The University of Nottingham
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Updated January 2012 – Safety Office

Safe Working with Ionising Radiation

These notes summarise the introductory lecture on radiation safety that forms an integral part of the induction training, and registration, of new radiation workers.

The objectives of the briefing are to enable you to become familiar with;
- The origin and types of radiation in use in the University,
- The biological consequences of radiation exposure,
- The level of risk involved with your work,
- The legal controls governing work with radioactive materials
- The procedures that have been established in the University to prevent harmful exposures,
- Practical protection against external and internal radiation exposure.

You will also receive practical instruction in your School in carrying out the techniques pertinent to your research safely.

Key Phone Numbers

University Safety Office - 13401
Dr J A Sutherland - University Safety and Radiation Protection Officer
Mr H Zuranski - Rad Protection Technician (contact for project registrations)
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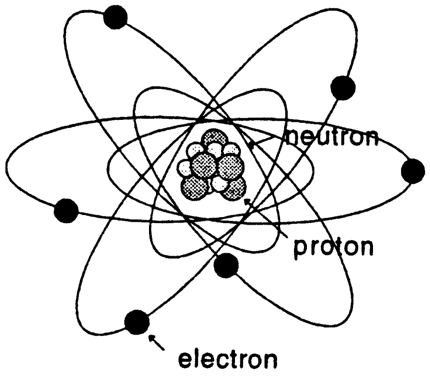
Basic Physics

Atomic Structure

Atoms

The simplest unit into which a substance can be broken down, while still retaining its unique identify and properties, is the atom. Atoms themselves consist of a central nucleus with a net positive electrical charge, orbiting around which are small lightweight negatively charges particles called electrons. The nucleus itself consists of protons and neutrons tightly bound together, the protons having a positive electrical charge and the neutrons no charge at all. The three particles making up the atomic structure are defined as the fundamental particles.



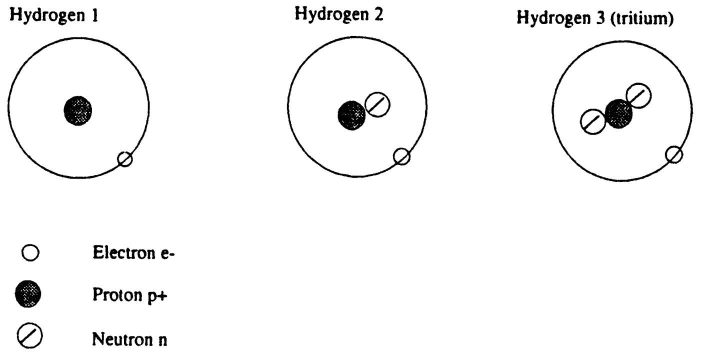
The mass of the orbiting electrons is negligible compared to the mass of the protons and neutrons, hence the mass of an atom is approximately equal to the number of protons and neutrons added together. This mass number is donated by the symbol A.

A particular combination of protons and neutrons is known as a nuclide.

The formal scientific notation for nuclides is $_Z{}^A$(element symbol), where A is the mass number and Z is the atomic number.

Isotopes

The atoms of a specific element must all contain the same numbers of protons, but they can have different numbers of neutrons. Atoms of an element that have differing numbers of neutrons are called isotopes of that element.



The three isotopes of hydrogen illustrated here are written as ^{1}H, ^{2}H and ^{3}H. These can also be written as Hydrogen –1, Hydrogen –2, and Hydrogen –3 since the atomic number is fixed for the element.

Radioactivity

For an atom to be stable the nucleus must contain a certain number of neutrons. If the number of neutrons is either greater or less than this value (which varies for different elements) the nucleus is unstable and decays by emitting energy in the form of radiation, and is said to be radioactive. Radioactivity can be defined as the process in which unstable atoms stabilise by emitting radiation. In the previous example of hydrogen, the tritium isotope is unstable and therefore radioactive. For radiation to be considered as ionising it must be capable of causing ionisation in the target material.

This distinguishes this type of radiation from other non-ionising types of radiation such as light, radio and microwaves.

Ionisation
When sufficient energy is given to an orbiting electron so that the electron is removed from the electric field of the nucleus, the atom is said to be ionised. This process can be caused by the interaction of photons or charged particles with an atom, resulting in an ion pair. The negative ion is the displaced electron, while the positive ion is the remaining atom that now has a net positive electrical charge. Photons and charged particles can indirectly cause multiple ionisation as they can cause release of single high-energy electrons, which may then have enough energy to ionise other atoms that they meet.

The ionisation potential is the minimum energy needed to ionise an atom by the removal of an electron from an outer orbital shell – i.e. an electron that is not tightly bound to the nucleus. In the case of the hydrogen atom, the energy required is about 13 electron volts (eV). Electromagnetic radiation of energy less than 12 eV is called non-ionising radiation, i.e. light, infra-red, UV, microwave and longer wavelength radiation.

Types of Radiation
There are a number of mechanisms by which a radioactive atom can decay. These are described below.

Alpha (α) particles
These particles consist of 2 neutrons and 2 protons that are bound together without any accompanying electrons. They behave like a single particle. Alpha particles are emitted from heavy nuclei containing a large number of neutrons and protons, such as uranium – 238 which decays to thorium-234

$${}_{92}^{238}\text{U} \rightarrow {}_{90}^{234}\text{Th} + {}_{2}^{4}\alpha$$

Note that the total mass number and atomic number on each side remains unchanged.

Alpha particles are relatively massive, have two positive charges and hence interact very readily with the material through which they pass. Because of this, alpha particles have a very short range of only a few centimetres in air and are easily stopped by a thin sheet of material (eg a single sheet of paper). They are capable of causing up to 1500 ionisations in the target material!

Beta (β) particles
These are high speed single electrons which are emitted from the nucleus. They arise from the change of a neutron into an electron and a proton inside the nucleus, i.e.

$$n \rightarrow p^{+} + e^{-}.$$

The electron (beta particle) is ejected from the nucleus (carrying away some energy) but the proton remains inside the nucleus. There is an increase in the number of protons by 1, due to the proton conversation. Beta particle decay is shown in the decay of cobalt-60 to nickel-60:

$${}_{27}^{60}\text{Co} \rightarrow {}_{28}^{60}\text{Ni} + \beta$$

Note that the atomic number increases by 1 during this decay but the atomic mass is unchanged, as the total number of neutrons and protons is unaffected by the neutron to proton conversion.

Beta particles are very much smaller than alpha particles, have a single electrical charge of –1, and have a range of up to several metres in air. Beta radiation can be completely stopped by approximately 1.0 cm perspex.

Each isotope produces a spectrum of energies but has characteristic maximum energy that determines its penetrating power and the distance of the radioactive "field" around it. Typically a β particle has a range of 4m in air for each 1MeV of energy.

Gamma (γ) radiation

Gamma radiation is a form of electromagnetic radiation and is emitted from the nucleus of the atom, often in association with alpha and beta particles. The gamma emission represents an adjustment in the energy and configuration of the nucleus following an alpha or beta transformation. Gamma rays are uncharged, have no mass and travel at the speed of light. They are correspondingly very penetrating, travelling up to several hundred metres in air and requiring significant thicknesses of relatively dense material to stop them (e.g. centimetres of lead or tens of centimetres of concrete).

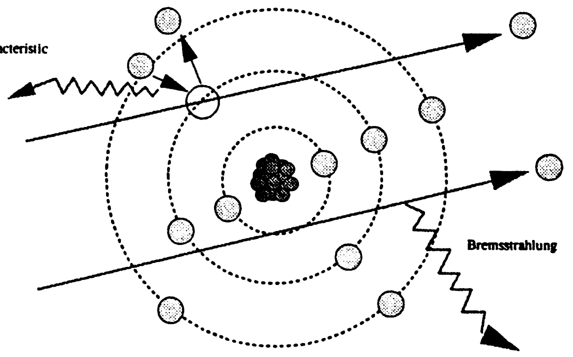
X-radiation

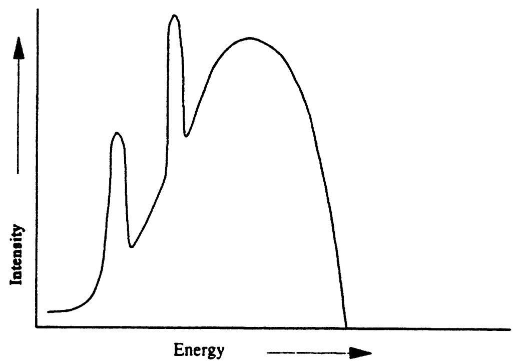
X-radiation is also a form of electromagnetic radiation and differs from □ rays only in its mechanism of production. While □ rays area a product of radioactive decay, X-rays are generally created artificially by an X-ray set. This has the advantage that should a problem arise then the generator can simply be switched off to make the situation safe.

X-rays are produced when high-speed electrons, produced for example in an X-ray tube, strike a solid target. The maximum energy of the X-rays in the spectrum produced is dependent upon the voltage applied across the electrodes of the X-ray tube - this applies the acceleration to the electrons thus increasing the energy with which they strike the target.

1. The incoming electrons have sufficient energy to eject an inner orbital electron from the target atoms. An electron from a higher orbit falls into the vacant space that remains in the inner orbit and in doing so emits a pulse of electromagnetic radiation, the energy of which is equal to the energy difference between the two orbits. The X-radiation produced by this process is referred to a "characteristic" X-radiation.

2. Incoming electrons will also interact with the field of force around the nucleus, and this process again results in the emission of X-radiation. The radiation produced by this interaction is referred to as "bremsstrahlung" radiation (bremsstrahlung is German for "braking radiation"). Bremsstrahlung radiation is emitted in a wide spectrum of energies.



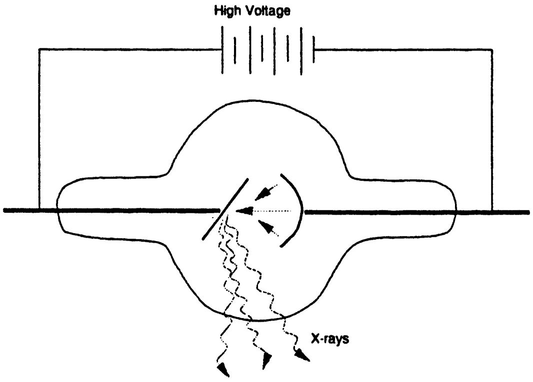


Thus a typical X-ray energy spectrum will be of a continuous nature and will show characteristic spikes at discrete energies that are dependent on the target material and the difference in the energies of its electron orbits.

X-ray tubes

A modern X-ray tube contains a cathode (-ve terminal) and an anode (+ve terminal), sealed inside an evacuated glass tube. The tube is located inside a steel housing with a lead lining – this is designed to provide shielding against unwanted stray X-rays and also gives protection against electric shock. The useful beam is allowed out through a thin window in the housing.

Electrons are emitted from the hot filament; by applying a high voltage these can be accelerated towards the target on the anode. When the target stops the electrons, X-rays are given off. Less that 1% of the energy of the electrons appears as X-rays; most of the remaining energy appears as heat. The target must have a high melting point and a high thermal conductivity in order to withstand the heating that occurs. Tungsten is commonly used as a target material. Various techniques, from simple radiation fins to complex rotating targets (with liquid coolants), are used to aid transfer of heat away from the target.



X-rays or Gamma-rays

Both X-rays and gamma rays are a form of electromagnetic radiation and differ only in their method of production. X-rays originate from the electron shells of the atom and are created when high speed electrons pass through the electron shells interacting with the orbiting electrons as they do so. Gamma-rays are emitted from the nucleus of an atom, often following other events eg the emission of an alpha or beta particle, as the nucleus seeks to achieve stability.

Neutron radiation

Some radioactive decay processes result in the emission of a neutron from the nucleus of the atom. Californium-252 decays by the emission of an alpha particle but may also spontaneously decay by the process of fission - resulting in the release of neutrons.

The element beryllium will also emit neutrons following the absorption of an alpha particle. This property is used to advantage in the manufacture of americium-241/beryllium neutron sources. The two materials are mixed together and the alpha particles from the americium-241 are absorbed by the beryllium, which in turn emits neutrons. Gamma radiation is also emitted from the decay of americium-241.

A common use for neutron sources is for moisture or density measurements of certain materials, for example soil, food or pavements. There are no neutron sources at the university.

The Half Life of a Radionuclide

The decay of a radioactive material is statistical in nature, ie it is impossible to predict when any individual atom will disintegrate. However due to the very large number of atoms in even the smallest radioactive source, the rate of radioactive decay for each radionuclide can be predicted.

A parameter often used when considering radioactive decay is the half-life. This is the time it takes for half of the radioactive material present to decay and is a constant for a specific radionuclide.

Decay is exponential and the half-life, $t_{1/2}$ is related to the decay constant, 8, by,

$$\mathbf{t_{1/2} = 0.693/8}$$

A useful form of this for calculating the fraction of material remaining after a given time is,

$$\mathbf{N/N_0 = exp(-0.693)\ t/\ t_{1/2})}$$

There will probably be decay tables within your laboratory to make life easier when it comes to adjusting stock records for short half-life materials and for disposal records.

Quantities and Units in Radiation Protection

Amount or concentration of radioactive substance
Activity: The amount of radioactive substance present is referred to as the "activity", defined as the number of nuclear transformations taking place in unit time. The SI unit for activity is the becquerel (Bq). One becquerel is one nuclear transformation per second. The previous special unit was the curie (1 Ci = 3.7×10^{10} Bq) (disintegration/sec).

The Bq is a very small unit hence for practical purposes we use kilo- or mega-becquerels (kBq/MBq).

Activity concentration. The "activity concentration" of a radioactive substance is the activity contained in unit mass of the substance. It is expressed in becquerels per gram ($Bq\ g^{-1}$).

Radiation Dose

(i) Absorbed dose- external radiation: There are a number of different quantities that can be used to express the general concept of "dose". The basic quantity is "absorbed dose" which is the energy deposited by ionising radiation in a medium per unit mass of the irradiated material. The SI unit for absorbed dose is the gray (Gy). The previous special unit was the rad (1 Gy = 100 rad).

(ii) Dose equivalent: To take account of the different biological effectiveness of different types of radiation, the quantity "dose equivalent" has been defined. This is obtained by multiplying the absorbed dose (Gy) by a quality factor (or *relative biological effectiveness*) for the type of radiation concerned.

Beta, gamma and X-ray radiation have a factor of 1; alpha and neutrons have factors up to 20.

The SI unit for dose equivalent is the sievert (Sv). The previous special unit was the rem (1 Sv = 100 rem).

It is unusual for the whole body to be uniformly irradiated so that the dose equivalent in all organs and tissues is the same. However, for most types of work it is adequate to make the simplifying assumption that a personal dosemeter worn on the trunk measures a representative "dose" for the whole body. This applies where an individual is only exposed to external radiation. It may also be necessary to wear extremity dosemeters, e.g. fingers with ^{32}P.

(iii) Committed dose - internal radiation: If a radioactive substance is taken into the body (injection, inhalation, inoculation), it begins to irradiate the tissues around it until it has been eliminated by metabolism or radioactive decay. The "committed dose equivalent" from a single intake of a radioactive substance is the total dose equivalent that an organ or tissue is "committed" to receive in this way in the following 50 years. This takes into account the radiological half-life of the material and its biological properties, i.e. its half-life within the body as it is metabolised and excreted, the way in which it is absorbed, how it is transported around the body and if it is concentrated in particular tissues.

(iv) Annual limits on intake (ALI): Annual limits on committed dose equivalent, or committed effective dose equivalent, are used to define limits on the amount of radioactive substance which may be taken in during the year - i.e. the quantity of an isotope which if taken into the body would result in an exposure equivalent to the dose limit.

The International Commission on Radiological Protection (IRCP) has calculated and published annual limits on intake (ALI) for all commonly encountered radioactive substances. Doses from internal radiation are often referred to in terms of fractions of ALI rather than of committed dose equivalent.

ALIs may be used to determine safe quantities for manipulating unsealed sources. For example an operation involving the injection of a radioisotope from a syringe has the risk that all the contents of the syringe could be injected into the worker. However, if the total activity is less than one tenth of the ALI for that isotope then if the worst happened the maximum internal dose would be 1/10th of the dose limit.

Relationship between activity and dose

Radiation dose is a measure energy transfer from the source to the target material. One gray is equivalent to 1 joule of radiation energy per kg of irradiated matter. Since, simplistically, a source emits radiation of certain energies in MeV (one MeV = 1.6×10^{-13} J), then if the activity of the source is known, the energy output can be calculated.

This can be taken further to calculate dose rates at a certain distance from a source, for a gamma emitter (quality factor = 1),

$$\textbf{Dose rate } (:\ \textbf{Svh}^{-1}) = \frac{\textbf{AEF x 0.16*}}{\textbf{d}}$$

Where A - source activity in MBq
E - gamma energy in MeV
F - fraction of disintegrations emitting energy E
d - distance from source in metres
* - energy in :J per MeV per MBq for equivalence with unit of dose rate.

For beta emitters dose rate calculations are more complex due to absorption of the radiation by air and the container for the source. An approximate dose rate at 0.1 m from a point source is given by,

$$\textbf{Dose rate } (:\ \textbf{Svh}^{-1}) = \textbf{1000 A}$$

In practice low energy beta radiation may be considerably or appreciably absorbed at this distance.

Biological Effects

Introduction

Radiation is a form of energy and, as radiation passes through a material, some of this energy may be deposited in the material. When ionising radiation passes through biological tissue, most of the energy deposited (>99%) goes into the production of heat. The rise in temperature is very small, eg 5 Sv of radiation energy (a potentially lethal dose) applied to soft tissue would raise the temperature by only about one-thousandth of one degree Celcius.

Important effects arise from the remaining 1% of the energy, which causes ionisation of the atoms in the tissue. This ionisation causes chemical changes through the breakage of chemical bonds and these changes lead to a range of damaging effects. The following sections explain how different radiation doses effect cells and describe how this cellular damage manifests itself in injury to the body.

Effects on Cells

Living systems are made up of cells. Cells can be thought of as “chemical factories” in which molecules carry out the tasks that keep cells working. Amongst these molecules are proteins and deoxyribo-necleic aid (DNA). These are vital to the continued working and replication of cells. Damage to these kinds of molecules can have serious consequences. Recovery may be possible by the manufacture of replacement molecules or the simple reversal of the damaging chemical changes by some biological repair system.

Current experimental evidence indicates that:

1. The cell nucleus is more sensitive to radiation damage than other parts of the cell. The nucleus controls the way that the cell works, and plays a particularly important part in cell division; and

2. Cells are much more radiosensitive during cell division than at other times and organs having cells that divide frequently are more at risk. For example, greater radiosensitivity is shown by the blood-forming organs and the lining of the gastro-intestinal tract (ie the gut walls), as these contain cells that divide frequently. Tissues showing the least radiosensitivity include muscle and nervous tissue (ie organs with cells that rarely divide).

There are basically three levels of damage that can occur to an individual cell. These are described below.

Massive damage

The result of doses of tens of sieverts. The cell may be killed immediately, or at least be made incapable of carrying out its normal function.

Intermediate damage

The result of doses of approximately 0.5 to 10 Sv. The cell cannot divide, but is otherwise unaltered and can still perform all of its other functions. The kind of damage is very important in tissues with rapidly dividing stem cells, as these cells provide a supply of replacement cells for special purposes.

Minor damage

The result of small to intermediate doses (less than about 0.5 Sv). There are no obvious visible short-term effects on tissues, although some damage can be seen in individual cells: eg chromosome changes in circulating white blood cells. The damaged tissues can function apparently quite normally although damage to cells has occurred, in particular to the DNA molecules. This can result in the occurrence of abnormalities that appear after cell division. This kind of cell damage can cause (or at least encourage) later cancers and genetic effects. The development of cancers can take from a few years (eg leukaemia) to up to thirty years (eg solid cancers such as in the lung or breast).

Cell repair

Cells are capable of repairing some of the damage that radiation causes, given the chance to do so. Damage resulting from a radiation dose can be reduced if the dose is delivered in two or more fractions, provided there is a big enough gap between fractions so that repairs can be made. Radiation effects thus depend on the dose, dose rate and the length of time between repeat exposures.

Circumstance/Effect	Approximate whole body dose
Background (UK)	2.6 mSv y^{-1}
World maximum	50+ mSv y^{-1}
Average radiation worker	1.5 mSv y^{-1}
Annual dose limit	50 mSv y^{-1}
Typical value for one chest X-ray	0.05 mSv
Average annual medical exam dose	0.3 mSv y^{-1}
Typical fluoroscopic examination	60 mSv
DETERMINISTIC EFFECTS	
Whole body exposure	
Detectable chromosome damage	above 0.1 Sv
Detectable blood count change	above 1 Sv
Radiation sickness	above 1 Sv
Possible death	above 3 Sv
Certain death	above 10 Sv
Localised exposures	
Erythema	above 5 Sv
Depilation - Temporary	above 4 Sv
(hair loss) - Permanent	above 7 Sv
Desquamation (death/loss of epidermis [skin])	above 20 Sv

Radiation Injuries

The cellular damage described in the previous section is manifested in a range of detrimental effects. These effects are conventionally divided into deterministic and stochastic effects.

(i) Deterministic effects

These are effects that are expected to occur above a certain threshold dose and are the result of extensive cell damage. Above this threshold, the severity of the effect is then directly dependent on the dose received by the part of the body exposed. Examples of deterministic effects are erythema (reddening of the skin), depilation (hair loss), nausea and blood count changes. These tend to be acute effects, which appear within days or weeks of an exposure. They are the result of relatively high exposures, certainly in excess of 0.2 Sv and more typically in excess of a few sieverts.

(ii) Stochastic effects

Stochastic effects are those effects where the probability of occurrence is proportional to the level of the radiation dose received. It is assumed that there is no threshold below which these effects cannot occur. An increase in dose will raise the probability that the effect will occur in the part of the body that has been irradiated. In contrast, the severity of the effect is independent of the dose received. Cancer and hereditary disorders are stochastic effects.

Cancer induction

Radiation induced cancers tend to occur some years after the radiation is received. Dormant periods range from a few years up to 30 years (or more). The risks of cancer induction depend upon a number of factors which include the type of radiation, the organs of the body which are irradiated and the age at exposure. It is now also thought that the risk of radiation induced cancer varies with the natural cancer rate. Therefore, individuals who have a higher risk of contracting cancer (eg due to factors such as smoking and the diet) also carry a higher risk of cancer induction following radiation exposure.

The probability of developing cancer from ionising radiation is derived from studies of populations that have been exposed. These include the Japanese atomic bomb survivors, radium dial painters and persons exposed during certain medical procedures. In many cases the exposures have been relatively high, with doses received mainly for acute (ie very short) exposures. Thus knowledge of the risks at these high exposure levels does exist.

Problems arise when estimating the risks at lower exposures. It is now assumed that at low doses the risk/dose relationship is linear and that no threshold of dose exists, ie there is no level of dose below which the chance of contracting cancer is zero.

Radiation Exposure amongst Workers at Nottingham University

Through the University's dosimetry arrangements there is a considerable amount of dose information going back over several decades. This information shows that the doses measured are insignificant in relation to the annual dose limits.
The statutory dose limits are at present are;

- 20 mSv for the whole body,
- 500mSv for the hands, other extremities or individual organs,
- 150 mSv for the lens of the eye,
- 13 mSv in any three months for a woman of reproductive capacity,
- 1 mSv to the foetus over the remaining term of a pregnancy once declared to the University. For breastfeeding mothers significant bodily contamination must be avoided. There is also a specific University safety policy relating to expectant and breastfeeding mothers.

The actual exposures measured reveal that;

- the average measured annual dose per radiation worker is around 100 :Sv,
- 60% of radiation workers receive no measurable dose,
- the highest annual whole body dose is in the region of 1mSv (one person only),
- 98 to 99% of annual exposures do not exceed 600 :Sv
- the highest lifetime dose amongst those who have worked with radioactive material is around 50mSv - this reflects 40 years work, the earlier years of which were probably in laboratories, or involved procedures, which although considered acceptable at that time did not achieve the standards that are now common place. Lifetime doses for those starting a career with radioisotopes would be expected to be considerably less that this.

Increased Radiosensitivity of The Foetus

The development of an adult human from an embryo requires repeated cell division and this results in increased radiosensitivity. The effects which occur depend upon the time of exposure in relation to conception. Animal experiments have shown that deterministic effects in offspring (eg malformation of developing organs) can occur from exposures received more than three weeks after conception. The dose threshold for these effects is about 0.1 Sv. This is about 100 times greater than the highest annual dose received by any radiation worker at the University.

It is possible that the developing foetus will also face an increased risk of stochastic effects such as childhood leukaemia. The greatest risk is associated with exposure during the first three months of pregnancy. Consistent risk factors have, however, yet to be established.

Legal Requirements

There are two sets of legislation, which apply to work with ionising radiation. One set concerns health and safety aspects of working with radiation. The main legislation is the **Ionising Radiation Regulations 1999** which is enforced by the Health and Safety Executive.

There are also regulatory requirements relating to medical exposures (diagnosis and treatment) to ensure that the intended patient exposure is radiologically and ethically appropriate and that those clinically and physically directing the exposure are competent.

The other area of legislation is concerned with environmental protection. This is achieved through the **Environmental Permitting Regulations** (which superseded the Radioactive Substances Act). This is enforced by the Environment Agency.

The University periodically receives visits by Inspectors from either the Environment Agency or the Health and Safety Executive to check compliance with the legal requirements.

Ionising Radiation Regulations 1999

These describe the steps which employers must take to minimise exposure to ionising radiation. The University is required to take all necessary steps to restrict, so far as is reasonably practicable, the extent to which people may be exposed to ionising radiation. This is achieved through the various procedural controls relating to the authorisation of radiation workers and radiation projects, and the designation of radiation areas, and the devising of safe procedures for handling or working with radiation sources.

Work with ionising radiation needs to be justified to ensure that there aren't equally effective non-radioactive techniques which could be used and that where this is not the case then the quantities of materials or size/power of source is the minimum necessary to achieve the desired outcome.

Restriction of exposure needs to be achieved primarily through engineering controls such as shielding, ventilation and containment features (e.g. fume cupboards and glove boxes). In some instances additionally personal protective equipment will be needed. This routinely requires the wearing of lab coats and disposable gloves but may also include eye or face protection, overshoes, respiratory protection or lead aprons.

The regulations specify the dose limits which must not be exceeded and criteria for designating laboratories as **controlled** or **supervised** areas along with restriction of access, classification of workers and monitoring work areas for contamination and leakage.

It is also a legal requirement to appoint **radiation protection supervisors** who are required to oversee radiation work and ensure that the **local rules** (which are also required by these regulations) are being followed. The local rules describe the administrative and procedural controls to restrict exposure and **it is essential that all radiation workers are familiar with, and follow, the University and School local rules, and other safety precautions relating to experimental procedures.**

There is a legal requirement to account for radioactive substances, i.e. keep records of what is where, although this is primarily regulated by the Environmental Permitting Regulations**. Radioactive sources also have to be kept in safe and secure storage locations**, hence padlocked fridges, **and properly labelled** with trefoil warning tape, source description i.e. isotope and quantity, date and the "owners" name.

There are additional controls relating to classified workers i.e. those who are liable to receive in excess of three tenths of the annual dose limit (more than 6 mSv per year for whole body). Measures include:

- Specific requirements relating to personal dosimetry and
- The provision of medical surveillance.
  [The overwhelming majority of radiation workers in the University are not classified due to the minimal level of radiation risk. However personal dosimetry is still carried out for those working with more energetic sources and this is supplemented by medical surveillance. This is to confirm that procedures to restrict exposure continue to be effective and to provide reassurance to the individuals.]
- There is a further requirement relating to *outside workers,* i.e. *classified workers* who work in a *controlled area* at another employers' site. This might require the issue of a radiation passbook to record dose estimates although in most cases it is sufficient, following liaison with the host organisation, to continue wearing your existing dose badge and establish a regime for replacement at the end of the wear period. Should this apply to your circumstances then please obtain further information from your RPS and the Safety Office.

There are particular requirements relating to **movement and transport** of radioactive sources. **They cannot be sent through the post or carried on public transport (bus, taxi, train, aircraft etc)**. In the event that your work may require moving or sending of radioactive sources beyond the site boundary then the radiation protection supervisor must be consulted in the first instance.

Environmental Permitting Regulations

This legislation controls the acquisition, use and disposal of radioactive materials by means of licences issued by the Environment Agency. The University is registered to acquire and hold certain quantities of certain categories of radioisotopes. For this reason **purchases must be approved by the RPS in advance**.

Similarly the University is authorised to accumulate and dispose of certain quantities of certain radioisotopes. This tightly prescribes the maximum quantity within any period, usually a month, which may be disposed of each specified isotope via any particular disposal route**. It is a serious offence to dispose of an isotope by a route that is not authorised or to exceed a quantity of isotope disposed of within the specified period.** For this reason there are rigorous accountancy procedures to ensure that the acquisition, use and disposal of radioisotopes is tracked and that the licence conditions are not contravened. Instruction in the use of isostock, which is the accountancy procedure for radiochemicals, will be given to radiation workers within a School. Any failure to follow the procedure will be treated seriously.

Principles of Protection from External Radiation

Protection Principles

The are four factors that affect dose to personnel: source activity, time, distance and shielding.

Source activity

The large the source activity, or the higher the rating of an x-ray set, the greater the potential dose to a person. Personal (and overall) doses can thus be minimised, if the smallest activity actually necessary for the work is used.

Time
The shorter the time spent near to the source, the smaller the dose to a person; this is an important factor to consider when planning work.

Distance
For penetrating radiations (such as X and ☐ radiations), the dose rate from the source follows an inverse square law relationship – but only if the radiation comes from a point sources.

If D = dose rate at 1 metre, then the dose rate at d metres = D/(d^2), eg

If the dose rate at 1 metre = 4 μSvh^{-1};
Then the dose rate at 2 metres = 4/(2^2) μSv h^{-1} = 1 μSvh^{-1};
And the dose rate at 0.5 metres = 4/(0.5^2) μSv h^{-1} = 16 μSvh^{-1};
At 1 mm, e.g. holding a vial = 4/(0.001^2) μSv h^{-1} = 4 000 000 μSvh^{-1}!!!

A similar relationship holds for ☐ radiation in a vacuum, but in air the relationship is modified by absorption of ☐ particles by the air. The effect of this relationship between dose rate and distance from the source, is to cause dose rates to increase very rapidly as the source is approached – and also to decrease dose rates rapidly when receding from the sources.

Shielding
Alpha (α) particles
Alpha particles are easily absorbed by matter: a thin sheet of paper is enough to completely stop even the most energetic alpha particle radiations (of energy typically 2.5-8.8 MeV). Alpha particles are of limited external hazard, but they can be very hazardous if the radioactive material is taken into the body.

Beta (β) particles
Beta particles are more penetrating than alpha particles and have a range of roughly 4 metres per MeV in air, or 3.5 mm per MeV in perspex – ie a beta particle with an energy of 2 MeV might be expected to be completely stopped by roughly 8 m or air, or 7 mm of acrylic (perspex). Light materials – i.e. less dense materials like perspex of aluminium – are a better choice for beta particle absorption than heavy materials – such as steel or lead; this is because heavier materials produce Bremsstrahlung radiation (X-ray) when they absorb beta particles.

Electromagnetic Radiations
Short wave (high energy) electromagnetic radiations – such as Bremsstrahlung, X-rays and γ rays, are even more penetrating than beta radiation. As the energy of the radiation increases, the radiation become more penetrating. Heavy (i.e. dense) shielding materials, eg concrete, steel or lead – can be used to reduce the intensity of these very penetrating radiations, although in theory the radiation cannot all be stopped.

For a single radiation energy, the attenuation of the radiation intensity follows an exponential law. This means that a fixed thickness of shielding material will only reduce the incoming radiation intensity by a fixed amount.

For example, if 1 cm of a shielding gives a factor 2 reduction – ie only one-half (50%) of the radiation gets through the shielding, then using 2 cm of materials as a shield would give a factor 4 reduction (only one-quarter [25%] transmitted). Using 3 cm of the material as a shield would give a factor 8 reduction (only one-eighth [12.5%] transmitted).

The thickness of material that causes the radiation transmission to be reduced by half is called the "half value thickness" or "Half Value Layer (HVL)"

Neutrons
Neutrons are similar to protons but are uncharged. Charged particles (such as alpha and beta particles) interact quire heavily with matter, and are fairly heavily absorbed by most materials hence they are not usually very penetrating. Due to their zero charge, neutrons interact fairly weakly with most matter – this makes neutrons a rather penetrating form of radiation that is quite difficult to shield/stop. Neutrons are usually shielded with proton-rich materials, i.e. hydrogen-containing, such as water, hydrocarbons (plastics, waxes) due to their similar sizes which are therefore most effective at absorbing by a series of collisions.

Handling of Unsealed Radioactive Materials

The following table summarises the key radiological properties of the most commonly used isotopes within the University.

Properties of Unsealed Isotopes in Common Usage

Isotope	Half-Life	Radiation Type	Energy	Range in Air	Dose Rate at 10 cm from 1 MBq**	Annual Limit on Intake*
Tritium	12.4 y	β	18.6 keV	6 mm		1 GBq
Carbon 14	5730 y	β	156 keV	24 cm		40 MBq
Sulphur 35	87.4 d	β	167 keV	26 cm		70 MBq
Phosphorus 33	25.6 d	β	250 keV	46 cm		80 MBq
Phosphorus 32	14.3 d	β	1.71 MeV	790 cm	1 mSvh^{-1}	8 MBq
Iodine 125	60.1 d	X γ	30 keV 35 keV	metres	14 μSvh^{-1}	1 MBq

* The ALI for each isotope may vary depending upon the form in which it is presented. Generally, isotopes incorporated into DNA precursors, e.g. tritiated thymidine, have lower ALIs than the elemental form (or e.g. tritiated water) because the activity will be concentrated into the cell nuclei.

** The dose rates are from unshielded point sources and indicates the potential dose to the hand when using suitable tools to manipulate sources and achieve dose reduction through distance. For phosphorus 32 the ∃ radiation would be partially absorbed by the wall of the container (75% for 1mm of glass) and 10% of the transmitted radiation would be absorbed by the 10 cm of air, hence the typical dose to the hand would be 0.2 mSvh^{-1}.

Exposure Pathways

External
External dose rates are important with gamma emitters such as caesium 137 and iodine 131 (and iodine 125 to an extent) and higher energy beta emitters such as phosphorus 32. In the case of the higher energy beta emitters there may also be exposure to

Bremsstrahlung X-rays. A special case of external exposure occurs where contamination is present on the skin.

Internal
Internal exposure occurs as a result of intakes of radionuclides into the body. There are three routes by which this can occur;

INGESTION - Intake of radioactive material via the mouth

INHALATION - Inhalation of radioactive material through the nose or the mouth (or both) with deposition in various parts of the respiratory tract.

DIRECT ABSORPTION - Where radioactive material is taken directly into the body e.g. via a cut or, in special cases, where radionuclides pass through unbroken skin, such as can occur with tritiated water.

To control intakes of radionuclides it is necessary to control both surface and airborne contamination in the workplace. Surface contamination may be spread by mechanical transfer form one object to another, or by deposition of airborne contamination. Airborne contamination may be generated directly (such as dusty process) or it may result from re-suspension of surface contamination.

General Principles of Protection Against Unsealed Radioactive Materials

The basic objective is to keep exposures as low as reasonably practicable, taking into account both external and internal pathways. The principles of protection can be summarised as follows:

Appropriately designed facilities

1. Containment of unsealed radioactive materials
2. Minimisation of contamination
3. Design for ease of decontamination
4. Ventilation of the work area
5. Shielding against external radiations (if necessary)
6. Provision of washing and changing facilities where appropriate

Control of work

1. The use of the minimum quantity of radioactivity
2. Segregation of work with unsealed radioactivity where appropriate
3. Suitable systems of work (with local rules)
4. Monitoring of the workplace
5. Personal monitoring if appropriate

Personal protective equipment

1. Wearing of protective clothing
2. Use of respiratory protective equipment if appropriate

Containment

Drip trays provide a very basic level of containment, ensuring that if glassware or other containers for radioactive solutions are knocked over the liquid does not contaminate bench surfaces or run down gaps or under equipment placed on the bench.

Another way to protect bench surfaces is to use replaceable coverings such as “Benchkote” or similar. These should be used with the absorbent side facing upwards and they should be replaced once they become damaged of contaminated.

The laboratory fume cupboard is an important piece of equipment, being essential for work involving primary synthesis of radiolabelled compounds, and advantageous for lower activity work. Aside from significantly reducing the potential for inhalation of airborne radioactivity a fume cupboard generally offers better containment than an open bench in the event of spills of radioactive liquids. If the sash is pulled downwards it will provide some protection of the worker against splashes and offer useful shielding against the external hazard from beta emitters.

In laboratories in which unsealed radioactive materials are handled the sinks used for disposal of liquid radioactive wastes will be identified and labelled for this purpose. Separate sinks are reserved for hand washing. It is also important to pay attention to the drainage system itself, since a leak may lead to lengthy decontamination work even if the radiological consequences are limited.

Storage and Labelling Of Unsealed Radioactive Materials

Provision should be made for safe storage of unsealed radioactive materials when they are not in use. This is especially important with the higher activities present in stock solutions.

1. Unused or partly used stock solutions should be kept in a locked fridge, cupboard, or other suitable store and not simple left out on benches in the laboratory.

2. Wherever possible the store must be reserved for radioactive material only. The bare minimum would be a part of the store reserved for radioactive materials only.

3. Within the store liquid solutions should be kept in unbreakable outer containers, in case the immediate containment were to fail.

4. All radioactive materials in the store should be labelled with the trefoil sign, details of the radionuclide, Isostock compound number, date and name of "owner".

5. Stores will be regularly inspected and unwanted radioactive materials removed and disposed of.

6. Freezers must be kept free from ice build-up. Attempting to remove a vial encased in ice may cause it to break and thereby contaminate the freezer and risk introducing the isotope into the person through being cut on the broken glass! Sublimation of tritium from some tritium sources can cause freezer ice to become contaminated with tritium.

7. Regular checks should be made for radioactive contamination.

8. Radioactive materials that must be left out in the laboratory should be clearly labelled with the trefoil sign.

9. Radioactive labels including adhesive tape should not be used unnecessarily e.g. to identify uncontaminated items or stick notices on the wall, otherwise the value of these warning labels is reduced.

Monitoring of the Workplace

Equipment for monitoring

Surface contamination monitoring is done with hand held monitors appropriate for the radionuclides in use. Monitors are labelled with the isotopes for which they are suitable and calibrated. Alternatively wipes may be taken and counted in a liquid scintillation counter or other equipment.

Routine surface contamination monitoring

This should be done on a frequent basis as the work progresses and should be "second nature" to all users of unsealed radioactivity. The contamination monitor should be kept close to hand and used to check for contamination at key points in the work.

1. When opening a new stock supply of a radionuclide (check for leakage in transit).
2. After disposing of liquid radioactive waste in a disposal sink (check that the sink and trap have been washed through).
3. On completion of work (check the area is left "clean")
4. When leaving the work area (check that you are not contaminated).

Personal Monitoring

Personal dosimetry is sometimes used, partly for reassurance purposes.

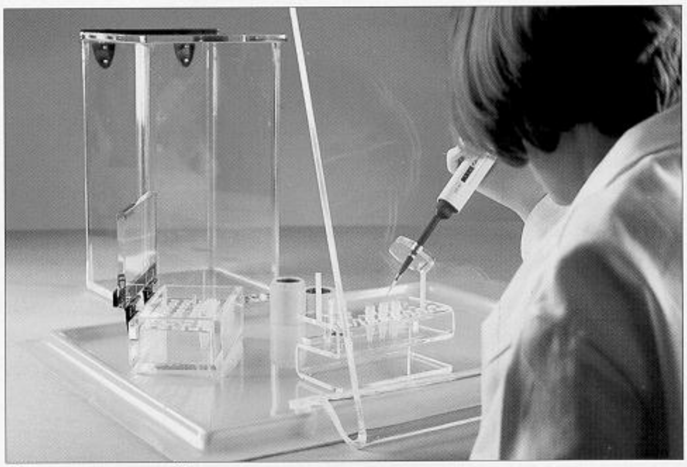
- Whole body dosimeters are provided other than to tritium, carbon 14, and sulphur 35 users (the low energy and range of emissions would not be detectable) and most X-ray equipment users (due to the inherent safety and shielding features of modern equipment). Dosimeters are generally issued on a quarterly basis. They must be worn when working with radioisotopes, kept away from radiation sources when not in use and exchanged promptly. **Beware sending your lab coat to the laundry with the dosemeter attached!**
- Extremity dosimeters, i.e. fingers, are issued to many phosphorus 32 workers, and to others working with energetic sources. These should be worn under the glove with **the film or chip facing the source** (this may mean on top of the finger for some manipulations and underneath, i.e. facing the palm for others such as when working with a vial).
- Simple checks can be made for uptake of iodine 125 using a suitable contamination monitor held up to the area of the thyroid. This method is capable of detecting an intake corresponding to 1% of an ALI. If contamination is detected you should inform your Radiation Protection Supervisor. Arrangements to accurately measure your uptake will be made.
- Tritium in urine monitoring should be considered for individuals using TBq quantities or more of tritium gas (TBq) or GBq quantities or more of tritiated compounds. This can detect single intakes of less than 1% of the ALI.

You may contact the Safety Office to obtain your personal dose information. All dose records are reviewed when the information is received from the dosimetry service (Landauer). Your RPS will be asked to investigate any readings of 0.5 mSv per month or greater.

Some Basic Working Practices

This section describes some basic aspects of work with unsealed radioactive materials that are not covered elsewhere in these notes.

1. Some activities increase the risk of intakes of radionuclides and are forbidden in any area where unsealed radioactivity is used. These include eating, drinking, smoking, etc. Similarly, mouth pipetting of radioactive solutions should be prohibited.



Beta starter pack in use

2. Despite the provision of easily cleaned surfaces for work areas, or the use of disposable coverings, it is still good practice to carry out wet manipulations over drip trays or similar.
3. Perspex shielding should be used with beta emitters phosphorus 32, especially when dispensing from stock solutions. This can include pipette and syringe guards and perspex blocks to hold "Eppendorf" and other reaction tubes.
4. Ambient dose rates from gamma emitters should be reduced using temporary lead shielding, including lead storage pots for stock solutions. Doses during dispensing can be reduced by using lead shielded syringe and vial guards.
5. Reduce the external hazard associated with directly handling of significant quantities of unshielded radioactive materials by the use of handling tongs.
6. Further reduce external doses by minimising the time spent performing these operations. It may be appropriate to practice difficult operations beforehand using non-radioactive materials.
7. The workplace should be kept tidy and uncluttered. In particular, fume cupboards should not be used to store equipment unnecessarily, and care should be taken with positioning of items in them to reduce the risk of potentially contaminated air spilling out from the aperture because of adverse flow conditions.

Work with Specific Radionuclides

Tritium

Tritium poses negligible external radiation hazard due to the very low energy of the β emission. It also poses a relatively low hazard internally, although if ingested as a tritiated organic compound it may present a significant risk due to its long radiological half-life and its proximity to tissues. Tritiated thymidine, for example, presents a particular risk due to its concentration within the cell nuclei. Its biological half-life is several months.

The risk from the ingested route is minimised by the fact that the majority of the material is broken down by the gastro-intestinal tract.

Although shielding is not required, work should be carried out over spills trays. As tritium can be absorbed through the skin, it is advisable to wear two pairs of gloves, especially for tritiated thymidine.

Contamination monitoring is by taking wipes from specified surfaces and performing liquid scintillation counting on these. It is assumed that a wipe will pick up 10% of the contamination.

Where tritiated compounds are stored in a freezer, the frost should be periodically checked for contamination to ensure that tritiated water vapour from radiolysis of the compounds has not escaped from the vials.

Carbon 14

This soft β emitter poses minimal external hazard except as a result of skin contamination. A kBq amount on the skin can cause high doses to be received by the immediately surrounding tissue. The isotope may be handled on the bench in a designated laboratory without protective shielding. Care needs to be taken to contain splashes or aerosols.

As the activities routinely handled are small there is a danger that it could be "forgotten" to record the use and disposal of the isotope. It is emphasised that the licences issued by the Environment Agency require all use and disposal to be recorded.

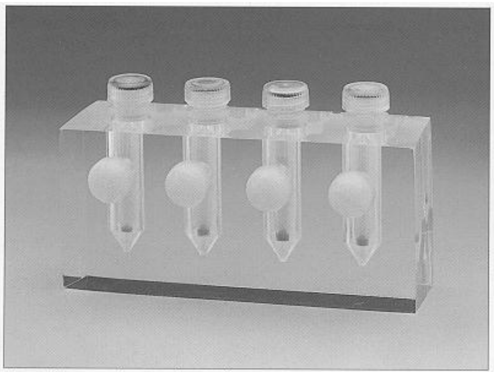
Some sample preparation procedures may involve volatile organic solvents which may consequently result in volatilisation of some of the label, e.g. Chloramphenicol Acetyl Transferase assays involving TLC.

Phosphorus 32

The main risk is the external dose to the hand. Fingertip dosemeters are provided where the work may entail significant activities of ^{32}P. The annual dose limit to the hand is 500 mSv and a person would need to be classified under the Ionising Radiations Regulations if their exposure was likely to exceed 3/10ths of this, i.e. 150 mSv. To put this into perspective, the cumulative dose to the hand over the year from manipulating 30 MBq at 10 cm distance could reach this in 25 hours.

Many techniques involve manipulating 1-2 MBq of ^{32}P in microcentrifuge tubes such as Eppendorfs. These, held directly in the fingers, could result in a dose rate exceeding 1-2 mSv per min per MBq!! **Eppendorfs must not be handled directly even for very short periods of time.**

Remote handling tools (tongs, forceps) should be used wherever possible to maintain distance from active samples. The components of the ICN "Versatainer" may be useful as a general purpose handling tool for microcentrifuge tubes and thus overcome the complaint that remote handling tools are cumbersome and unwieldy. The internal acrylic lid of this container has an indentation for holding tubes (from a number of suppliers). During use, the upturned lid provides a degree of shielding for the fingers without being cumbersome.



Beta heavy duty tube rack

Disposable gloves must always be worn. These should be regularly monitored and changed since the material provides negligable shielding and any contamination on them may give the hand a very high dose.

Stock containers, sample tubes, gels etc must be handled and stored within appropriate shielded containers.

The correct wearing of dosemeters is essential to provide reassurance that such high doses are not being received.

Due to the penetrating nature of ^{32}P β radiation, aqueous waste disposals should be accompanied by flushing of the sink with copious amounts of water. The sink trap should be monitored to confirm that the trap does not contain residual radioactive waste that could give an external dose to others.

Beta waste safes

Solid waste should be held in perspex waste boxes at the workstation prior to sending for final disposal.

Phosphorus 33

The possibility of using ^{33}P should always be considered. It has the particular advantage that its β energy is significantly less than ^{32}P. Consequently external dose rates are substantially less than those arising from similar ^{32}P work. The longer half -life might also be an advantage under some circumstances.

It can be also used as an alternative to ^{35}S. Although twice as penetrating as ^{35}S, ^{33}P does not produce volatile impurities which can give rise to airborne radiation hazards. The sensitivity of ^{33}P is about 20% greater than that of ^{35}S - advantageous with techniques such as reverse transcriptase PCR using microsatellite probes.

For a range of techniques ^{33}P nucleotides are incorporated more efficiently than thionucleotides whilst giving greater resolution than ^{32}P. The lower activity of ^{33}P is a disadvantage for probe production however.

Stock containers, sample tubes and gels must be stored adequately shielded. However much work can be done without the shielding that would be required for work with ^{32}P.

Sulphur 35

The external dose hazard is low. Acrylic screens and shielding is recommended only for high activity stock solutions. Generally, sample tubes need not be placed in acrylic microcentrifuge-tube holding blocks.

There is a potential internal hazard when using ^{35}S amino acid and thionucleotide preparations from volatile impurities that form from radiolysis reactions that occur during storage. These impurities are likely to consist of hydrogen sulphide, sulphur dioxide, methyl mercaptan and acidic gases. (*Stabilised formulations of* ^{35}S *reportedly contain less volatile material after storage than standard preparations.*).

According to manufacturers' safety recommendations concerning volatile contamination problems from the use of ^{35}S, **this radionuclide must not be used in thermal cycling** as persistent contamination of the equipment's heating block will occur regardless of whether tubes or plates are used. The observed contamination of PCR blocks also suggests a potential for aerial contamination arising from the use of this radionuclide in this particular application.

Where possible, ^{33}P is preferred to ^{35}S for PCR experiments where a lower energy β emitter than ^{32}P is needed.

Stock vials must always be opened in a fume cupboard.

It is advantageous to open new vials containing frozen stock whilst still frozen as this reduces the potential for aerosol generation when removing the protective foil.

Work with ^{35}S labelled tissue culture should be conducted in Class II cabinets that are ducted to the outside rather than of the recirculating type as the latter may reintroduce volatile contaminants into the workplace.

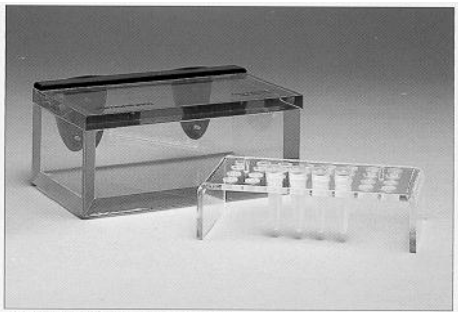
Iodine 125

The risk is the external dose from the γ and X-ray radiation and internal dose from inhalation of volatile ^{125}I.

Lead acrylic screens must be used at all times when working with ^{125}I.

Two pairs of gloves should be worn as iodine labelled materials can penetrate gloves to be absorbed by the skin.

All ^{125}I waste must be held in a lead or lead acrylic screened container.



^{125}I work box and insert

Acidification of ^{125}I solutions can liberate a significant proportion of the label as volatile iodine therefore requiring use of a fume cupboard. This would be a gaseous disposal and is only allowed if the fume cupboard is authorised in the Environment Agency licence for this - **this is generally not the case, check with your RPS if this type of work is involved**.

Freezing of solutions can also liberate volatile ^{125}I, hence vials which have been in the freezer must be opened in the fume cupboard.

Stock vials must be opened in the fume cupboard.

Volatile ^{125}I products in liquid waste can be minimised by its addition to a pre-prepared solution of 25g sodium thiosulphate and 2g sodium iodide in 1 litre of 1M NaOH.

The particular risk from internal iodine is to the thyroid. ^{125}I binding to this will occur within an hour or so of exposure to it. Those performing iodinations, or other processes involving large activities, should routinely monitor their thyroid an hour or so after completing the work. A contamination monitor with a thin crystal scintillation probe should be placed over the gland. If activity is detected, your RPS should be informed and arrangements will be made for the dose to be accurately assessed by Medical Physics at the QMC.

Before commencing decontamination procedures, any spillage of ^{125}I solutions should be treated with a sodium thiosulphate solution to reduce the level of volatile iodine present.

Contamination Procedure

The following information should be displayed in your laboratory in the form of a notice. The location of the emergency kit for the laboratory suite should also be specified. The kit contains the basic equipment needed to deal with a spillage. You should consult your RPS if you have any doubts about dealing with a spillage.

DECONTAMINATION PROCEDURES

Personal decontamination

Medical emergencies take priority over decontamination procedures.

Skin contamination
Sites of contamination should be washed or scrubbed gently using warm water, soap and a soft nail brush. Do not break the surface of the skin or allow contamination to enter the bloodstream. Ensure uncontaminated cuts or sores are covered with a waterproof dressing prior to washing. Extensive contamination should be washed in a shower.

Persistent skin contamination
Use 4% solution of potassium permanganate and allow to dry. Brown staining removed with 5% solution sodium metabisulphite. Dry and monitor.

Hair
Use ordinary shampoo. Limit spread. If persistent, cut hair.

Finger nails
Use soft nail brush. Carefully cut nails. Calamine lotion may be used. Allow to dry and brush nails inside a plastic bag.

Eyes
Normal 0.9% saline in eye wash.

Mouth
Advise subject not to swallow. Remove dentures. Copious mouth washes and brush teeth.

Ears and Nose
Obtain medical help. Swabs and cotton buds. Blow nose, use ear wash.

Open wounds
Irrigate with sterile water or saline.

Minor spills on benches and floors

1 Demarcate the affected area.
2 Wear disposable gloves and overshoes if necessary. Change these at intervals if they become contaminated.
3 Drop paper tissues/towels on the affected area to limit the spread of contamination.
4 Mop up spilled material, working from periphery inwards. Wash affected area placing contaminated towels in plastic bags.
5 Monitor surface and repeat washing if necessary.
6 **Report incident to RPS - Assess amount and cause of accident**
7 Account for the material disposed of in the radioisotope records.