PRACTICAL RADIATION TECHNICAL MANUAL

INDIVIDUAL MONITORING

IAEA
International Atomic Energy Agency

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INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2004

INDIVIDUAL MONITORING
IAEA, VIENNA, 2004
IAEA-PRTM-2 (Rev. 1)

Printed by the IAEA in Vienna
April 2004

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 Nos. 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 Organisation, 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 Technical Guidance Modules for Occupational Protection, held from 7 to 11 September 1992, in Vienna, Austria. The content was agreed by a committee comprising Deping Li (China), F. Bermann (France), F.E. Stieve (Germany), G.J. Koteles (Hungary), S.P. Kathuria (India), S.K. Wanguru (Kenya), G. Severuikhin (Russian Federation), C. Jones and C.R. Jones (USA), W. Forastieri (representing ILO), R. Wheelton (United Kingdom) and R.V. Griffith (IAEA). Major contributions were made by R. Wheelton, who also contributed to the present revision, which was prepared by the Radiation Monitoring and Protection Services Section of the IAEA.

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IAEA PRACTICAL RADIATION TECHNICAL MANUAL

INDIVIDUAL MONITORING

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 Manual to provide adequate training, instruction or information on individual monitoring for all employees engaged in work with ionizing radiations.

INDIVIDUAL MONITORING

Introduction

Sources of ionizing radiation have a large number of applications in the workplace. The exposures of the individual workers involved may need to be routinely monitored and records kept of their cumulative radiation doses. There are also occasions when it is necessary to retrospectively determine a dose which may have been received by a worker.

This Manual explains the basic terminology associated with individual monitoring and describes the principal types of dosimeters and other related techniques and their application in the workplace.

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. Most of the dosimeters and techniques described in this Manual can only be provided by qualified experts.

1. MEASUREMENT OF PERSONAL DOSES

Individual monitoring is the measurement of radiation doses received by individual workers. The methods available generally require that the radiation sources and the potentially exposed workers be identified.

Workplace monitoring is used to determine the potential for exposure of personnel to ionizing radiation, including the magnitude of any likely doses. Workplaces are designated as controlled areas if specific protective measures or safety provisions are, or could be, required for:

(a) controlling normal exposures or preventing the spread of contamination during normal working conditions; and
(b) preventing or limiting the extent of potential exposures.

The working area is designated as a supervised area if it is not already designated as a controlled area and if occupational exposure conditions need to be kept under review even though specific protection measures and safety provisions are not normally needed.

Workers who regularly work in controlled areas should have their personal doses routinely assessed. Those who work full time in supervised areas and/or occasionally in controlled areas should also be considered as potential candidates for individual monitoring.

Individual monitoring is used to verify the effectiveness of radiation control practices in the workplace. It is also used to detect changes in the workplace, confirm or supplement static workplace monitoring, identify working practices that minimize doses and provide information in the event of accidental exposure.

Workplace categorizations to identify which workers need individual monitoring.

Workplace monitoring to identify controlled and supervised areas.

Individual monitoring for workers in controlled areas.

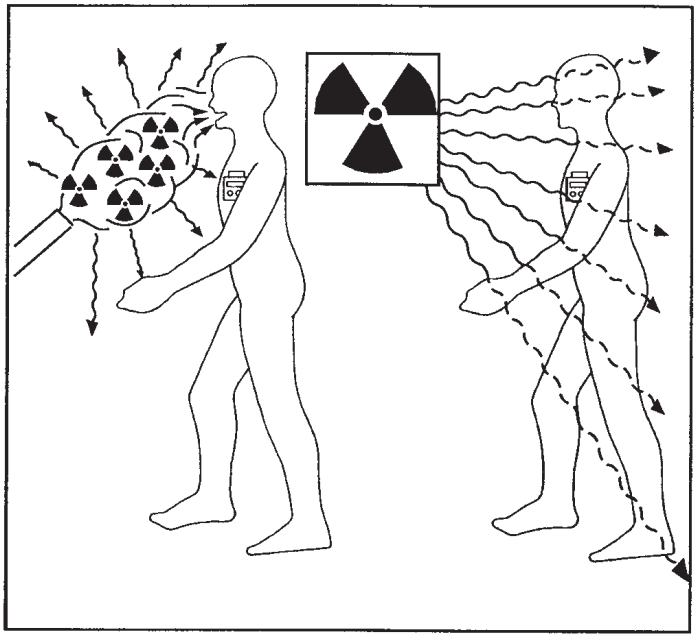
Personal dosimeters are also used for environmental assessments and other purposes.

2. DOSIMETRY FOR EXTERNAL AND INTERNAL EXPOSURES

External dosimetry is the measurement of doses due to radiation sources that are outside the exposed worker's body. Such doses are usually measured by a suitable personal dosimeter (sometimes called a radiation badge) that is worn by the worker. It is assumed that the dosimeter will provide a representative measurement of radiation which has been absorbed by the worker's body. The dosimeter should be worn throughout periods of possible exposure to monitor the individual's cumulative dose. Appropriate action may then be taken, as necessary, to ensure that reference levels and limits are not exceeded.

In addition to external exposure, personnel who work with unsealed radiation sources may also receive exposure from radioactive material taken into the body. Radioactive material that enters the body may accumulate in specific organs and emit radiations that are absorbed by the surrounding body tissues. Internal doses received by the organs or whole body can be significant for even small intakes of radioactive material.

Both the external and the internal doses must be assessed to determine the total 'effective dose' accumulated by the workers.



Dosimetry for external and internal exposure.

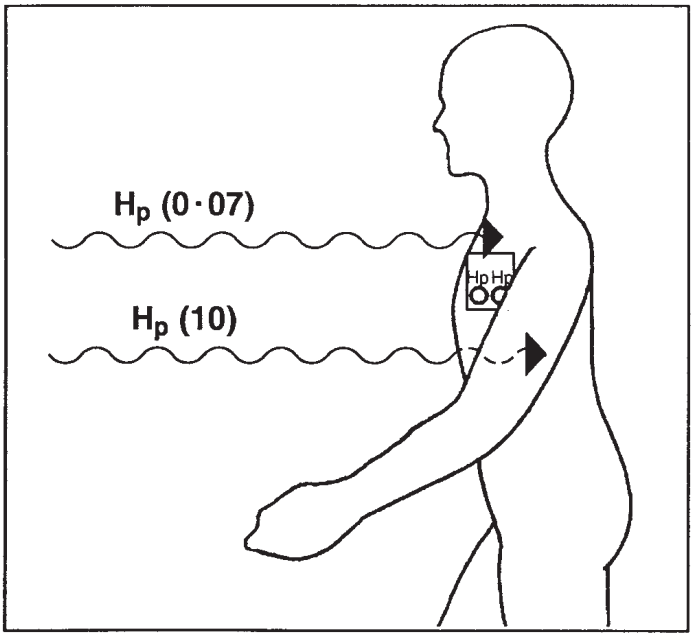
Dosimeters are used to monitor external exposure.

Workers who are exposed to contamination may require dosimeters and monitoring for internal exposure.

3. ASSESSMENT OF EXTERNAL EXPOSURES

Personal dosimeters are designed to measure the dose in soft tissue at a defined depth below a specified point on the body. The quantity personal dose equivalent $H_p(d)$ is normally determined at two depths, d = 0.07 and 10 mm, as measures of exposure to weakly and strongly penetrating radiations respectively. The former is representative of dose to skin and the latter represents dose to the blood forming organs. If exposure to the eye is of particular concern, a depth of 3 mm represents the eye lens.

The personal dose equivalent at 10 mm depth, $H_p(10)$, is used to provide an estimate of effective dose for comparison with the appropriate dose limits. As $H_p(0.07)$ is used to estimate the equivalent dose to skin, it should be used for extremity monitoring, where the skin dose is the limiting quantity.



Assessments of external exposure.

Dosimeters measure doses at defined depths and positions on the body.

Measured doses are compared with dose limits.

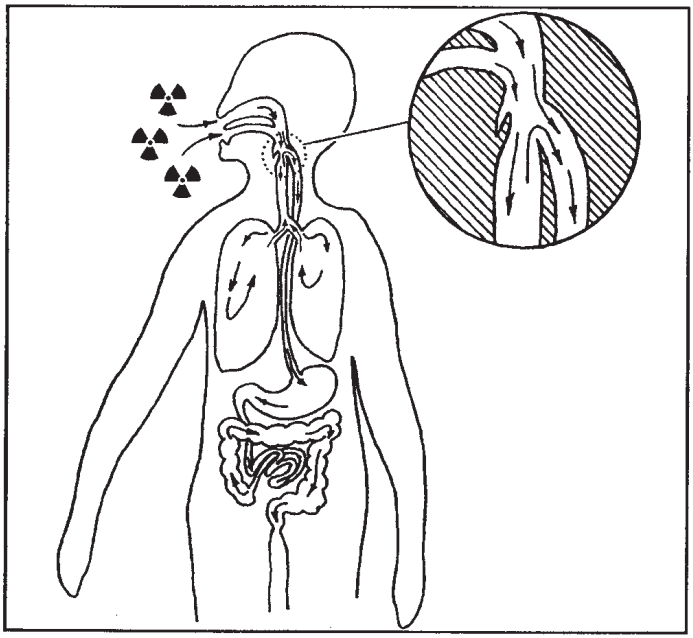
4. ASSESSMENT OF INTERNAL EXPOSURES

Internal exposures occur when radionuclides have been inhaled, ingested or otherwise taken into the body through wounds and intact skin. A proportion of inhaled material will eventually be swallowed. Radionuclides inside the body are called internal emitters.

The physical and chemical form of a radionuclide influences its uptake and movement inside the body and determines where it decays and how long it remains. Some internal emitters are quickly excreted, others are distributed in the body and may be retained for many years. For example, radioiodine (like non-radioactive iodine) is taken up by the thyroid gland in the neck, and radium (in suitable form) is deposited on bone. The consequent internal dose depends on the 'biological half-life' of the radionuclide, that is the time for its incorporated activity to be reduced to 50% by the processes of radioactive decay and excretion.

Internal doses cannot be measured directly; they can only be inferred from measured quantities such as the body activity content, excretion rates or airborne concentrations of radioactive material. The committed effective dose from an estimated intake may then be calculated using the dose coefficient (committed effective dose per unit intake) of the radionuclide of interest specified for inhalation or ingestion as appropriate. Dose coefficients have been calculated for hundreds of different radionuclides.

For occupational exposure, the committed effective dose to the worker is integrated over the fifty years following the intake (E_{50}), irrespective of the age of the adult at time of intake. This assessment of internal exposure may then be compared against relevant effective dose equivalent limits.



Assessment of internal exposure.

Radionuclides taken into the body are called internal emitters.

Which organs receive a dose depends on the internal emitter.

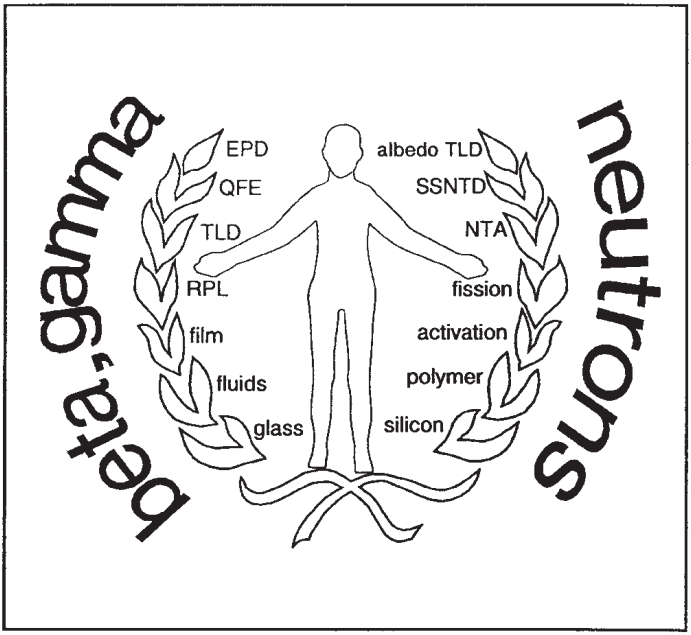
A dose continues to be received while the internal emitter remains.

5. RADIOSENSITIVE MATERIALS FOR USE AS DOSIMETERS

Many materials which exhibit measurable, radiation related changes are used as dosimeters. The changes may only occur in response to a specific type of radiation. Some display colour changes at very high doses or dose rates. These include: solid polyvinylchloride and some glasses; solutions of ferrous sulphate and chloroform; and the gases acetylene and nitrous oxide.

Materials that are suitable indicators of much lower doses undergo changes that can only be measured after suitable processing in a laboratory (passive detectors). Photographic emulsions (films) are extensively used as passive dosimeters. Thermoluminescent (TL) and radio-photoluminescent (RPL) materials are also important for personal dosimetry. After exposure to ionizing radiation, thermoluminescent dosimeters (TLDs) and RPL glasses emit light under the influence of heat and ultraviolet radiation, respectively.

The common dosimeters listed will be described in more detail but RPL glass (gamma) and polymer (neutron) bubble dosimeters are not widely used and are not further discussed here. Solid state or silicon dosimeters are described in the Manual on Workplace Monitoring for Radiation and Contamination.



Dosimeter types and the radiations they measure.

Many radiosensitive materials are used to form dosimeters.

Dosimeters respond to limited radiation types and energies.

Passive dosimeters require processing by suitable laboratories.

6. DOSIMETRY SERVICES FOR MEASURING EXTERNAL EXPOSURE

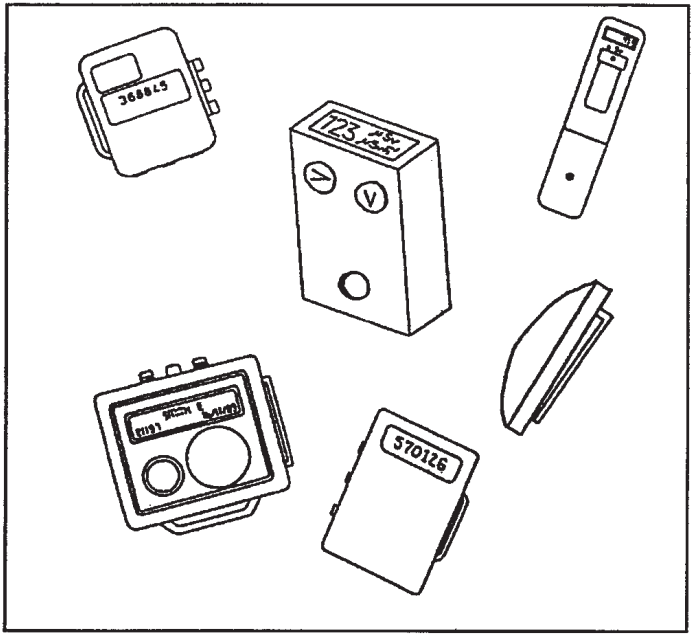
There are hundreds of dosimetry services around the world. They normally operate to agreed international standards and perform intercomparisons to ensure uniformity of results. Some countries have officially approved services with legislation requiring their dosimeters to be used.

Some dosimeters have several components to extend their response to more than one radiation or energy range. The dosimeter(s) used must be capable of measuring the radiations to which the wearer is exposed. More than one dosimeter may be required.

The magnitude of potential doses and the type of dosimeter used influence the wearing period, that is how frequently the dosimeter should be changed. Passive dosimeters should be worn for shorter wearing periods (for example, four weeks) when there is a risk of greater exposure. Climatic conditions and dosimeter availability may also influence the wearing period.

Whole body dosimeters should be fastened to the outside of clothing between the neck and the waist facing forward. Protective clothing, if used, may cover the dosimeter but pocket items, such as coins, should be kept clear.

Personal dosimeters must not be put through mail inspection X ray machines, worn during medical exposures or used for static environmental monitoring.



A wide range of dosimeters are available.

Dosimetry services offer different types of dosimeters.

The dosimeter issued to a worker must be appropriate to the work.

The dosimeter must be correctly used by the worker.

7. FILM BADGE DOSIMETERS

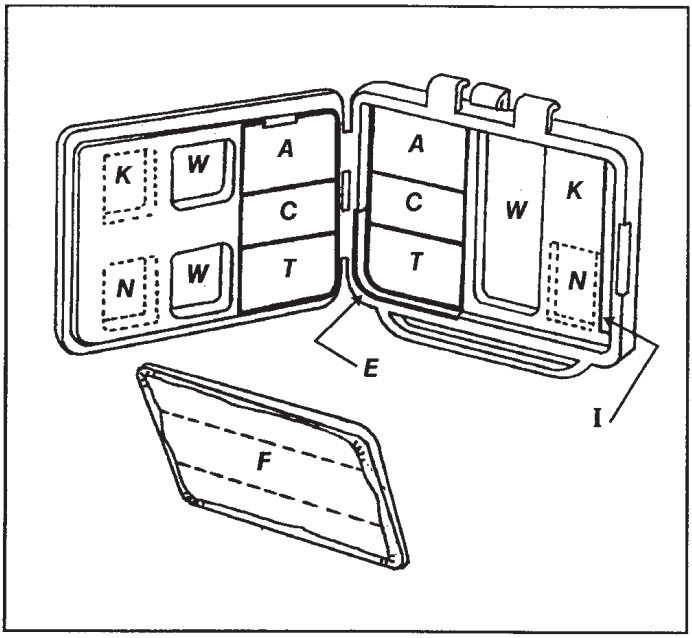
A film badge dosimeter consists of a photographic film (F) and filters in a holder.

The film usually has two emulsions of 'fast' and 'slow' sensitivities extending the dose response from 100 μSv to 10 Sv. The emulsions may be on the same or separate bases and sealed in paper to prevent their exposure to light. An identification mark printed on the wrapper appears on the developed film.

Photographic emulsion and tissue do not absorb radiation energy in the same proportion: film is not 'tissue equivalent' and must be used with a holder. The arrangement of filters in the holder may vary with different services. The films and holders of different services must not be mixed.

The indicated areas of the illustrated dosimeter are:

W — window which allows all radiation which can penetrate the wrapper to reach the film;
N — thin plastic filter which attenuates beta radiation depending on its energy;
K — thick plastic filter which attenuates low energy photon radiations and absorbs all but the highest energy beta radiation;
A — aluminium filter used with area K to assess doses from photons with energies from 15 to 65 keV;
C — composite of cadmium and lead filters to assess doses from thermal neutrons which interact with the cadmium;
T — composite of tin and lead filters used with area C to assess doses from thermal neutrons;
E — edge shielding to prevent low energy photons entering around area T;
I — indium foil sometimes included to detect fast neutrons (see Section 15).



A film badge dosimeter.

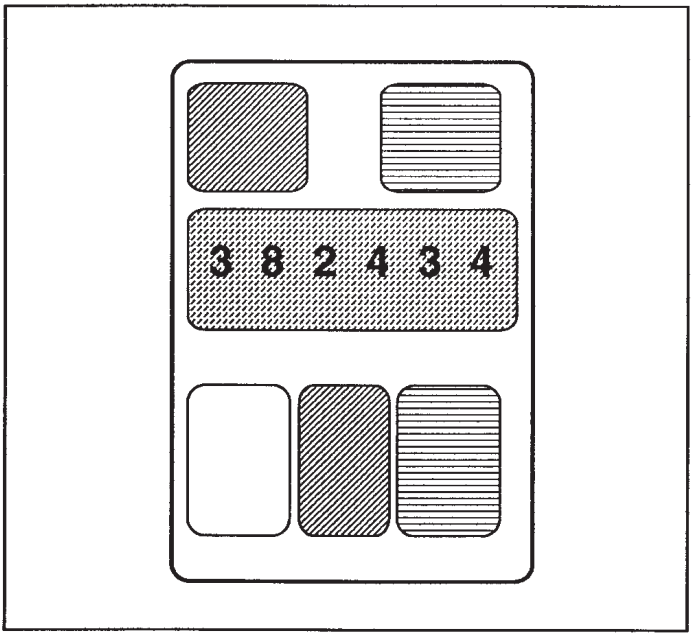
A film badge requires a suitable film and film holder.

The holders contain different filter areas.

8. FILM BADGE DOSIMETRY

The holder creates a distinctive pattern on the film indicating the type and energy of radiation to which it was exposed (discrimination). Cumulative doses from beta, X, gamma and thermal neutron radiations are calculated by measuring the optical densities (darkness) of film under the filters and comparing the results with calibration films that have been exposed to known doses. Films provide a permanent record that can, if necessary, be reassessed.

Holders must not be used if filters are missing or they become contaminated. Radioactive contamination produces non-uniform black patches on the developed film. Films are also adversely affected by light (if the wrapper is damaged), heat, liquids, partial shielding and static electricity discharges. The latent image on undeveloped film fades with time, limiting possible wearing periods to three months in ideal conditions. Excessive fading occurs in relative humidity which exceeds 55%.



A film dosimeter pattern after exposure to different types of radiation.

Doses are assessed by measuring the densities under the filter areas.

Different radiations produce characteristic filter patterns.

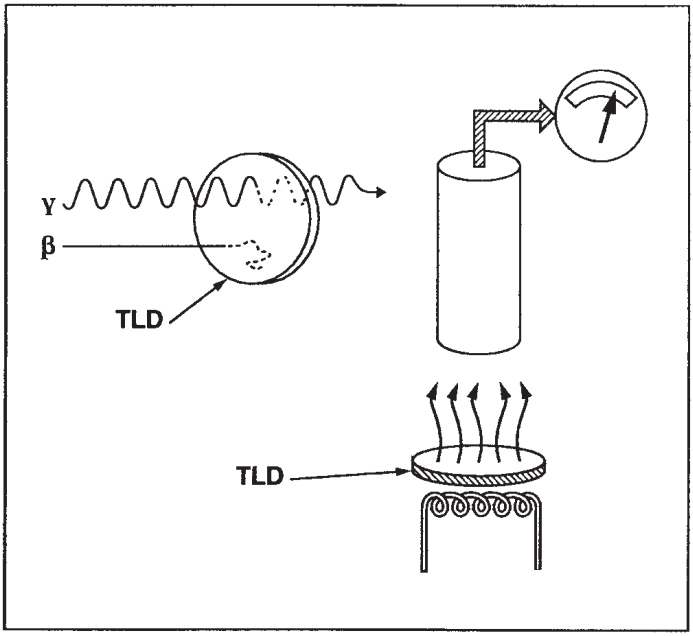
The worker must use the film correctly and avoid causing damage to it.

9. THERMOLUMINESCENCE DOSIMETRY (TLD)

Thermoluminescence is a physical characteristic of certain crystalline materials called phosphors. They absorb energy from ionizing radiation and release it as light when heated above 100 to 200oC. The intensity of the light may be measured and related to the radiation dose of the phosphor.

Several phosphors form useful TLDs. Calcium sulphate and calcium fluoride are very sensitive detectors but are not tissue equivalent. Like film, they require filters to match their energy response to that of tissue. Lithium fluoride (LiF) has a linear response between 100 μSv and 5 Sv but is usable up to about 1 kSv. Compared with LiF, lithium borate has a wider, more uniform energy response to photons but is more sensitive to thermal neutrons. Both LiF and lithium borate are approximately tissue equivalent and are used in dosimeters that do not require complex filter systems.

Lithium borate's sensitivity to thermal neutrons is due to the ^{6}Li and ^{10}B content. The ^{6}Li can be reduced (7.4% down to 0.01%) for LiF dosimeters suitable for beta and photon radiations. Pure ^{7}Li and natural lithium or lithium enriched in ^{6}Li are used to measure mixed gamma and thermal neutron radiations.



A TLD which is exposed to radiation is later heated to determine the dose.

TLDs absorb radiation energy which is later released as light.

Various TLD materials vary in their radiosensitivities.

10. TLDs TO MEASURE BODY DOSES

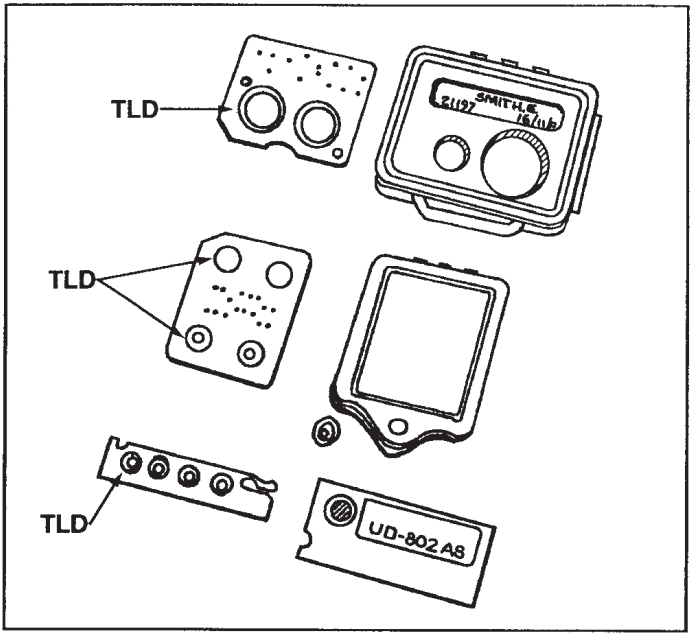
Many dosimetry services, both large and small, use TLDs as a convenient means of monitoring whole body exposure to beta, X and gamma radiations.

Dosimeters vary in design but typically comprise two or more LiF detectors. These can be chips, discs in a polytetrafluoroethylene (PTFE) matrix, or powders. They are used in cards designed for automated readout. A reader decodes holes in the card which provide information about the wearer; it heats the TLD and measures the light emission. The TLDs are then annealed and reused. It is important to keep the discs clean and dry.

Personal details about the wearer can be printed on the outside of the dosimeter. The shape of the card ensures that it is correctly located inside a holder by the user. Some of the discs must be used behind filters to simulate measurements of $H_p(0.07)$ and $H_p(10)$.

In general, TLDs are not designed to provide discrimination between the types and energies of radiations and the lack of qualitative data places greater responsibility on the user to ensure that it is correctly used and not contaminated.

TLDs are less affected than film badges by fading and ambient conditions. Consequently, they are more appropriate for wearing periods of up to three months. They are also more suitable, but not ideal, dosimeters for mixtures of weakly penetrating (less than 500 keV) beta and (less than 20 keV) photon radiations.



Different commercially available whole body TLDs.

TLDs are kept clean and dry in specially designed holders.

TLDs measure doses but, unlike film badges, are not discriminatory.

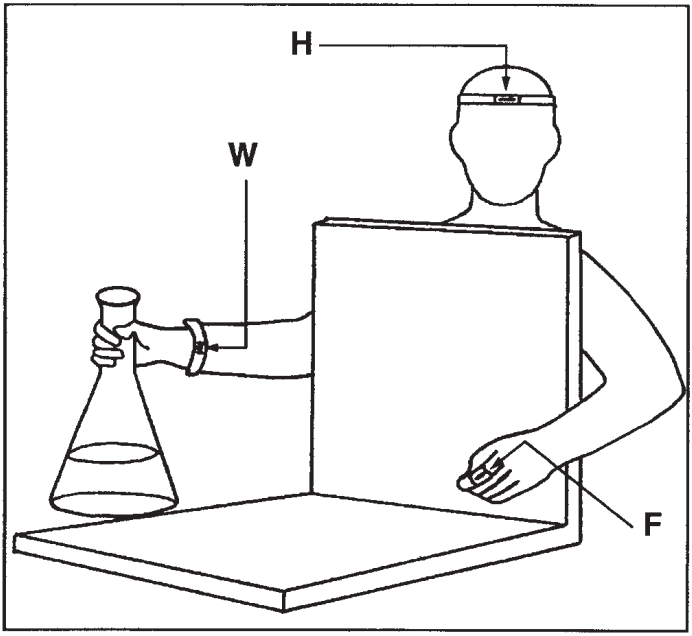
TLDs are less easily damaged than film badges and can be used longer.

11. TLDs TO MEASURE EXTREMITY DOSES

Some work may expose the extremities or other parts of the body to significantly more radiation than the whole body receives. Examples include: the manipulation of short range, energetic sources; situations in which extremity shielding is impractical; and work that involves parts of the body being closer to collimated radiation beams.

In such circumstances, TL materials are used to measure the doses to specific parts of the body. The discs mentioned (see Section 10) are less than 15 mm in diameter by 0.5 mm in thickness and chips are 3 mm square by 1 mm in thickness. Rods of a size of 1 mm by 6 mm and extruded lithium fluoride ribbons are also available. They may be contained in unobtrusive rings and fingerstalls (F) to measure finger doses. Powders require careful handling to avoid inducing thermoluminescence by grinding or shaking, but sachets containing just a few milligrams may be fitted to straps and worn on the wrist (W) or ankle or as a headband (H).

The interpretation of a recorded extremity dose may require knowledge of the radiation energy if the exposure is due to weakly penetrating beta radiation (less than 500 keV) or photon radiation (less than 20 keV).



Wrist, head and finger TLDs.

Small TLDs are ideal extremity dosimeters.

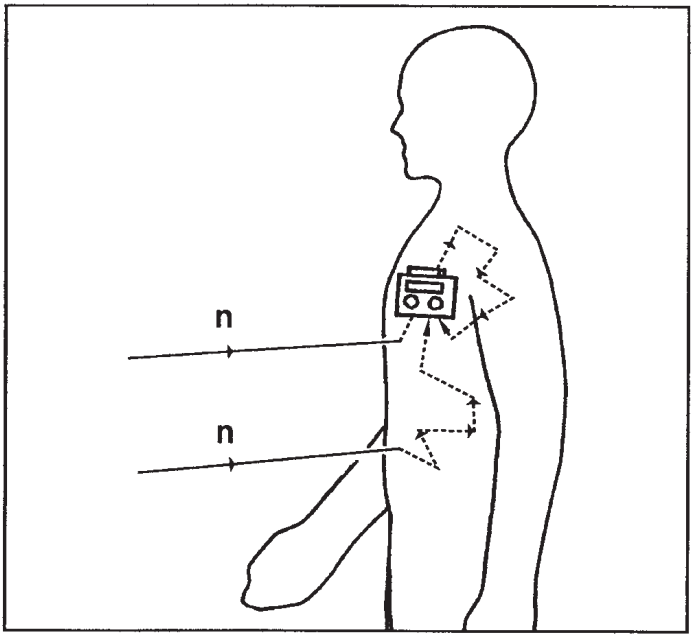
Extremity dosimeters are used when parts of the body are more exposed than others.

12. ALBEDO NEUTRON DOSIMETERS

Albedo dosimeters are designed to record neutron doses by using the body as a moderator to reduce intermediate and fast neutrons to thermal energies.

Doses as low as 100 μSv may be measured using LiF TLDs made with natural or lithium enriched in ^{6}Li. For neutrons with energies above 10 keV the sensitivity is significantly reduced and the measurement must be multiplied by a correction factor which is dependent on the neutron spectrum. Factors appropriate to nuclear power reactors vary between 10 and 70.

The albedo method is only satisfactory if the spectrum remains nearly constant. It is unsatisfactory for applications in which a major fraction of the dose equivalent is due to neutrons above a few hundred keV. It is generally inappropriate, for example, for industrial use of neutron sources (^{252}Cf, AmBe, etc.) or deuterium–tritium generators which have a large fraction of neutron energy above 1 MeV. In these situations, a constantly changing work geometry is likely to produce highly variable spectra.



Albedo TLDs measure neutrons that the body has thermalized.

Albedo TLDs measure fast and intermediate energy neutron doses.

Albedo TLDs must be in close contact with the body.

Albedo TLDs may be unsuitable for general industrial application.

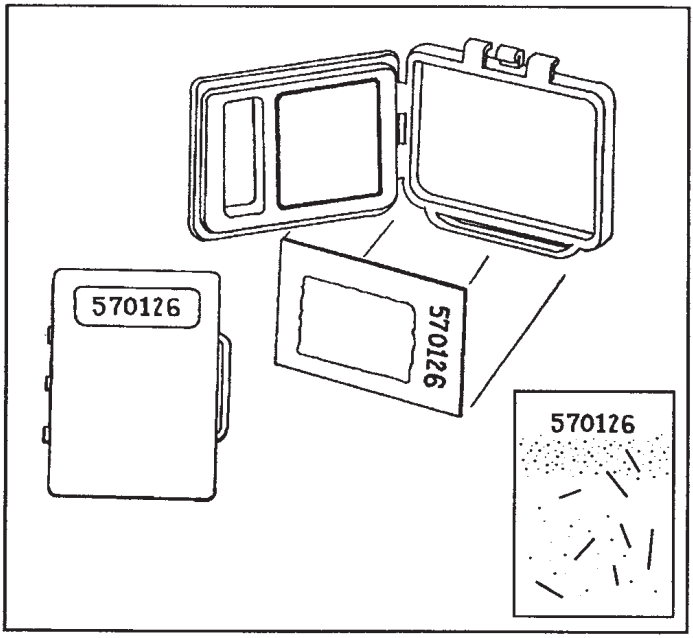
13. NUCLEAR EMULSION NEUTRON DOSIMETERS

A nuclear emulsion (nuclear track analysis, NTA) dosimeter comprises a film and holder designed to detect fast and thermal neutrons of energies above 0.7 MeV.

The film (typically an emulsion of a thickness of between 24 and 33 μm on a base) is prepared in dry nitrogen and sealed inside a special wrapper. When it is in the holder, incident fast neutrons interact (elastic scattering) with hydrogenous material surrounding the film and produce recoil protons. Thermal neutrons interact with nitrogen in the emulsion and thereby produce 0.6 MeV protons. The protons form ionization tracks in the emulsion. A dose of 50 μSv from AmBe neutrons will produce about one track per square millimetre. When the film is processed these can be counted using a high power ($\times$ 1000) microscope.

The difficult task of identifying tracks is aided by a lead filter in the front of the polypropylene holder which reduces fogging (film darkening) caused by X and gamma radiations. A boron loaded plastic filter at the back of the holder absorbs albedo thermal neutrons.

Track fading is minimized by the moisture proof wrapper but the latent (undeveloped) images still fade with time, limiting possible wearing periods to one or two months in ideal conditions. The wrapper must not be damaged nor the film subjected to excessive heat.



An NTA dosimeter and processed film.

An NTA dosimeter comprises a film and holder.

Processed films reveal tracks in the emulsion caused by neutrons.

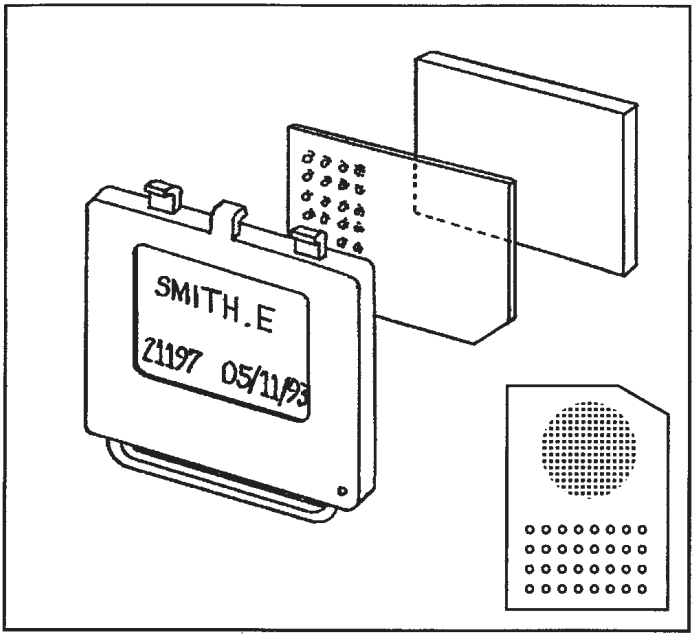
14. SOLID STATE NEUTRON TRACK DOSIMETER

A solid state neutron track dosimeter (SSNTD) utilizes suitable plastic such as polyallyldiglycol carbonate (PADC or CR-39) as the detector in a holder to detect neutrons of energy above 150 keV. This can be extended to include thermal neutrons by placing a polyamide or boron insert in contact behind the PADC.

When the detector is in the holder, incident fast neutrons interact (by elastic scattering) with hydrogen atoms in the polypropylene holder and produce recoil protons. Thermal neutrons interact with nitrogen in the polyamide insert, if used, and produce 0.6 MeV protons. The protons directly damage the surface of the detector. When the detector is processed, including an electrochemical etch, the damage forms visible pits. At low (× 40) magnification, their number can be counted automatically by an image analyser and related to the neutron dose equivalent.

A system of holes in the detector may be used for decoding by the reader to identify the wearer. The detector may be purchased with a layer of protective plastic or sealed in a bag to prevent scratching or buildup of background tracks due to alpha particles from natural radon and radon daughter products.

Since solid state neutron track dosimeters are not sensitive to photons and do not have serious fading problems, they may be worn for 3 months or longer.



An SSNTD dosimeter and processed insert.

A track etch dosimeter comprises a PADC insert and a suitable holder.

Processed PADC inserts reveal pits caused by neutrons.

15. CRITICALITY NEUTRON DOSIMETERS

Criticality dosimeters are used in nuclear installations where the movement of reactor fuel raises the possibility of a criticality accident. This includes fuel handling and reprocessing areas and facilities where ^{233}U, ^{235}U or ^{239}Pu are used in quantities greater than a few grams.

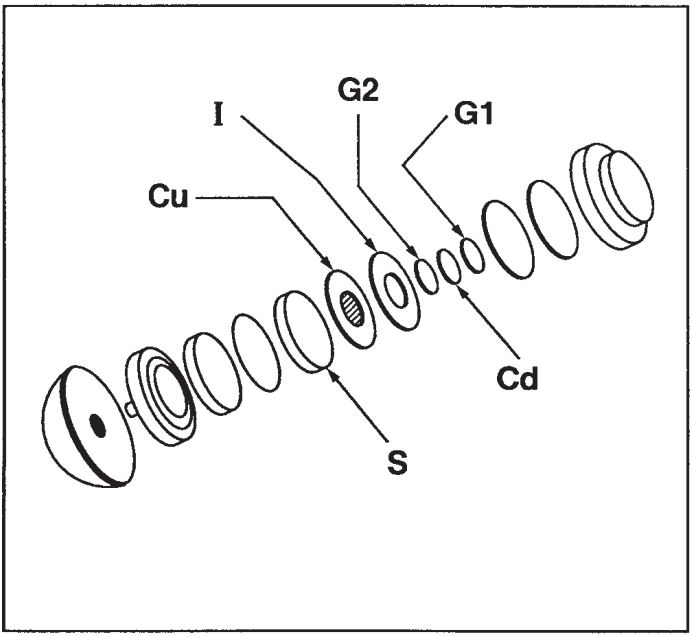
The activation foils used in such dosimeters become radioactive when irradiated by the large release of neutrons associated with a criticality accident. They are unsuitable for routine neutron dosimetry because of their poor sensitivity and rapid loss of information (decay) following exposure.

A criticality dosimeter (locket or button) is a small box usually containing several foils to provide information on the neutron dose and energy spectrum:

gold — thermal neutron measurement (G1, G2)
indium — thermal and fast neutron measurement (I)
copper — intermediate neutron measurement (Cu)
sulphur — fast neutron measurement (S).

Cadmium (Cd) is used to shield foils to differentiate between thermal neutron and intermediate neutron exposure. Following exposure, the induced radioactivity is measured by counting the beta or gamma radiation emitted by the foil. The activity is proportional to the neutron dose.

In a different form of criticality dosimeter, fissile materials are placed between track etch detectors (see Section 14). Fission fragments damage the plastic when the fissile materials are exposed to neutrons of certain energies. The materials used in these fission dosimeters are radioactive even before they have been exposed to neutrons.



An exploded view of the components of a criticality locket.

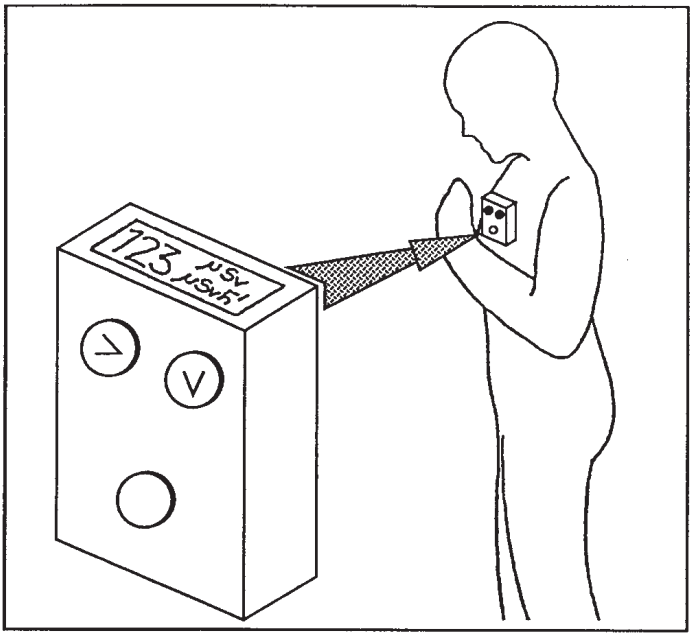
Neutrons cause nuclear interactions, activation and fission in foils.

Various activation foils are used in criticality lockets.

16. DIRECT READING DOSIMETERS

Direct reading (active) dosimeters are lightweight, compact instruments that provide an immediate indication of the dose or dose rate. Wide variations exist in their cost and design but, in general, such devices have an unsatisfactory energy response which may be either heightened or poor at low photon energies. They often have no response to beta radiations. Ionization chambers, Geiger counters and solid state detectors form the basis of these dosimeters (see Sections 10, 12 and 18 of the Manual on Workplace Monitoring for Radiation and Contamination (IAEA-PRTM-1)).

An electronic personal dosimeter (EPD) incorporating multiple, energy compensated solid state detectors has been developed to measure $H_p(10)$ and $H_p(0.07)$ to the accuracy required of passive dosimeters. These devices measure instantaneous dose rates and record peak dose rates, dose equivalent and chronological details. Adjustable dose and dose rate alarms are provided and the dosimeter may be linked to a computer to transfer long term measurements of dose to an appropriate record.



An electronic personal dosimeter.

Various detectors are used to make direct reading dosimeters.

Dose and dose rate readings and alarms are possible using EPDs.

17. QUARTZ FIBRE ELECTROMETERS

A quartz fibre electrometer (QFE, QFElectroscope, QF dosimeter or condenser-type dosimeter) is designed to provide a direct reading of cumulative exposure.

Cylindrical and about the size of a pen, a QFE contains:

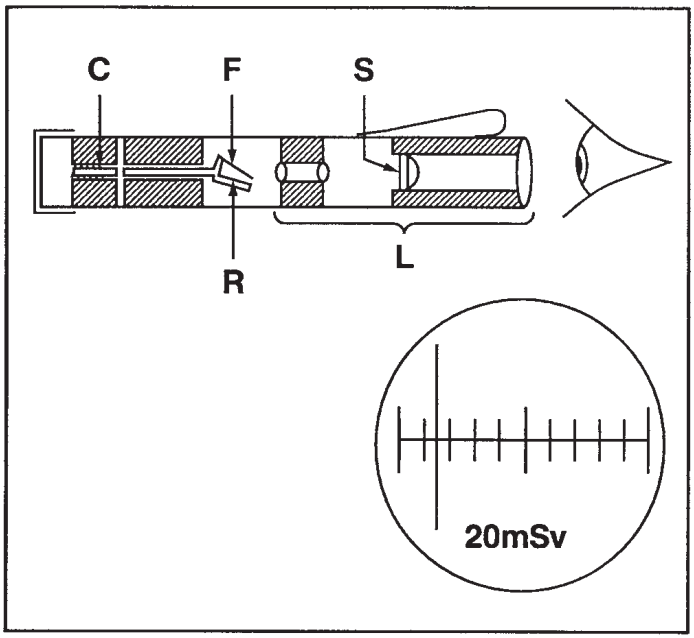
C — spring-loaded charging pin;
F — quartz fibre;
L — lens system.
R — repellor;
S — reticle;

When plugged into a charger, electrical charge flows up the charging pin to the quartz fibre and repellor. A light illuminates the inside of the QFE so that the position of the quartz fibre is seen as the repellor and fibre repel each other. The amount of charge is adjusted so that the fibre's deflection is set against zero on the scaled reticle.

When ionizing radiation ionizes the air in the chamber, the charge on the fibre and repellor is reduced allowing the fibre to move towards the repellor. If the QFE is held up to light and viewed, the fibre appears to indicate the dose received on the reticle.

QFEs with maximum ranges of 2 mSv to 10 Sv are available. Different types detect thermal or fast neutrons, betas or low or high energy photons. A tissue equivalent QFE is also available but it does not respond to all radiations. Accuracy of measurement is poor.

QFEs are sensitive to shock, vibration, temperature, environmental contamination and other factors which can affect the rate at which charge dissipates to produce erroneous indications of the dose received. However, they are relatively inexpensive and provide immediate approximations of dose for emergency workers.



Reading the scaled reticle of a quartz fibre electroscope (shown in section).

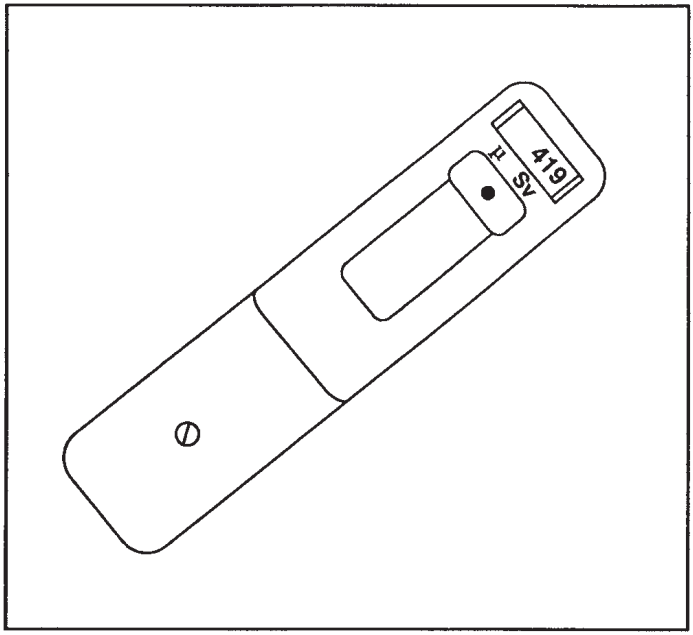
QFEs provide convenient direct readings of exposure.

QFEs are less accurate than other dosimeters and easily affected by shock.

18. USE OF DIRECT READING DOSIMETERS

Direct reading dosimeters have numerous applications which are complementary to those of passive dosimeters. Most importantly, in emergencies and other situations in which acute exposures are possible, they can confirm that the doses received do not exceed dose limits. Alarm dosimeters should be pre-set sufficiently below the limits to allow time for workers to retreat. Workers regularly at high risk should use direct reading dosimeters that cannot be switched off.

Direct reading dosimeters typically measure doses as low as 1 μSv, which is at least ten times more sensitive than many passive devices. At low dose rates the accuracy of the measurement may be poor but adequate and frequent readings will permit work to be analysed to determine which parts of a procedure contribute most to the overall dose. Audible indications of dose rate also maintain a worker's awareness of exposure so that procedures can be refined to optimize the dose received. Dosimeters issued to monitor personal doses should not be confused with others which may be used for environmental measurements.



A direct reading dosimeter.

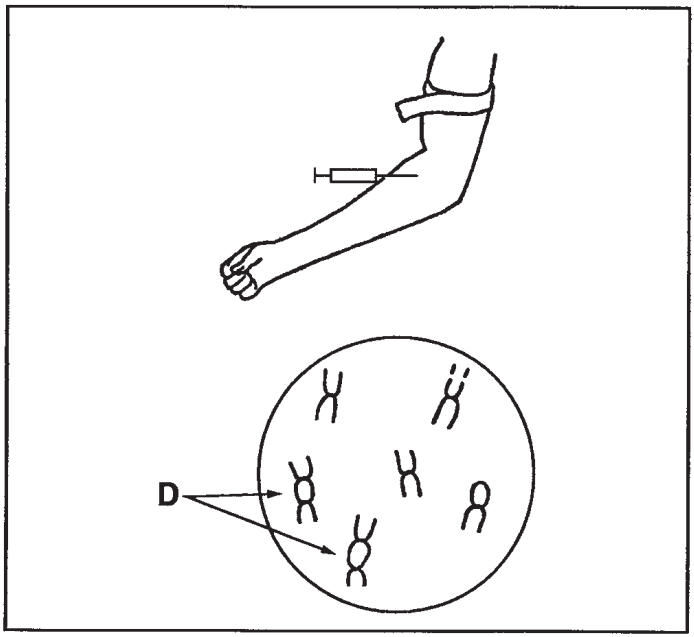
Active (direct reading) dosimeters have many useful applications.

Some dosimeters achieve high sensitivity but at reduced accuracy.

19. BIOLOGICAL DOSIMETRY FOR ASSESSING EXTERNAL EXPOSURE

Small changes in the body that result from exposure to radiation may be measured as indicators of such exposure. However, the techniques possible are of low sensitivity and involve sample processing which is viable only after suspected accidental exposure. Possible indicators include biochemicals released by certain irradiated organs, and induced biophysical states in tooth enamel, fingernails and bone from which signals are measurable using instruments such as an electron spin resonance spectrometer. Cellular changes such as reduced hair diameter, sperm abnormalities and a reduced peripheral blood cell count have also been studied. Indications of the whole body dose may be calculated by measuring the decline of circulating white blood cells (lymphocytes) in the few days after an acute irradiation of more than about 0.5 Sv.

A more sensitive and reliable estimate of whole body dose is obtained by examining blood cells for evidence of radiation damage (chromosome aberrations). Lymphocytes are treated with chemicals to stimulate cell division and stained so that the chromosomes (strands of genetic material) are visible under a microscope. At least 500 cells of a blood sample are examined usually to determine the number of dicentrics (D), aberrations which have two centromeres. The incidence of dicentrics per cell is dose dependent and measurable above doses of about 100 mSv of ^{60}Co gamma rays, 50 mSv of 250 kV_p X rays and 10 mSv of approximately 1 MeV neutrons.



A blood sample is taken for chromosome aberration analysis.

Some biochemical and biophysical changes are dose dependent.

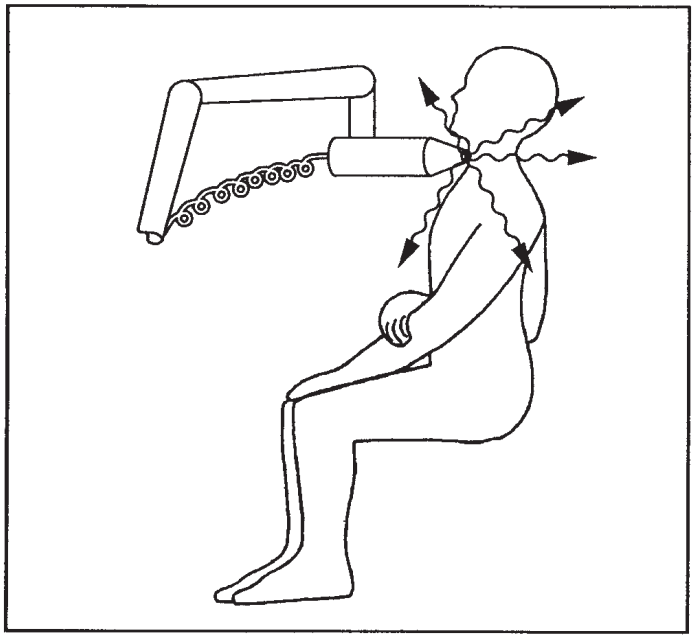
Blood chromosome aberrations are good indicators of dose.

20. ORGAN MONITORING FOR INTERNAL EXPOSURE

Internal emitters of penetrating radiations may be quantified by in vivo monitoring. This requires suitable arrangements of monitoring instruments to measure the radiations as they emerge from the body.

The measurements are normally made with scintillation or solid state detectors which are described in Sections 15 and 18 of the Manual on Workplace Monitoring for Radiation and Contamination (IAEA-PRTM-1). A number of detectors are often arranged in arrays to increase their surface area and detection efficiency. The systems are calibrated using phantoms which simulate the measurement geometries. A simple calibration may be based on a tissue equivalent container filled with a solution of the radionuclide(s) being investigated. However, more complex phantoms which accurately represent the human body may be needed. When properly calibrated, the system can be used to (a) identify the internal emitters and (b) determine the total activity in the body.

Simple, portable systems may be used for specific tasks. For example, the uptake of radioiodine in the thyroid may be measured by a detector placed at the neck. Similar systems may be used to assess contaminated wounds.



A measurement of radioiodine uptake in the thyroid gland.

In vivo monitoring is used to detect radiations as they leave the body.

Appropriate detectors can identify and quantify an internal emitter.

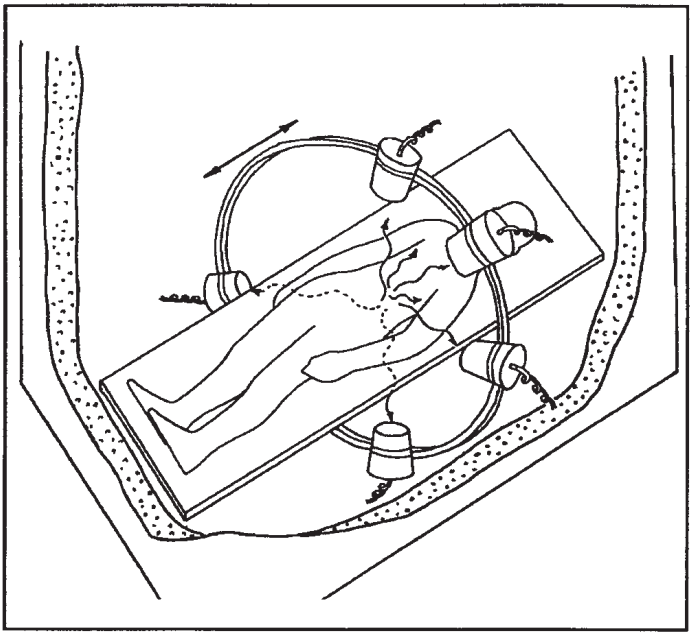
Measurement systems need to be calibrated.

21. BODY MONITORING FOR INTERNAL EXPOSURE

In vivo monitoring of the whole body, except the lower legs, may be carried out by seating the worker on a tilted chair in front of a large area detector. By replacing the chair with a concave bed, all parts of the body will be equidistant from the detector and a very uniform response is obtained. These systems, properly calibrated, can be used to identify the radionuclides present as well as the total activities in the body.

If the detectors are arranged to scan the worker by moving the detectors or the bed or both, the identities of the radionuclides, the total activities and their distribution in the body can be determined. Four, six or eight large detectors are often arranged above and below the bed to increase the detection efficiency. Such systems, called whole body monitors, are usually housed inside shielded rooms reducing background radiation and allowing even lower activities to be measured.

Shielded facilities are essential to detect the weakly penetrating, low energy X rays emitted by plutonium in the lung.



A whole body monitor inside a shielded room.

In vivo whole body monitors often comprise several detectors.
Lower activities are measured by detectors inside a shielded room.
The identity, quantity and distribution of activity can be measured.

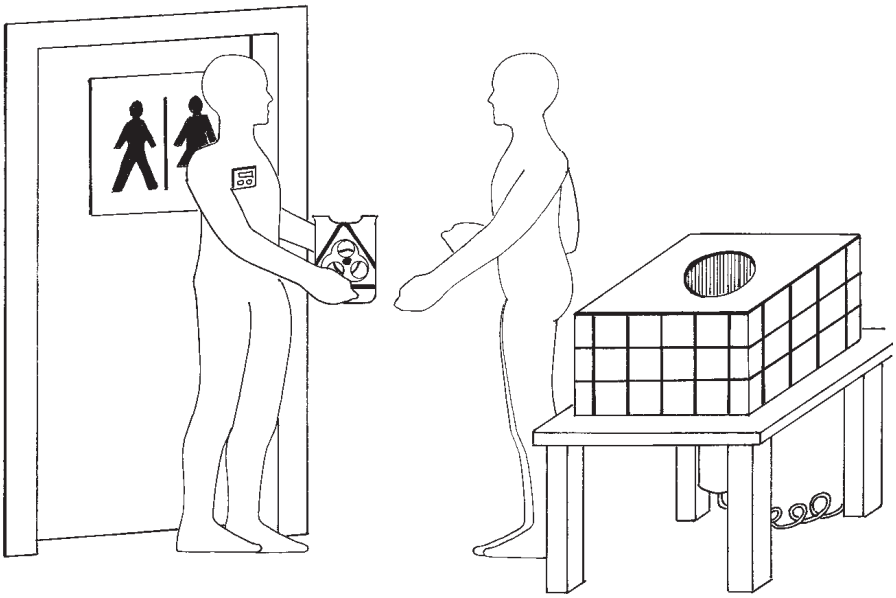
22. BIOLOGICAL ASSESSMENTS OF INTAKES OF RADIOACTIVITY

The committed dose from an intake of radioactive material is often determined indirectly by measuring the activity excreted from the body and calculating the total intake or specific organ retention of radioactivity (see Section 23).

Faecal sampling is a sensitive method used primarily to estimate intakes of insoluble material. A large fraction of an intake is cleared in the faeces within the first few days, even when the initial intake was inhaled. Urine sampling is commonly used to monitor for soluble materials that readily enter but then are cleared from the blood and systemic circulation of the body. Analysis may necessitate samples being accumulated over a period (days) to obtain average excretion rates or, for example, to be measurable.

The number and timing of samples taken need careful consideration based on the biological and physical characteristics of the radionuclide(s) and other factors. Chronic exposure to radionuclides with either a short physical half-life or rapid clearance rate requires more frequent (weekly) sampling. Analyses for long lived or tenaciously retained radionuclides may require less frequent (monthly or annual) sampling or the analyses may yield additional information if carried out after a worker's period of absence from the workplace. Acute internal exposures are assessed by obtaining a series of faecal and/or urine samples and monitoring the declining excretion of activity. The results are then related back to the time of the suspected exposure to calculate the total intake of radioactivity.

Other methods of screening for intakes include monitoring nose blows and nasal swabs, measuring breath for volatile liquids or materials that are metabolized to gases, and assaying blood and other serum such as sweat (tritium excretion). These techniques are generally only qualitative and their use for dose assessment will be highly uncertain.



Biological samples are collected to estimate intakes of radioactivity.

A proportion of an internal emitter is excreted.

Urine and faeces are collected to measure excreted radioactivity.

Excretion rates are calculated to determine the total intake.

23. COMPARTMENT MODELS FOR CALCULATING INTERNAL EXPOSURE

In the absence of specific information related to the conditions of an exposure, the International Commission on Radiological Protection (ICRP) recommends the use of compartment models for calculating internal doses.

The general model for the gastrointestinal tract has four compartments:

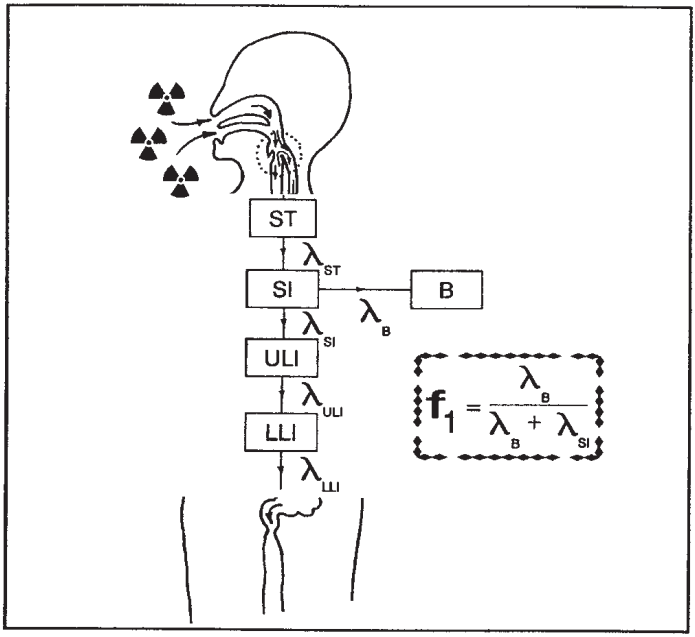
ST — the stomach, from which no absorption occurs. Nuclides pass to the next compartment, on average, within one hour (1 h).

SI — the small intestine, in which absorption takes place. The gut uptake fraction which is absorbed into the body fluids (labelled B) depends on the nuclide and is called the f_1 value. For caesium the f_1 value is 1, i.e., it is all absorbed, but for insoluble plutonium the absorption fraction is only 10^{-5} (1/100 000) and the majority is excreted in the faeces. The mean residence time in the small intestine is 4 h.

ULI — the upper large intestine, where the mean residence time is 13 h.

LLI — the lower large intestine, where the mean residence time is 24 h. This organ will be the most heavily irradiated if the absorption fraction is low, particularly for short physical half-life emitters of relatively non-penetrating radiation.

The model is used with measured excretion rates to determine the total intake. The ICRP publishes much more detailed information for use with the models.



The gastrointestinal tract compartment model with the uptake fraction f_1.

Compartment models of the body represent organs containing radioactivity.

Mathematical equations express the movement and uptake of radioactivity.

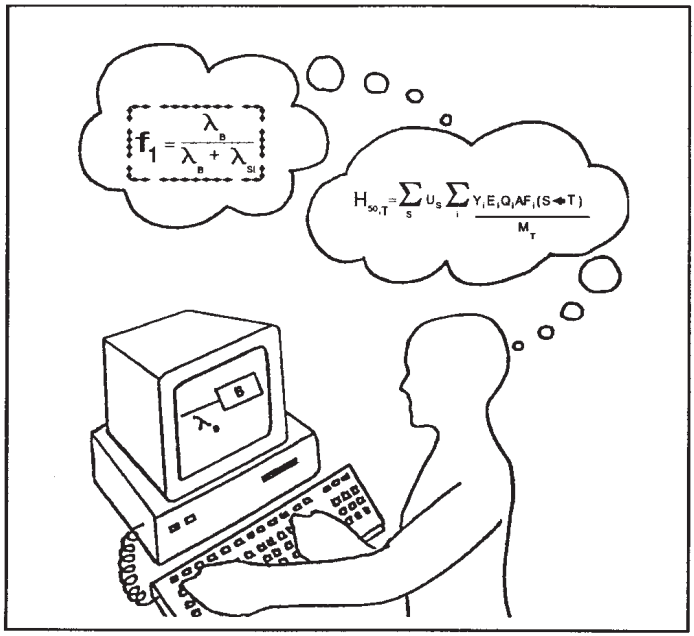
Measurements and models explain the behaviour of internal emitters.

24. DOSES TO LUNGS AND OTHER ORGANS

The lung model now used has 33 compartments over the extrathoracic and thoracic regions. Doses are calculated for inhaled particles which may be absorbed with a timescale that is fast (F), moderate (M) or slow (S). The solubility of inhaled materials was previously classified in terms of whether the material was likely to be cleared from the lung within a day or less (D), within a few weeks (W), or was insoluble and retained in the deep lung for more than a year (Y).

Material which crosses the lung wall or is absorbed from the small intestine enters a transfer compartment comprising the body fluids, blood or lymph. It may then be directly excreted (half of it within 6 h, that is a half-time of 6 h) or transferred to a body organ. A radiation dose is received as the radionuclide decays in the lungs, gastrointestinal tract or bladder, transfer compartment or in specific organs. All of the energy of alpha or low energy beta emissions is likely to be absorbed within the organ, but if photons are emitted, the source organ(s) will also irradiate other target organs.

The International Basic Safety Standards provide the dose per unit intake (dose coefficients) for a number of ingested radionuclides and inhaled particles of different lung classes.



Committed dose calculations using dose per unit intake and uptake measurements.

Various biological and physical factors affect the organ dose(s).

Models predict dose per unit intake for different classes of emitters.

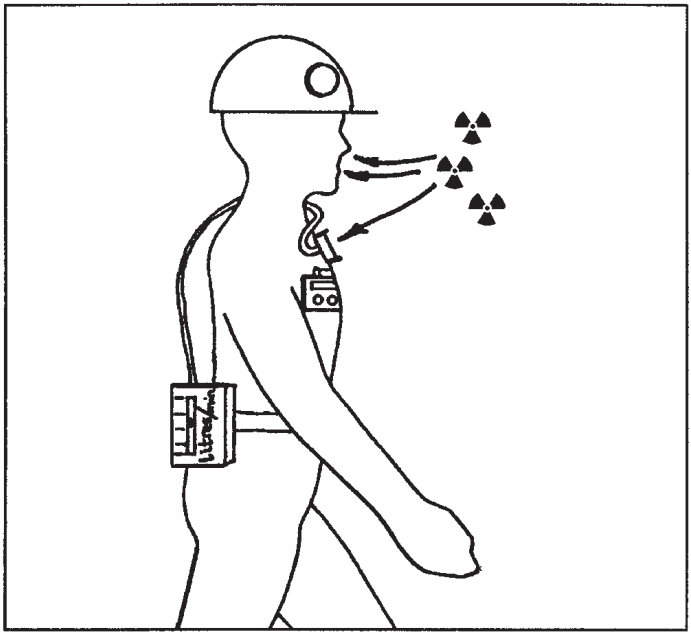
The source organ and possibly other target organs receive dose(s).

Calculations of organ dose(s) use biological and in vivo measurements.

25. PERSONAL AIR SAMPLERS FOR ASSESSING INTERNAL EXPOSURE

Biological assessments and in vivo monitoring require significant investment in resources and expertise. For more routine assessments of the probable intake of activity, personal air samplers (PASs) are issued and the results used to select individuals for further assessments. PASs are small, battery powered, filtered air pumps which the workers wear with the air intake as close as possible to the nose and mouth. Sections 5 and 28 of the Manual on Workplace Monitoring for Radiation and Contamination (IAEA-PRTM-1) provide further details.

At the end of each working period, the filter papers are assessed for contaminants and the activity concentrations (Bq m^{-3}) are calculated using the known air flow rate. The results are compared with an appropriate reference level such as the derived air concentration (DAC) or fractions of it. The DAC relates to a specific radionuclide and specified physical parameters (e.g., particle size). If breathed at a given rate for a working year, a DAC would result in the worker receiving the annual limit on intake from that radionuclide.



A PAS is worn to measure the probable intake of radioactivity.

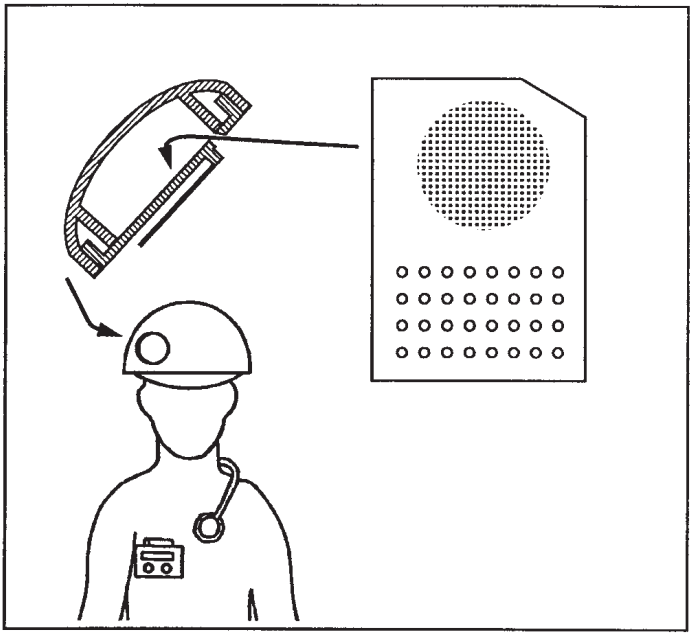
PASs are used with DAC to determine probable low internal doses.

PAS screening to select workers for biological and in vivo measurements.

26. RADON DOSIMETERS FOR ASSESSING INTERNAL EXPOSURE

Miners receive potentially significant lung doses from naturally occurring radon gases (especially radon-222) and their solid decay products. Large spatial and temporal variations occur in the concentrations of these radioactive gases. The short half-life daughters may also not be in equilibrium with the parent, i.e., their concentrations are not simply related to that of the parent gas. Measurements of the concentrations of radon and/or the daughters are often inadequate because of these variations. Integrating dosimeters are required.

PASs and passive TLDs (see Section 9) are unsuitable for measuring the radon daughters under mining conditions. A radon track etch dosimeter (see Section 14) has been more successful. It is essentially a small diffusion chamber into which radon can enter but not the daughters or dirt. Daughters formed inside the chamber emit alpha particles which leave tracks on the detector. When the detector is processed, the pits are counted to provide assessments of doses greater than about 0.2 mSv. The dosimeter should be attached to the outside of a helmet or clothing. However, a dosimeter carried in the pocket will provide a measurement. When they are not being worn, personal dosimeters should be stored with control dosimeters to enable the occupational exposure to be assessed. It may also be necessary to directly measure a gas/daughter equilibrium factor in the workplace in order to convert the measured gas concentrations to doses to workers.



A radon dosimeter with processed PADC insert.

Variable exposure to radon should be measured using a dosimeter.

PADC radon dosimeters perform satisfactorily in mining conditions.

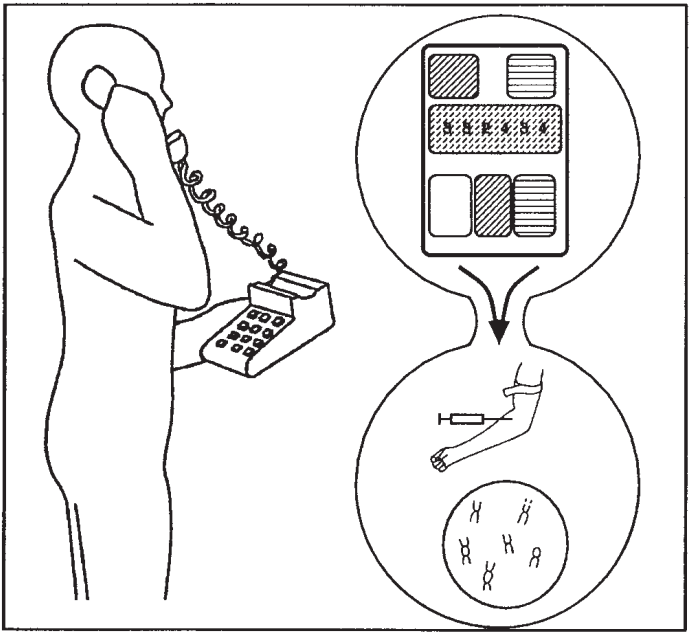
Equilibrium factors and background doses are used to assess doses to miners.

27. INVESTIGATION LEVELS FOR USE WITH RECORDED DOSES

Personal dosimeters, when properly selected, used and assessed by qualified experts, give accurate estimates of external dose. However, the dose measured by a dosimeter only indicates the dose received by the worker. Measured doses should always be evaluated to ensure that the recorded dose is a true representation of the dose received by the worker. Unexpected results should be more fully investigated.

Accidental exposure conditions can be reconstructed to directly measure the doses received by the worker.

Additional personal monitoring should be considered. For example, if PAS results exceed an agreed reference level (such as 30 DACh or 30 h exposure at the DAC), excreta samples could be requested or in vivo measurements provided. If a worker's dosimeter shows contamination, urine analysis could be considered. Dosimeter results exceeding 100 mSv may be confirmed by chromosome aberration analysis. Chromosome aberrations persist over many years. Therefore an investigation must take into account any medical exposures or prior occupational exposure.



An investigation into a high film badge dose may require blood chromosome aberration monitoring.

Dosimeters represent the doses received by the wearer.

Investigation levels are set to examine high and unexpected results.

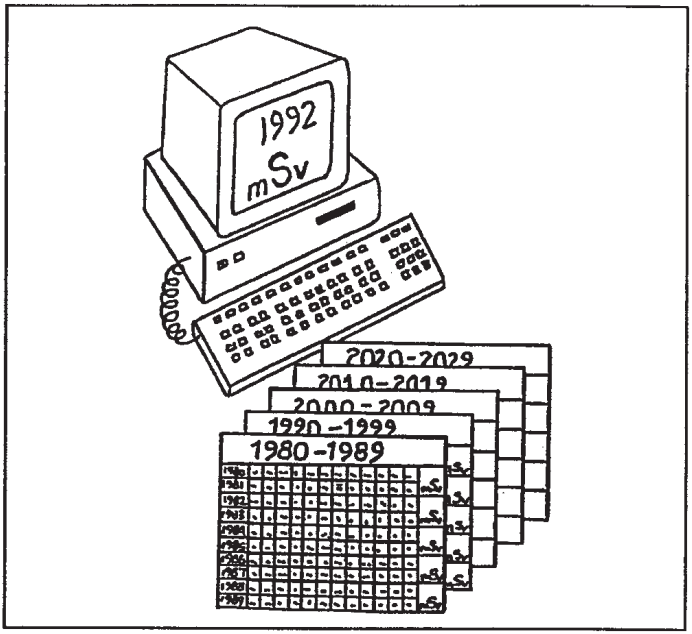
Investigations involve analysis and, possibly, special dosimetry.

28. DOSE RECORDS

Dosimeter results should be formally recorded and kept in compliance with regulatory requirements. These will specify the retention period(s) (at least thirty years) and often the format. Dose records have the following purposes.

(a) They demonstrate compliance with regulatory requirements, showing that controls are used to keep doses as low as reasonably achievable and that dose limits are not exceeded.
(b) They indicate trends, such as increased doses, to alert the employer/RPO when practices or equipment deteriorate.
(c) They allow workers and employers to compare procedures and identify the best practical means of working which result in the lowest doses.
(d) They aid the medical adviser's assessments and means of controlling detriment to an individual worker.
(e) They provide long term medical and legal assurance for both worker and employer in the event that the worker contracts a radiation linked disease in later life.
(f) They supply data for epidemiological and other studies into the biological effects of ionizing radiation.

Dose records should contain the results of all special dosimetry including assessments of doses to individual organs. Each worker should have only one current dose record, which should be protected against loss or damage. When employment is terminated, a summary of doses received should be prepared that the worker may make available to a new employer, as appropriate.



Computerized dose records provide a convenient means of storing and analysing measurements.

Dose records are kept in suitable format for a range of purposes.

Short and long term analyses of occupational exposure are carried out.

One dose record containing all dosimetric results should be kept for each worker.

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