Energy compensated instruments are only capable of detecting penetrating radiations.

Dose rates are measured for various reasons: to control task related doses; to check on the adequacy of shielding for stored sources; for transport purposes; and to ensure that all potential external exposures are identified. Measurements may be compared against appropriate reference levels, such as: limits for different categories of transport package, and reference levels to classify the workplace.



Dose rates are measured around a transport package.

Dose rate meters must be suitable for the intended application and used to determine external exposure in the workplace.

23. PROCEDURE FOR USING A DOSE RATE METER

Before attempting to make a radiation measurement it is essential for the user to be completely familiar with the features and controls of the instrument. The following procedure can then be used to measure external exposure.

(i) Check the test or calibration certificate. Confirm that the last formal test date, test conditions and result are satisfactory. Check the last routine test result.

(ii) Assess the radiation to be measured. Judge whether the instrument is suitable to obtain the measurement required.

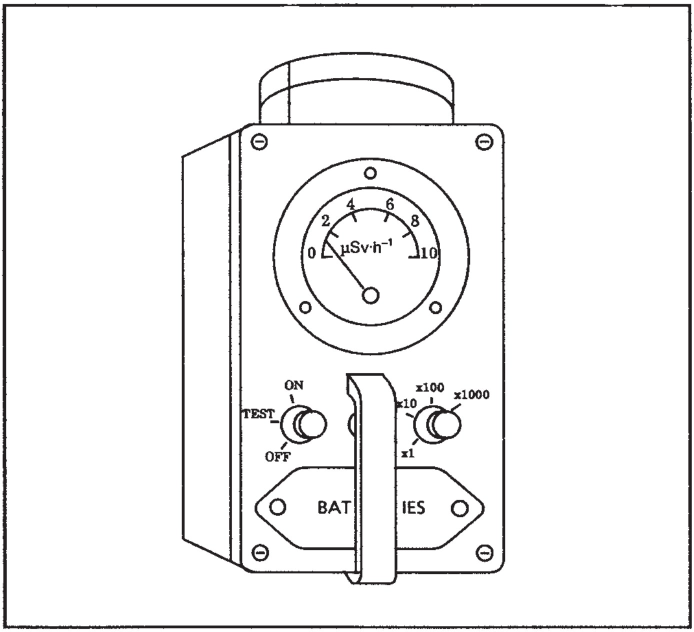
(iii) Set the instrument's parameters. Test the battery, adjust the detector voltage and set the zero as necessary.

(iv) Obtain the measurement. On multirange instruments, start on the maximum and then switch successively to lower ranges until an appropriate reading is obtained. Check the range setting and note the reading. Repeat the measurement with and without a buildup cap or with a beta/gamma shutter open and closed. Check the stability of the readings for different orientations of the instrument.

(v) Assess the result. Decide whether there are any factors which have influenced the result such as: small beam size; a non-isotropic or pulsing radiation field; temperature, humidity or air pressure effects; or interference from radiofrequency or magnetic fields.

(vi) Apply correction factors. Multiply the reading by any relevant correction or calibration factors.

(vii) Record the result. Decide whether the result is reasonable by comparison with previous measurements or calculations. Keep a written record of the conclusions.



It is important to understand the controls and the display of a dose rate meter before attempting to use it.

The user of a dose rate meter must understand the instrument used and follow a procedure to obtain a meaningful measurement.

24. TESTING AND CALIBRATING SURFACE CONTAMINATION METERS

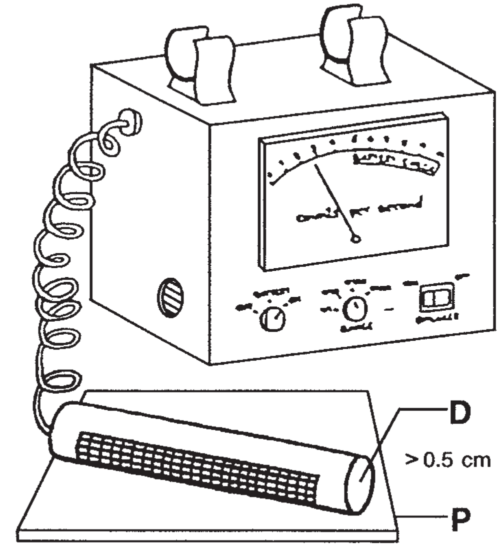
Each surface contamination meter is designed and type tested to measure a specific range of contaminants. Its response to contamination will depend upon:

(i) The type and energy of the radiation or, precisely, the radionuclide which forms the contamination.
(ii) The instrument's intrinsic detection efficiency for each radionuclide, which is determined by the detector's characteristics, the window area and thickness and the dimensions of any protective grille.
(iii) The detection geometry, including the detector's dimensions, the nature of the contaminated surface and the detector-to-surface distance.
(iv) Inherent electrical noise, ageing or fault conditions in the instrument's components.

Each instrument must be tested before first use, at regular intervals (annually) and after any repair which may have affected the instrument's performance. These tests are conducted by qualified experts using calibrated, uniformly contaminated plaques (P) with an active area of similar dimensions to the detector (D). The radionuclide used must emit radiations similar to those of potential contaminants. The objectives are:

(i) To determine the operating voltage for each detector, especially interchangeable probes. Other electrical and mechanical features may also be tested.
(ii) To obtain or confirm the detection efficiency (*E* counts per disintegration) of the instrument for each appropriate radionuclide. Using the detection efficiency, a calibrated response can then be provided to the user to convert readings (cps or s^{-1}) to $Bq \cdot cm^{-2}$. The linearity of response and interrange differences may also be investigated.

The instrument user should keep a certificate relating to the last formal test and should carry out routine checks on the instrument. Sources are available for this purpose which are sometimes attached to the instrument's window cover. The battery condition should be checked each time the instrument is used.



$$Z_{cps} = Y_{Bq} \times E = X_{Bq \cdot cm^{-2}}$$

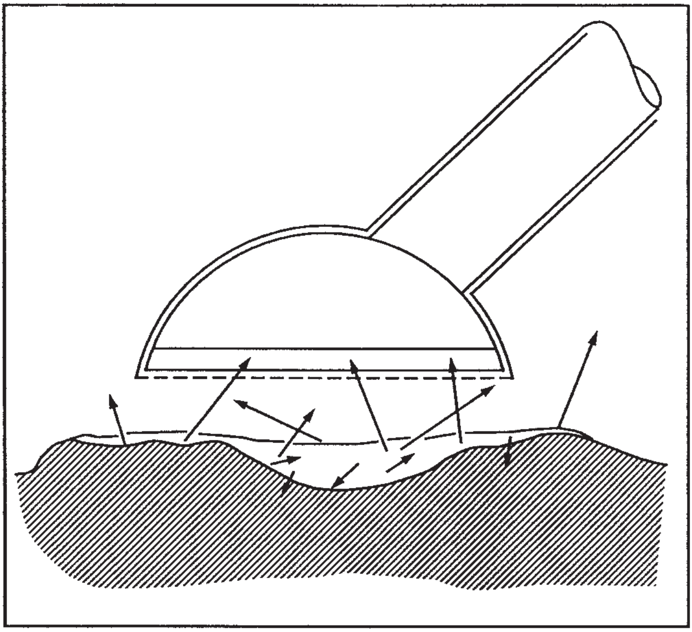
A surface contamination meter is tested against a calibrated source.

Surface contamination meters must be formally tested and calibrated at appropriate intervals.

25. USE OF A SURFACE CONTAMINATION METER

A suitable surface contamination meter should be available wherever unsealed radioactive substances such as liquids and powders are in use. However, care must be taken to avoid the instrument contacting potentially contaminated surfaces.

Instruments which comprise a ratemeter and probe provide versatility both in the range of detectable radionuclides (using different probes) and the ease with which readings can be taken. The surfaces of the body, of protective clothing, of working areas (benches, floors, etc.), of plumbing and transport packages are some of the surfaces that should be routinely monitored for spillages or contamination.



A surface and scintillation detector showing that a thick layer of contaminated material and wet or uneven surfaces reduce the detection efficiency for alpha and low energy beta radiations.

The user of a surface contamination meter must understand the instrument used and follow a procedure to obtain a meaningful measurement.

26. PROCEDURE FOR USING A SURFACE CONTAMINATION METER

(i) Check the test or calibration certificate. Confirm that the last formal test date, test conditions and result are satisfactory. Check the last routine test result.

(ii) Assess the potential contaminant radionuclide. Judge whether the instrument is suitable.

(iii) Set the instrument's parameters. Test the battery, adjust the detector voltage and set the zero as necessary. Start multi-range instruments on the minimum.

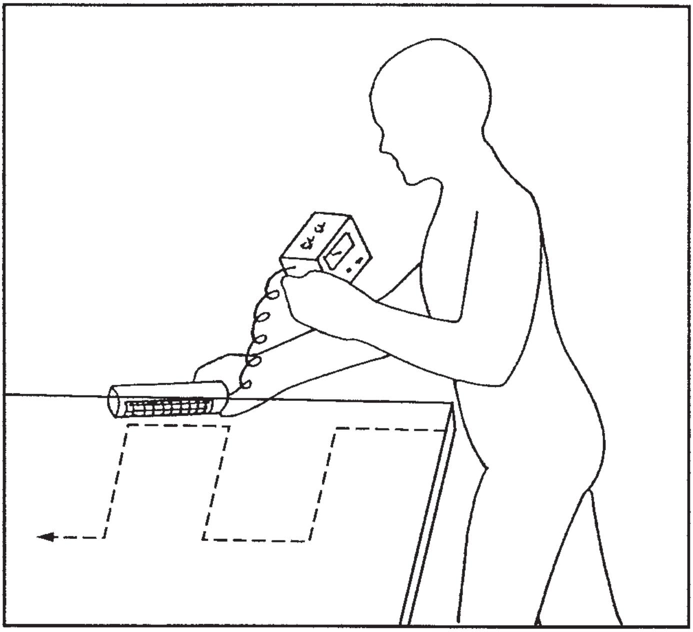
(iv) Obtain a background reading (s^{-1}) at about 1 m from the contaminated surface.

(v) Obtain a reading from the contaminated surface. At a speed appropriate to the detector's capabilities, scan the instrument or its probe over the surface at a distance which avoids contact. Hold the detector at the calibration distance (about 0.5 cm) from the contamination to obtain the surface reading.

(vi) Calculate the indicated total surface contamination. Subtract the background from the surface reading. Then use the appropriate calibration data to convert the corrected measurement from a count rate to a value of surface contamination (in $Bq \cdot cm^{-2}$).

(vii) Assess the result. Decide whether there are any factors which could influence the result such as: the curvature of the surface; 'self absorption' of radiation within thick contamination; a wet or uneven surface masking alpha and low energy beta emitters.

(viii) Record the result. Compare the result with expectations or previous measurements. Keep a written record of the conclusions.



Working surfaces are surveyed to detect potential surface contamination.

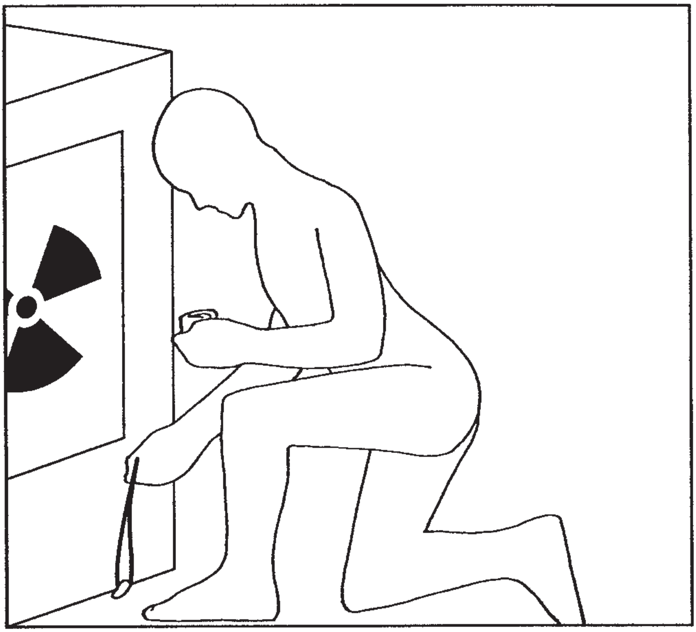
Surface contamination meters must be suitable for
detecting the contaminant to determine
the potential internal exposure in the workplace.

27. SPECIAL SURFACE CONTAMINATION MONITORING TECHNIQUES

Surface contamination meters indicate the total contamination which includes that which is fixed to the surface and that which is removable. Total contamination may constitute an external hazard but only that which is removable is an internal hazard. The direct measurement may suffice as an indicator of the potential internal hazard, but there may be situations where the extent of removable contamination has to be measured.

The removable contamination may be assessed by using a moistened filter paper to wipe an area of contaminated surface and measuring the amount of activity on the wipe. It is normally assumed that only about 10% of the removable contamination transfers to the wipe. The measured activity is multiplied by ten and divided by the area wiped to complete the assessment.

This technique is also used: to assess contamination by alpha and low energy beta emitters which are difficult to detect by direct methods; to measure contamination in places which are inaccessible to an instrument; and to obtain a measurement in the presence of very high backgrounds.



Wipes are taken from an otherwise inaccessible surface in the vicinity of high background radiation from a source store.

Wipe tests are used to assess surface contamination when direct measurements using a surface contamination meter are not possible.

28. THE MEASUREMENT OF AIRBORNE CONTAMINATION

Airborne contamination meters may be grouped as follows:

(i) 'Personal' air samplers (PASs) which draw 2–4 litres per minute ($L \cdot min^{-1}$) of air through a filter;

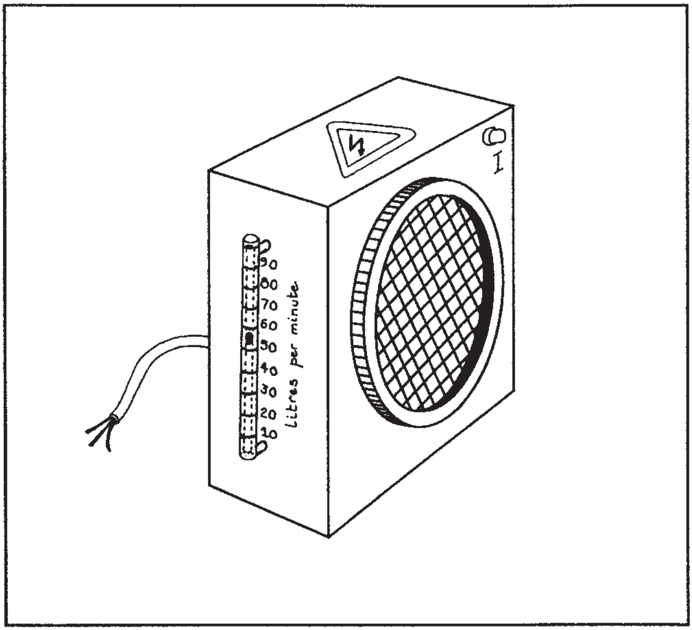
(ii) Battery powered samplers which sample about 10 $L \cdot min^{-1}$;

(iii) Generator powered samplers which typically operate at 30, 60 or 100 $L \cdot min^{-1}$; and

(iv) 'High volume' samplers capable of sampling 1000 $L \cdot min^{-1}$ for environmental rather than workplace monitoring.

Passive air samplers may readily demonstrate the presence of aerosols in the workplace but the interpretation of the results is more difficult. Static samplers are influenced by the proximity of building surfaces, and PAS filters risk contact and being wiped or contaminated. Filter papers must also be handled with care before and after sampling to ensure that they are kept flat, undamaged and not contaminated by contact. By marking the potentially active face of the filter prior to use, better care may be provided during the filter's transfer to a laboratory for the activity to be measured. Notes should be taken of the sampling period, the flow rates at the start and finish, and sampling location(s).

If the contaminant is identified, air sampling may determine the total airborne activity concentration (in $Bq \cdot m^{-3}$). The assessment will include respirable and non-respirable aerosols. In order to assess the actual risk to an exposed worker, analysis of the particle size or a respirable particle collector will be required.



A portable, generator powered static air sampler.

Airborne contamination measurements depend upon
an appropriate choice of sampler and careful handling of filters.

29. CRITERIA FOR THE SELECTION OF MONITORING INSTRUMENTS

Factors which affect the choice of radiation monitoring instruments for any particular application include:

(i) the type of radiation to be measured;
(ii) dose, dose rate or contamination measurements;
(iii) the energy response of the instrument;
(iv) unwanted responses and overload performance;
(v) the sensitivity and range of measurements required;
(vi) the speed with which the instrument responds;
(vii) logarithmic/linear analogue scales or digital displays and ease of use;
(viii) illuminated display and/or audible output;
(ix) response in ambient temperatures, humidities, radiofrequencies, magnetic fields, etc.;
(x) intrinsic safety in explosive/flammable locations;
(xi) ease of decontamination;
(xii) battery availability and life expectancy;
(xiii) size, weight and portability;
(xiv) ruggedness, reliability and serviceability;
(xv) initial and ongoing maintenance costs.

A wide range of radiation monitoring instruments is manufactured.

The instrument used to monitor the workplaces must be appropriate and efficient for the application.

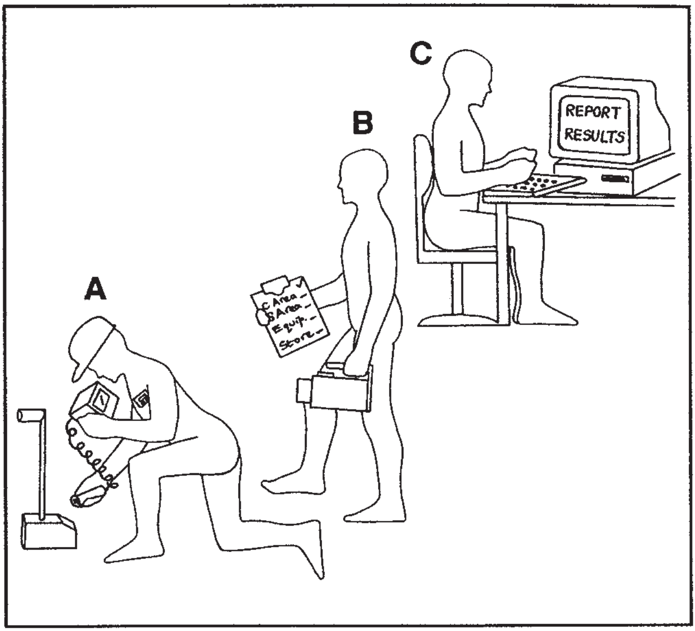
30. EXPERTISE IN RADIATION MONITORING

Monitoring should be carried out whenever work involves the production, processing, handling, use, holding, storage, moving, transport or disposal of radiation sources. Three levels of expertise are required:

(A) *Task related monitoring:* performed by a radiation worker as a standard procedure particularly when specific operations may involve an increased hazard.

(B) *Routine monitoring:* carried out by a Radiation Protection Officer to confirm a safe working environment. Surveys should be conducted at appropriate regular intervals but not to a predictable timetable. The measurements are intended to confirm the extent of static designated areas in the workplace, to prove the adequacy of measures against external and internal hazards and to reveal any deterioration in the standard of radiation safety. A record should be kept for two years from the date on which the surveys are carried out.

(C) *Special monitoring:* carried out by a qualified expert. It is likely to require the use of non-standard instrumentation, interpretation of complex measurements or application of the results in order to reach appropriate conclusions. A report should be kept detailing the measurements, the conclusions and any recommendations which arise from them.



Task related, routine and special monitoring carried out in the workplace.

Workplace monitoring for radiation and contamination should be carried out at three levels of expertise.

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A qualified expert, a librarian or the IAEA can recommend further materials on workplace monitoring for radiation and contamination.