Manual on NUCLEAR GAUGES

Incorporating:
Applications Guide
Procedures Guide
Basics Guide

PRACTICAL RADIATION SAFETY MANUAL

Manual on NUCLEAR GAUGES

Incorporating:

Applications Guide

Procedures Guide

Basics Guide

INTERNATIONAL ATOMIC ENERGY AGENCY

MANUAL ON NUCLEAR GAUGES
IAEA, VIENNA, 1996
IAEA-PRSM-3 (Rev.1)

Printed by the IAEA in Austria
March 1996

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: NUCLEAR GAUGES

Nuclear Gauges

Modern, especially automatic, production methods need to be constantly monitored in order to check the quality of the products and to control the production process. Such monitoring is often carried out by quality control devices using the unique properties of ionizing radiation. These devices are called nuclear gauges. They do not need to be in contact with the material under examination and so can be used to monitor: high speed processes; materials with extreme temperatures or harmful chemical properties; materials that are damaged by contact; and packaged products. The beta, gamma and X radiations used do not damage or change the material in any way. However, neutron radiation can be used specifically to induce changes such as radioactivity as a means of detection.

Types of Gauge

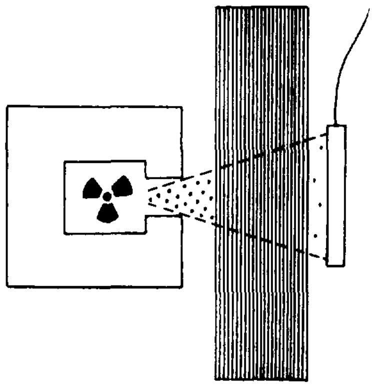
Installed gauges usually operate automatically. They are either of fixed or scanning (moving back and forth) type. Portable gauges are intended for use in different locations.

All installed and portable gauges consist of a source housing from which the radiation is emitted and at least one detector which either measures the dose rate after the radiation has interacted with the material or identifies the type and energy of the radiation that reaches it. Gauges can be categorized according to what happens to the radiation before it reaches the detector. There are three categories:

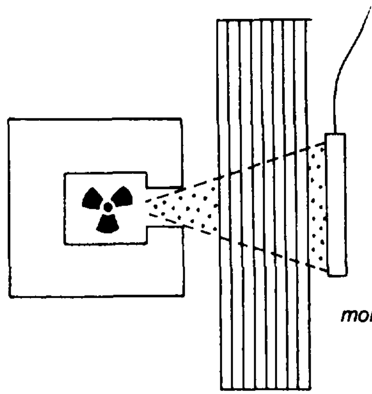
(1) Transmission gauges
(2) Backscatter gauges
(3) Reactive gauges.

Transmission Gauges

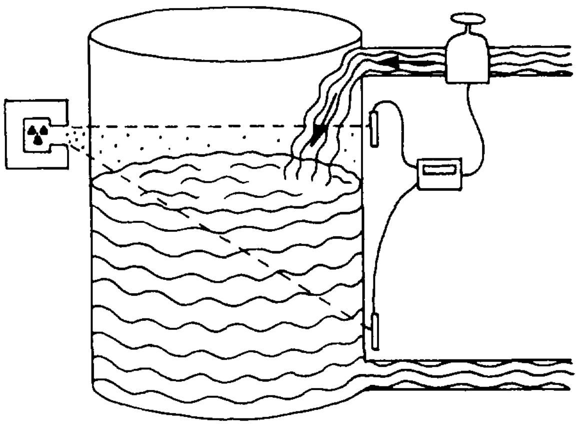
The source housing and the detector are on opposite sides of the material. The radiation is attenuated as it travels through the material and the detector measures a dose rate (or count rate).



Transmission gauge monitoring dense material.



Transmission gauge monitoring less dense material.



Transmission level gauges.

If there is constant geometry, i.e. the radiation passes through a constant thickness of material or through a pipeline or vessel, the detector will measure or respond to changes in the density of the material through which the radiation has travelled. If the radiation has to travel through a more dense material its attenuation increases and the count rate is reduced. The detector similarly senses a reduction in density. This principle is used by density gauges (for example to control the density of cement and drilling lubricants flowing through pipelines) and by level gauges to control the minimum and maximum contents of vessels.

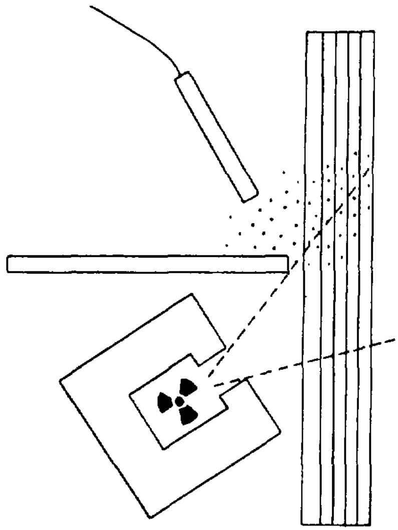
If the density of the material is constant the detector will measure or respond to changes in the geometry such as the thickness of the material passing between the source and detector. The attenuation will increase with increased thickness. This principle is used by thickness gauges, for example to control the production of sheet metal. The radiation source is chosen to provide the range and penetration needed.

Radiation source	Typical transmission gauge applications
Promethium-147 (beta)	Density of paper
Thalium-204 (beta)	Thickness of paper, rubber and textiles
Krypton-85 (beta)	Thickness of cardboard
Strontium/ yttrium-90 (beta)	Thickness of thin metals; tobacco content of cigarettes and packages
X rays	Up to 20 mm steel; liquid level in cans
Americium-241 (gamma)	Up to 10 mm steel; contents of bottles
Caesium-137 (gamma)	100 mm steel; contents of pipelines/ tanks
Cobalt-60 (gamma)	Contents of coke ovens, brick kilns, etc.

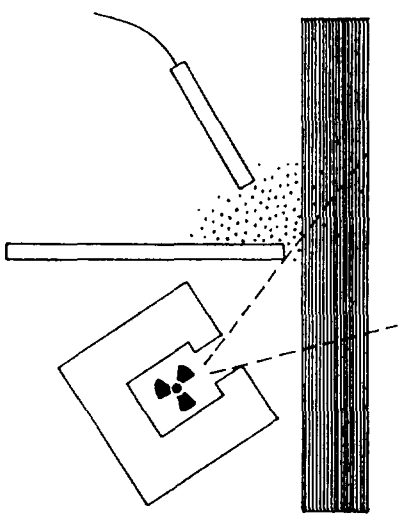
The beta source activities usually range from 40 MBq to 40 GBq while gamma sources usually contain between 0.4 and 40 GBq.

Backscatter Gauges

The detector and the source housing are mounted on the same side of the material. The detector is shielded against primary radiation. The radiation enters the material and interacts with the atoms and molecules. There will be more interactions in thicker or more dense materials. The detector measures the secondary radiations which are scattered back from the interactions. Again, if there is constant geometry, the gauge will indicate the material density and if the density is constant, the gauge will indicate the material thickness.



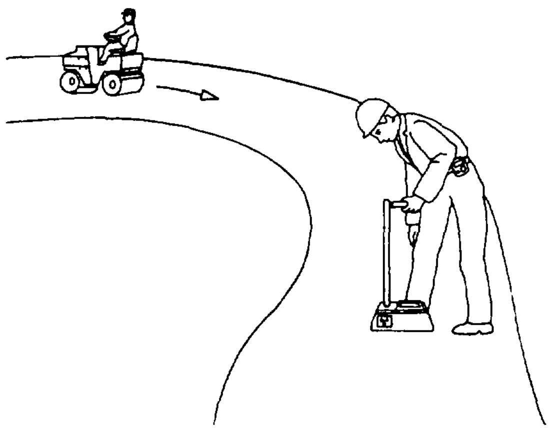
Backscatter gauge monitoring dense material.



Backscatter gauge monitoring less dense material.

The radiation source is carefully selected to suit the application. Backscatter gauges which use gamma and X radiation can be more sensitive to the presence of lighter elements, such as carbon, than transmission gauges using the same primary radiation.

If neutron radiation is used, the amount of backscatter can indicate how many hydrogen atoms are present in the material. This principle is used, for example, by: moisture gauges in paper production; road gauges that measure the characteristics of tarmacadam surfaces; and porosity gauges which measure the water or hydrocarbon content of subsurface rocks.



A portable backscatter gauge monitoring the characteristics of a tarmacadam road surface.

Radiation source	Typical backscatter gauge applications
Promethium-147 (beta)	Thickness of paper; thin metal coatings
Thalium-204 (beta)	Thickness of thin rubber and textiles
Strontium/ yttrium-90 (beta)	Thicknesses of plastics, rubber, glass and thin light alloys
Americium-241 (gamma)	Up to 10 mm glass and 30 mm plastic
Caesium-137 (gamma)	Glass beyond 20 mm; rock/coal densities
Americium-241/beryllium	Detection of hydrocarbons in rocks

The beta source activities usually range from 40 to 200 MBq while gamma sources can contain up to 100 GBq.

Reactive Gauges

Certain low energy gamma and X rays can ionize specific atoms, causing them to emit fluorescent X rays of characteristic energy. The detector measurement of the fluorescent X rays indicates not only the presence of the specific atoms but also the amount in the material. This principle is used by gauges which analyse the constituents of materials such as ores and alloys and by gauges that measure the thickness of coatings on substrates of dissimilar materials.

Electrically operated high energy neutron generators can be used to induce non-radioactive substances to become radioactive. The radionuclides formed emit characteristic gamma rays which can be identified by their energy. These gauges or logging tools are used to prospect for oil.

Radiation source	Reactive gauge application
Iron-55 (0.21 MeV X ray)	Analysis: low mass elements 0–25 μm plastic on aluminium
Americium-241	Analysis: medium mass elements 0–100 μm zinc on iron
Cadmium-109 (0.088 MeV X ray)	Analysis: high mass elements
X ray (up to 60 kV)	Analysis: range of elements
Neutron generators	Analysis of hydrocarbons in rocks

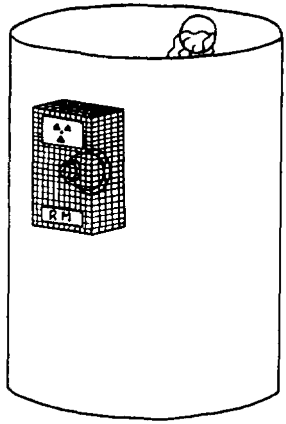
The source activities used range from about 200 MBq to 40 GBq.

Equipment Used for Gauging

The radioactive closed sources used in gauges are often in Special Form (see Basics Guide), especially the gamma emitters. The source should be locked into the housing which is usually a sealed, shielded container.

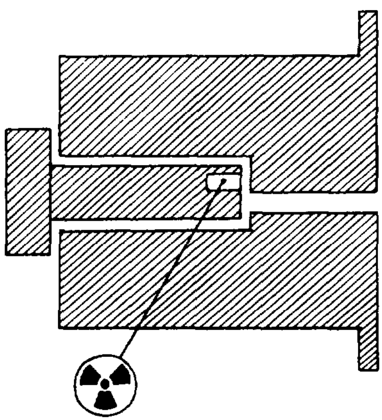
Gamma source housings normally incorporate lead shielding designed to collimate the radiation into a primary beam and direct it into the material towards the detector's position. The shielding should preferably reduce all readily accessible dose rates outside the housing to less than

$7.5\,\mu Sv \cdot h^{-1}$. Weight constraints may prevent this, in which case a simple mechanical guard or barrier should prevent access.

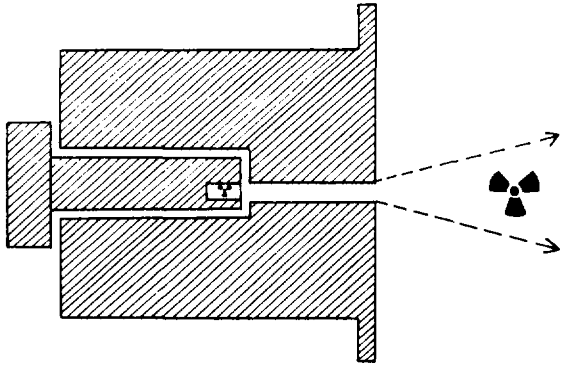


A mechanical guard preventing access to high dose rates close to a level gauge source housing.

A shutter should be provided so that the radiation source can be completely surrounded by shielding when it is not in use. It is often possible to arrange for the shutter to close automatically when there is no material in front of the gauge. A clear indication should be provided and maintained to show whether the shutter is open or closed.

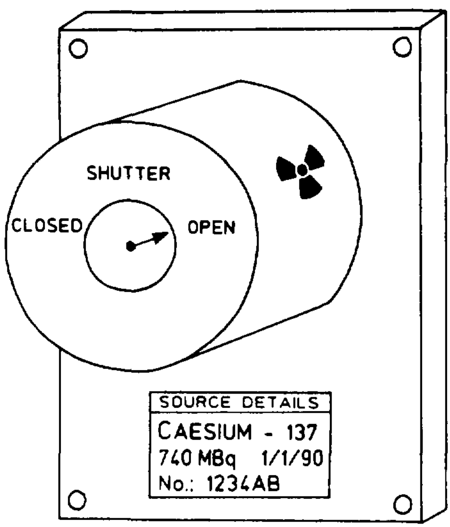


A gamma source housing (sectioned) with its shutter closed.



*A gamma source housing (sectioned)
with its shutter open.*

Details of the installed source, including the name of the radionuclide, its activity on a specified date and its serial number, should be shown on a tag on the outside of the source housing.



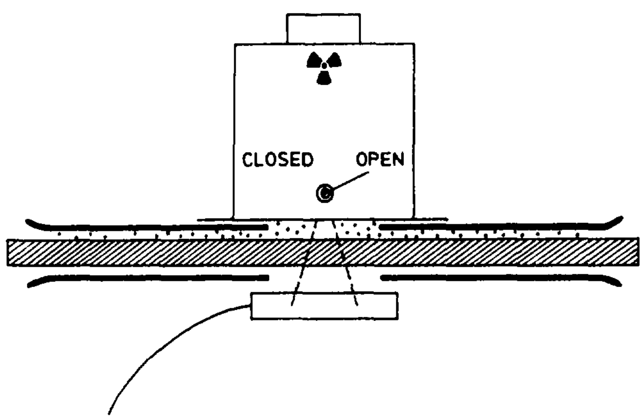
*Clear markings on
the outside of the gauge source housing.*

The gauge housing and any guard which marks the extent of a Controlled Area should display suitable warning notices.

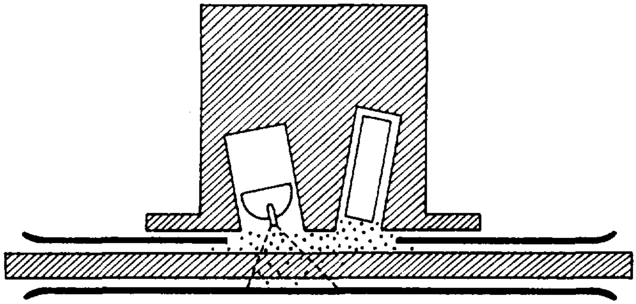
Radiation Protection for Gauges

The main consideration for gauges, especially those which contain beta emitters, is to prevent access to the very high dose rates which are normally in the primary beam close to the outside of the gauge. This can be achieved by arranging for the material to be measured to provide the necessary shielding and by arranging automatic shutters to close when the material is not there. Alternatively, it can be made physically impossible for anything other than the material to enter this area.

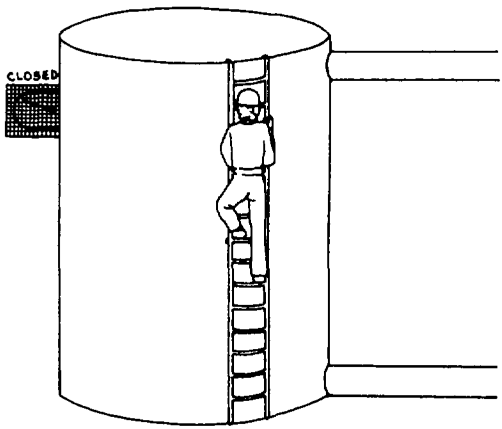
Controlled Areas may be necessary on both sides of the material of both transmission and backscatter gauges. Access to these areas, and to the primary beam, can be prevented by fitting narrowly separated parallel plates, called guide plates, through which the material must pass. Access to the primary beam of a level gauge mounted on a large vessel should be possible only when either the gauge is removed from its installed position or the vessel is opened for access. Sufficient warnings should be given to ensure that the gauge shutter is locked in the closed position before these actions are taken.



Shielding for a transmission gauge to prevent access to the primary beam and scattered radiation.



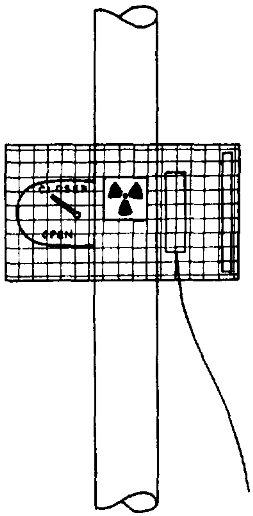
Shielding for a backscatter gauge (shown sectioned) to prevent access to backscattered and transmitted radiation.



A level gauge shutter closed before maintenance is carried out inside the vessel.

Local shielding which it has been necessary to add to a gauge, for example as a beam stop to attenuate the beam after it has passed through the detector, should be fixed in place. Essential shielding should, where practicable, be interlocked with the gauge shutter. This means that the shielding is mechanically or electrically linked to the shutter so that the shutter automatically closes when the shielding is removed. A notice which bears the trefoil symbol and a suitable legend should be displayed on essential shielding.

The type of shielding material which might be needed will depend on the type and energy of radiation it is to attenuate. Gauges that contain beta emitters may still need shielding against X rays (bremsstrahlung) which are generated when the beta particles are absorbed by surrounding heavy materials. Measuring the range of the radiation or the half value thickness will indicate which shielding materials, and what thickness, to use.

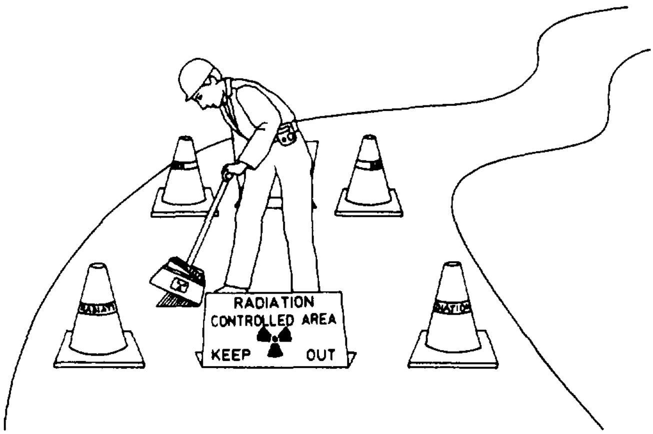


A mechanical guard and beam stop prevent access to the primary beam of a transmission density gauge.

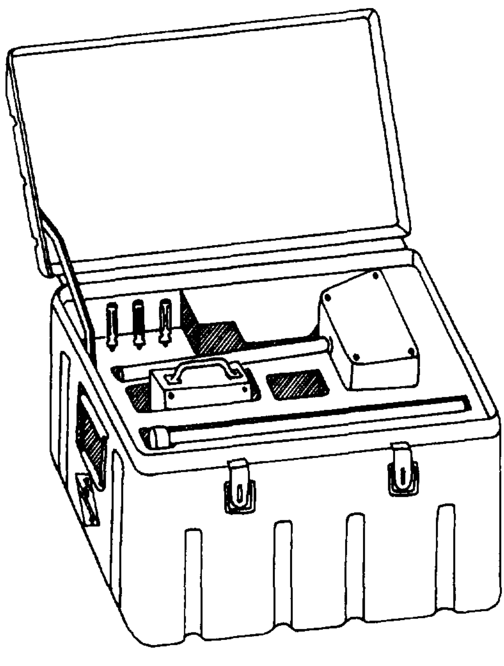
Distance can be at least as effective as shielding materials in reducing the dose rate. A suitable dose rate meter is necessary for monitoring purposes and establishing that radiation levels are satisfactory.

Portable Gauges

It is not always feasible to install an interlocked shutter in the source housing of a portable gauge and extra care needs to be taken to ensure that the useful beam is not directed towards the operator. When the shutter is open dose rates around the gauge may be such as to require the establishment of a Controlled Area which will need to be identified by a barrier, suitable notices or other means.



A controlled area in which a portable backscatter gauge is being used.



A transport container for a portable gauge.

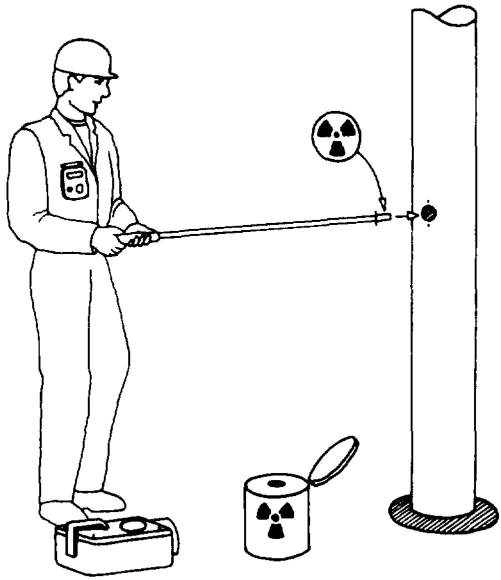
Portable gauges should be transported in accordance with transport regulations. Where the housing of the gauge does not meet these requirements, gauges should be placed within a suitable container that satisfies the transport regulations. Type A containers are often adequate for gauges that contain relatively low activities but if the activity exceeds limits which are specified in the IAEA Regulations for the Safe Transport of Radioactive Materials then a Type B container will be required. These containers are more rigorously tested and certified. In addition to appropriate documentation the transit case will need to display labels to identify the associated dose rates as either Category I, II or III:

Transport container label category	Maximum allowed dose rates ($\mu Sv \cdot h^{-1}$)	
	At the surface of the container	At 1 m from the surface of the container
I	5	—
II	500	10
III	2000	100

The labels have to be marked with the name of the radionuclide and the activity contained (for example 200 MBq). Category II and III labels must be marked with the transport index, which is the maximum dose rate at 1 m from the container surface measured in $\mu Sv \cdot h^{-1}$ divided by ten. For example, if 12 $\mu Sv \cdot h^{-1}$ is the maximum measured dose rate at 1 m from a container, its transport index would be 1.2.

Handling of Sources

Some gauges, for example reactive gauges, require sources to be changed periodically. Others, for example backscatter gauges (logging tools) used at different locations to measure the characteristics of subsurface rocks, need the source and the gauge housing to be transported separately. These and other source changing operations require special, long handled tools. Their length will range between 10 cm and more than 1 m, depending on the nature of the radioactive sources being manipulated and the frequency of the work.



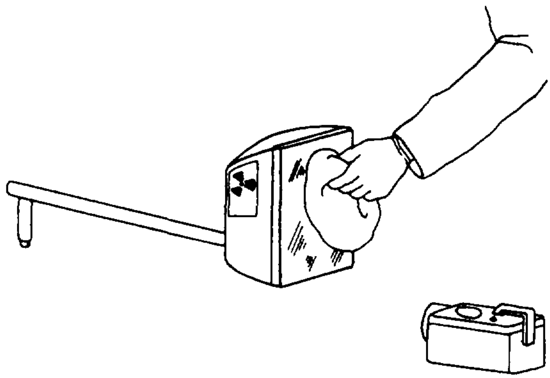
A long handling tool is used to transfer a gamma source from its transport container to the gauge.

The operator should have ready access to a suitable dose rate meter with which to monitor source handling procedures.

Maintaining Gauges

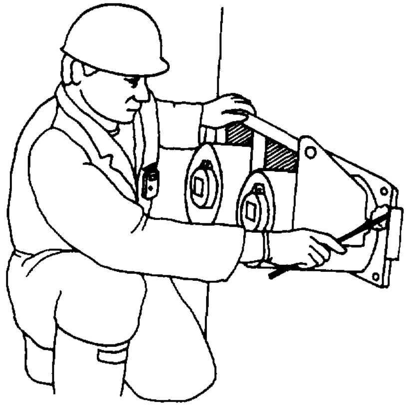
Gauges are often installed in industrial plants and exposed to the weather and other conditions which can cause a significant deterioration of the container's markings and even the shutter mechanism. Regular maintenance of moving parts and refurbishment is therefore particularly important. Such work should not involve removing the source.

The condition of portable gauges can also rapidly deteriorate when, like road gauges and ore analysis gauges, they are used under site conditions. Daily cleaning and regular maintenance are vital. A dose rate meter should be used to confirm that the shutter is closed before these operations are carried out.



A check is made to ensure that the shutter is closed before carrying out essential maintenance on a gauge.

It is likely that the source will give reliable service for a number of years. Leak tests should be carried out at the intervals required by the regulatory authority or recommended by the manufacturer or following any incident in which the source might have been damaged. Permanently installed sources are generally subject to less demanding conditions but even here should be tested at least every two years. They need not be wiped directly. A piece of moistened paper or cloth can be used to wipe around the container where radioactive substance might be expected to emerge if the source was leaking. Sources which are manipulated or are subjected to more adverse conditions will need to be leak tested much more frequently, for example biannually. They are usually tested more directly by wiping a surface that has been in direct contact with the source. Care needs to be taken with sealed sources which emit low energy radiation. Directly wiping the surface of the source could damage a thin 'window' where the radiation is intended to emerge. Wipes should only be handled with tweezers or tongs. Sensitive detectors are needed to measure accurately how much radioactive substance is on a wipe but gross contamination will possibly produce a significant dose rate. For example, gross contamination in excess of 600 kBq caesium-137 or much less cobalt-60 will produce measurable dose rates of at least 5 $\mu Sv \cdot h^{-1}$ at 10 cm. The amount of leakage which is acceptable is much lower than this.



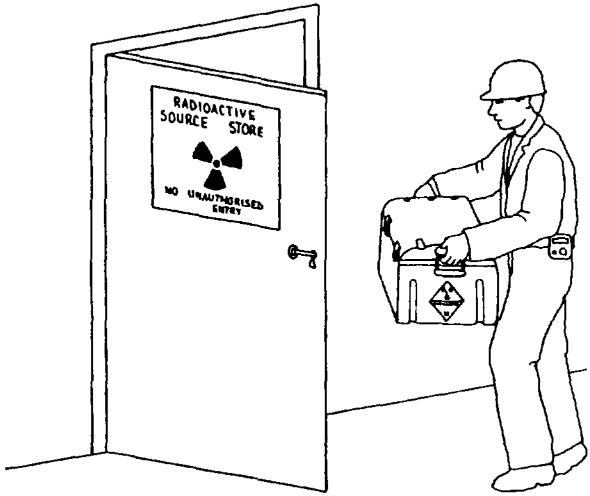
A leak test being carried out on an installed gauge which contains a permanently housed source.

Storage and Accounting for Gauges

Gauges awaiting installation, and portable gauges and interchangeable sources, may only have sufficient shielding to enable them to be carried for short periods and to be transported. No one should stay close to or handle them for longer than is necessary. A special store reserved for the purpose should be provided where gauges and their sources can be kept while they are not in use. This store should not contain other hazardous materials such as chemicals or compressed gases. It should be dry and, if necessary, ventilated. Clear warning notices should be displayed. The dose rates outside should generally be less than 7.5 $\mu Sv \cdot h^{-1}$ or, preferably, less than 2.5 $\mu Sv \cdot h^{-1}$.

The store should be kept locked to prevent unauthorized persons entering the higher dose rate areas inside or tampering with a gauge or its sources. The key should be kept in a safe place.

A record should be kept showing where each source is at all times. A weekly check might be made on portable gauges and sources to ensure that they are safely stored. A less frequent check, perhaps monthly, may be more appropriate for installed gauges.



A portable gauge
is returned to the source store.

Worker Protection

Workers operating in areas where gauges are installed are not likely to be exposed to significant radiation levels and do not need to wear dosimeters.

Source changing operations can result in the operator accumulating a dose over a short period of time. The dose should be kept as low as reasonably achievable by using the handling tools provided and practising efficient procedures that will keep the exposure times as short as possible. Therefore, it may be necessary for the operator to wear a personal dosimeter while working close to the source container. In the manipulation of sources that emit short range radiation, it may also be necessary to measure the doses to the hands to ensure that they do not accumulate significant dose.

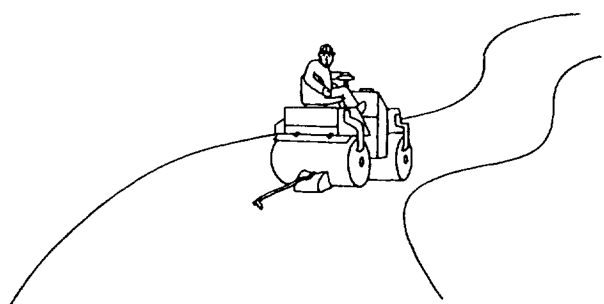
Dealing with Emergencies

It is important to be both able to identify, and prepared to deal with, problems involving a nuclear gauge. A thorough assessment of the equipment and its use will indicate 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. For example, the plans might define immediate actions to deal with the following:

— a gauge or a source that has been lost or stolen;
— 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 after a shutter or warning signal failure;
— the exposure of a person because of a failure of the equipment or procedures.

If a radioactive source is lost, even while within its housing, attempts should be made to find it as quickly as possible. High sensitivity radiation monitoring instruments, capable of measuring low dose rates or contamination, can help to detect radiation from the source, especially if it is unshielded.

A source suspected of leaking a radioactive substance must be isolated as soon as possible. Direct contact with the source and its housing should be avoided. Surfaces that come into both direct and indirect contact with the leaking radioactive source will become contaminated. Measures should be taken to prevent ingestion of radioactive substances that can result when clothing and surfaces of the body become contaminated. Specialist help and the use of surface contamination meters will be needed to identify the affected surfaces and to carry out effective decontamination procedures.



An incident which might result in the release of radioactive substance causing surface contamination.

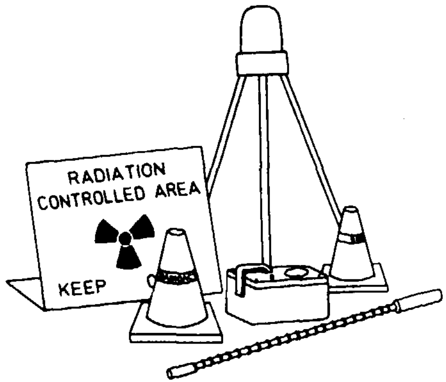
Any incident which may have resulted in an internal or an external dose to a person should be investigated. It is important to determine whether a suspected or reported dose was received and whether any part of the body has received a much higher dose which might result in localized tissue injury.

PROCEDURES GUIDE: NUCLEAR GAUGES

Follow authorized procedures when working with nuclear gauges.

Only trained and authorized workers should carry out the work. If appropriate, the workers 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.



Use only established methods, suitable equipment and a sealed source of an activity which is appropriate to the gauge's purpose. A portable gauge should be used only when all the necessary ancillary equipment which is associated with the particular gauge is also available. This might include source handling tools, barriers, warning notices and signals and a dose rate meter.

Keep safe and properly stored:

— any source or housing which is waiting to be installed;

— any source housing which has been removed from its installation; or,

— any portable gauge which is temporarily not in use.

Make regular, for example weekly, entries in a record to show that a check has been made on the stored items.

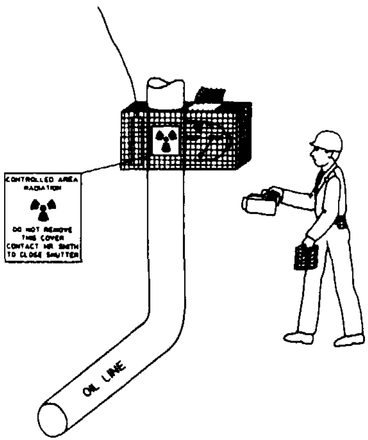
Keep a record to show where installed gauges are.

Keep the key for the source store in a safe place.

Before removing a gauge or interchangeable source from the store remember to record who has them and where they are being moved to.

Check that the container is locked and use a dose rate meter to confirm that the source is shielded. This also serves as a check on the dose rate meter.

Attach two transport labels to the container and display warning placards on the vehicle. Keep the container segregated from the occupants.



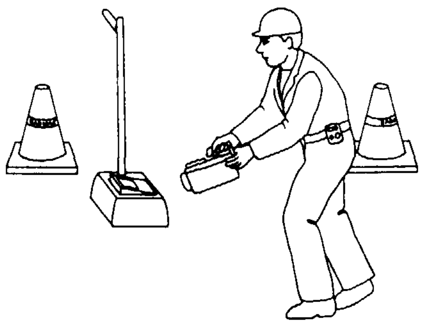
Check installed gauges periodically, for example monthly, to confirm that they are safely installed. Measure accessible dose rates and ensure that a physical barrier marks the extent of any Controlled Areas.

Block any gaps in the shielding which might be inaccessible to the dose rate meter but not to fingers and hands. This is especially important if the gaps provide access to the primary beam.

Check that the shielding is firmly secured.

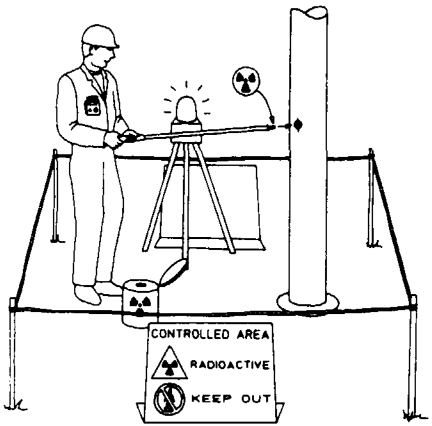
Check that warning signs are readable, especially on shielding and access doors or panels.

Maintenance workers should be reminded which person is to be contacted to ensure that the shutter is locked in the closed position before they enter these areas.



Before using a portable gauge, or working on an installed gauge, set up a barrier and warning signs either to mark the extent of the Controlled Area or as an indication to other persons in the vicinity to keep clear. Never leave a Controlled Area unattended.

Whilst working with a gauge, keep the dose rate meter with you and switched on. Use the dose rate meter to check that the shutter has closed after you have used a portable gauge. Likewise, check that the shutter is locked in the closed position before removing an installed gauge from its position.

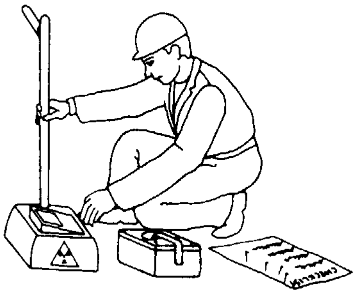


Unless you are specifically trained and authorized to do so:

— never attempt to remove a source from its housing; and,

— never attempt to modify or repair the housing.

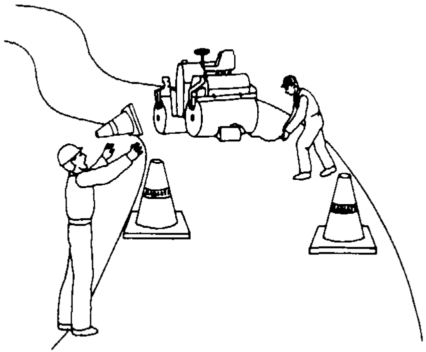
Appropriate handling tools and approved procedures must be used by persons who are responsible for manipulating sources. A source must not be allowed to be in contact with any part of a person's body.



Carry out the necessary routine maintenance. A portable gauge may require attention after each use but, before closely examining it remember to use the dose rate meter to check that the shutter has closed or the source is otherwise safely shielded. Installed gauges will need less attention. Keep a record to show that the regular maintenance has included, for example:

(1) Cleaning the outside of the housing to remove grit and moisture.
(2) Ensuring that external surfaces of the gauge are kept in good condition and that labels, warning signals and the tag displaying details of the source remain legible.
(3) Using recommended lubricants to clean and maintain any moving parts.
(4) Examining any screws and nuts for tightness.
(5) Checking to see that the source is securely held within the housing and that uniform dose rates are measurable on all external surfaces of the housing.
(6) Examining source handling tools for damage to springs, screw threads or the like.
(7) At the recommended intervals, and in the prescribed manner, carrying out leakage tests.

Report any faults to your supervisor.



If a gauge is involved in an accident or incident stay calm.

If the gauge is undamaged do what is necessary to make it safe. For example, using a dose rate meter, confirm that the shutter is closed and place the gauge in its transport container.

If the housing appears to be damaged move away from it and keep others away. Measure the dose rates and set up a barrier which marks the Controlled Area.

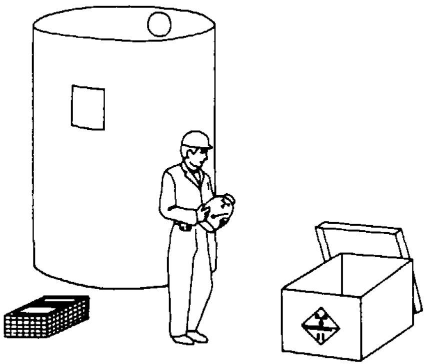
If it is suspected that the source has been very badly damaged, prevent access to those surfaces which might be contaminated by the radioactive substance. Detain anyone who may either have received a radiation dose or been in contact with a contaminated surface. Stay close but outside the marked area and send someone to inform your supervisor and obtain help. A leak test will indicate whether a source has been seriously damaged. A gauge which might be damaged should not be reused until it has been examined and, if necessary, repaired by a competent, authorized technician.

When work involving portable gauges or interchangeable sources is completed, a dose rate meter should be used to confirm that the sources are safely shielded.

Ensure that any container still displays two legible transport labels. If a vehicle is used, it should display warning pacards to transport the container back to the source store.

A note of the return of sources should be made in the record book.

In the event of loss or theft of a source, inform your supervisor at once.



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

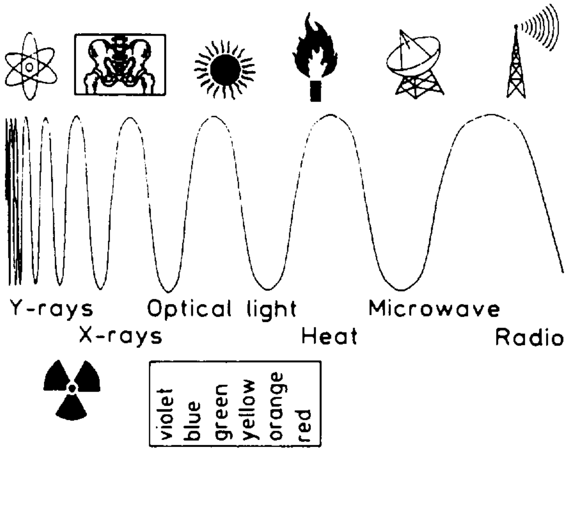
BASICS GUIDE FOR USERS OF IONIZING RADIATION

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.

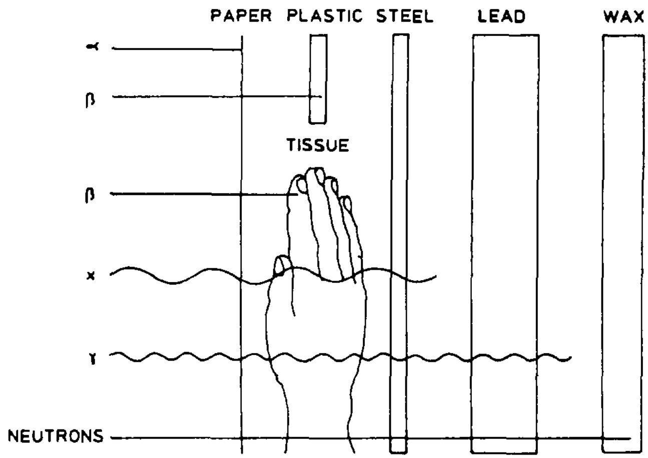
Radionuclide	Maximum beta particle energy (MeV)	Maximum range			
		Air (mm)	Plastic (mm)	Softwood (mm)	Aluminium (mm)
Promethium-147	0.23	400	0.6	0.7	0.26
Thalium-204	0.77	2400	3.3	4.0	1.5
Phosphorus-32	1.71	7100			
Strontium-90/ Yttrium-90	2.26	8500	11.7	14.0	5.2

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.

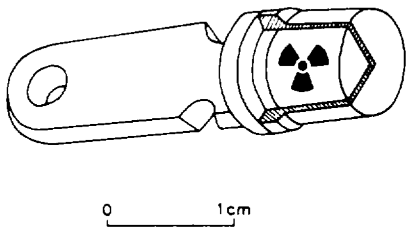
Neutrons behave in complex ways when travelling through matter. Fast neutrons will scatter (bounce) off much larger atoms and molecules without losing much energy. However, in a collision between a neutron and a small atom or molecule, the latter will absorb a proportion of the neutron's energy. The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

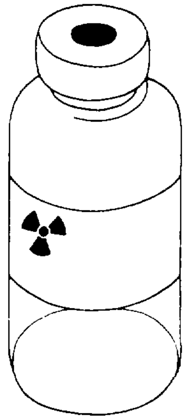


A sealed source, showing the encapsulated radioactive substance.

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

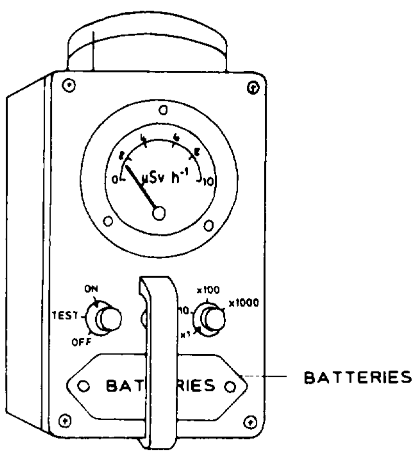
Measurement of Radiation

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 $mrem \cdot h^{-1}$.



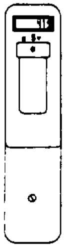
A typical dose rate meter.

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

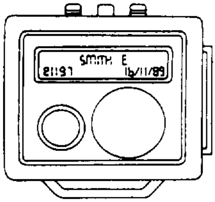
Most dose rate meters are battery powered and some have a switch position that enables the user to check the battery condition, i.e. that it has sufficient life remaining to power the instrument. It is important that users are advised not to leave the switch in the battery check position for long periods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

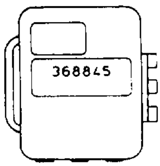
A dosimeter measures the total dose accumulated by the detector over a period of time. For example, a dosimeter would record 20 μSv if it was exposed to 10 $\mu Sv \cdot h^{-1}$ for two hours. Some dosimeters can give an immediate reading of the dose. Others, like the film badge and the thermoluminescent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



(a) Electronic dosimeter



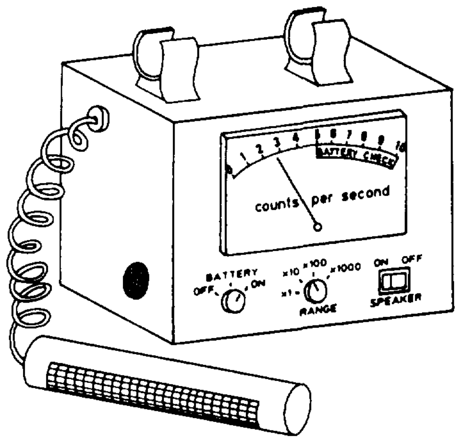
(b) Thermoluminescent dosimeter



(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.

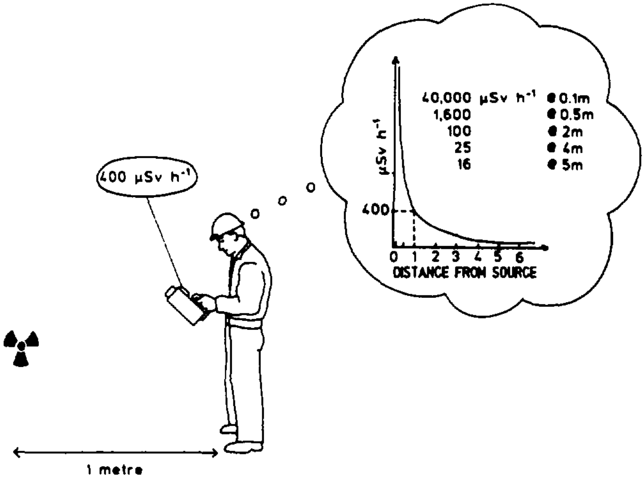
For example:

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.

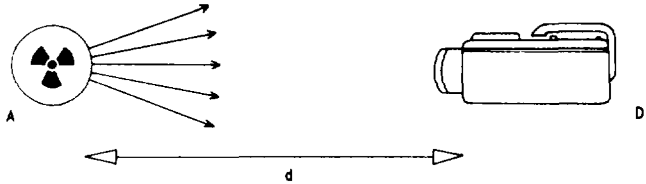
The dose rate is obtained using the equation:

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

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 $\mu Gy \cdot h^{-1}$?

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

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

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

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

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

$$d = 80 \text{ m}$$

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.

Printed by the IAEA in Austria
March 1996
IAEA-PRSM-3 (Rev.1)