Manual on SHIELDED ENCLOSURES

Incorporating:
Applications Guide
Procedures Guide
Basics Guide

PRACTICAL RADIATION SAFETY MANUAL

Manual on SHIELDED ENCLOSURES

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Applications Guide

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Basics Guide

INTERNATIONAL ATOMIC ENERGY AGENCY

MANUAL ON SHIELDED ENCLOSURES
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FOREWORD

The use of radiation sources of various types and activities is widespread in industry, medicine, research and teaching in virtually all Member States of the IAEA and is increasing. Although a number of accidents have caught the attention of the public in recent years, the widespread use of radiation sources has generally been accompanied by a good safety record. However, the control of radiation sources is not always adequate. Loss of control of radiation sources has given rise to unplanned exposures to workers, patients and members of the public, sometimes with fatal results.

In 1990 the IAEA published a Safety Series book (Safety Series No. 102) providing guidance on the safe use and regulation of radiation sources in industry, medicine, research and teaching. However, it was felt necessary to have practical radiation safety manuals for different fields of application aimed primarily at persons handling radiation sources on a daily routine basis, which could at the same time be used by the competent authorities, supporting their efforts in the radiation protection training of workers or medical assistance personnel or helping on-site management to set up local radiation protection rules.

A new publication series has therefore been established. Each document is complete in itself and includes three parts:

— **Applications Guide** — which is specific to each application of radiation sources and describes the purpose of the practice, the type of equipment used to carry out the practice and the precautions to be taken.

— **Procedures Guide** — which includes step by step instructions on how to carry out the practice. In this part, each step is illustrated with drawings to stimulate interest and facilitate understanding.

— **Basics Guide** — which explains the fundamentals of radiation, the system of units, the interaction of radiation with matter, radiation detection, etc., and is common to all documents.

The initial drafts were prepared with the assistance of S. Orr (UK) and T. Gaines (USA), acting as consultants, and the help of the participants of an Advisory Group meeting which took place in Vienna in May 1989: J.C.E. Button (Australia), A. Mendonça (Brazil), A. Olombel (France), F. Kossel (Germany), Fatimah, M. Amin (Malaysia), R. Siwicki (Poland), J. Karlberg (Sweden), A. Jennings (Chairman; UK), R. Wheelton (UK), J. Glenn (USA) and A. Schmitt-Hannig and P. Zúñiga-Bello (IAEA).

These drafts were revised by R. Wheelton from the National Radiation Protection Board in the UK and B. Thomadsen from Wisconsin University in the USA. In a second Advisory Group meeting held in Vienna in September 1990, the revised drafts were reviewed by P. Beaver (UK), S. Coornaert (France), P. Ferruz (Chile), J. Glenn (USA), B. Holliday (Chairman; UK), J. Karlberg (Sweden), A. Mendonça (Brazil), M.A. Mohamad-Yusuf (Malaysia), J.C. Rosenwald (France), R. Wheelton (UK), A. Schmitt-Hannig (Germany), and P. Ortíz and P. Zúñiga-Bello (IAEA). Finalization of all six manuals was carried out by A. Schmitt-Hannig, Federal Office for Radiation Protection (Germany) and P. Zúñiga-Bello (IAEA).

CONTENTS

APPLICATIONS GUIDE: SHIELDED ENCLOSURES

Need for Shielded Enclosures

In all applications of ionizing radiation, the radiation dose to the users, and to others in the vicinity, must be kept as low as reasonably achievable and, in any case, below internationally agreed dose limits. This is possible by applying a combination of four methods:

(1) By using a source which is the most suitable for the particular application. As radioactive sealed sources and machines involve only an external hazard they are, in general, preferable to open sources. The hazard is further minimized by choosing a source of sufficient activity, and the most appropriate radiation energies for the application.
(2) By keeping the time that the user and others are exposed to the radiation as short as possible.
(3) By maintaining the necessary distance between the source and the user and greater distances between the source and other persons.
(4) By placing suitable shielding materials of sufficient thickness around the source or the application.

Physical means exist to ensure that: exposure times are kept to a minimum; barriers remain in place to keep people away from the hazardous areas; and shielding materials are in place before a source can be exposed. These engineered controls are preferable to administrative controls which rely on individuals obeying instructions not to remain longer than necessary near sources, not to pass barriers, and to use shielding materials.

Forms of Shielded Enclosure

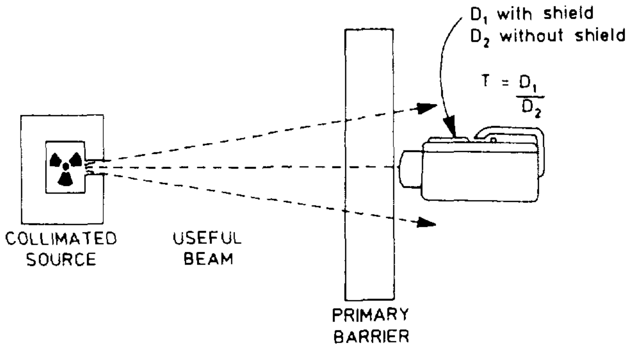
A shielded enclosure is an enclosed space engineered to contain ionizing radiation and to provide adequate shielding for persons in the vicinity. They range in size from relatively small cabinets, for example to contain the X ray machines used to examine unopened mail and baggage; through walled compounds in which radiography is carried out; to large chambers in which very high doses are delivered for irradiation purposes such as disinfestation, sterilization and the induction of changes in the matter being irradiated. An enclosure is essential for work with a radiation source that has a high dose rate output. To rely on distance alone to reduce the dose rate would require a prohibitively large exclusion zone. Similarly, other sources need to be suitably enclosed to be used close to areas that are either occupied, or to which persons have a right of access.

The design principles are similar for all enclosures although different characteristics are incorporated depending on whether the enclosure is to be suitable for X ray, gamma or neutron radiation.

Primary Shielding for Enclosures

Sufficient shielding will be required to reduce the accessible, transmitted dose equivalent rates to an acceptable level, for example 7.5 $\mu Sv \cdot h^{-1}$. There may be a need for a Controlled Area outside an enclosure.

The amount of shielding needed, and consequently the cost, can be minimized by restricting the number and area of internal surfaces that primary radiation is allowed to strike. This higher energy radiation will need primary barriers, which are either comparatively thicker or made using different materials. The restrictions can often be achieved by collimating the radiation source, that is reducing and shaping the radiation to a useful beam which can then be directed only towards suitable barriers.



The transmission factor as an indication of the effect of the primary barrier.

To estimate the necessary thickness of a primary barrier its transmission factor T must first be calculated. If D_1 is the maximum dose rate to be allowed (for example 7.5 $\mu Sv \cdot h^{-1}$) at a position close to the outside surface of the barrier and D_2 is the dose rate at the same place when the barrier is not there, then T is equal to D_1 divided by D_2. To calculate D_2, the enclosure's designer will need *design parameters, which are basic assumptions about:*

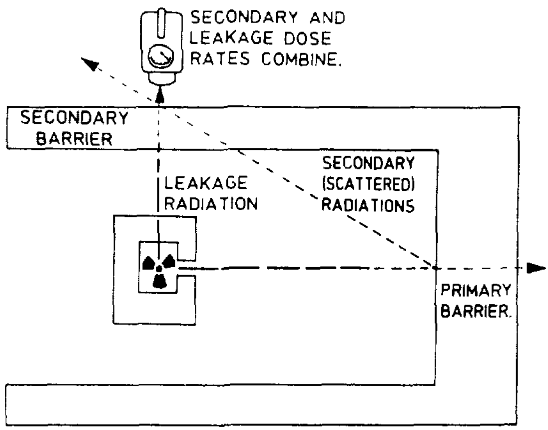
- which radionuclides or machines are to be used;
- the upper limit of activity of the radioactive source or the electrical parameters of the machines that can be used; and
- the minimum distances between the radiation source and the barrier's internal surface.

An accurate estimate of the thickness of the shield needed requires transmission graphs which are published for different radionuclides (and machine parameters) and different shielding materials. However, a simplified estimation of the primary barrier's thickness which may tend to overestimate the shielding is possible. If the calculated transmission factor, D_1/D_2, is one-tenth then a primary barrier equivalent to a tenth value thickness (TVT, see Basics Guide) is used; to obtain a reduction of one-hundredth, two TVTs are used; for a reduction of one-thousandth, three TVTS are used; and so on. The HVTs (half value thicknesses) and TVTs are dependent on the primary radiation's energy.

Radiation source	Typical primary barrier thicknesses	
	Lead (mm)	Concrete (cm)
Dental, veterinary X ray	0.5	5
Medical, diagnostic X ray	2	15
Industrial X ray (250 kV)	10	50
Iridium-192 (1 TBq)	70	60
Cobalt-60 (185 GBq)	180	80
Linear accelerator (8 MV)	300	200

Secondary Shielding for Enclosures

Barriers (often called secondary barriers) are required to provide sufficient shielding for secondary radiation which is scattered out of the useful beam and also leakage radiation which has been transmitted through the sides of the housing which contains the radioactive source or X ray machine. Although the secondary radiation has lower energies than the primary radiation, leakage radiation (which must not be confused with tests for leakage of radioactive substance which are carried out on sealed sources) sometimes has energies as high as those of the primary radiation. This often dictates the thickness of secondary shielding required, which is then calculated in a manner similar to that used to calculate the primary barrier thickness.



Secondary barriers are used to shield secondary radiations.

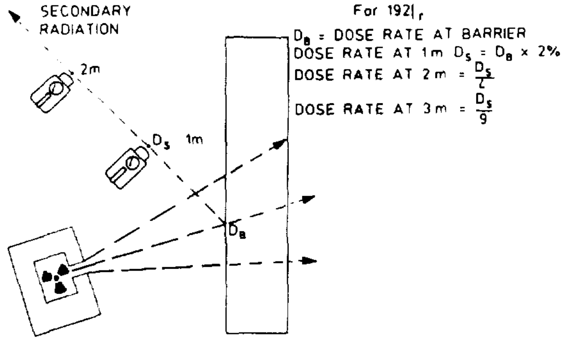
Various standards set limits for leakage of radiation from X ray machine housings and gamma radiography exposure containers. The latter are used for industrial radiography and are described in the Applications Guide on Gamma Radiography.

The radiation leakage from an industrial X ray machine must not exceed 10 $mSv \cdot h^{-1}$ at 1 m from where the X rays originate. Linear accelerators and other very high voltage machines should not leak more than 0.1% of the dose rate in the useful beam. Such machines only leak radiation whilst they are electrically supplied. However, dose rates will exist constantly around exposure containers. The containers may be Class M — mobile, or Class F — fixed. The latter are designed to shield much higher source activities than those usable outside an enclosure. If the ISO 3999-**** Apparatus for Gamma Radiography — specifications concerning the construction, markings and dose rate limits are complied with, the maximum dose rates around an exposure container will be as follows:

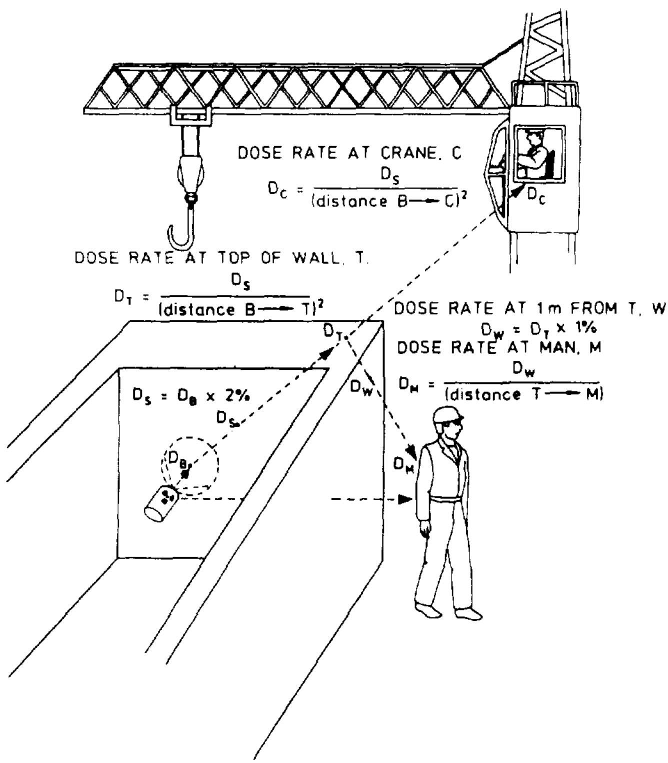
Class of exposure container	Maximum allowed dose rate ($\mu Sv \cdot h^{-1}$)			
	On external surface of container		50 mm from external surface of container	1 m from external surface of container
Class M	2000	or	1000	50
Class F	2000	or	1000	100

Complex calculations are necessary to obtain precise values of the dose rates due to scattered radiation. These take into account the energy of the radiation before it interacts, the size of the beam, the nature of the medium with which the radiation interacts and the direction of scatter. However, for large area primary beams, a very much simplified estimation of the dose rates due to scattered radiation can be made. This assumes that the dose rate at 1 m from the scattering point will be a small, fixed percentage of the dose rate at the scattering point. The following values would tend to overestimate the scattered dose rates:

Radiation source	Maximum scatter to 1 m from the scattering point
Industrial X rays (100 to 300 kV)	3.6%
Iridium-192 gamma radiations	2%
Cobalt-60 gamma radiations	1%



Using the figures given to estimate the scattered dose rate at 1 m from the wall, floor, radiographed object or other scattering point, the consequent dose rates at greater distances can be calculated using the inverse square law.



Calculation of dose rates outside an open-topped enclosure.

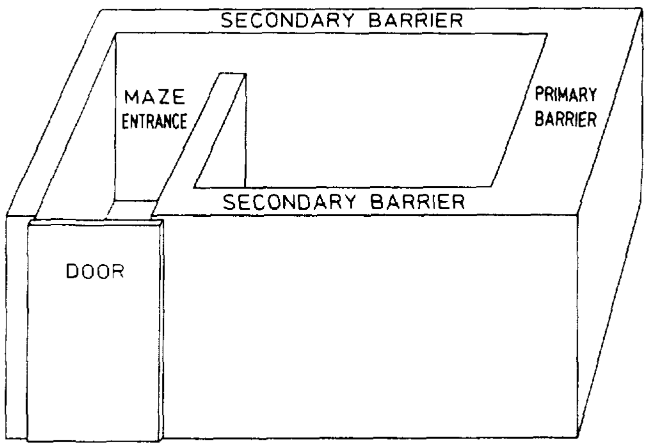
When the scattering medium is either a very large area or a large volume, direct radiation measurements suggest that it is prudent to assume that the dose rate decreases only as the inverse of the distance. The calculations used to obtain estimates of dose rate outside an enclosure, for example at a crane driver's position and at ground level, are shown in the illustration.

Determining the effective energy of scattered radiation is difficult but, because specific shielding materials are more effective attenuators of this lower energy radiation, the shield thicknesses required will normally be a fraction of those necessary for the primary radiation energies. Secondary barriers which shield combined leakage and scattered radiation are often about one half the thickness of the primary barriers required for an enclosure.

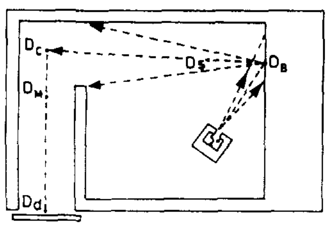
Enclosure Design Considerations

Doors that are to form part of the secondary barriers to shield industrial radiography sources are very heavy and costly to engineer. Only small doors need to be fitted if the objects to be radiographed are small or the enclosure is open-topped to allow cranes to be used to lift the objects into the enclosure. The height of the wall then becomes an important feature of the shielding. This is a common design but radiation scattered over the wall may become excessive if the design parameters are not followed in practice. The design may be compromised if, for example, X radiography is introduced into an enclosure which has been designed only for gamma radiography, the useful beam is raised above the horizontal or the collimation is not maintained. The amount of scatter may also be affected by changes above the enclosure such as the installation of new ventilation ducting. The users of these enclosures need to be aware of crane drivers or other personnel working above ground level or plans to construct new multilevel buildings in the vicinity of the enclosure.

The dose rate at the door can be significantly reduced, thereby relieving the engineering problems, by incorporating a maze entrance in the design of the enclosure. The dose rate 1 m down the sheltered leg of a maze, the corner of which is irradiated by gamma radiation, is about 10% of the dose rate at the corner centre; it decreases approximately as the inverse square of the distance from the corner towards the door. A similar effect is achieved for other radiation although the percentage scatter may be significantly higher, for example about 25% for neutron radiation.



An open-topped enclosure with maze entrance.



DOSE RATE AT CORNER OF MAZE, C.

$$D_C = \frac{D_S}{(\text{distance } B \rightarrow C)^2}$$

DOSE RATE AT 1 m. INTO MAZE, M.

$$D_M = D_C \times 10\%$$

DOSE RATE AT DOOR, d.

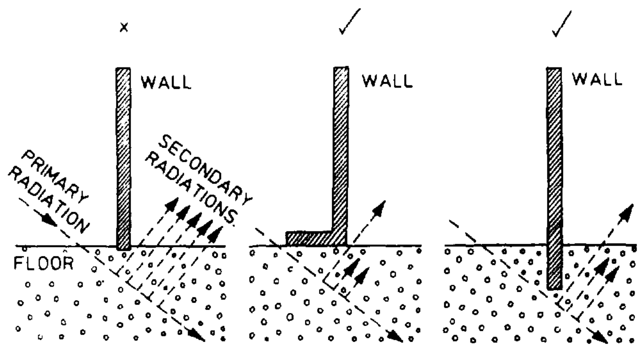
$$D_d = \frac{D_M}{(\text{distance } C \rightarrow d)^2}$$

Calculations of the dose rate at the maze entrance to an enclosure.

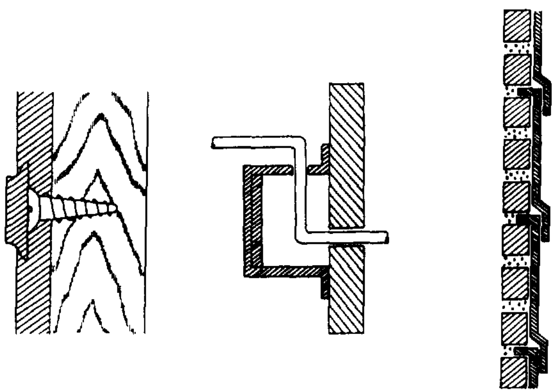
Shielding Design Considerations

Radiation which either penetrates or scatters around weaknesses in the shielding can cause significant dose rates outside an enclosure. Such weaknesses often occur where shielding is penetrated by pipework, ducting or fasteners (for example, screws), around doors and windows, and where shielding materials abut. The weaknesses are not always foreseen during the design of the enclosure and they sometimes occur after a period of wear (for example, door supports), shielding damage, movement of shielding, or building settlement.

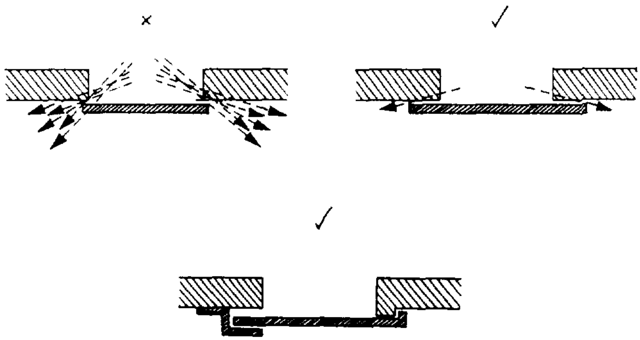
Various design techniques can be used to avoid introducing weaknesses. Radiation monitoring using a dose rate meter outside the enclosure and regular maintenance will identify faults developing before they become serious.



Methods to prevent radiation scattering under a wall.



Methods to close shielding weaknesses.



Methods to prevent radiation scattering around doors.

Control of Access to Enclosures

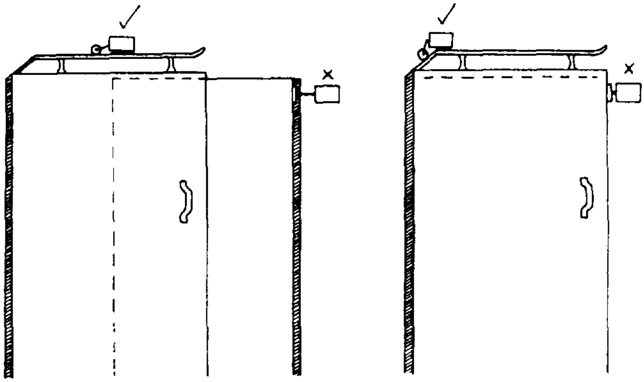
An enclosure may contain a Controlled Area requiring access to be restricted at all times. However, when a primary beam is about to be exposed there is a particular need to ensure that no one accidentally remains inside. It is also necessary to prevent anyone accidentally entering whilst a useful beam is exposed. Devices which are installed to achieve these objectives must be effective. They must operate in such a way that failure of the device automatically prevents or terminates the radiation hazard.

When a primary beam is about to be exposed, a clear pre-exposure warning signal should be given both inside and outside the enclosure. The signal should last at least ten seconds to allow anyone inside the enclosure who hears or sees the signal to take action. Notices should explain the meaning of the signal and the actions which must be taken. When the radiation source is a machine or a source operated electrically, some form of control device should be installed to enable any person trapped to shut off the electricity supply. For example an emergency stop button or wire should be located where it can be reached without passing through the primary beam. In other cases, a trapped person should be able to either leave the enclosure immediately or take refuge in a shielded area such as a maze entrance where there should be provision to communicate with the people outside.

Whilst a primary beam is exposed, exposure warning signals, which are separate and distinguishable from the pre-exposure signals, should be provided and explained both inside and outside the enclosure. Small cabinets, for example of less than 0.2 m^3, will only need an exposure warning and no internal signals or control devices.

Suitable interlocks should be installed to form a mechanical or an electrical link between the exposure control and the door or other means of access to an enclosure. These will either prevent a person entering during an exposure or immediately make safe the radiation source as someone attempts to enter. One such device which has wide application is a mechanical interlock called a captured-key system. In its simplest form, the system is a door lock which simultaneously holds two unique keys: a door key and a control key. One or other of the keys is always held by the door lock. When the door is locked closed the door key is held but the control key can be removed and used to unlock the control and expose the useful beam. The control key cannot be removed from the control panel until the radiation source is made safe. The door key cannot be turned to unlock the door until the control key is back in the door lock. Anyone entering the enclosure should take the door key to prevent the source being exposed. The same key can be used inside the enclosure to initiate the pre-exposure signal thereby ensuring that a check is made to see that no person is accidentally shut inside the enclosure. Such a device is called a search and lock-up system and is essential in enclosures which contain radiation sources of very high output.

Electrical switches can be mounted on doors in various ways to operate as interlocks. Simple push button switches which are depressed by a closing door are not always reliable. The primary beam could be accidentally emitted if the switch develops a fault. A more effective device, for example, is one mounted at the trailing edge of a sliding door so that the open door depresses the button and the primary beam can be emitted only when the door is closed and the button is released. In this position the interlock will fail to safety.



Fail-to-safety installation of a door interlock:
(a) door open; (b) door closed.

It is important to ensure that if a radiation source is made safe automatically by the action of an interlock, it should remain so until the primary beam is exposed by the operator at the control. The exposure of a primary beam in an enclosure must not commence on the mere act of closing a door.

Where reasonably practicable, the control point for all radiation sources should be outside the enclosure. This is an essential requirement for sources with an extremely high output, for example more than 10 $mSv \cdot min^{-1}$ at 1 m. In any case, the dose rate at any control point should not exceed 2 $mSv \cdot h^{-1}$.

Worker Protection

Each time an enclosure is entered, after a primary beam has been emitted, the operator should carry a dose rate meter which is switched on. Measurements should be made close to where the primary beam would be, to confirm that the source has been made safe. Additionally, a dose rate alarm may be installed inside the enclosure to indicate when a fault has occurred.

At regular intervals of perhaps four months and whenever an unusual primary beam direction is used, a radiation survey should be carried out by making dose rate measurements around the outside of the enclosure. If practicable, physical restrictions should be placed on the collimator to ensure that the primary beam cannot be used other than within the constraints allowed by the design parameters.

By using a well designed and maintained enclosure, it is possible that the operator will rarely, if ever, be required to work in dose rates which exceed 7.5 $\mu Sv \cdot h^{-1}$. It is unlikely that the worker will accumulate in excess of three-tenths of any relevant dose limit in a calendar year. Nevertheless, it may be desirable for workers who regularly enter enclosures to wear personal dosimeters.

Dealing with Emergencies

The high output of radiation sources that are often used in enclosures can cause accidents and incidents of a serious nature. However, the protection offered by the permanent nature of the facility should reduce these risks. Even when a problem arises, it should be easier to regain control than is normally the case for portable equipment.

Nevertheless, a thorough assessment of the equipment, the enclosure and the procedures used is necessary to identify any abnormal situations which might occur. Contingency plans are needed which can be implemented quickly and effectively to regain control in the event that a problem arises. Practising the contingency plans will indicate whether any special equipment will be needed to deal with reasonably foreseeable incidents.

The plans might, for example, define immediate actions to deal with the following:

- physical damage to a source housing that has been crushed or involved in a fire or explosion;
- leakage of radioactive substance from a sealed source;
- the discovery of unacceptably high dose rates as a result of damage to the enclosure or failure to work within the design parameters;

- the exposure of a person because of one of the incidents described or because of the failure of an interlock or a warning signal;
- a radioactive source failing to return to its safe, shielded position.

If a source is suspected of leaking radioactive substance, surfaces that may come into both direct and indirect contact with the radioactive substance will become contaminated. Precautions should be taken to prevent ingestion of the radioactive substances that can result when clothing and surfaces of the body become contaminated. Effective decontamination will require expert assistance.

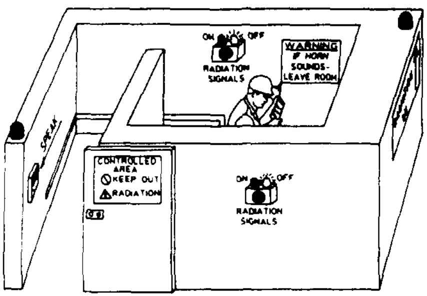
Any incident which may have resulted in an internal or external dose to a person or any high dose reported on a dosimeter should be investigated. It is important to determine whether the suspected or reported dose was actually received and also whether some part of the body has received a much higher dose which might result in localized tissue injury.

PROCEDURES GUIDE: SHIELDED ENCLOSURES

Use and maintain the shielded enclosure for the purpose for which it was intended.

Only trained and authorized workers should enter the enclosure. If appropriate, such persons should have had medical examinations and wear dosimeters.

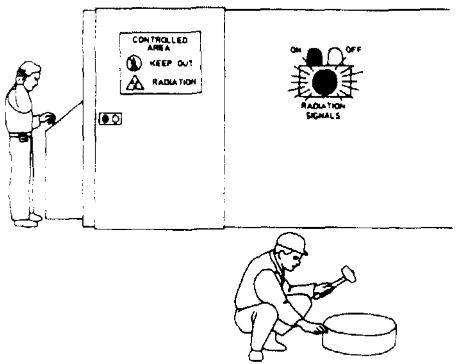
Before proceeding with the work, read and ask questions about these safety guides. Discuss with your colleagues your contributions to this important work.



Examine the enclosure and identify its main features such as the primary and secondary barriers.

Read the enclosure's design parameters, if they are available, and compare the radiation source in use with that originally intended. Establish that the maximum output of the source in use and its collimation are within the specifications. Investigate the constraints on the beam direction and recent typical workload for the beam directions normally used.

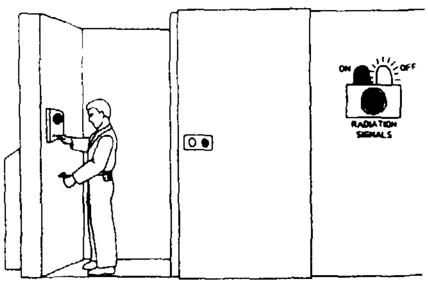
It may be prudent to display the design parameters inside the enclosure.



Regularly examine the installed pre-exposure and exposure warning signals. Check that they work and that anyone inside the enclosure would always receive a warning that an exposure sequence has started. If necessary, two pre-exposure signals should be designed so that at least one will always work. Confirm that audible signals will be heard if there are noisy surroundings and that visible signals are prominent enough to be seen.

Keep the signals clearly labelled so that both authorized and unauthorized persons, inside and outside the enclosure, will understand their meaning and any actions which need to be taken when the signals are given.

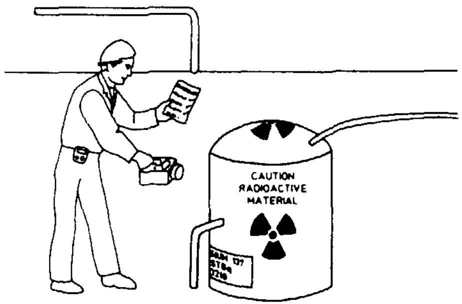
Report any faults to your supervisor



Examine the installed safety features, including the means provided for any person trapped inside the enclosure to stop an exposure and to contact the outside.

Check that the interlocks function and will either prevent anyone accidentally entering or will immediately cancel an exposure taking place when the door is opened.

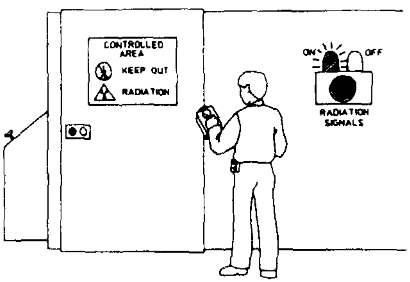
Report any faults to your supervisor



In the case of sealed sources, use a dose rate meter to check that the source is safely shielded before carrying out routine maintenance on the installed exposure container or source housing. Keep a record to show that the regular (weekly, monthly, annual or biannual) maintenance has included, for example:

(1) Cleaning the container, removing any grit and moisture.
(2) Using recommended lubricants to clean and maintain any moving parts.
(3) Checking screws and nuts for tightness and looking for damage to screw threads and springs.
(4) Confirming that the source locking mechanism works.
(5) Checking that the source housing displays: the trefoil symbol and a suitable warning; the name of any radionuclide contained; the activity and reference date of sealed sources; and identification numbers for the container and sources.
(6) Carrying out, at the recommended intervals, and only when trained and authorized to do so, out tests for leakage of radioactive substance in the appropriate manner required by the regulatory authority or recommended by the manufacturer of any sealed sources in use.

Report any faults to your supervisor

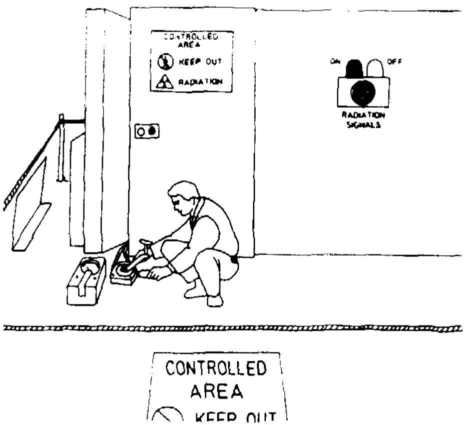


Check the enclosure at an appropriate frequency, for example at three-month intervals, for damage to doors, pipe and cable shield boxes, or other potential shielding defects.

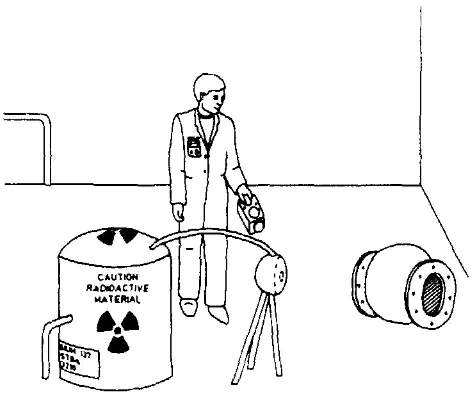
Measure the accessible dose rates during normal source exposures. Be aware that if the whole detector is not irradiated, for example when making measurements close to narrow gaps around doors, the reading may be less than the dose rates which actually exist. In addition, radiation scattered over a wall may combine with transmitted (leakage and primary) radiation to produce a maximum reading a few metres away from outside surfaces of the enclosure.

Dose rate measurements should be made at positions above ground level even some distance from the enclosure.

Repeat the measurements on every occasion that the useful beam is used in abnormal situations or is operated at the limits of the design parameters.



If it is impossible to use an enclosure which is not completely closed, that is to adapt an existing enclosure to carry out gamma radiography using a portable, projection-type exposure container with the control point outside the enclosure, ensure that the dose rate at the control point is always less then 2 $mSv \cdot h^{-1}$. Barriers and notices should be set up to mark any Controlled Areas near the door or elsewhere and other procedures should be used as described in the Procedures Guide.

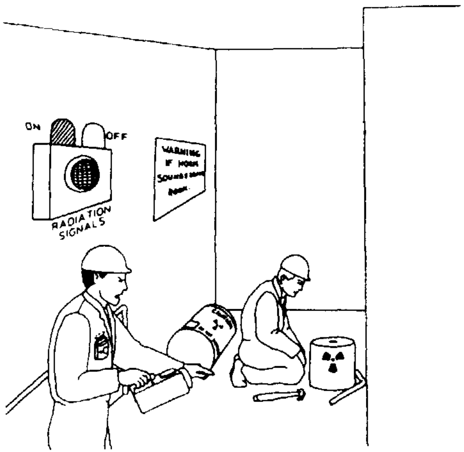


At the end of an automatically timed exposure, or after operating the control to terminate the exposure, cautiously enter the enclosure carrying a dose rate meter which is switched on.

Make measurements close to where the primary beam would be expected and then around the source housing to confirm that the source has been fully and safely shielded.

The irradiated objects or tubes through which sealed sources are guided can now be safely handled.

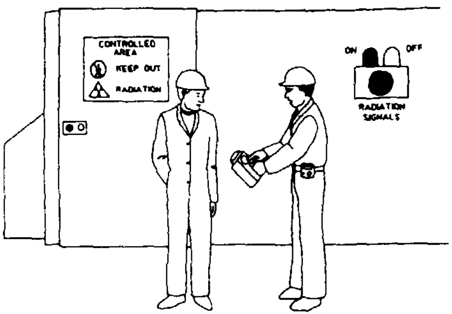
Keep the dose rate meter operating until you leave the enclosure.



If the radiation source, or the enclosure, develops a fault or an incident becomes apparent whilst someone is inside the enclosure, stay calm. The person should leave the enclosure immediately.

If it is possible, the controls should be used to return the source to its shielded position. If this cannot be done, make dose rate measurements in the vicinity of the enclosure and set up barriers to mark the extent of any Controlled Areas.

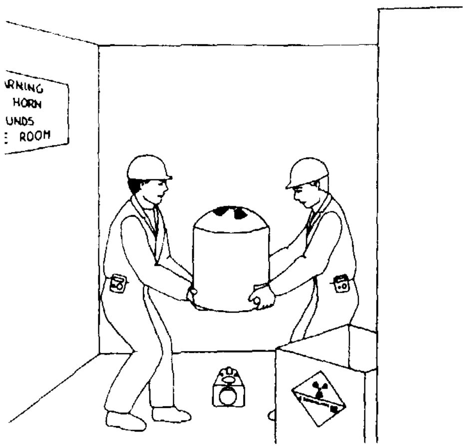
If it is possible without receiving unnecessary doses, seal the enclosure door and stay close to the area to prevent people entering. Send someone to inform your supervisor.



Give careful consideration before implementing any plan to rectify a fault or recover sealed sources which are exposed but nevertheless shielded inside an enclosure. Options may be available which involve minimal risk or dose to those persons involved.

The advice of the equipment manufacturer or other qualified experts should be sought.

The examination of similar equipment may present a solution to the problem or suggest special tools which may be helpful.



As soon as you have no further use for a radioactive source or the equipment which houses it, it should preferably be returned to the manufacturer or supplier. If any other method is used it must comply with your government's laws for that particular method of disposal.

Radioactive substances being sent for disposal must be appropriately packaged and transported in accordance with the IAEA Regulations for the Safe Transport of Radioactive Material.

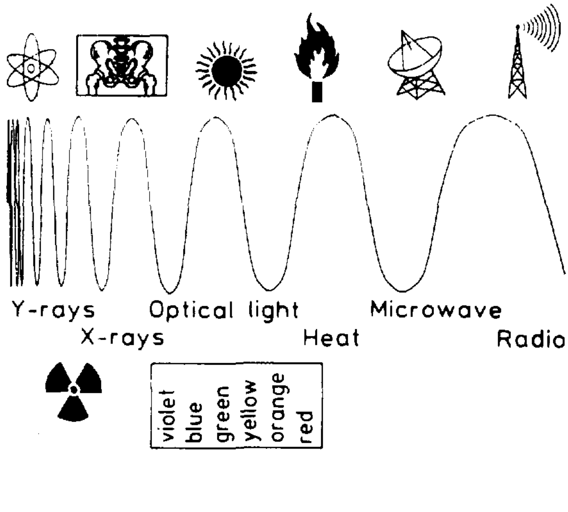
BASICS GUIDE FOR USERS OF IONIZING RADIATION

Production of Radiation

Radioactive substances are predictable and continuous emitters of energy. The energy emitted can be in the form of alpha (α) particles, beta (β) particles and gamma (γ) rays. Interaction of these radiations with matter can, in certain circumstances, give rise to the emission of X rays and neutron particles.

Gamma and X rays consist of physical entities called photons that behave like particles, suffering collisions with other particles when interacting with matter. However, large numbers of photons behave, as a whole, like radio or light waves. The shorter their wavelength the higher the energy of the individual photons.

The very high energy of gamma rays and their ability to penetrate matter results from their much shorter wavelengths.



Spectrum of radiations similar to gamma rays.

X rays are produced by an X ray machine only when it is electrically supplied with thousands of volts. Although they are similar to gamma rays, X rays normally have longer wavelengths and so they carry less energy and are less penetrating. (However, X rays produced by linear accelerators can surpass the energies of gamma radiation in their ability to penetrate materials.) The output of X radiation generated by a machine is usually hundreds or even thousands of times greater than the output of gamma radiation emitted by a typical industrial radioactive source. However, typical teletherapy sources are usually thousands of times greater in output than industrial radiography sources.

The gamma rays from iridium-192 (^{192}Ir) are of lower energies than those of cobalt-60 (^{60}Co). These are useful differences which allow selection from a wide range of man-made radionuclides of the one that emits those radiations best suited to a particular application.

Beta particles are electrons and can also have a range of energies. For example, beta particles from a radionuclide such as hydrogen-3 (^{3}H) travel more slowly and so have almost one hundredth of the energy of the beta particles from a different radionuclide such as phosphorus-32 (^{32}P).

Neutron particle radiation can be created in several ways. The most common is by mixing a radioactive substance such as americium-241 (^{241}Am) with beryllium. When it is struck by alpha particles emitted by the americium-241, beryllium reacts in a special way. It emits high energy, fast neutrons. Americium-241 also emits gamma rays and so from the composite americium-241/beryllium source are produced. Another way to create neutrons is using a radiation generator machine combining high voltages and special targets. Special substances in the machine combined with high voltages can generate great numbers of neutrons of extremely high energy.

Alpha particles in general travel more slowly than beta particles, but as they are heavier particles they are usually emitted with higher energy. They are used in applications which require intense ionization over short distances such as static eliminators and smoke detectors.

Radiation Energy Units

A unit called the electron-volt (eV) is used to describe the energy of these different types of radiation. An electron-volt is the energy aquired by an electron accelerated through a voltage of one volt. Thus, one thousand volts would create a spectrum (range) of energies up to 1000 eV. Ten thousand volts would create X rays of up to 10 000 eV. A convenient way of expressing such large numbers is to use prefixes, for example:

1000 eV can be written as 1 kiloelectron-volt (1 keV);
10 000 eV can be written as 10 kiloelectron-volts (10 keV);
1 000 000 eV can be written as 1 megaelectron-volts (1 MeV);
5 000 000 eV can be written as 5 megaelectron-volts (5 MeV).

Radiation Travelling Through Matter

As radiation travels through matter it collides and interacts with the component atoms and molecules. In a single collision or interaction the radiation will generally lose only a small part of its energy to the atom or molecule. However, the atom or molecule will be altered and becomes an ion. Ionizing radiation leaves a trail of these ionized atoms and molecules, which may then behave in a changed way.

After successive collisions an alpha particle loses all of its energy and stops moving, having created a short, dense trail of ions. This will occur within a few centimetres in air, the thickness of a piece of paper, clothing or the outside layer of skin on a person's body. Consequently, radionuclides that emit alpha particles are not an external hazard. This means that the alpha particles cannot cause harm if the alpha emitter is outside the body. However, alpha emitters which have been ingested or inhaled are a serious internal hazard.

Depending upon their energy, beta particles can travel up to a few metres in air and up to a few centimetres in substances such as tissue and plastic. Eventually, as the beta particle loses energy, it slows down considerably and is absorbed by the medium. Beta emitters present an internal hazard and those that emit high energy beta particles are also an external hazard.

Radionuclide	Type of radiation	Range of energies (MeV)
Americium-241	alpha gamma	5.5 to 5.3 0.03 to 0.37
Hydrogen-3	beta	0.018 maximum
Phosphorus-32	beta	1.7 maximum
Iodine-131	beta gamma	0.61 maximum 0.08 to 0.7; 0.36
Technetium-99m	gamma	0.14
Caesium-137	beta	0.51 maximum
(Barium-137m)	gamma	0.66
Iridium-192	beta gamma	0.67 maximum 0.2 to 1.4
Cobalt-60	beta gamma	0.314 maximum 1.17 and 1.33
Americium-241/ beryllium	neutron gamma	4 to 5 0.06
Strontium-90/ (Yttrium-90)	beta beta	2.27 2.26
Promethium-147	beta	0.23
Thalium-204	beta	0.77
Gold-198	beta gamma	0.96 0.41
Iodine-125	X ray gamma	0.028 0.035
Radium-226	alpha beta gamma	4.59 to 6.0 0.67 to 3.26 0.2 to 2.4

Heavier atoms such as those of lead do absorb a greater part of the beta's energy in each interaction but as a result the atoms produce X rays called bremsstrahlung. The shield then becomes an X ray emitter requiring further shielding. Lightweight (low density) materials are therefore the most effective shields of beta radiation, albeit requiring larger thicknesses of material.

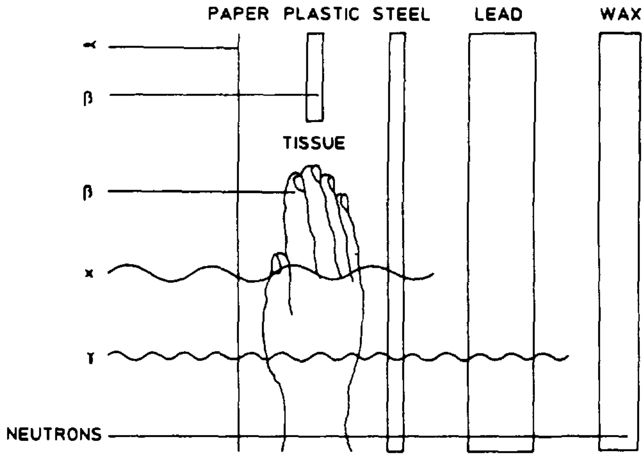
Radionuclide	Maximum beta particle energy (MeV)	Maximum range			
		Air (mm)	Plastic (mm)	Softwood (mm)	Aluminium (mm)
Promethium-147	0.23	400	0.6	0.7	0.26
Thalium-204	0.77	2400	3.3	4.0	1.5
Phosphorus-32	1.71	7100			
Strontium-90/ Yttrium-90	2.26	8500	11.7	14.0	5.2

Gamma rays and X rays are more penetrating. However, as they cause ionization they may be removed from the beam or lose their energy. They thus become progressively less able to penetrate matter and are reduced in number, that is attenuated, until they cease to be a serious external hazard.

One way of expressing the quality or penetrating power of gamma and X rays also provides a useful means of estimating the appropriate thickness of shields. The half value thickness (HVT) or the half value layer (HVL) is that thickness of material which when placed in the path of the radiation will attenuate it to one half its original value. A tenth value thickness (TVT) similarly reduces the radiation to one tenth of its original value.

Radiation producer	HVT and TVT values (cm) in various materials					
	Lead		Iron		Concrete	
	HVT	TVT	HVT	TVT	HVT	TVT
Technetium-99m	0.02					
Iodine-131	0.72	2.4			4.7	15.7
Caesium-137	0.65	2.2	1.6	5.4	4.9	16.3
Iridium-192	0.55	1.9	1.3	4.3	4.3	14.0
Cobalt-60	1.1	4.0	2.0	6.7	6.3	20.3
100 kV_p X rays	0.026	0.087			1.65	5.42
200 kV_p X rays	0.043	0.142			2.59	8.55

Material which contains heavy atoms and molecules such as steel and lead provide the most effective (thinnest) shields for gamma radiation and X rays.



The penetrating properties of ionizing radiations.

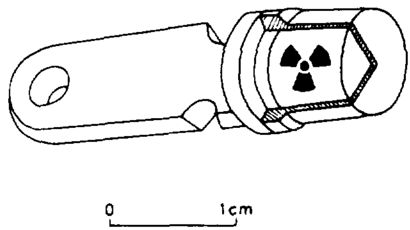
Neutrons behave in complex ways when travelling through matter. Fast neutrons will scatter (bounce) off much larger atoms and molecules without losing much energy. However, in a collision between a neutron and a small atom or molecule, the latter will absorb a proportion of the neutron's energy. The smallest atom, the hydrogen atom, is able to cause the greatest reduction in energy.

Hydrogenous materials such as water, oil, wax and polythene therefore make the best neutron shields. A complication is that when a neutron has lost nearly all its energy it can be 'captured', that is absorbed whole by an atom. This often results in the newly formed atom becoming a radionuclide, which in many instances would be capable of emitting a gamma ray of extremely high energy. Special neutron absorbing hydrogenous shields contain a small amount of boron which helps to absorb the neutrons.

Damage to human tissue caused by ionizing radiation is a function of the energy deposited in the tissue. This is dependent on the type and energies of the radiations being used. Hence the precautions needed to work with different radionuclides also depend on the type and energy of the radiation.

Containment of Radioactive Substances

Radioactive substances can be produced in any physical form: a gas, a liquid or a solid. Many medical and most industrial applications use sources in which the radioactive substance has been sealed into a metal capsule or enclosed between layers of non-radioactive materials. Often these sources are in 'Special Form' which means that they are designed and manufactured to withstand the most severe tests, including specified impact forces, crushing forces, immersion in liquid and heat stress, without leaking radioactive substance.

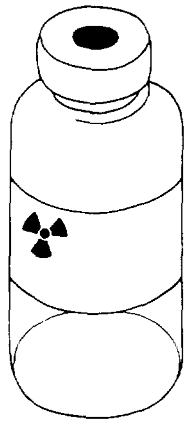


A sealed source, showing the encapsulated radioactive substance.

All sealed sources are leak tested after manufacture and the test (also called a wipe test) must be repeated periodically throughout the working life of the source. More frequent testing is required for sealed sources which are used in harsh environments or in applications that are likely to cause them damage. Most sealed sources can remain leak-free and provide good, reliable service for many years but eventually must be safely disposed of and replaced because the activities have decayed below usable levels.

Sealed sources present only an external hazard. Provided that the source does not leak there is no risk of the radioactive substance being ingested, inhaled or otherwise being taken into a person's body.

Unsealed radioactive substances such as liquids, powders and gases are likely to be contained, for example within a bottle or cylinder, upon delivery, but may be released and manipulated when used. Some unsealed sources remain contained but the containment is deliberately weak to provide a window for the radiation to emerge. Unsealed radioactive substances present both external and internal hazards.



A bottle of radioactive liquid.
The rubber cap sealing the bottle may be removed or pierced to extract liquid.

The Activity of Sources

The activity of a source is measured in becquerels (Bq) and indicates the number of radionuclide atoms disintegrating per second (dps or s^{-1}).

1 Becquerel is equivalent to 1 atom disintegrating per second

Industrial and medical applications usually require sealed sources with activities of thousands or millions of becquerels. A convenient method of expressing such large numbers is to use prefixes, for example:

1 000 becquerels is written 1 kilobecquerel (1 kBq);
1 000 000 becquerels is written 1 megabecquerel (1 MBq);
1 000 000 000 becquerels is written 1 gigabecquerel (1 GBq);
1 000 000 000 000 becquerels is written 1 terabecquerel (1 TBq).

The activity of a source is dependent on the half-life of the particular radionuclide. Each radionuclide has its own characteristic half-life, which is the time it will take for the activity of the source to decrease to one half of its original value. Radionuclides with short half-lives are generally selected for medical purposes involving incorporation into the body via oral, injection or inhalation, whereas those with relatively longer half-lives are often of benefit for medical, therapeutic (external or as temporary inserts) and industrial applications.

Radionuclide	Half-life[a]	Application
Technetium-99m	6.02 h	Medical diagnostic imaging
Iodine-131	8.1 d	Medical diagnostic/ therapy (incorporated)
Phosphorus-32	14.3 d	Medical therapy (incorporated)
Cobalt-60	5.25 a	Medical therapy (external) Industrial gauging/radiography
Caesium-137	28 a	Medical therapy (temporary inserts) Industrial gauging/radiography
Strontium-90	28 a	Industrial gauging
Iridium-192	74 d	Industrial radiography, or medical therapy
Radium-226	1620 a	Medical therapy (temporary inserts)
Iodine-125	60 d	Medical diagnostic/therapy
Americium-241	458 a	Industrial gauging
Hydrogen-3	12.3 a	Industrial gauging
Ytterbium-169	32 d	Industrial radiography
Promethium-147	2.7 a	Industrial gauging
Thalium-204	3.8 a	Industrial gauging
Gold-198	2.7 d	Medical therapy
Thulium-170	127 d	Industrial radiography

[a] The abbreviation 'a' stands for 'year'.

When radioactive substances are dispersed throughout other materials or dispersed over other surfaces in the form of contamination, the units of measurement which are most commonly used are:

(a)	for dispersion throughout liquids	$Bq \cdot mL^{-1}$
(b)	for dispersion throughout solids	$Bq \cdot g^{-1}$
(c)	for dispersion throughout gases (most particularly air)	$Bq \cdot m^{-3}$
(d)	for dispersion over surfaces	$Bq \cdot cm^{-2}$

An older unit of activity which is still used, the curie (Ci), was originally defined in terms of the activity of 1 gram of radium-226. In modern terms:

1 Curie is equivalent to 37 000 000 000 dps, that is 37 GBq:

1 nCi	1 μCi	1 mCi	1 Ci	10 Ci
37 Bq	37 kBq	37 MBq	37 GBq	37 TBq

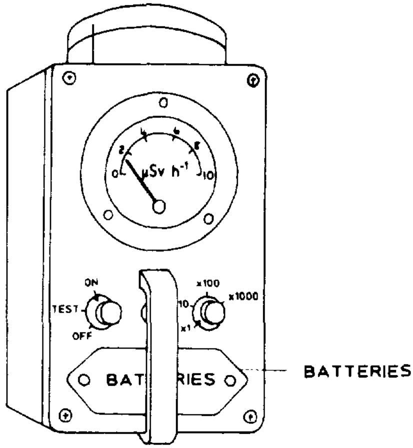
Measurement of Radiation

Ionizing radiation cannot be seen, felt or sensed by the body in any other way and, as has already been noted, damage to human tissue is dependent on the energy absorbed by the tissue as a result of ionization. The term used to describe energy absorption in an appropriate part or parts of the human body is 'dose'.

The modern unit of dose is the gray (Gy). However, in practical radiation protection, in order to take account of certain biological effects, the unit most often used is the sievert (Sv). For X ray, gamma and beta radiation, one sievert corresponds to one gray. The most important item of equipment for the user is a radiation monitoring device. There are instruments and other devices that depend on the response of film or solid state detectors (for example, the film badge or thermoluminescent dosimeters).

Two types of instruments are available: dose rate meters (also called survey meters) and dosimeters.

Modern dose rate meters are generally calibrated to read in microsieverts per hour ($\mu Sv \cdot h^{-1}$). However, many instruments still use the older unit of millirem per hour ($mrem \cdot h^{-1}$). 10 $\mu Sv \cdot h^{-1}$ is equivalent to 1 $mrem \cdot h^{-1}$



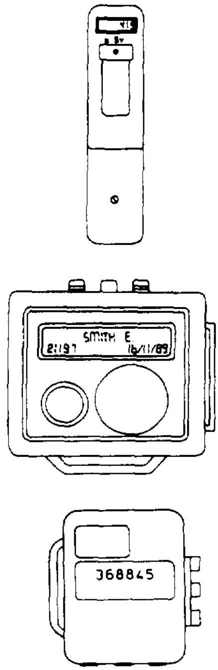
A typical dose rate meter.

Neutron radiation can only be detected using special dose rate meters.

Most dose rate meters are battery powered and some have a switch position that enables the user to check the battery condition, i.e. that it has sufficient life remaining to power the instrument. It is important that users are advised not to leave the switch in the battery check position for long periods and to switch off when not in use. Otherwise the batteries will be used unnecessarily.

A check that an instrument is working can be made by holding it close to a small shielded source but some instruments have a small inbuilt test source. Workers should be instructed on the use of test sources since regular checks will not only increase their own experience but give them confidence and provide early indication of any faults. It is important that users recognize the great danger of relying on measurements made using a faulty instrument.

A dosimeter measures the total dose accumulated by the detector over a period of time. For example, a dosimeter would record 20 μSv if it was exposed to 10 $\mu Sv \cdot h^{-1}$ for two hours. Some dosimeters can give an immediate reading of the dose. Others, like the film badge and the thermoluminescent dosimeter (TLD), can only provide a reading after being processed by a laboratory.



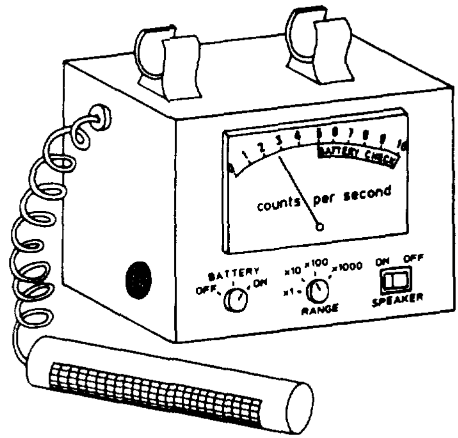
(a) Electronic dosimeter

(b) Thermoluminescent dosimeter

(c) Film badge dosimeter

Personnel dosimeters.

A third type of instrument will be needed by users of unsealed sources: a surface contamination meter. This is often simply a more sensitive detector which should be used to monitor for spillages. When the detector is placed close to a contaminated surface the meter normally only provides a reading in counts per second (cps or s^{-1}) or sometimes in counts per minute (cpm or min^{-1}). It needs to be calibrated for the radionuclide in use so that the reading can be interpreted to measure the amount of radioactive substance per unit area ($Bq \cdot cm^{-2}$). There are many surface contamination meters of widely differing sensitivities. The more sensitive instruments will indicate a very high count rate in the presence of, for example 1000 $Bq \cdot cm^{-2}$ of iodine-131, but different detectors measuring the same surface contamination will provide a lower reading or possibly no response at all. When choosing a detector it is best to use one that has a good detection efficiency for the radionuclide in use and gives an audible indication. The internal hazard created by small spillages can then be identified and a safe working area maintained.



A typical surface contamination meter.

Radiation and Distance

Ionizing radiation in air travels in straight lines. In such circumstances the radiation simply diverges from a radioactive source and the dose rate decreases as the inverse square of the distance from the source.

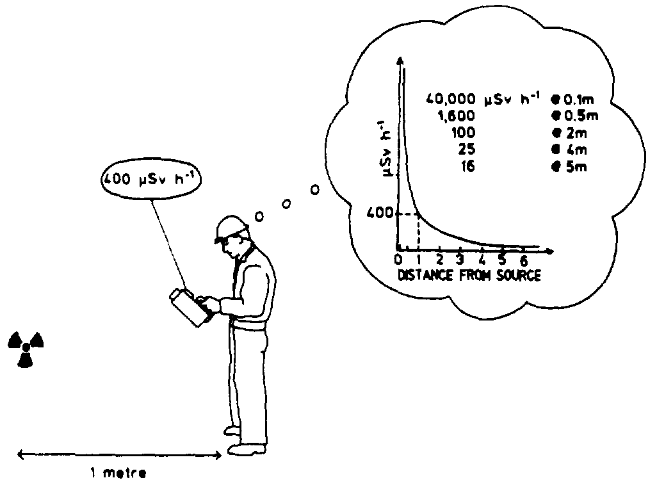
For example:

If the measured dose rate at 1 m is 400 $\mu Sv \cdot h^{-1}$;
the expected dose rate at 2 m is 100 $\mu Sv \cdot h^{-1}$;
the expected dose rate at 10 m is 4 $\mu Sv \cdot h^{-1}$;
the expected dose rate at 20 m is 1 $\mu Sv \cdot h^{-1}$; etc.

Distance has a major effect in reducing the dose rate.

Solid shields in the radiation path will cause the radiation to be attenuated and also cause it to be scattered in various directions. The actual dose rate at a point some distance from a source will not be due only to the primary radiation arriving from the source without interaction. Secondary radiation which has been scattered will also contribute to the dose rate.

However, it is simple to calculate the dose rate at a distance from a source. The primary radiation energies will be constant and known if the radionuclide is specified.



After measuring the dose rate, estimates can be made of the dose rates at different distances from the source.

The dose rate is obtained using the equation:

$$\text{Dose rate} = \frac{\text{Gamma factor} \times \text{Source activity}}{(\text{Distance})^2}$$

Gamma factor is the absorbed dose rate in $mSv \cdot h^{-1}$ at 1 m from 1 GBq of the radionuclide;
Activity of the source is in gigabecquerels;
Distance is in metres from the source to the point of interest.

Gamma emitting radionuclide	Gamma factor Γ
Ytterbium-169	0.0007
Technetium-99m	0.022
Thulium-170	0.034
Caesium-137	0.081
Iridium-192	0.13
Cobalt-60	0.351

However, the dose rate from the source is best determined using a reliable dose rate meter.

Notation for the examples of calculations.

Examples of Calculations

(1) What will be the dose rate at 5 m from 400 GBq of iridium-192?

$$\text{Dose rate} = \frac{\Gamma \times A}{d^2} = \frac{0.13 \times 400}{5^2}\ \text{mSv}\cdot\text{h}^{-1}$$

$$= 2.08\ \text{mSv}\cdot\text{h}^{-1}$$

(2) A dose rate of 1 $mGy\cdot h^{-1}$ is measured at 15 cm from a caesium-137 source. What is the source's activity?

$$\text{Dose rate} = 1\ \text{mSv}\cdot\text{h}^{-1}$$

$$= \frac{0.081 \times \text{activity}}{0.0225}\ \text{mSv}\cdot\text{h}^{-1}$$

$$\text{Activity} = \frac{1 \times 0.0225}{0.081}\ \text{GBq} = 0.278\ \text{GBq}$$

(3) A dose rate of 780 $\mu Gy\cdot h^{-1}$ is measured from 320 GBq cobalt-60. How far away is the source?

$$\text{Dose rate} = 0.78\ \text{mSv}\cdot\text{h}^{-1}$$

$$= \frac{0.351 \times 320}{d^2}\ \text{mSv}\cdot\text{h}^{-1}$$

$$\text{Distance} = \sqrt{\frac{0.351 \times 320}{0.78}}\ \text{m} = 12\ \text{m}$$

(4) A 1.3 TBq iridium-192 source is to be used. What distance will reduce the dose rate to 7.5 $\mu Gy \cdot h^{-1}$?

$$\text{Dose rate} = 0.0075 \ mGy \cdot h^{-1}$$

$$= \frac{0.13 \times 1.3 \times 1000}{d^2}$$

$$\text{Distance} = \sqrt{\frac{0.13 \times 1.3 \times 1000}{0.0075}} \ m = 150 \ m$$

(5) A dose rate of 3 $mSv \cdot h^{-1}$ is measured at 4 m from a gamma emitting source. At what distance will the dose rate be reduced to 7.5 $\mu Sv \cdot h^{-1}$?

$$\text{Dose rate} = \frac{\text{Gamma factor} \times \text{Activity}}{(\text{Distance})^2}$$

Gamma factor × Activity is the source output and is constant. Therefore, Dose rate × $(\text{Distance})^2$ is constant.

Hence, $0.0075 \times d^2 = 3 \times 4^2$

$$d = \sqrt{\frac{3 \times 4^2}{0.0075}} \ m$$

$$d = 80 \ m$$

Radiation and Time

Radiation dose is proportional to the time spent in the radiation field. Work in a radiation area should be carried out quickly and efficiently. It is important that workers should not be distracted by other tasks or by conversation. However, working too rapidly might cause mistakes to happen. This leads to the job taking longer, thus resulting in greater exposure.

Radiation Effects

Industrial and medical uses of radiation do not present substantial radiation risks to workers and should not lead to exposure of such workers to radiation in excess of any level which would be regarded as unacceptable.

Possible radiation effects which have been considered by the international bodies (e.g. the International Commission on Radiological Protection, International Atomic Energy Agency) are:

(a) Short term effects such as skin burns and eye cataracts;
(b) Long term effects such as an increased disposition to leukaemia and solid cancers.

Current recommendations for dose limitations are contained in IAEA Safety Series No. 115. In summary, these are:

(a) No application of radiation should be undertaken unless justified;
(b) All doses should be kept as low as achievable, economic and social factors being taken into account; and
(c) In any case, all doses should be kept below dose limits.

For reference, the principal dose limits specified in IAEA Safety Series No. 115 are:

Adult workers	20 mSv per year (averaged over five years)
Members of the public	1 mSv per year.

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