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Manual on GAMMA RADIOGRAPHY

Incorporating:
Applications Guide
Procedures Guide
Basics Guide

PRACTICAL RADIATION SAFETY MANUAL

Manual on GAMMA RADIOGRAPHY

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Applications Guide

Procedures Guide

Basics Guide

INTERNATIONAL ATOMIC ENERGY AGENCY

MANUAL ON GAMMA RADIOGRAPHY
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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. Zuniga-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. Zuniga-Bello (IAEA). Finalization of all six manuals was carried out by A. Schmitt-Hannig, Federal Office for Radiation Protection (Germany) and P. Zuniga-Bello (IAEA).

CONTENTS

APPLICATIONS GUIDE: GAMMA RADIOGRAPHY

Radiography

A defect in a weld between two sections of pipeline or some other flaw in a casting or metal component could have catastrophic consequences when the pipeline or object is put to use. Radiography reveals such imperfections using the unique properties of ionizing radiation to penetrate these important components without damaging them. The radiographer produces a radiograph which is a permanent photographic record of the non-destructive test (NDT). The procedure is also called quality assurance (QA) testing.

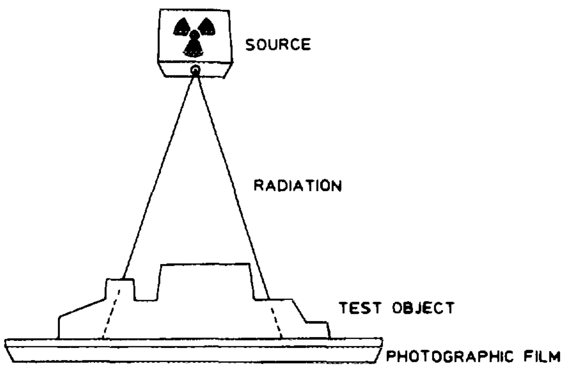


Diagram of a radiographic arrangement.

Radiation Used for Radiography

Gamma radiography uses gamma radiation. The necessary equipment is highly portable and ideally suited to the sometimes remote and often difficult working conditions on construction sites.

Iridium-192 is ideal for radiography but other radionuclides can be used depending on the characteristics of the object material.

Radionuclide	Gamma energies (MeV)	Optimum steel thickness (mm)
Cobalt-60	High (1.17 and 1.33)	50–150
Caesium-137	High (0.662)	50–100
Iridium-192	Med (0.2–1.4)	10–70
Ytterbium-169	Low (0.008–0.31)	2.5–15
Thulium-170	Low 0.08	2.5–12.5

The radiation must have enough energy to penetrate straight through the object but with sufficiently reduced attenuation when passing through a flaw. The increased transmission through the flaw must produce a darker image on the developed film. The activity of the source determines how much radiation is available. Too much adds fog to the film, darkening it overall and reducing the likelihood of identifying the flaw. It also requires safety precautions over a wider area. A low activity source will require longer exposure times to allow sufficient radiation to reach the film to create the images. The longer exposures extend the duration of the work and require the safety precautions to be enforced for longer times.

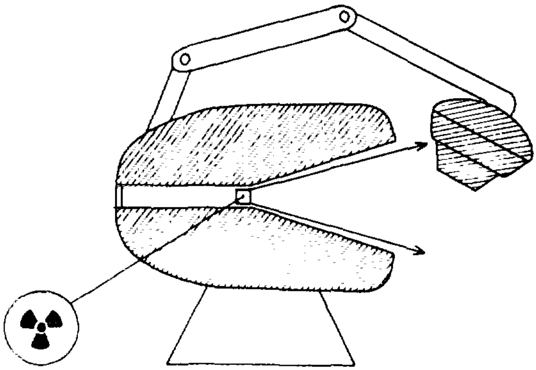
Equipment Used for Radiography

Radiographic sealed sources are special form, stainless steel capsules containing a high activity. Their gamma emissions are continuous and to be transported and carried the sources need to be housed in special portable containers. These exposure containers (in some countries also called cameras) totally surround the source with shielding such as lead or, more effectively, uranium. Many types of containers are manufactured but not all are internationally available or used. All generally operate by exposing the useful radiation in one of three ways:

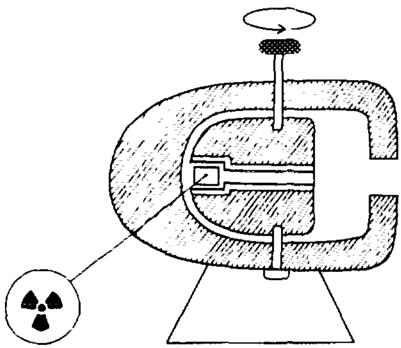
(1) Part of the shielding is taken away;

(2) The source is moved to a deliberately thin part of the shielding but remains inside the container; or

(3) The source is fully removed from the container.



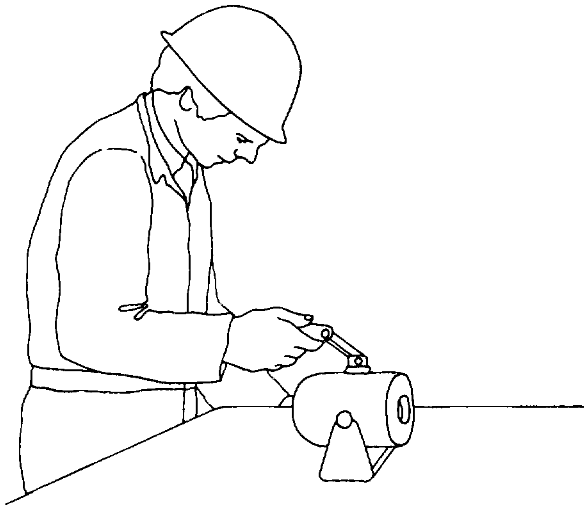
Removable shutter exposure container.



Rotating shutter exposure container.

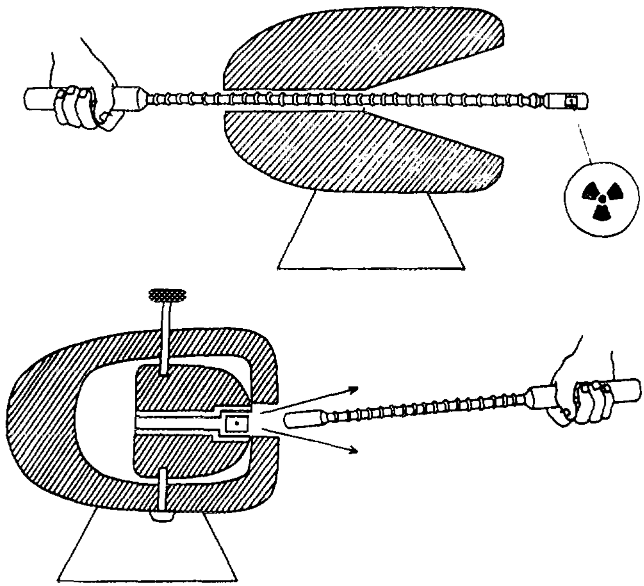
The first two types are often called shutter or beam containers. They collimate the radiation that is released, shaping and limiting the size of the beams that emerge.

The shutter mechanisms are sometimes automatic and sometimes manual. For the latter it is important for the radiographer to stand behind the container, using its shielding to minimize the radiation dose that he or she is likely to receive.



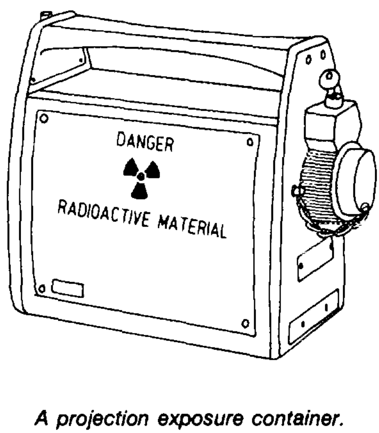
A radiographer stands behind a shutter exposure container to use its shielding.

Situations occur where beam radiography using shutter containers is not possible. This may be because the container will not fit into the available space or a film area to be exposed exceeds the beam size. The manufacturers will provide special long handling tools designed to remove the source from the container. The source can then be installed in a suitable collimator or used to carry out panoramic radiography. For the latter, there are no restrictions on the beam direction. The radiographer usually gets higher doses from this kind of work. Stringent procedures are needed to ensure that the length of the handling tool of say 1 m is maintained between the radiographer and the source. Contact with a high activity source for a few seconds could cause a tissue injury which would not become apparent for several weeks.



Special handling rods are needed to remove sources from shutter exposure containers to carry out panoramic radiography.

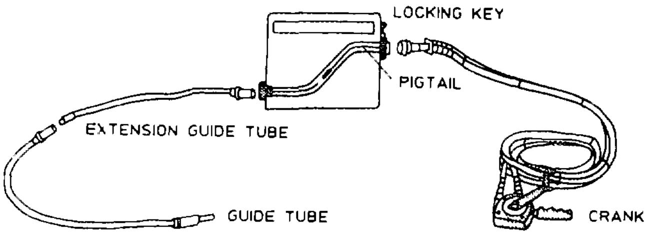
The most widely used equipment is now of the third type. It is called the projection container or crank-out camera and its use is described in detail later in this Manual. The design ensures that the radiographer can nearly always be protected by exposing the source from a distance.



A projection exposure container.

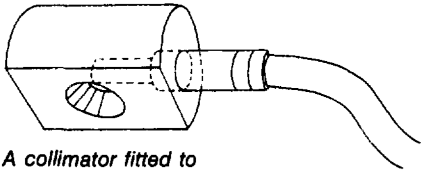
Projection Containers

The source for the projection container is mounted on the end of a flexible wire called the pigtail. The non-active end of the pigtail partly protrudes from the container and is secured by a locking ring holding the source in the centre of the shield. The S-shaped tube through the shield does not allow the radiation a straight short path to the outside. A transit plug closes the exit port and prevents grit from fouling the S-tube. Ancillary components of the projection container include the control cable and crank, the guide tube and the extension guide tube (which is not always needed). A variety of collimators fit the end of the guide tube — the snout.

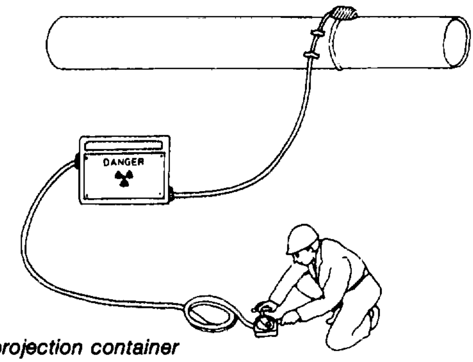


A projection exposure container (sectioned to show S-tube) and ancillary components.

To operate the projection container the snout is positioned close to the object, the cable is connected to the pigtail and the cable housing and guide tube are connected to the container. Securing the cable housing to the container involves rotating the locking ring which releases the pigtail. Turning the crank then drives the cable, pushing the pigtail out of the container and along the guide tube until the source reaches the snout. The guide tube and the collimator must be firmly secured by tape or held by a stable support to prevent movement as the source enters the snout. Reversing the crank control retracts the source.



A collimator fitted to a guide tube snout.



An assembled projection container arrangement in use.

Possible Problems with Containers

It is vitally important to carry out regular maintenance of all radiographic containers and ancillary equipment in accordance with the manufacturer's instructions. It is worthwhile keeping a record of the maintenance checks and tests necessary and a note that they have been carried out at the appropriate intervals. Mechanical and automatically operated components are most vulnerable and become critical if their failure is likely to result in the source remaining exposed. The radiographer's experience and the technical operators handbooks supplied with the equipment should make it possible to identify possible malfunctions and their remedies. For example, although projection containers have proved very reliable and have helped to reduce the doses received by radiographers, there are a number of potential problems:

(1) The end of the cable may run through the crank because of a cable fault or a failure to secure the guide tube or snout.

(2) The crank may become difficult or impossible to turn after it has been fouled by grit from the cable or container.
(3) If the cable or pigtail is kinked it might weaken and break.
(4) The cable–pigtail connection may uncouple because of damage, wear or grit fouling.
(5) The cable housing may disconnect from the container because of a fault or rough handling.
(6) The cable housing may be crushed, trapping the cable.
(7) The guide tube may be crushed or guide tube connectors become burred, trapping the source or pigtail.

Recognizing these possible faults can help to prevent them from occurring. The equipment should be regularly examined and if necessary repaired by a competent technician or the damaged component should be replaced before the equipment is reused.

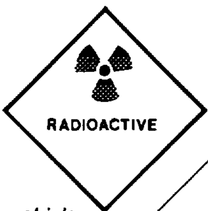
Requirements for Exposure Containers

Radiographic equipment which displays a statement that it meets ISO 3999 — Apparatus for gamma radiography (ISO/TC 85.SC 2 N 78) — specifications has been manufactured to the highest possible standard and is least likely to cause problems. To ensure that the container continues to meet the standard it should be kept clean so that the trefoil warning symbol and the word 'Radioactive' stay readable. The lock which secures the source should be maintained. The activity of any new source that is installed must not exceed the container's rating, for example 4 TBq iridium-192, specified on the container. Compliance will ensure that the following dose rate limits (for a Class P, portable container) are not exceeded:

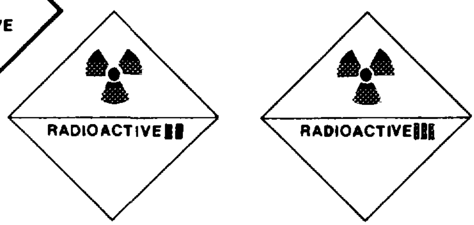
2000 $\mu Sv \cdot h^{-1}$ (200 $mR \cdot h^{-1}$) on any external surface of a container;
500 $\mu Sv \cdot h^{-1}$ (50 $mR \cdot h^{-1}$) at 50 mm from any external surface of a container;
20 $\mu Sv \cdot h^{-1}$ (2 $mR \cdot h^{-1}$) at 1 m from any external surface of a container.

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 container.

Containers that satisfy ISO 3999-* * * * are also often used as transport containers. Most are tested and certified to Type B standard which will withstand severe impact forces, crushing forces, immersion in liquid and heat stress without loss of the radioactive contents or significant loss of shielding. To be transported these containers only need appropriate documentation and labels to identify the associated dose rates as either Category II or Category III. The vehicles used also usually need to display placards.



A vehicle placard.



Category II and Category III labels.

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

The container labels have to be marked with the name of the radionuclide, the activity contained (for example 400 GBq) and the transport index. The transport index is the maximum dose rate at 1 m from the container's 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.

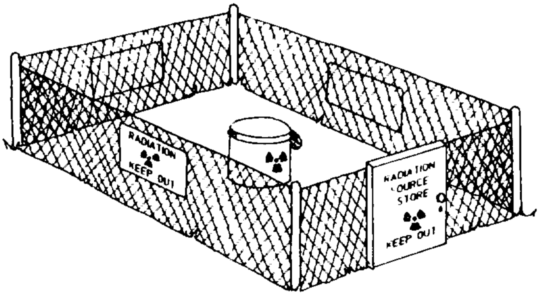
Leakage Tests for Radiographic Sources

Leakage tests should be carried out at the intervals required by the regulatory body or recommended by the source manufacturer or following any incident in which the source might have been damaged. They can be carried out by simply wiping any surface that has been in contact with the source such as the inside of the S-tube or the guide tube and assessing whether there is any radioactive substance on the wipe. A better assessment requires a short rigid guide tube like a snout which fastens directly onto the container. A piece of absorbent paper or cloth is placed in the short tube and the source is wound out as if for radiography, so that the source gently presses into the wipe. Wipes should only be manipulated using tweezers or tongs. Sensitive radiation detectors are needed to measure accurately how much radioactive substance is on a wipe but gross contamination will produce a dose rate. For example, gross contamination in excess of 600 kBq caesium-137 or much less iridium-192 and 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 less.

Storage of Equipment

Exposure containers only have sufficient shielding to enable them to be carried for short time periods and to be transported. No one should stay close to them for longer than is necessary. When a source is used regularly on a site, a special store should be reserved for keeping the exposure container while it is not in use. The site operator's co-operation is needed so that the store can be isolated and in particular positioned well away from other hazardous materials such as explosives and corrosive substances. The store should display clear warning notices and be dry inside. The dose rates accessible outside the store should be as low as reasonably practicable; less than 7.5 $\mu Sv \cdot h^{-1}$ or, preferably, less than 2.5 $\mu Sv \cdot h^{-1}$.

A lock should be kept on the door to prevent unauthorized people entering the area of higher dose rates or tampering with the container. The key should be kept in a safe place.



Typical store for exposure containers.

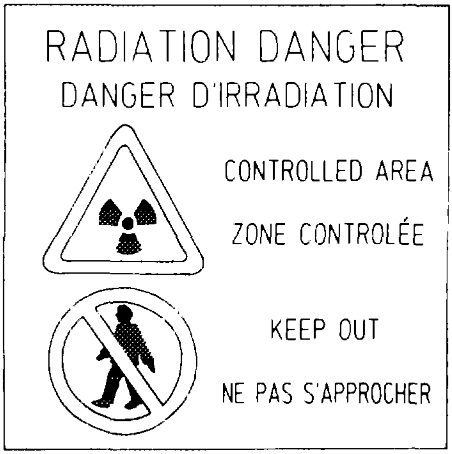
A record should be kept showing where each source is at all times. On days when the source and container are not used a check should be made to see that they are still safely stored.

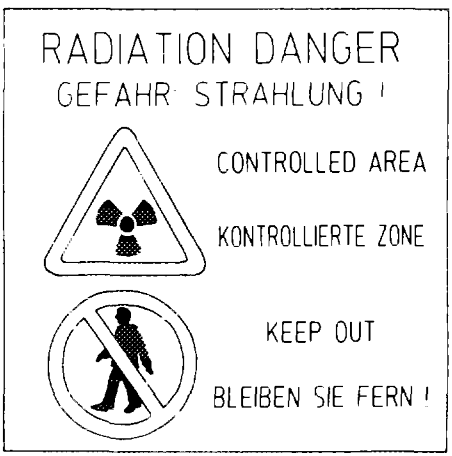
Radiography Procedures

When a radiographic source is exposed it will produce dose rates greater than 7.5 $\mu Sv \cdot h^{-1}$ over a very large area. The maximum size of the area can be calculated if the radionuclide and its activity are known. In general, such areas should be designated Controlled Areas and access to them should be prohibited to everyone except the radiographer and authorized helpers. Sometimes, on a construction site, the Controlled Area extends above and below the level on which the radiographic equipment is situated.

Beam radiography produces the smallest Controlled Areas, especially if the beam is directed downwards into the ground. Another way of reducing the size of the Controlled Area is by setting up local shielding around the radiographed objects to further attenuate the beam when it has passed through the photographic film. Such beam stops can be made from lead or any such heavy metal.

Enough barrier-making equipment and sufficient warning notices must be provided to mark the boundaries of all of the Controlled Areas. The warning notices should be in the local language so that everybody in the vicinity will understand what is happening and why they are not allowed to pass the barriers. In any case, make sure that there are enough helpers to walk around the outside of the barriers to stop people crossing them.





Warning notices should be in the local language.

A loud pre-exposure warning signal such as a whistle should be used by the radiographer to warn the helpers and others when he or she is about to expose the source. A light, a large notice or some other suitable exposure warning should be placed as close as possible to the exposed source position as a further warning to anyone who gets past the helpers and the barriers. It is best to carry out radiography when and where it is least likely that other people will be working nearby.

The radiographer should carry a dose rate meter which is switched on at all times when he or she is carrying an exposure container, setting up a radiographic shot or fixing and removing radiographic films. The radiographer and the helpers must wear personal dosimeters while working close to the exposure container and entering Controlled Areas. Workers need to receive regular, usually annual, medical examinations or reviews of health and records need to be kept of the doses they accumulate throughout the years. The measured annual cumulative dose to the whole body should not be allowed to exceed the limit.

Dealing with Emergencies

The radiographer must remain alert at all times when using a radioactive source. If the normal procedure for producing radiographs is disrupted or the equipment begins to malfunction the radiographer should retreat to obtain assistance and consider further actions. Contingency plans should be made in advance on the basis of the critical assessment the radiographer has made of such situations. Practising the contingency plans will indicate whether any special equipment will be needed to deal with the foreseeable incidents. A basic emergency kit might include four bags of lead shot, each containing 2 kg of shielding, a 1 m or 1.5 m long handling tong, and a selection of hand tools.

In order to rectify a fault it may be necessary to work close to the source position. Excessive doses could result in a short time unless the plan is prepared in detail and efficiently carried out. Most source recoveries achieved by radiographers have resulted in less than a 10 mSv whole body dose, which is below the relevant annual dose limits.

Use local shielding to cover the source whenever it is practicable; keep at least 1 m between the source and those involved in the plan; and, if practicable, do not allow anyone to be exposed for longer than it would take to accumulate 10 mSv at 1 m from the source being recovered. For example:

Iridium-192 source activity (TBq)	Dose equivalent rate at 1 m ($mSv \cdot h^{-1}$)	Time to accumulate 10 mSv at 1 m (min)
0.75	97.5	6.2
2.0	260	2.3
3.7	481	1.3

The people involved must not receive doses unnecessarily. Difficult tasks that involve working close to the source should be shared by several people to distribute the dose. Under no circumstances should the source or any part of the guide tube which might contain the source be in contact with a person's body. A sufficient dose could be received in seconds to cause tissue injury that will not become apparent for several weeks. Under no circumstances should any action be taken that risks cutting or otherwise destroying the source.

Any incident which may have resulted in an excessive 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 received and whether some part of the body has received a much higher dose which might result in localized tissue injury.

If a radioactive source is lost, even within its container, it should be found as quickly as possible. Radiation monitoring instruments will be needed to help to locate the source. High sensitivity instruments (capable of measuring low dose rates or contamination) can help to detect radiation from distant or shielded sources. Low sensitivity instruments (capable of measuring high dose rates) are needed close to unshielded sources. Do not search 'blindly' for a source in an area where the dose rate exceeds the range

Do not directly handle radiographic sources.

of the available instruments. Move away until the instrument is again able to indicate the dose rate and calculate the distance to the source. Similar measurements from other directions may help to pinpoint the source.

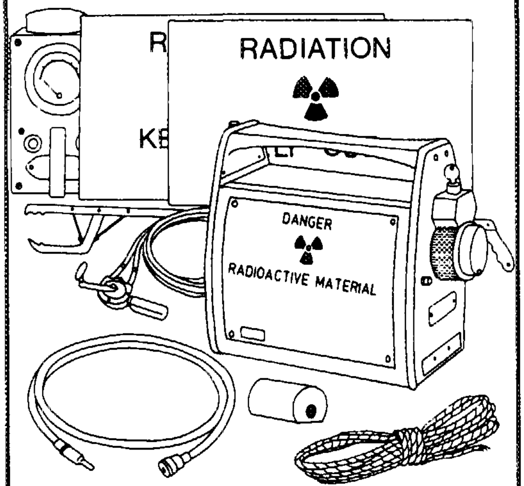
When a radiographic source no longer has a useful purpose it should be properly disposed of. This might be achieved by returning it to its country of origin or placing it in the care of an authorized receiver.

PROCEDURES GUIDE: GAMMA RADIOGRAPHY

Follow authorized procedures when carrying out gamma radiography.

Only trained radiographers and authorized helpers who have had medical examinations and wear a dosimeter should carry out radiography. In normal circumstances, such workers should not have received greater than a dose limit (50 mSv to the whole body) in the current calendar year.

Before proceeding with the work, read and ask questions about these safety guides. Discuss the contributions all the workers involved will make to this important work.



Rehearse the procedures and only use equipment that has been specifically manufactured for gamma radiography. The radiographer should be familiar with all of the equipment, its mode of operation and potential problems. An understanding of the source, its appearance and how it is to be exposed are particularly important.

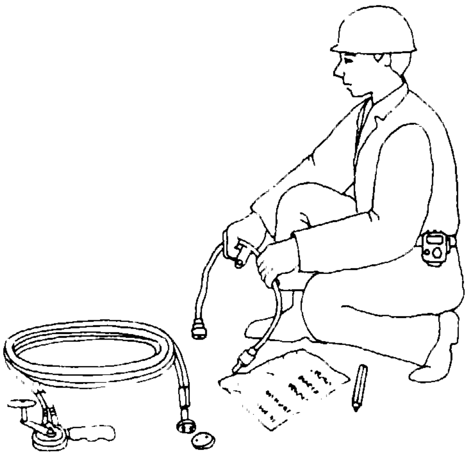
Only carry out radiography when all the necessary equipment is available:

- a suitable source housed in an appropriate container;
- guide tubes, control cables or other source handling tools;
- collimators; barrier-making equipment;
- warning notices and signals;
- dose rate meter; and
- emergency kit.

Record weekly maintenance carried out on the container, for example:

(1) Clean the container, removing grit and moisture.
(2) Use only recommended lubricants to clean and maintain any moving parts.
(3) Check screws and nuts for tightness and screw threads and springs for damage.
(4) Confirm that the source locking mechanism works.
(5) Remove the cover to examine the end of the pigtail for cleanliness, wear or damage. A wear gauge should be used.
(6) Connect the control cable to the pigtail and check by gently pulling or twisting that it does not accidentally disconnect.
(7) With the transit plug still in place, connect the cable housing to the locking ring and ensure a firm connection.
(8) Disconnect the cable housing and cable, relock the pigtail and then remove the transit plug from the guide tube port.
(9) Connect the guide tube, checking for crossed threads and a firm connection.
(10) Remove the guide tube and replace the transit plug.
(11) Check that warning plates and source details are readable.
(12) Measure the dose rates close to the container's surface.

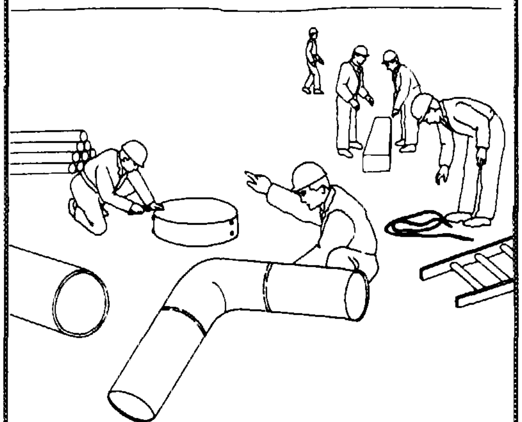
Report any faults to your supervisor.



Keep a record to show that weekly maintenance has been carried out on ancillary equipment, for example:

(1) Check the control cable crank and container connection ring or other source handling tool for loose fittings.
(2) In a clean area, wind out a short length of cable to check for kinks and a smooth crank movement.
(3) Use only recommended lubricants to clean and maintain moving parts.
(4) Examine the cable end for damage or wear. A wear gauge should be used.
(5) Examine the control cable housing for tears, dents or other damage which might affect cable movement.
(6) Examine guide tube and extension tubes for burred connector threads, dents or grit which might affect source movement.

Report any faults to your supervisor.



Prepare each radiographic shot in advance.

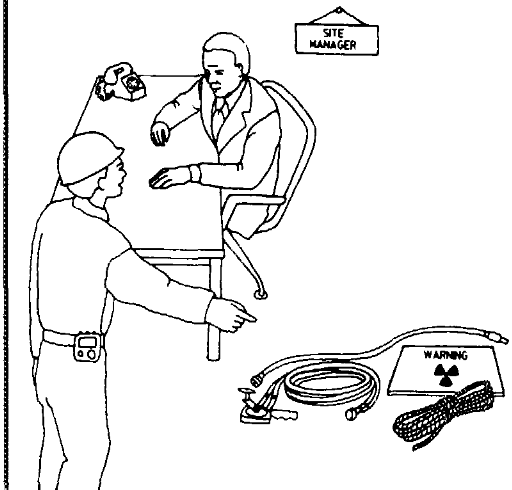
Consider moving the object to a place set aside for radiography where it will be either easier to prevent access or possible to do radiography without disrupting other construction work.

Calculate the current activity of the source and the exposure times needed.

If possible, choose shots which use a collimated beam and consider which beam directions are least likely to be occupied.

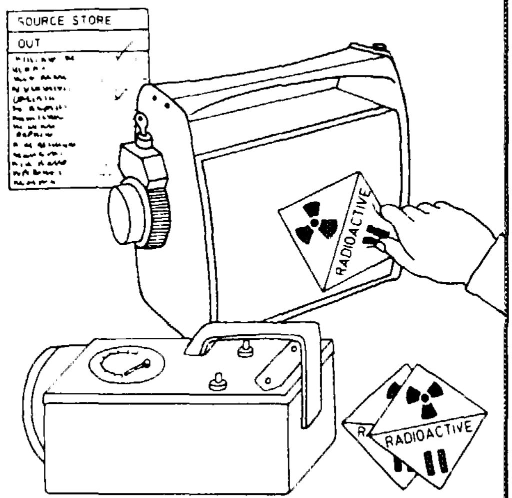
Examine whether it will be possible to use local shielding.

Calculate where the barriers will need to be to mark the Controlled Area and discuss with the site management when, and for how long, the area can be cleared of other workers.



Advise site management precisely when and where radiography will be carried out. Obtain any necessary permits and collect all documents.

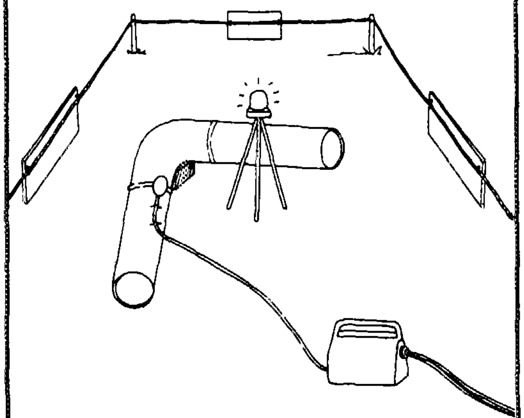
Take all ancillary equipment to the location in advance. Deliver the barriers before the scheduled time, especially if only a short period (for example a meal break) has been set aside for the radiography to be carried out.



Collect the source store key and sign the source out.

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 by comparing the reading with those previously obtained.

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



On site, at the arranged time, instruct helpers to first erect the barriers and warning notices and then to search the area to confirm that it is clear of other workers. Meanwhile, firmly fix the collimator in position and lay the guide tube out straight, checking that it was not damaged in transit.

Remove the container's transit plug (keep it clean and safe) and connect the guide tube.

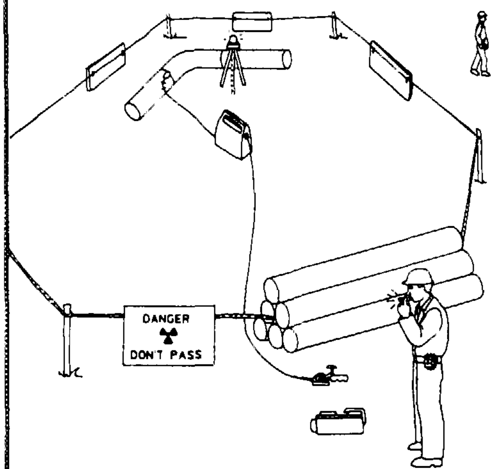
Place the control crank near the container, uncoil the control cable and form it in a long loop, again checking for transit damage.

Unlock the container and remove the pigtail cover. Turn the control crank to reveal the cable and connect the cable to the pigtail. Confirm that this is a good connection before turning the crank to bring the control cable housing to the container to be secured.

Lay out the control cable as straight as possible and place the control crank preferably outside the marked area behind any available body shield.

Place a warning light or large notice near the collimator to mark the exposed source position.

The equipment is now ready to carry out a test exposure.



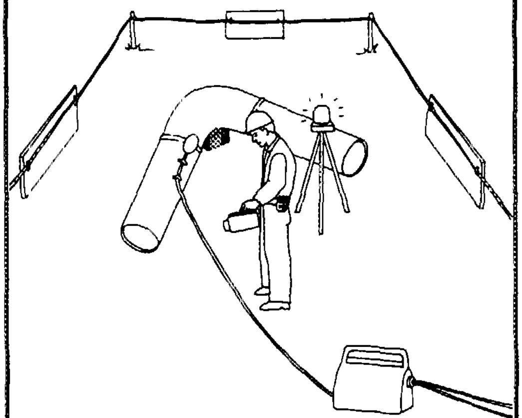
When the helpers have checked that the area is clear and have taken up their positions at the barrier in order to prevent unauthorized access, sound a pre-arranged signal (for example, a loud whistle) to warn everyone near the Controlled Area that the source is about to be exposed.

Turn the crank quickly whilst counting the revolutions to ensure that the source is driven the full extent of the guide tube and into the collimator.

Leave the Controlled Area by the safest and, if practicable, the shortest route.

Dose rates in excess of 7.5 $\mu Sv \cdot h^{-1}$ will briefly occur at the barriers as the source travels along the guide tube but when the source is in the collimator the barrier should properly mark the extent of the Controlled Area.

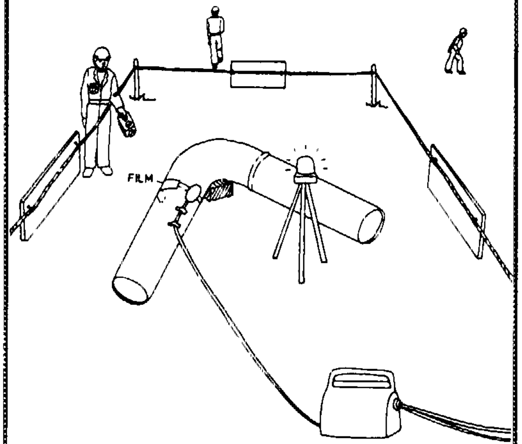
Use the dose rate meter to check that the barrier is positioned in the correct place, especially along the beam direction. Move the barrier positions if necessary.



Return to the control quickly and turn the crank whilst counting the revolutions to ensure that the source is fully retracted into the container.

Use the dose rate meter to check the guide tube from the collimator to the container and finally check the dose rates at the container to confirm that the source is safely shielded.

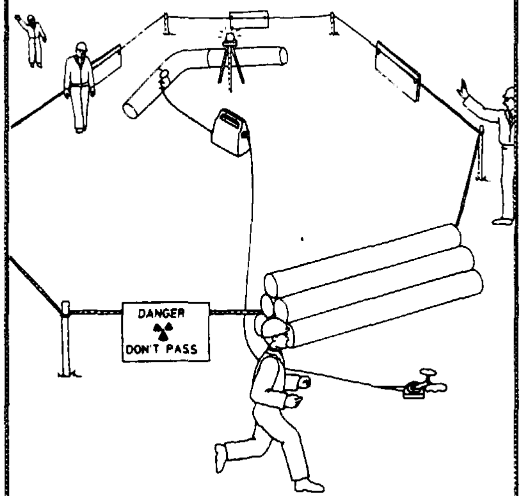
The photographic films and film identification markers can now be attached.



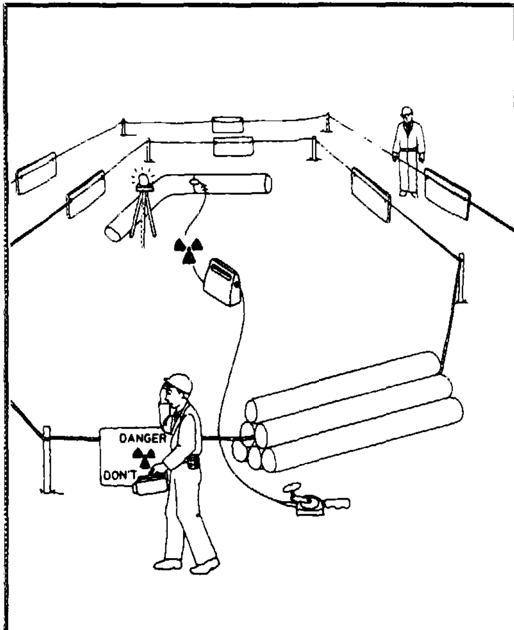
Expose the source as previously described and time the exposure to produce the radiograph. For short exposure times it might not be possible to completely leave the Controlled Area. A convenient point should be taken up where the measured dose rate is as low as practicable and in any case is less than 2 $mSv \cdot h^{-1}$.

After each exposure use the dose rate meter to check the guide tube from the collimator to the container and finally check the dose rates at the container to confirm that the source has safely retracted.

The guide tube and collimator can now be safely handled and repositioned, together with the next film and identification markers.



Throughout each exposure stay alert and use the dose rate meter to confirm that the exposure is proceeding normally. If anything unexpected happens, such as someone entering the Controlled Area or a site emergency, quickly return to the control and retract the source.



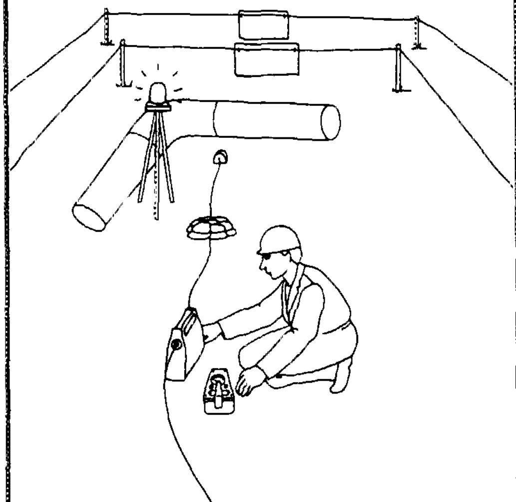
If for any reason the source fails to retract, stay calm and move away to the barrier.

Measure the dose rates and, if necessary, reposition or set up new barriers. Stay close to the area to prevent people entering and send helpers to inform the site management and to bring the emergency kit.

The contingency plan should follow previously agreed stringent guidelines using time, distance and shielding to limit individual doses.

If the crank will not turn it may be necessary to dismantle the control to pull the control cable back by hand.

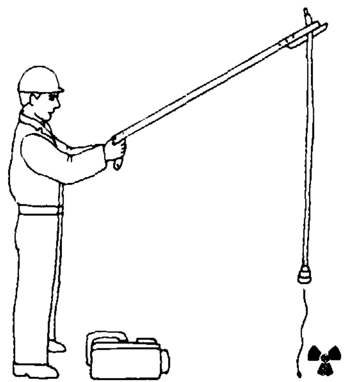
If the pigtail has detached from the cable or the source has stuck in the guide tube it will first be necessary to locate the source. Winding out the cable might push the source back into the collimator.



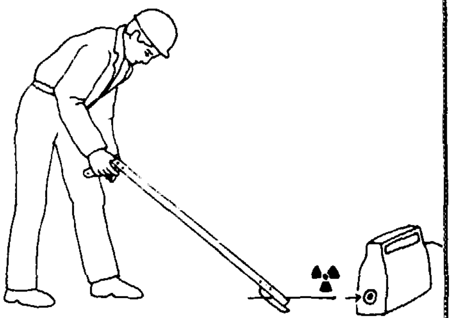
If shielding is placed on top of the guide tube close to the container and the control cable housing is then pulled, that part of the guide tube containing the source will eventually be pulled under the shielding.

The dose rate being measured at some distance away will then fall.

Placing more shielding on top of the source will allow closer access either to disconnect the guide tube from the container or to carefully cut the plastic sheath and unwind the wall of the guide tube.

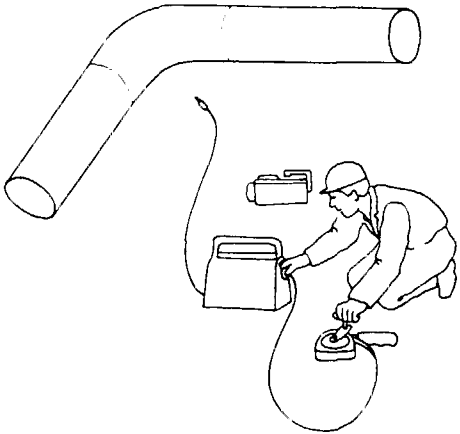


Handling tongs can be used to lift an end of the guide tube so that the source pigtail slides out onto a solid surface.



Using the handling tongs the pigtail can be picked up and placed back in the container.

UNDER NO CIRCUMSTANCES SHOULD THE SOURCE BE ALLOWED TO COME INTO CONTACT WITH THE HANDS OR ANY OTHER PART OF THE BODY.



After the final exposure or when it needs to be moved to another area the radiography equipment must be disassembled.

Use the dose rate meter to check the guide tube from the collimator to the container and finally measure the dose rates at the container to confirm that the source is safely shielded.

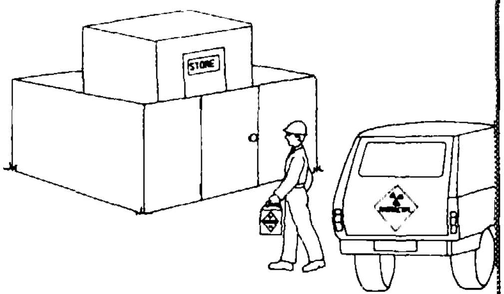
Form the control cable in a long loop with the crank near the container.

Keep the dose rate meter working by your side and disconnect the cable housing from the container, if necessary turning the crank slightly to achieve this.

Lock the pigtail in the container and turn the crank to reveal the connection between the cable and the pigtail. Disconnect the cable and fit the pigtail cover.

Coil the control cable and set it aside. Disconnect the guide tube from the container and insert the transit plug in place.

Lock the source in the container.



Ensure that the container still displays two legible transport labels. Safely return the container to the source store. If a vehicle is used it should display warning placards and the container should be secured away from the occupants.

Wipe the container clean before placing it in the store and note its safe return in the record book.

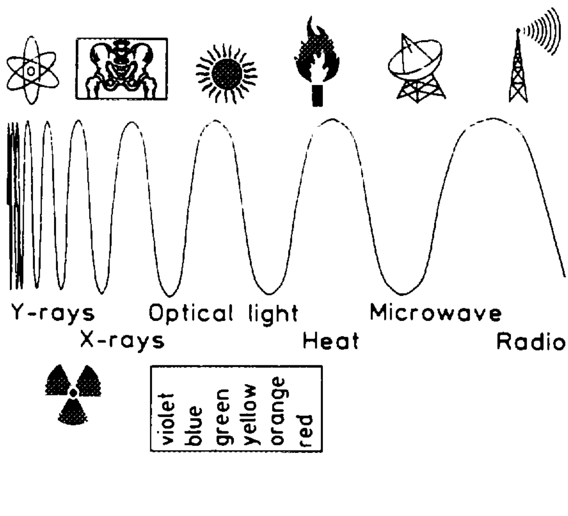
Return the key to a safe place and maintain the security of the store at all times.

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.

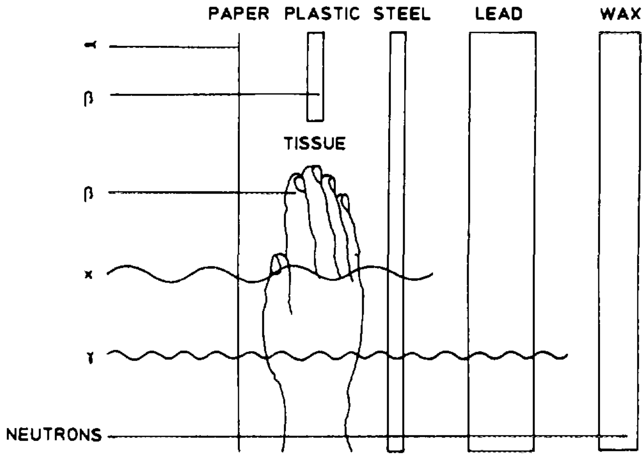
Radionuclide	Maximum beta particle energy (MeV)	Maximum range			
		Air (mm)	Plastic (mm)	Softwood (mm)	Aluminium (mm)
Promethium-147	0.23	400	0.6	0.7	0.26
Thalium-204	0.77	2400	3.3	4.0	1.5
Phosphorus-32	1.71	7100			
Strontium-90/ Yttrium-90	2.26	8500	11.7	14.0	5.2

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.

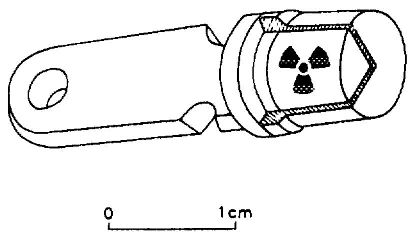
Neutrons behave in complex ways when travelling through matter. Fast neutrons will scatter (bounce) off much larger atoms and molecules without losing much energy. However, in a collision between a neutron and a small atom or molecule, the latter will absorb a proportion of the neutron's energy. The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

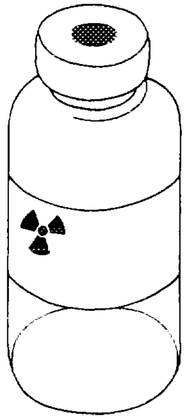


A sealed source, showing the encapsulated radioactive substance.

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

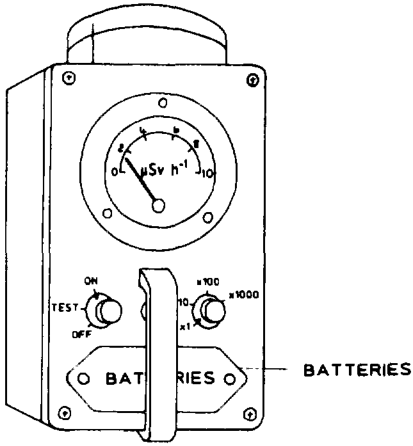
Measurement of Radiation

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



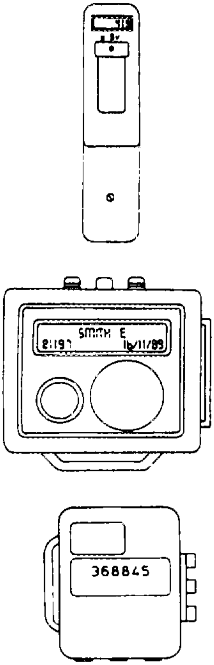
A typical dose rate meter.

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.



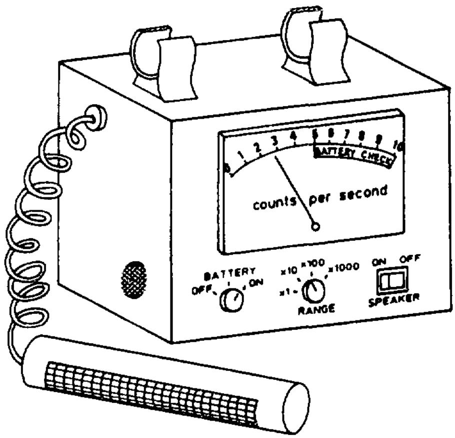
(a) Electronic dosimeter

(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.

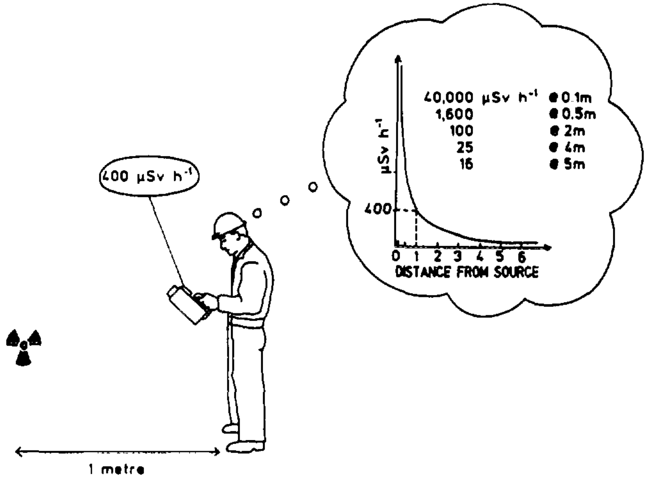
For example:

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.

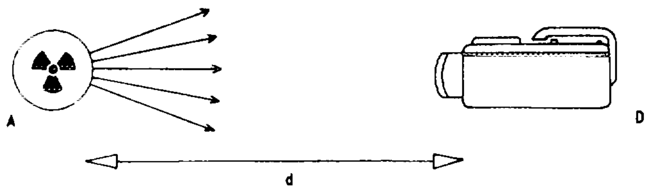
The dose rate is obtained using the equation:

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

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

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

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

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

(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.

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