

# 1. Radiations and Radionuclides

## 1.1 Units of Energy

The energies of emitted particles or radiations are quoted in units of electron volts (eV).

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ Joules}$$

1 eV is the energy acquired by an electron in falling through a potential difference of one volt.

Examples of energies:

Iron 59 gamma rays	= 1.1. and 1.29 MeV
Carbon 14 beta particles	= 159 keV
Sodium 22 gamma rays	= 1.28 MeV

Energy information is important in defining the appropriate shielding.

## 1.2 Atomic and Nuclear Structure

Each element exists as several different nuclides, a nuclide being an atom characterised by a given number of protons and of neutrons in its nucleus. Atoms of a given element have the same number of protons and its nuclides differ by having different number of neutrons. Different nuclides of the same element are also called 'Isotopes' of that element.

For example:  ${}^1\text{H}, {}^2\text{H}, {}^3\text{H}$   
 ${}^{11}\text{C}, {}^{12}\text{C}, {}^{13}\text{C}, {}^{14}\text{C}$   
 ${}^{31}\text{P}, {}^{32}\text{P}, {}^{33}\text{P}$

Most nuclides are stable but in the case of **radionuclides** the nucleus is unstable. Particles or radiation are given off by radionuclides and an atom of a different element is formed. If the new atom is also unstable further nuclear transformations and emissions occur until a stable nucleus is formed.

Nucleus                      Protons and Neutrons

Atomic Number (Z) = Number of protons in the nucleus

Neutron Number (N) = Number of neutrons in the nucleus

Atomic Mass (A) = Z + N

Notation                       $\begin{matrix} A \\ Z \end{matrix} \text{X}$

Hydrogen                       ${}^1_1\text{H}$

Helium                          ${}^4_2\text{He}$

Oxygen                          ${}^{16}_8\text{O}$

### 1.3 Isotopes

The chemical properties of an element are determined by the number of electrons and hence the number of protons in the element. However, if additional neutrons are added to the nucleus then the physical properties of the element change. These are called **Isotopes** (from the Greek 'Same state or place') and may be stable or unstable.

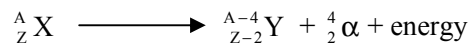
Hydrogen	${}^1_1\text{H}$	${}^3_1\text{H}$	
Sodium	${}^{22}_{11}\text{Na}$	${}^{23}_{11}\text{Na}$	${}^{24}_{11}\text{Na}$
Iodine	${}^{124}_{53}\text{I}$	${}^{125}_{53}\text{I}$	${}^{131}_{53}\text{I}$

### 1.4 Radioactivity

#### (a) Alpha ( $\alpha$ ) Emissions

Alpha particles are doubly charged helium nuclei. Their kinetic energies are of the order of several MeV. Each particle has a single discrete energy characteristic of the radionuclide.

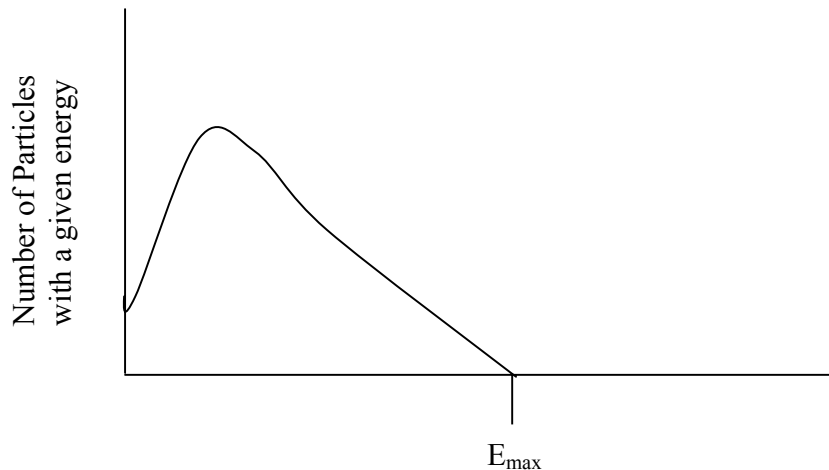
Alpha decay - helium nucleus (2p, 2n)



#### (b) Beta ( $\beta$ ) Emissions

$\beta$  particles are electrons of kinetic energy ranging up to 3 MeV. The energies of  $\beta$  particles from any particular radionuclide are not single valued but range from zero up to a maximum value which is characteristic of the nuclide. The distribution curve which shows how the number of  $\beta$  particles varies with energy (in MeV) is the  $\beta$  spectrum of the radionuclide.

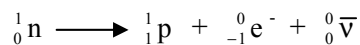
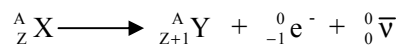
Both  $E_{\text{max}}$  and the precise shape of the  $\beta$  spectrum are characteristic of the radionuclide. The average  $\beta$  energy is about 3/5 of the  $E_{\text{max}}$ .



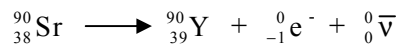
### Positron ( $\beta^+$ ) Emissions

$\beta^+$  particles are the same mass as electrons but with an equal and opposite charge. (Strictly speaking electrons emitted from radionuclides should be called  $\beta^-$  particles but they are often simply called  $\beta$  particles).

An extra feature of  $\beta^+$  emissions is that  $\beta^+$  particle eventually reacts with an electron in the material through which it is passing. This causes the annihilation of both particles and the conversion of their masses to energy, the energy appearing as two gamma ray ( $\gamma$ ) photons whose energies are equal to the mass equivalents to the positron and electron. Thus positron emission is **always** accompanied by  $\gamma$  emissions.

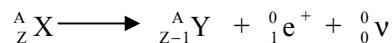


$\bar{\nu}$  = antineutrino

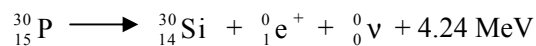
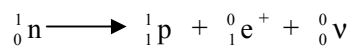


(Strontium to Yttrium)

#### ***For Positrons***



$\nu$  = Neutrino



**Note:** These particles are emitted in a spectrum of energies up to a maximum ( $E_{\max}$ ). The energy essentially being shared between the electron or positron and the antineutrino or neutrino.

### (c) Gamma ( $\gamma$ ) Emissions

This occurs only in conjunction with other types of radioactive decay.  $\gamma$  radiation is an electromagnetic radiation. A radionuclide may give several characteristic  $\gamma$  rays but the energy of each is single valued and characteristic of the nuclide. Typical  $\gamma$  energies are in the range of 0.1 to 2 MeV.  $\gamma$  emission occurs when decay leads to a product nucleus in an excited state and the excited nucleus loses its excess energy by emitting the  $\gamma$  radiation.

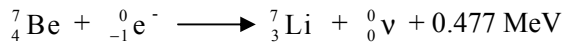
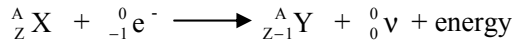
### (d) X-radiation

X-rays are identical in to  $\gamma$  radiation but are due to the excited state of electrons not nuclear excitation. When an electron in an atomic shell falls to a lower energy, the excess energy is emitted as X-rays of a characteristic energy and frequency.

X-rays are also produced when a beam of electrons are stopped by a target.

(e) Electron Capture

Some elements can capture an inner orbital electron into the nucleus. Following this process there is an empty space in the inner orbital shell of electrons which will be occupied by an electron from a higher shell with the emission of an appropriate amount of energy in the form of X-rays. Gamma ray emission may also follow from the nucleus.



(f) Internal Conversion

If a nuclide is in an excited state after decay it can emit a  $\gamma$  ray and forming a stable state but also the energy can instead be transferred to an orbital electron which is then ejected from the atomic shell. This is called Internal Conversion.

**1.5 Radioactive Decay**

The number of radionuclide breakdowns (or events) per second (N) is proportional to the number of radioactive atoms present at that time.

$$\frac{dN}{dt} = -\lambda N$$

where  $\lambda$  is the decay constant

$$N_t = N_0 e^{-\lambda t}$$

When  $N_t = \frac{N_0}{2}$  i.e. the activity has decreased by half

$$t = \frac{T_{1/2}}{2} = \text{Half Life}$$

$$\frac{N_0}{2} = N_0 e^{-\lambda T_{1/2}}$$

$$\ln_e 2 = \lambda T_{1/2} \text{ which is equal to } T_{1/2} = \frac{0.693}{\lambda}$$

**1.6 Units of Radioactivity**

The original unit, the Curie (Ci), was defined in relation to the emissions of 1 gram of radium 226.

The SI unit, the Becquerel (Bq), has now been introduced and is equal to one transformation per second.

1 Curie	=	$3.7 \times 10^{10}$ disintegrations per second
1 milliCurie (1mCi)	=	$3.7 \times 10^7$ disintegrations per second
1 microCurie (1 $\mu$ Ci)	=	$3.7 \times 10^4$ disintegrations per second

1 Bequerel	=	27.03 picoCuries
1 mCi	=	37 MBq (MegaBequerels)
1 $\mu$ Ci	=	37 kBq (KiloBequerels)

The Bequerel, in appropriate amounts, is the unit used in all legislation e.g. Registration and Authorisation Certificates.

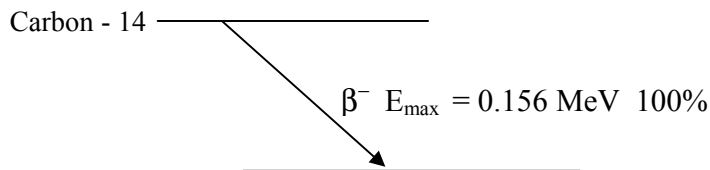
The main suppliers of radioactivity (e.g. Amersham International) use both units and are phasing in the Bequerel.

### 1.7 Decay Schemes / Physical Data

Decay schemes show a representation of the radiations emitted, the energy of the radiation the percentage of the transformation producing the radiation. The direction of the arrow in the decay scheme shows the effect on atomic number ( $Z$ ), arrow pointing to the right shows an increase in  $Z$ , arrow pointing to the left shows a decrease in  $Z$  and arrows pointing straight down show no effect on  $Z$  (e.g. gamma ray production).

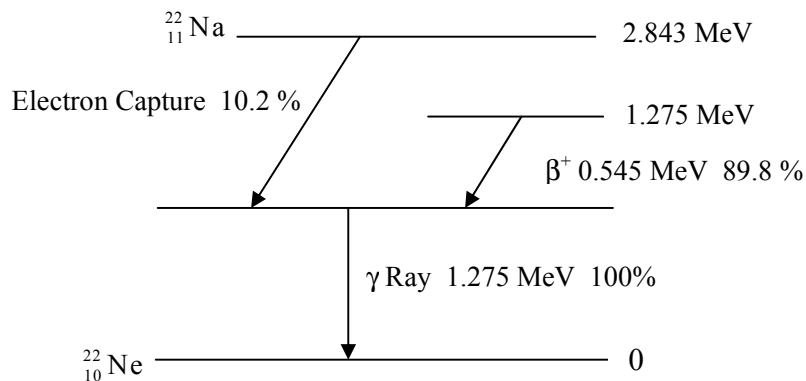
A knowledge of decay schemes is important for radiation protection purposes. It is necessary for deciding about the type and degree of radiation hazard and for certain calculations for example radiation dose rates.

Some decay schemes are simple, e.g.:

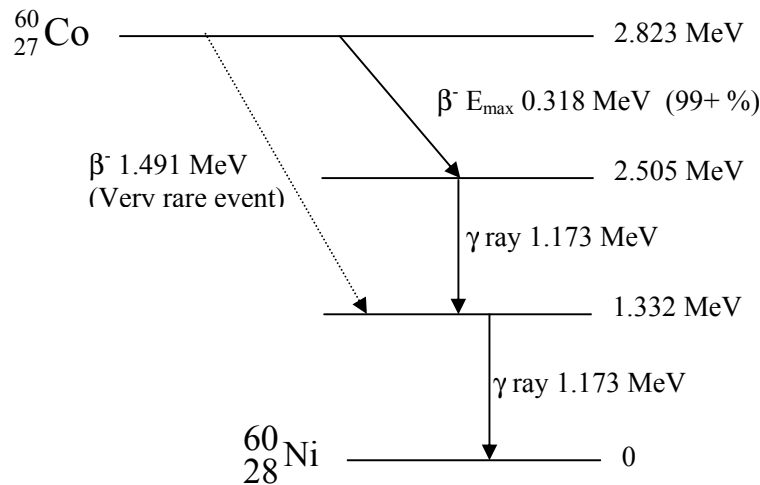


This means that all disintegrations (100%) involve the emission of  $\beta^-$  particles and that the maximum energy of the  $\beta$  spectrum is 0.156 MeV. This nuclide is called a pure  $\beta$  emitter because no  $\gamma$  radiation is involved in its decay.

For many radionuclides several means of decay occur and only a percentage of the total number of disintegrations occurs by each process. For example Sodium 22:



For Cobolt 60,



Isotope	Half Life	Type of Decay (Particle Energies in MeV)	Gamma Ray Energies (MeV)
Co-60	5.26 years	$\beta^-$ 0.31 MeV (100%) 1.48 MeV (approx 0.01%)	1.17 MeV - 100% 1.33 MeV - 100%
Iodine - 125	60 Days	Electron Capture 100%	0.035 MeV - 7 % 0.027 MeV - TeX-rays
Phosphorus - 32	14.3 Days	$\beta^-$ 1.71 MeV (100%)	-----

## 2. Properties of Radiation

$\alpha$ ,  $\beta$  and  $\gamma$  radiations all lose energy by causing IONISATIONS in the material through which they pass. The ions are not produced uniformly but form tracks in the material.

Ionisation has two important consequences in radiation protection:

1. Ionisation in biological tissues causes changes in biomolecules and this can lead to eventual observable radiation damage to the irradiated organisms;
2. Very sensitive methods exist for the detection of ionisation (and of some other effects which ionising radiations produces in materials). This is a feature which allows sensitive monitoring of contamination and of radiation doses and dose rates.

The ABSORPTION of various radiations can be summarised as follows:

### 2.1 Alpha Particles

As these are relatively large and double charged particles, they interact strongly with matter. Consequently, ions are formed close together, giving a track with a high ion density. They lose their energy in a short distance and thus have a short range.

### 2.2 $\beta^-$ and $\beta^+$ Particles

These are lighter particles compared to  $\alpha$  particles and have only one charge. They therefore interact less strongly with an absorbing material. Their ranges are longer because of the lower ion densities in their tracks.

Annihilation reaction  $\gamma$  rays always follow  $\beta^+$  emissions but electromagnetic radiation of a different kind also results from  $\beta^-$  emissions. Deceleration of  $\beta^-$  particles occurs when they pass close to the nucleus and the resultant loss of energy appears as X-rays; these X-rays are called **Bremsstrahlung** radiation (German for Breaking Radiation).

Most of the  $\beta^-$  energy is lost by ionisation and only a small proportion as bremsstrahlung. The proportion lost as bremsstrahlung increases with the  $\beta^-$  energy and also the atomic number of the absorbing material.

### 2.3 $\gamma$ and X Radiations

As these are electromagnetic radiations they travel much further than particulate radiations of the same energies. The electrons produced by primary ionisations form secondary ion-tracks with an ion density comparable to that in  $\beta$  tracks but the distance between interactions in the primary  $\gamma$  track itself is much greater.

### 2.4 Range of Particulate and Electromagnetic Radiations

The higher the ion density produced by the radiation the shorter its range, that is, the shorter the distance it travels through an absorbing medium.

The penetrating power therefore increases in the order:

$$\alpha < \beta < \gamma \text{ or X-ray for a given energy.}$$

A fundamental difference between particulate radiation and electromagnetic radiation is that  $\alpha$  and  $\beta$  particles are completely absorbed by a thick enough absorbing material whereas  $\gamma$ -rays and X-rays are in theory never completely stopped but are only attenuated. The electromagnetic radiations have no finite range.

$$\text{Range of } \alpha \text{ particles} = \frac{E}{1000} \text{ grams cm}^{-2} \text{ (where } E = \text{Energy of } \alpha \text{ in MeV)}$$

Beta particles are emitted from any radioactive nucleus with energies varying over a wide range from zero to a maximum which typically would be in the range 0.1 to 3 MeV (the average beta energy is about one third the maximum energy). The range can be expressed approximately as:-

$$\text{Range of } \beta = \frac{E_{\max}}{2} \text{ gram cm}^{-2} = \frac{E_{\max}}{2d} \text{ cm}$$

Where  $E_{\max}$  = maximum energy in MeV and  $d$  = density

#### (a) Alpha and Beta Particles

Ranges of  $\alpha$  and  $\beta$  particles are usually given in  $\text{mg/cm}^2$  because in these units the range is, to a good approximation, independent of the density of the absorbing material. The range in centimetres decreases as the density of the absorber increases. A thickness of  $1 \text{ mg/cm}^2$  is the amount of absorber in the section of the cross sectional area  $1 \text{ cm}^2$  and of mass 1 mg.



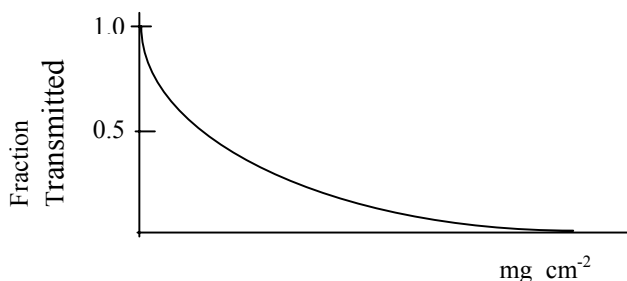
To calculate the range in centimetres from the value in  $\text{mg}/\text{cm}^2$ , use the formula:

$$\frac{\text{mg cm}^{-2}}{\text{mg cm}^{-3}} = \text{cm} \quad (\text{where mg cm}^{-3} \text{ is the absorber density in these units})$$

Typical ranges of  $\alpha$  and  $\beta$  particles:

Type of Source	$\text{mg cm}^{-2}$	In Tissues	In Air
$\alpha$	A few depending on the energy	Approx 50 $\mu\text{m}$	centimetres
$\beta$ :-			
H-3 ( $E_{\text{max}}$ 0.018 MeV)	Approx. 5	Approx. 500 $\mu\text{m}$	Approx. 4 cm
C-14 ( $E_{\text{max}}$ 0.156 MeV)	30	0.3 mm	Approx. 20 cm
P-32 ( $E_{\text{max}}$ 1.7 MeV)	800	8 mm	Approx. 600 cm

These are for total ranges but considerable absorption occurs in much smaller thickness.



## 2.5 **Gamma Rays**

Unlike charged particles, gamma rays do not directly cause ionisation of the matter through which they travel. There are interactions, however, which transfer the kinetic energy of the gamma photon into the kinetic energy of electrons and it is these secondary particles which cause ionisation.

There are three important processes involved in the absorption of gamma rays, and each contributes to the value of the Absorption Coefficient.

### a. **Photoelectric Effect**

In this process the incident  $\gamma$  ray ejects one of the orbital electrons from an atom of the material and gives almost all of its energy to the electron which then travels through the material ionising and exciting the atoms of the material. The incident  $\gamma$ -ray disappears.

### b. **Compton Scattering**

The incident  $\gamma$ -ray is scattered by an orbital electron of an atom in the material yielding up some of its energy to the electron and going off at a reduced energy and in a different direction. The struck electron may have any energy from zero up to a maximum of about two thirds of the incident  $\gamma$ -ray energy and this energy is dissipated in ionisation and excitation. Clearly the scattered  $\gamma$ -ray can undergo further scattering process until it is completely absorbed in a photoelectric collision.

c. **Pair Production**

This is only important for  $\gamma$ -rays of energy greater than 1 MeV ( $\gamma$ -ray energy greater than twice the electron rest energy) and involves the  $\gamma$ -ray producing a positron-electron pair in the field of a nucleus of the material. The incident  $\gamma$ -ray is completely converted to produce the positron-electron pair and thus is absorbed. The  $\gamma$ -ray energy is dissipated by the electron and positron in ionisation and excitation along their tracks.

Most  $\gamma$ -rays from radioactive materials lie in the energy range 0 - 2 MeV and in this range pair production is relatively unimportant. At low energy and for materials of high atomic number the photoelectric effects have to be considered.

The absorption of a beam of  $\gamma$ -rays follows an exponential i.e.

$$I = I_0 e^{-\mu x}$$

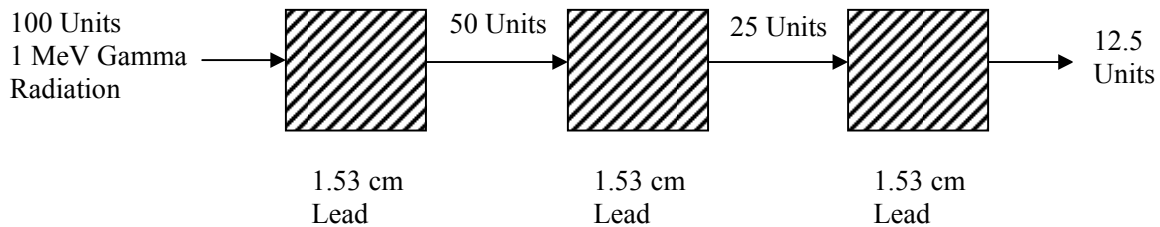
Where  $I_0$  = Incident Intensity  
 $I$  = The intensity after travelling through a distance of  $x$  of absorber  
 $\mu$  = Is a constant, characteristic of the material and of the energy of the  $\gamma$ -rays.  
 $x$  = Distance traversed (absorber thickness)

2.6 **Half Value Thickness**

This is the thickness of absorber required to attenuate the beam by 50% and provides a simple method of calculating shield requirements. This value is of course energy dependent:

e.g. 1MeV  $\frac{I}{I_0} = 0.5 = e^{-0.04(11.35)x}$  Where  $x = 1.53$  cm

Hence to attenuate a beam by 1/8<sup>th</sup> requires 3 half thicknesses



3.0 **Units of Dose**

As we have seen radiation causes ionisation and it is in this way that it produces biological sequelae. It can also be quantified by the amount of ionisation it produces in air (Roentgen - R).

3.1 **Unit of Absorbed Dose**

The Unit representing energy deposited in a specific medium for all types of radiation is the **Gray (Gy)**.

$$1 \text{ Gray} = 1 \text{ Joule kg}^{-1}$$

(The previous unit was the **Rad** and 1 Gray is equivalent 100 Rads)

Absorbed Dose rate is given as Grays per hour.

### 3.2 Unit of Dose Equivalent

The **Sievert (Sv)** was introduced to take account of the Linear Energy Transfer of the radiation i.e. the way biological damage arising from identical absorbed doses varies due to the localised energy deposition within the cell.

$$\text{Sievert} = \text{Grays} \times \text{Quality Factor (QF)}$$

(The previous unit for dose equivalent was the **Rem** and 1 Sv is equivalent to 100 Rem)

Although the Sievert is not a true measurable physical unit, it does enable radiation doses to be quoted in units which will, in a generalised way, represent the likely biological effectiveness of the doses.

Absorbed Equivalent Dose Rate is given as Sieverts  $\text{h}^{-1}$

### 3.3 Quality Factors (QF)

External Exposure	Quality Factor (QF)
X and $\gamma$ radiation	1
Electrons and $\beta$ Particles	1
Protons (according to energy)	1-3
Neutrons (according to energy)	3-10
Heavy recoil nuclei	20

Modifying factor for the lens of the eye:

1 for QF of 1

3 for QF of 10 or more

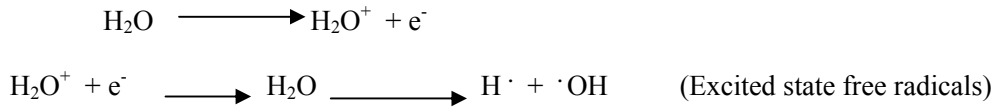
Internal Exposure	Quality Factor (QF)
X, $\gamma$ radiations and electrons	1
Electrons of $E_{\text{max}} = 0.03 \text{ MeV}$	1.7
Neutrons from spontaneous fission	8
$\alpha$ particles	10
Fission fragments and recoil nuclei	20

### 3.3 Correlation between Quality Factor (QF), Specific Ionisation and Linear Energy Transfer (LET)

QF	Specific Ionisation (Ion pairs per $\mu\text{m}$ in water)	LET (keV / $\mu\text{m}$ )
1	100 or less	3.5 or less
1 - 2	100 - 200	3.7 - 7
2 - 5	200 - 650	7 - 23
5 - 10	650 - 1500	23 - 53
10 - 20	1500 - 5000	53 - 175

#### 4.0 Biological Effects of Radiation

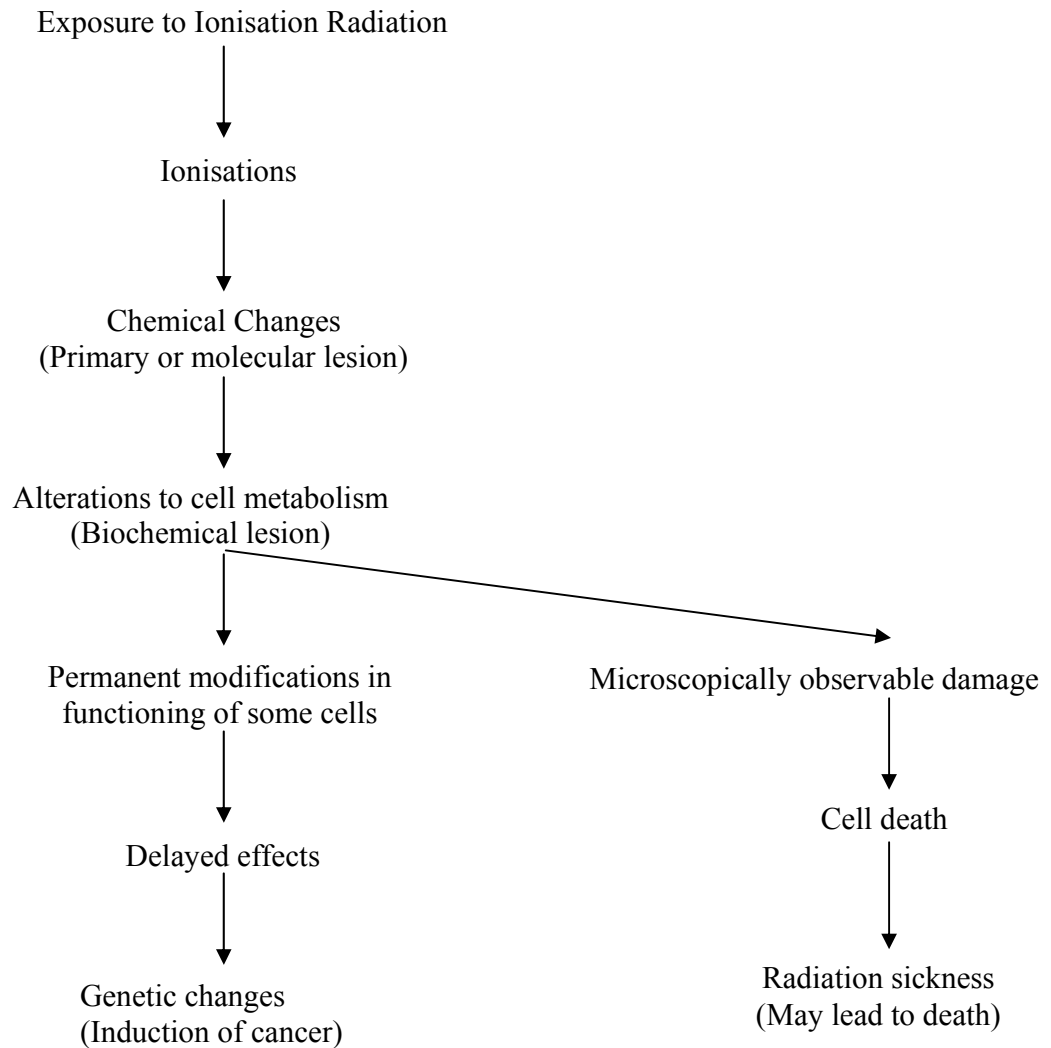
The biological effects of radiation are brought about following ionisations in tissue. As the vast quantity of intra and extra cellular material is water, then the effects of ionisations in water are important.



These uncharged free radicals are extremely reactive as they have unstable electron shells and probably are the factors which initiate damage to important macromolecules in the cell.

Evidence for target being DNA in nucleus:

- Microbeam irradiation of the nucleus is more sensitive than cytoplasm;
- 'Suicide' experiments using heavily labeled  $^3\text{H}$ -thymidine (DNA),  $^3\text{H}$ -Uridine (RNA) and  $^3\text{H}$ -amino acids (proteins) showed that the DNA was the most sensitive target.



The types of observable effects can be divided into:-

#### 4.1 *Non-Stochastic Effects*

These effects have a threshold dose below which the effect does not appear; the severity of the effect increases with dose above the threshold.

Non-stochastic effects include radiation sickness, cataracts and damage to the skin.

#### 4.2 *Stochastic Effects*

These have no threshold dose. The *probability* of the effect increases with dose but the severity is not a function of dose.

Stochastic effects include cancers and genetic effects in succeeding generations. The latter are caused by irradiation of germ cells.

#### 4.3 *Concepts of levels of Radiation*

Background radiation	1-2 mSv per year
Diagnostic chest X-ray	0.4 mSv
Detectable changes in blood cell numbers	250 - 500 mSv (Single whole body dose)
Median lethal dose range	5 - 7 Sv (Single whole body dose)
Course of radiotherapy for a tumour	30 - 40 Sv (localised and spread over time)

#### 4.4 *Radiation Effects*

a). Acute Effects  
Radiation Syndromes

##### Haematopoietic Syndrome

- 2 - 10 Sv whole body irradiation;
- Causes severe damage to the blood forming tissues;
- Risk of immune suppression and infection (Lack of white blood cells - granulocytes, lymphocytes);
- Risk of bleeding (Lack of platelets);
- Death within 10 - 20 days.

##### Gastrointestinal Syndrome

- 10 - 30 Grays whole body irradiation;
- Causes severe damage to the cells lining the gastrointestinal tract;
- Fluid loss, electrolyte imbalance, pathogens enter the body;
- Death within 3 - 4 days

Central nervous System Syndrome

- 50 - 100 Grays;
- Rapid response, damage to blood vessels, compromise of normal brain function;
- Death within 1-2 days.

Acute Effects

<b>Time After Exposure</b>	<b>&gt; 8 Grays</b>	<b>5 Grays</b>	<b>2 Grays</b>
1 <sup>st</sup> Week	Nausea and vomiting after 2 hours		
	Diarrhoea, vomiting, inflammation of throat	No definite symptoms	
2 <sup>nd</sup> Week		Loss of hair, loss of appetite, general malaise, fever and pallor	Loss of hair, loss of appetite, sore throat
3 <sup>rd</sup> Week			
	<b>Death</b>		<b>Recovery</b>

Radiosensitivity

Early blast cells in cell renewal system

Relative Radiosensitivity

- Sensitive - Spermatogonia, lymphocyte, erythroblasts, other haematopoietic tissues;
- Less Sensitive - epithelium of the small intestine, stomach, colon, hair follicle of the skin, epidermis of the skin;
- Resistant - Central nervous system, muscle, bone, collagen.

Effects on other tissues

1. **Skin** - Erythema (reddening of the skin), blister-formation, hair loss dry-moist desquamation (loss of skin cells), ulcer, chronic dermatitis (inflammation of the dermis, tissue under the surface epithelium);
2. **Foetus/Embryo** - First 6 weeks of pregnancy is highly susceptible to damage (period of organogenesis);
3. **Reproductive System** - Male testes (0.5 - 3 Gray) causes temporary streilisation, 6 Gray and above causes permanent streilisation;

4. **Lung, Kidney and Bone** - Vascular damage;
5. **Lens of the Eye** - Cataract induction by neutrons.

#### Chronic Effects

- a. **Genetic Effects** - Probably about 10% of natural mutations are due to background radiation, dose of 0.3 - 0.8 Grays would double natural mutation rate.
- b. **Carcinogenic** - Lung cancers in Uranium Miners;  
Leukaemia and cancers in Hiroshima atom bomb survivors;  
Childhood leukaemia *in utero* irradiation;  
Early radiologists;  
Radium painters - bone tumours;  
Irradiation of patients with arthritic condition of the spine;  
Breast cancer in TB patients
- c. **Life Shortening** - Animal experiments suggest ageing effects other than carcinogenic actions.

In defining protective doses assume:

- Linear dose response curve (reduce dose from 1 Gray to 0.01 Gray reduces delayed effect by 100);
- No effect of time-course (single short dose gives same effect as dose spread over a longer time scale).

Both assumptions are likely to be conservative estimates.

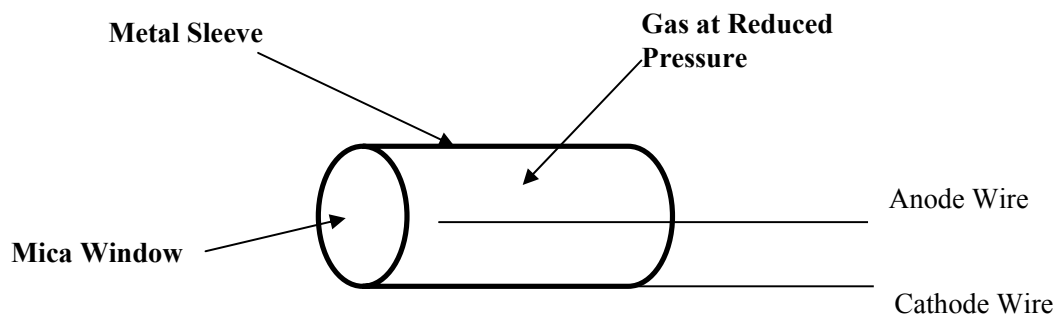
## 5. Principles of Radiation Detection

This section will give a brief overview of the main types of detectors used for radiation monitoring (either for dose estimation or contamination detection).

It is obviously essential to use an appropriate monitor for the particular radiation source you are using as no one device is appropriate (or indeed will detect) all types of radiation at all energies.

### 5.1 The Geiger-Muller Tube

If radiation falls on a gas at reduced pressure, ion-pairs formed in the gas can be collected - rather the electrons travel rapidly away to the anode and the +ve gas ions will eventually travel to the cathode.



What happens depends on the voltage applied.

At LOW Voltage

One collects merely the ion produced, and the number produced depends on the particle energy (provided the particle is totally absorbed in the chamber). Thus the current depends on the radiation level and particle energy, but is pulsed enabling both to be read. Useful for detecting alpha particles. Called ***Ionisation Chamber*** region (Region B of the graph).

At INTERMEDIATE Voltage

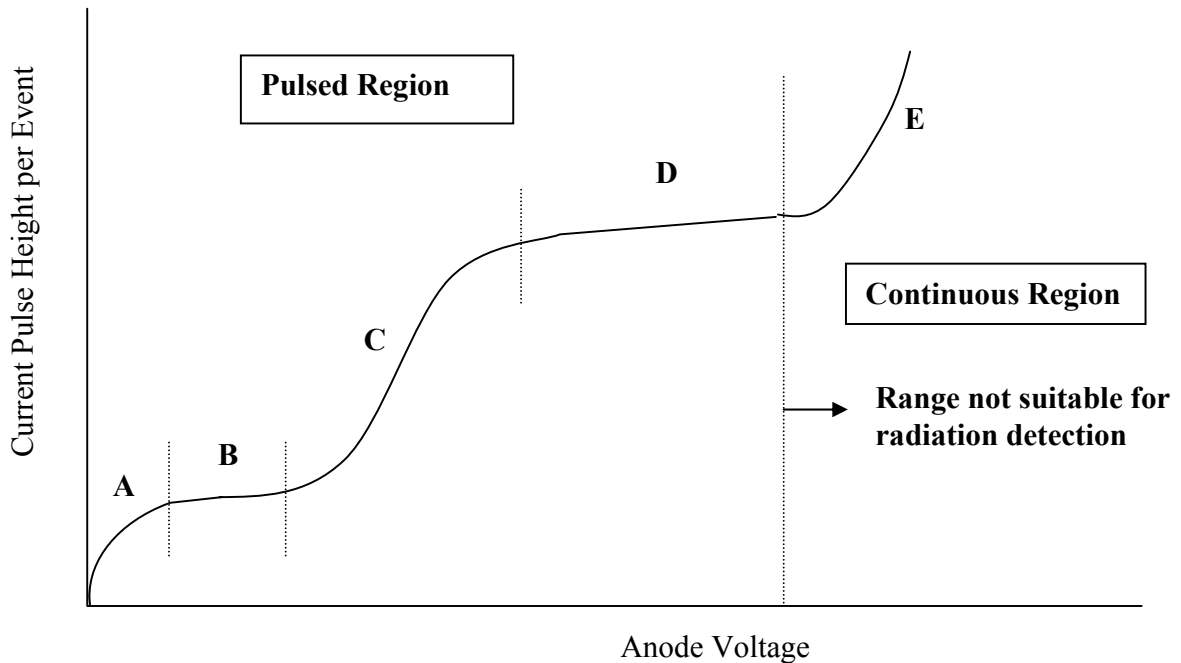
Electrons are accelerated, especially in the high voltage gradient near the anode wire, so much so that some secondary ionisation occurs due to the speed of the primary electrons. the current pulse height is proportional to the particle energy, as above, but much amplified by secondary ionisation making detection easier. Again, current is pulsed - pulse height is dependent on particle energy and pulse number on radiation level. ***Proportional Region*** (Region C of the graph).

At HIGH Voltage

A plateau is reached where amplification by secondary ionisation is unaffected by voltage over a range. This is because each absorption event leads to momentary saturated ionisation of all the gas in the chamber. This is the region normally used for counting. The pulse height is independent of the particle energy and depends only on the design of the tube. The pulse frequency, or course, depends on the radiation level. ***Geiger-Muller Region*** (Region D of the graph).

At VERY HIGH Voltage

Uncontrolled ionisation occurs and the tube does not respond to radiation. (At the Geiger-Muller region ionisation is self-terminating if the radiation stops, but here the voltage is so high it directly ionises the gas). ***Discharge Region*** (Region E of the graph).



The actual voltages of these regions depend on the design of the tube, but the Geiger region is easy to find.

**NOTE:** The Geiger tube needs to be coupled to a voltage source and counter (or scaler). Often these are combined, and the scaler may also contain a pulse height analyser of some sort, with or without print-out.

### Problems

1. Thickness of the mica window:
  - $^3\text{H}$  betas will not penetrate the window and
  - $^{14}\text{C}$  betas will only penetrate especially thin windows.
2. Efficiency of detection
  - Clearly gamma rays of high energy will not be detected efficiently;
  - Efficiency will also depend on the geometry of the source/detector;
  - There will be some self-absorption by the source itself.
3. Dead time correction
  - If there is a high radiation field, then events occurring so rapidly that they are not detectable (dead time - time for the tube to deionise after one detection event). Serious underestimation of radiation field / contamination can be made because of this.
4. Mixed Radiation Field
  - The monitors may detect both gammas and betas, thus shielding may then attenuate the betas.

### **5.2 Scintillation Counters**

As seen above, the Geiger-Muller tube will not detect all radionuclide radiations e.g. tritium ( $^3\text{H}$ ). Due to its increased sensitivity, the scintillation counter can be used to identify a broader range of radionuclides.

The scintillation counter has three main parts:

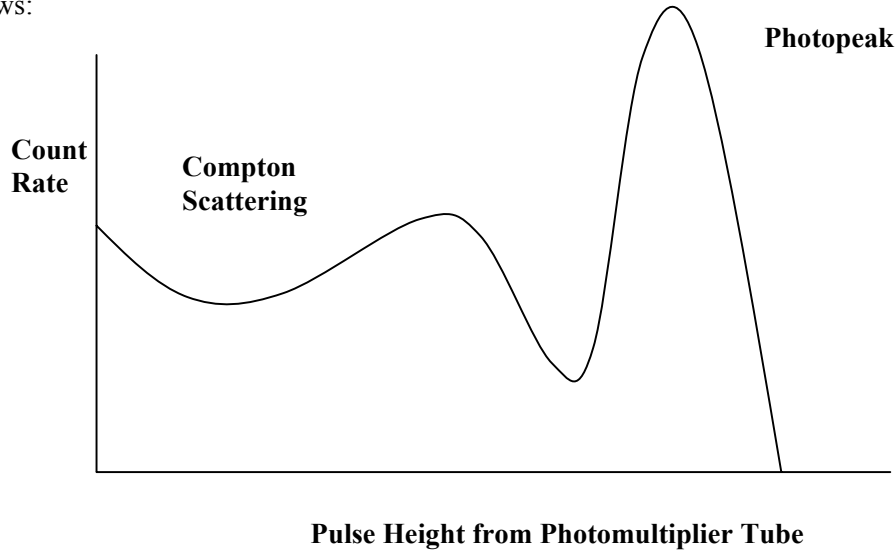
- The scintillant or fluor;
- A light detector - usually a photomultiplier tube;
- Electronic power supply and analysis system.

The scintillant or fluor may be either external to the radiation source (e.g. a crystal) or may be mixed with the radiation source e.g. liquid fluors (for  $^3\text{H}$ ). Scintillants are of many types and choice of the appropriate one depends on what you want to detect.

What happens in the fluor is that incident radiation causes orbital electrons in the fluor to be raised to a higher energy state, from whence they relax down again with the release of a flash of light. Thus an incident  $\beta$  or  $\gamma$  will cause tracks of light in the fluor which for all practical

purposes are instantaneous. The photomultiplier tube picks up these flashes of light and records them.

$\gamma$ -rays are, of course, either absorbed to give the photo-electric effect at a definite energy or partially absorbed to give the Compton scattering. This shows in the scintillation counter as follows:



The pulse height of the photopeak is characteristic of a particular radionuclide in a given setup and so a pulse-height analyser, especially a multi-channel one, can be used to measure simultaneously two radioisotopes in a double labeling experiment.

Scintillation probes are used for the detection of low energy X-rays and  $\gamma$ -ray emitters of a variety of energies. Different probes are available with different sensitivities.

**NOTE:** One important point is that in quite weak radiation fields these scintillation meters can be overloaded **AND NO RESPONSE FROM THESE MACHINES OCCURS.**

### 5.3 *Monitoring Radiation for Hazard*

Essentially, monitoring follows the principles of radiation detection. Hand held radiation monitors are of various types and an appropriate monitor must be selected. A Geiger-Muller tube probe on a flexible cable, connected to an electronic unit will give read-outs in terms of clicks from a built in speaker and pulse rate shown on a panel meter. It is not very easy to assess the radiation dose rate with such a device because the response depends on:

- Whether the radiation can enter the instrument (No use for  $^3\text{H}$ );
- How far the instrument (i.e. the G-M tube) is from the source;
- What efficiency the counter has.
- etc.

37 GBq (1 Curie) would produce  $3.7 \times 10^{10}$  disintegrations per second but at best only a fraction of these would enter the tube and only a fraction would cause a detection event. So one may say that 37 kBq very close to a G-M tube could produce something like 1000 events (e.g. clicks) per second. Contamination of 37 kBq is quite a lot and certainly requires rapid attention, although it

would not be especially dangerous at that level, unless permanently very close or in contact with the body or ingested, but see lecture on radiation hazards.

The hand-held monitor is most useful for detecting if contamination has occurred and where it is - on the bench, flooring, clothing, hands (you should be wearing gloves anyway!).

Scintillation probes are used for detecting  $\gamma$ -ray and X-ray emitters. Again the same problems with efficiency and geometry are important. Calibration information is available with each probe and enables estimates of contamination levels to be determined.

Tritium ( $^3\text{H}$ ) monitoring is not easy. The only effective way is to take swabs and elute these into a liquid scintillant and put them into a liquid scintillation counter. This is a slow process since you do not get an immediate read-out. On the other hand,  $^3\text{H}$  and  $^{14}\text{C}$  in glass are pretty effectively screened (it depends on the thickness of the vial for  $^{14}\text{C}$  and radiation from  $^3\text{H}$  rarely gets through any glass vessel).

$^{14}\text{C}$  as  $\text{CO}_2$  can only be monitored with special gas monitors and  $^{14}\text{CO}_2$  is clearly hazardous because it can be breathed in.

#### 5.4 *Dose Monitoring Devices*

Various types of detectors are available for continuous monitoring of radiation fields on personnel. There are three major systems that are used:

- Optically Stimulated Luminescence (OSL): In this system a badge containing aluminium oxide ( $\text{Al}_2\text{O}_3$ ) is used to accumulate the radiation dose. The aluminium oxide is then exposed to selected frequencies of laser light which causes the aluminium oxide to become luminescent and this luminescence is measured to determine the dose received.
- Thermoluminescence Dosimeter (TLD): In this system a badge containing Lithium Fluoride (LiF) is used to accumulate the radiation dose. The badge is then heated to release the radiation dose as light which is then measured to determine the radiation dose received.
- Film Badges: In this system, a strip of film is in the badge and the film will directly detect the amount of radiation received by the wearer.

### 6. **Radiation Standards**

These are derived from ultimately from the Recommendations of the International Commission on Radiological Protection: ICRP Publication 60 (1991). This publication contains an assessment of the risks of detrimental effects of radiation doses.

In this publication the Commission defines the objectives of radiation protection, review current estimates of risk and proposes a system of dose limitations containing recommended dose equivalent limits. The Commission distinguishes stochastic effects of radiation (e.g. cancer induction) where the probability of the effect happening is regarded as a function of dose without threshold, from non-stochastic effects (e.g. death, cataract formation) where the severity of the detriment varies with dose and where there is usually a clear threshold dose.

The Commission has recommended an occupational dose equivalent limit for the whole body of 20 mSv per year to prevent, with dose equivalent for the lens of eye of 150 mSv per year and for skin, hands and feet of 500 mSv per year. No one in research or teaching laboratories should not approach the above limits in their normal work.

The above values are used to determine the dose rates for external radiation in the workplace and for the contamination of surfaces and air. From the derived , reference levels can be defined for example  $3/10^{\text{th}}$  of the annual basic occupational exposure limit. Thus for research laboratories, areas defined as 'Controlled Areas' (ICRP Working Conditions A) are areas where workers may receive  $3/10^{\text{th}}$  of the 20 mSv per year occupational dose limit. For laboratories where it would be unlikely that persons would exceed the  $3/10^{\text{th}}$  of the Exposure Limit, the radiation dose limitation might be determined by working to  $7.5 \mu\text{Sv hr}^{-1}$ . Thus external radiation monitoring would be to ensure that the dose equivalent rate was not exceeded either outside shielded enclosures or beyond external radiation areas marked by warning signs and barriers.

## 7. Hazards From Ionising Radiations

A reasonably clear distinction can be drawn between external radiation and contamination hazards. In general, there is an external radiation exposure risk from any device in which electrons or heavy particles are accelerated and from sealed or unsealed sources. Unsealed radioactive materials are also a potential contamination hazard.

### 7.1 External Radiation Hazards

Vacuum tubes in which electrons are accelerated by potentials greater than 5 kV may be hazardous due to the emission of X-rays, but current flowing and the construction of the equipment will obviously influence the degree of the exposure risk. Where electron beams of a few microamps are accelerated up to 10 - 15 kV, glass vacuum tubes usually have sufficiently thick walls to absorb almost all the X-rays produced; this might not apply however in a device in which beams of many milliamps are produced. This-windowed tubes (e.g. image intensifiers) may be hazardous because the electrons can emerge and cause serious skin burns or eye damage. Most standard equipment, such as cathode ray oscilloscopes or television monitors, operating even up to about 20kV are safe since the case-work provides additional shielding and flat faced cathode ray tubes are thicker than normal to withstand air pressure.

Electron microscopes are not normally regarded as producers of X-rays, but since they operate at potentials in the range of 50 kV to 100 kV, due regard must be paid to the possibility of X-rays being emitted in unexpected directions.

Radiation from radioactive materials may be of three main types, alpha particles ( $\alpha$ ), beta particles ( $\beta$ ) and gamma rays ( $\gamma$ ). Alpha particles are not normally considered to be an external radiation hazard since they can be stopped very easily and are unable to penetrate more than the outer layers of the skin. Beta particles on the other hand can cause serious skin burns while gamma rays are generally capable of penetrating appreciable thickness of material.

It should not be forgotten that Bremsstrahlung radiation arising from the absorption of  $\beta$  particles can become significant in the case of pure  $\beta$  emitters.

The external radiation hazard from most devices producing X-rays whether useful or otherwise, is removed as soon as the machine is switched off. The risk from radioactive materials in the form of sealed or unsealed sources differs since there is no way of preventing emission of radiation. Remember that in the case of heavy particle accelerators or of materials exposed to neutrons, the target and the irradiated material themselves may become radioactive.

### 7.2 Contamination Hazard

Radioactive materials completely sealed in a metal, glass or plastic container constitute an external radiation hazard only but an entirely different state of affairs exists if they are unsealed , when they will almost invariably give rise to a contamination hazard. Here the main risk arises

from materials entering the body by ingestion, inhalation or through intact or broken skin. The amount of radioactive material constituting an appreciable internal contamination hazard is considerably less than that necessary to give a significant external radiation exposure since in this case body tissues are irradiated at extremely close range.

Alpha emitters are a major problem as in general they cause a much greater amount of biological damage per unit of absorbed dose than do  $\beta$  or  $\gamma$  emitters. Strict precautions against external radiation should be taken when handling megabecquerel quantities of  $\gamma$  and/or  $\beta$  emitters. Contamination however may present serious problems at kilobecquerel levels. The following examples may be useful :-

The  $\gamma$  dose rate at 1 cm from 37 MBq (1 mCi) of  $^{60}\text{Co}$  is about  $132 \text{ mSv hr}^{-1}$

The dose rate from 37 MBq (1 mCi) of most  $\beta$  emitters at a distance of 3 mm is about  $30 \text{ Sv hr}^{-1}$

### 7.3 *Annual Limit of Intake (ALI)*

The ALI is the quantity of radionuclide which when taken into the body will lead to a dose commitment of 20 mSv. The ALI depends on the route of exposure as well as the radionuclide e.g. the ALI for inhalation is usually different for ingestion. Factors which determine the ALI include:

- Type and energy of the radiation;
- Physical half life;
- Biological half life;
- Concentration of the radionuclide in a particular organ;
- The chemical nature of the labeled compound.

Examples of ALIs are given in Appendix 3.

## 8. **Control of External Radiation and Contamination Hazards**

The basic principles of external radiation control can be stated simply as:

- **Distance;** Radiation follows the inverse square law, so distance is a powerful and inexpensive method for reducing the dose received.
- **Shielding;** Shielding is the second method which can be applied: as a working principle, it can be assumed that the effectiveness of a shielding material is roughly proportional to its density for a given radiation energy e.g. 5 cm of concrete are approximately equivalent to 1 cm of lead.
- **Time;** Restriction of the working time can also reduce the total dose received and may permit operations even in regions of relatively high dose rate.

Cleanliness and tidiness in working methods are vital for the control of contamination. Impervious and easily cleaned surfaces for work benches, floors and walls are essential, but unless care is taken in working methods they can be virtually useless. The avoidance of ingestion and inhalation of radionuclides is of paramount importance. For this reason eating, drinking and smoking are barred from laboratories.

Protective clothing (e.g. gloves and laboratory coats) should be worn at all times when unsealed sources are handled. Operations liable to cause dust or spray raise particular problems because of the ensuing inhalation risk.

It is clearly vital that contamination of the working area should be kept to an absolute minimum. To ensure this is the case suitable and sufficient monitoring (with the appropriate type of monitor) of surfaces should be performed before and after work with unsealed sources. It should also be noted that contamination at levels which are far below those which constitute a biological hazard can completely invalidate the results of experimental work.

### ***8.1 Methods of Handling Sealed Sources***

A sealed source may be defined as a preparation of radioactive materials in solid, liquid or gas phase in a permanently sealed container such that under normal circumstances no leakage can take place.

There is no contamination hazard from such a source unless leakage occurs. For this reason, the Ionising Radiations Regulations 1999 require that all sealed sources are tested for leakage at least every 24 months.

As an example, a capsule of aluminium or steel containing  $^{60}\text{Co}$  in metallic form is unlikely to suffer damage if it is dropped; a source of this nature may safely be handled in any laboratory provided that relevant precautions are taken against external radiation. The same degree of safety does not apply to a liquid or gaseous material, particularly when sealed in glass. Such sources may be used only in areas of the standard required for handling one hundredth of the quantity of the same material when unsealed.

The relevant requirements regarding X-ray equipment apply to sealed sources. Since the radiation from radioactive materials cannot be switched off as can a X-ray tube, the following precautions should be observed.

When not in use, the source must be placed in a shielded container or a place of storage such that the level of radiation 5 cm from the surface does not exceed  $2.5 \mu\text{Sv hr}^{-1}$ . The container must bear the radiation trefoil symbol and an indication of the contents. Where there is a possibility of leakage of radioactive gas (e.g. from a radium source) air and dust monitoring must be carried out at frequent intervals and smear tests should be made on the surface of the container.

A notice bearing the radiation trefoil symbol together with the word **RADIATION** must be displayed outside the room in which the sealed source is used. In addition, the level of radiation must be specified if this is liable to exceed  $7.5 \mu\text{Sv hr}^{-1}$  at any readily accessible point in the area during normal operations.

### ***8.2 Methods of Handling Unsealed Radioactive Materials***

All work with unsealed radioactive materials should be segregated from other work and, where possible, carried out in a laboratory reserved for this work alone. Where work involves the use of widely different levels of activity, separate rooms are preferred. Counting apparatus should normally be situated in a separate room.

The standard of cleanliness in a laboratory used for radioactive work must be much higher than normal. The untidy and careless worker is a danger not only to themselves but also to others in the laboratory.

Signs bearing the trefoil radiation symbol together with the word **RADIATION** must be displayed on the doors of all laboratories in which radioactive work is carried out.

Eating, drinking and smoking or the application of cosmetics must not take place in the laboratory; no food, drink, cups etc must not be brought into the laboratory.

Pipettes must be syringe or bulb operated and flexible polythene wash bottles are recommended.

Gloves must be worn for all work with unsealed radioactive materials. The surgical technique should always be used when putting on or removing the gloves to avoid contaminating the hands and the inside surfaces of the gloves. Gloves must be disposed of after use.

Protective clothing must be worn at all times in the laboratory and must be reserved for this purpose alone. Due to the risk of contaminating other work, this rule applies even at very low levels of activity. All protective clothing worn in laboratories must be removed before leaving and left in or immediately outside the laboratory; the latter place should then be regarded as an active area.

To avoid the spread of contamination in the event of a breakage or spill, all work should be carried out in double containers over large trays, such trays should be lined with absorbent paper to restrict the spread of liquid.

All reagents, tools, and where possible apparatus used in a radioactive work area should be clearly labeled with radioactive warning tape.

All radioactive preparations must also be marked with details of the chemical compound, radionuclide, activity and date. Gummed labels are undesirable.

These materials should not normally be removed from the radioactive work area. If it is essential, however, to take any equipment out of the active area, then this should be done only after the item has been rigorously monitored and found to be free of contamination.

Adequate shielding and remote handling facilities, if necessary, should be provided; distance is the best method for reducing dose, and the use of simple devices (e.g. for opening stock containers) should be regarded as routine. Shielding of  $\beta$  emitters need not involve more than a sheet of thick Perspex, but shielding for  $\gamma$ -ray emitters should consist of interlocking lead bricks. It is difficult to lay down a level of activity above which shielding is essential since it depends on the material and the type of work, but its use should be considered when handling quantities in excess of 37 MBq (1 mCi). The protection of the eyes is most important, due to the risk of inducing cataracts.

Glass blowing should be avoided in laboratories; where such work is essential, blowing by mouth is not permissible.

All operations involving the production of vapour, spray, dust or radioactive gas whether necessarily or accidentally should be carried out in a good fume cupboard which is clearly labeled for radioactive work. Electrical heating is preferable to gas in laboratories handling radioactive materials. The preferred method of evaporation is from above, by means of an infra-red lamp since this reduces the risk of splashing and spraying.

Local arrangements for radioactive waste are as follows:-

- Liquid waste which is miscible with water should be diluted if necessary and released to designated drains with copious amounts of water to ensure adequate dilution. The activities permitted to be disposed of by drain are given in the Certificate of Authorisation under the Radioactive Substances Act 1993 and **must not** be exceeded.

- Liquid waste which is not miscible with water must **not** be released to drain. This applies in particular to hydrocarbon scintillant fluids/residues. These must be stored in a secure manner pending disposal.
- Solid waste must be deposited in appropriately labeled waste bins.

It is essential that, on leaving the laboratory, every worker should wash their hands thoroughly preferably also gently scrubbing their hands (especially around their nails) with a nail brush. Hands should then be monitored with an appropriate monitor to ensure that no contamination is present.

It is strongly advised that manipulative work with radioactive materials should be carried out only during normal working hours, when full emergency facilities are available. The counting of samples of low activity is excluded from this recommendation. If it is essential to carry out work with radioactive materials after normal working hours, then the School/Unit rules should be adhered to.

## 9. Designation of Work Areas

The Ionising Radiations Regulations 1999 require an employer to designate areas depending on the dose that workers may receive. These designations are as follows

- **Controlled Area**
- **Supervised Area**
- **Non-designated Area**

A 'Controlled Area' is one where special precautions need to be applied to minimise the dose to workers as they may receive a whole body dose of 6 mSv or upward over a year. Examples of such areas are:

- If an employee works in an area with an external dose rate of  $7.5 \mu\text{Sv hr}^{-1}$  or above for 8 hours a day every day, they will receive approximately 6 mSv over the year;
- If workers have an Annual Limit of Intake of about 100 ALI for an inhalable radionuclide or 10 ALI for non-inhalable radionuclide they will require special precautions to avoid receiving a dose of 6 mSv per year.

If an area is designated as a 'Controlled Area', the Ionising Radiations Regulations 1999 require the employer to provide local rules for use of ionising radiations. The University has produced a set of Local Rules for Work With Ionising Radiations which covers work with such radiation in any work area including controlled areas. All 'Controlled Areas' must have suitable demarcation from normal work areas and have appropriate signs on access to warn of the potential high dose rates in the area. The University Radiation Protection Adviser will determine which areas should be designated as a 'Controlled Area'.

Only workers who are designated as 'Classified Workers' can work in Controlled Areas **UNLESS** there is a written 'System of Work' been produced. Only work defined in the System of Work can be performed by non-classified workers in 'Controlled Areas'. The University Radiation Protection Adviser will determine which workers will be designated as 'Classified Workers'.

The University has defined areas to be designated as radiation 'Supervised Area' as one where the dose rate is between  $2.5 \mu\text{Sv hr}^{-1}$  and  $7.5 \mu\text{Sv hr}^{-1}$  or any area where a person may receive a dose of 1 mSv per year. These are areas which are separate from the normal work bench. Access to these areas should be restricted to authorised personnel only though workers do not need to be designated as 'Classified Workers' to work in such areas. The University Radiation Protection Adviser will designate 'Supervised Areas'.

Non-designated areas are those where the dose rate is below  $2.5 \mu\text{Sv hr}^{-1}$  or the annual dose will be less than 1 mSv per year. These areas are not usually segregated from other work areas except that special precautions may need to be taken e.g. use of spill trays and access to a designated radioactive waste drain.

## **10. Procedures for the Removal of Radioactive Contamination**

Unless bench surfaces are kept free of contamination there is a risk that particulate material might enter the body by ingestion following the transfer of material from hand to mouth.

Contamination left on the benches might also subject the hands of workers using the bench to significant levels of external radiation.

Contaminated clothing could, similarly, subject the body to external radiation. If external surfaces of the body are not decontaminated, radionuclides may enter the body by diffusion through the skin. The skin, itself, would also suffer a direct exposure to radiation if contamination was allowed to remain.

Clearly it is important that all spillages whether onto either the skin or the bench surfaces must be quickly removed.

Initially handfuls of paper tissues are used to absorb and wipe up any spilled radionuclides and to swab gross contamination from skin surfaces.

### **10.1 Simple Case of Contamination on Hands**

PVC gloves are a good substitute for rubber gloves when working with aqueous solutions, but suffer rapid damage from some solvents e.g. acetone. After removal of gloves, the hands should be monitored.

Usually washing with soap and water or other detergent and water will remove the contamination. The hands must be dried before monitoring or  $\alpha$  emitting radionuclides and some weak  $\beta$  emitters will suffer self-absorption in the moisture film on the skin.

### **10.2 Persistent Hand Contamination**

Get someone to help you and while they monitor try the following procedures:-

- If lipid (oil, fat, grease) is involved, clean hands using a mixture of EDTA and 'Swarfega'. The hands must be dry before using this mixture.
- Using soap and warm water and a soft brush, brush hands for several minutes, rinse, dry and remonitor. Try soap, water, titanium dioxide paste as an alternative to brushing.
- As a last resort (which is often necessary with  $^{32}\text{P}$ ) attempt to gently remove the outer dead cell layers of the skin. Immerse the hand in saturated potassium permanganate

solution. Rinse with water and wash with 5% aqueous solution of sodium metabisulfite. **NEVER** continue these procedures to the extent of damaging the skin. Seek advice from the School/Unit Radiation Protection Supervisor (RPS) or the University Radiation Protection Advisor (URPA).

### 10.3 *Contamination of the Eyes*

Irrigate with tap water or using 500 ml bottles of sterile saline solution which may be available in first aid boxes (check use-by date). Seek medical advice as soon as practicable.

### 10.4 *Contamination of Wounds*

If the wound is bleeding seriously, then all efforts should be dedicated to stopping the bleeding.

Usually small cuts are caused by broken glassware. If the glass is contaminated some radioactivity may enter the wound. It is therefore important that help is obtained and that the cut is washed in running water in an attempt to remove the radioactivity from the wound. It is advisable to monitor the wound and the object which caused the wound. Contamination found on the object will help in assessing the extent of the contamination.

### 10.5 *Contamination of Clothing*

Get help, carefully remove contaminated clothing and place in large polythene bag. Short lived radionuclides will decay allowing the clothes to be sent for normal laundering. Clothing contaminated with long lived radionuclides should either be disposed of as radioactive waste or may be cleaned by careful detergent washing in the laboratory.

### 10.6 *Decontamination of Surfaces*

The following procedures are suggested, but when specialised problems are encountered, it is important to get the advice of the University Radiation Protection Adviser.

Materials to be Removed	Method
Water soluble substances	Water and damp tissues usually work
Lipids (oil, fat, grease etc.)	Organic solvents ( <b>Do NOT use flammables</b> )
Ions (e.g. K <sup>+</sup> )	Water plus relevant carrier (e.g. KCl for K <sup>+</sup> ions)
Carbonates	Dilute HCl

**NOTE: During any decontamination procedure ensure that the monitoring equipment does not become contaminated by careless handling.**

## 11. Monitoring

The success of the control of hazards from radioactive materials or other sources of ionising radiations is assessed by monitoring. Several different types of instruments are required as no single instrument is suitable for measuring all types of radiation. It is customary in some cases to use more than one instrument to measure levels of radiation. There are, in addition many occasions when the reading obtained on a given instrument may be misleading.

### 11.1 *Personal Monitoring*

The purpose of personal monitoring is to assess the dose received by the individual. The main concern is with the 'Whole-Body' dose from external radiation but doses to particular areas such as fingers or eyes may be important. The doses to internal organs from radioactive materials which have entered the body are difficult to assess and special methods are necessary.

Whole body external doses are measured by one of three main types, Optical Luminescence Dosimetry (OLD), ThermoLuminescence Dosimetry (TLD) and film badges (see Section 5.4). These badges should be worn on the upper part of the trunk, generally on the lapel. Although it is often assumed that it records the whole body dose, this is true only if the person is in a uniform radiation field which is rarely the case. Work close to sources of small dimensions or with devices producing narrow beams (e.g. X-ray generators) involves the exposure to very non-uniform radiation fields. In these cases there is no simple method of obtaining a better estimate of the whole body dose, but it is important to measure the intense local doses.

### **11.2      *Radiation Monitoring***

The purpose of radiation monitoring is to find the areas in which appreciable dose rates exist so that appropriate measures, such as the provision for shielding may be taken to reduce the dose to personnel. It is however no substitute for personal monitoring.

### **11.3      *Monitoring for Surface Contamination***

Regular contamination monitoring is required only in areas where unsealed radioactive materials are handled. Contamination of surfaces in research and teaching laboratories should not exceed  $37 \text{ kBq m}^{-2}$  ( $10^{-4} \text{ } \mu\text{Ci cm}^{-2}$ ).

Sealed sources, however, must be leak tested at least every two years (preferably every year) or if it is suspected the source may have been damaged (e.g. dropped etc) to comply with the Ionising Radiations Regulations 1999.

The monitors used should be carefully selected to ensure that it will be able to detect the type of radiation being emitted.

## **12.      *Guidance Notes for Workers Using Ionising Radiations***

### **12.1      *Responsibilities of the Individual Workers***

The experimenter has a legal responsibility not to put himself or others at risk by his acts or omissions. The experimenter must be certain that they:-

- He/she is familiar with the main physical properties and biological effects of the radionuclides or other sources of ionising radiations they are using;
- He /she knows the main chemical and physical properties of any radioactive chemical they are using;
- Has taken all necessary precautions to reduce the radiation and fire hazards to a minimum;
- Has available appropriate monitoring equipment which he/she knows how to use and is appropriate for the type of radiation emitted
- Knows what to do in the event of an accident;
- Is familiar with the University's Local Rules for Work with Ionising Radiations and other relevant Codes of Practice.

The University has produced a set of Local Rules for work with Ionising Radiations and all workers should be aware of the contents of this document (copies can be viewed on the Environmental Health and Safety Services website at URL Address:

<http://www.st-andrews.ac.uk/services/safety/webpages/radiation/contents.html>

An outline of the Local Rules requirements for work with ionising radiations that workers and Principal Investigators should comply with is given in Appendices 5 and 6.

The Local Rules require in particular that each worker:

- Applies for registration as a radiation worker;
- Undergoes appropriate training in radiation safety unless the University Radiation Protection Adviser on behalf of the Radiations Hazards Sub-committee is satisfied that he has adequate experience;
- Wears any personal monitoring devices stipulated by the University Radiation Protection Adviser on behalf of the Radiations Hazards Sub-committee and carries out routine environmental monitoring as requested;
- Submits a risk assessment for the proposed work with ionising radiations or modification of a current project on the appropriate form (see Appendices 7, 8 and 9) and returns it to the School/Unit Radiation Protection Supervisor;
- Orders radioactive materials only according to procedures laid down by the School/Unit Radiation Protection Supervisor;
- Informs the School/Unit Radiation Protection Supervisor immediately of the loss of any radioactive material;
- Ensures the School / Unit has appropriate Certificate of Registration and, if necessary, Certificate of Authorisation for the disposal of radioactive wastes;
- Maintains records of waste disposal for the information of the School/Unit Radiation Protection Supervisor to ensure compliance with the Certificate of Authorisation;
- Notifies the School/Unit Radiation Protection Supervisor of the intention to transport radioactive material outwith the School/Unit and adheres to the transport regulations laid down by the University Radiation Protection Adviser (see University's 'Local Rules for Work with Ionising Radiations');
- In the case of academic staff members, ensures that safe working procedures are followed by any undergraduate research student or technician under their supervision;
- Report any accident to the School/Unit Radiation Protection Supervisor.

### 13. Working Procedures.

How do you tackle your first radioactive project without undue hazard and without contravening the Statutory and Local Rules?

Work with unsealed radioactive sources is managed through the computer programme entitled RadProt. his programme can be accessed at the following website:

<https://portal.st-andrews.ac.uk/radprot/open/>

There are two databases - Live programme which stores legally required data under the Radioactive Substances Act 1993 and a Training programme which is the same as the Live programme except that the data is not the University's legally required data. It is recommended that when first using this programme you practice on it using the training programme first.

Access to the RadProt **Live** programme is by your e-mail Username and Password. Access to the RadProt **Training** programme is by the following:

Username: user

Password: user

A step guide which may help in the requirements for using ionising radiations is given in Appendix 5 and 6.

#### 13.1 Project Design

Discuss the project with your supervisor, decide on the radionuclides to be used and calculate the quantities required to produce a reasonable count. Work out the techniques to be used and see if any awkward problems (e.g. vapours, aerosols, high radiation fields etc.) are likely to be encountered. Finally consider how you are going to dispose of your waste. If this cannot be done safely and legally, you will not be allowed to start.

If you are using unsealed sources then you should open the radProt Live programme and complete the Assessment part of this programme. You should then save this and it will be sent automatically to the correct people for approval.

If you using sealed radioactive sources or X-rays you should submit the risk assessment of your project on the appropriate forms given in Appendices 7 or 8 to your School/Unit Radiation Protection Supervisor. No new project involving the use of ionising radiation may commence until the project has been approved by the University Radiation Protection Adviser.

#### 13.2 Registration of Workers

##### Undergraduates

Undergraduates will not normally be designated as 'Classified Workers' and all undergraduate work with ionising radiations comes into a special category of 'Approved Scheme of Work'.

Guidance on the levels of exposure and activities with unsealed sources by undergraduates is given by ICRP 60 and from the Department of Education and Skills / Scottish Executive. A figure of 500  $\mu\text{Sv}$  per year may be taken as a guide to the maximum annual exposure that an undergraduate may receive from external sources as a result of experiments with ionising radiations. In work with unsealed sources the maximum permitted activity per experiment should not exceed the values reported in Appendix 9.

Where more than one radionuclide is used the activities should be reduced proportionally.

In some cases unsealed sources will need to be shielded to ensure that the undergraduate does not receive a dose of greater than 500  $\mu\text{Sv}$  per year.

In the case of labeled compounds of possibly higher toxicity e.g.  $^3\text{H}$ -Thymidine, lower activity limits are appropriate.

If undergraduates intend to work with radioactivity in final year projects, then they must register on the RadProt Programme

Undergraduates are allowed to use X-ray generators or particle accelerators but only under direct visual supervision of an appropriately qualified member of staff. A notice to this effect must be posted beside each X-ray machine.

### **13.3 Radiation Workers**

Any person other than an undergraduate intending to begin work involving the use of ionising radiations must apply to the University Radiation Protection Adviser through the School/Unit Radiation Protection Supervisor to be approved as a Registered Radiation Worker. For work with unsealed sources, then they must register on the Radprot programme. For work with sealed sources or X-rays then they must complete the form in Appendix 8 and hand it to their Departmental Radiation Protection Supervisor.

Radiation workers who may be designated as a 'Classified Worker' will be required to be medically examined by the University Occupational Health Physician before starting radiation work and at intervals thereafter. A final examination may be required when a 'Classified Worker' leaves the University. The results of such medical examinations are confidential and are communicated to the University Radiation Protection Adviser as 'Satisfactory' or 'Unsatisfactory'.

Registered workers must, before starting work, sign a form to the effect that they will comply with the current edition of the University's 'Local Rules for Work with Ionising Radiations'. Workers must also comply with the School/Unit local rules for work with ionising radiations.

The University Radiation Protection Adviser on behalf of the Radiations Hazards Sub-committee will decide whether or not a worker is to be designated as a 'Classified Worker' and the type of monitoring required. Classified workers are permitted to receive up to the annual dose equivalent level of 20 mSv per year. Designation of workers as 'Classified' is not required if the worker receives a dose of  $3/10^{\text{th}}$  or less of the annual limit of 20 mSv per year.

Non-Classified Workers can only work in 'Controlled Areas' where there is a written Approved Scheme of Work.

Certain work e.g. that involving electron microscopes or gas chromatography apparatus which radioactive sources, can be carried out by non-registered workers after a radiation survey of the apparatus.

### **13.4 Purchase and Storage of Isotopes**

Only a person authorised by their Head of School/Unit (e.g. the School/Unit Radiation protection Supervisor) is permitted to order radiochemicals. This is done by the DRPS on the RadProt programme. No order should be placed which may exceed the limits set by the SEPA Certificates of Registration or Authorization.

Arrangements must be made with the supplier (or delivery company) that the radionuclide(s) are received by a member of staff and locked away in a designated store as soon as practicable. All unsealed sources that arrive must be receipted by the DRPS and this will allow aliquots to be removed from the source by workers. If it is not receipted then the Radprot programme will not allow aliquots to be removed.

**NOTE: Sources must never be delivered and left unattended as this is a contravention of the requirements of the SEPA Certificate of Registration and may result in prosecution.**

It is vital that the School/Unit produce specific written procedures for the acceptance of radionuclide sources. These procedures should include:

- Check that appropriate documentation has arrived with the source;
- Check the source is that which was ordered;
- The amount present is that which was ordered;
- There is an appropriate label on the source identifying the radionuclide and the activity of the source;
- The source is not leaking from its container;
- The source is given an appropriate identification mark as soon as possible;
- The 'Sealed Radioisotope Source Record' form for the isotope is completed;
- The source is then placed in a safe place under lock and key;

When a source is received, the accompanying documents should be examined and the source unpacked as soon as possible to ensure that it is as ordered.

Every time any radioactive material is used, the details must be entered on the Source Record on the RadProt system.

### **13.5      *Dispensing***

Dispensing from stock containers must not be undertaken by undergraduates or supervised workers. The latter can however dispense if procedures and limits are set in a specific Approved Scheme of Work.

Since the specific activity of stocks are very high, special precautions must be taken when dispensing from open sources. Normally, a special area equipped with fume cupboards, lead shielding and drip trays is set aside for the purpose. Dispense in this area only. Plan your moves beforehand (e.g. switch the monitor on before starting, arrange for rinsing and disposal of syringes and pipettes). Handle source with tongs, do not hold in the hand.

### **13.6      *Experimental Procedures***

After dilution, specific activities are normally much lower but bear in mind that the  $\gamma$  field from a large volume of dilute solution can still be quite high. Use shielding and distance as appropriate.

The other danger is contamination, especially of other workers. For this reason, all sources (i.e. anything which is radioactive) must be labelled to show nature and amount of activity and put in

a safe place before being left unattended. Technicians and cleaners should not be regarded as expendable.

### **13.7 Waste Disposal**

Once radioactive material has been 'signed out' and dispensed, it remains your responsibility until it has been safely and legally disposed of and the disposal recorded on the Radprot system.

Dispose of waste by the proper routes and don't mix incompatibles. Follow University arrangements as given in Section 8.2.

As far as water soluble solutions are concerned, you must record all disposals to drain on the Radprot programme. If you do not record this disposal, the system will believe the radioactivity is still in use and could possibly mean that the system will believe we are at our Limit set in the Certificate of Authorisation and thus stop all further work. Ensure that you are not going to exceed the Authorised total and enter the activity disposed of.

Do not produce, without authorisation, non-volatile active derivatives in organic solvents as they are difficult and expensive to dispose of.

In the case of solid waste there is a legal requirement setting of 4 MBq as the maximum activity permitted per plastic or multi-layer sack.

### **13.8 Spills**

In the event of a spill, keep your head and avoid the spread of contamination.

Very small spills can be dealt with by absorbing onto filter paper or tissue. Disposal of heavily contaminated tissues must be done under the supervision of the University radiation Protection Adviser or the School/Unit Radiation Protection Supervisor.

In the case of larger spills, possibly involving contamination of a person, call for assistance without leaving the laboratory. **Remember that the main objective is the avoidance of unnecessary spreading of contamination.**

### **13.9 Reporting Procedures**

Any accident or Near Miss must be reported **IMMEDIATELY** possibly via the School/Unit Radiation Protection Supervisor to the University Radiation Protection Adviser.

<b>Name</b>	<b>Office Tel. Ext</b>	<b>Home Telephone No.</b>
Dr. P.W. Szawlowski (Deputy Director, EHSS)	2753 / 2750	01333 450014

## **14. Expectant and Breastfeeding Mothers**

The Ionising Radiation Regulations 1999 require an employer to perform a specific risk assessment on expectant mothers or breastfeeding mothers. This is to ensure that the mother and foetus/young child are not exposed to significant doses of radiation during this sensitive period.

To ensure that such a risk assessment can be performed it is recommended that expectant mothers notify their Head of School/Unit as soon as it has been confirmed they are pregnant. This will allow the risk assessment to be performed and appropriate control measures to be implemented to minimise the risks to mother and foetus/child.

There are specific legal effective dose equivalent whole body limits for for pregnant women and women of child bearing age (see Appendix 2).

Further information on this matter can be obtained in Section 9 of the University's 'Local Rules for Work with Ionising Radiations'.

**NOTE:** It is not a legal requirement that expectant mothers must tell their Head of School/Unit and mothers can choose to keep this information private.

## APPENDIX 1

### SI Units in Radiation Protection

	SI Unit	Old Unit
Radiation Dose	Gray (Gy) = $1 \text{ J kg}^{-1}$	Rad = $100 \text{ ergs g}^{-1}$ ( $10^{-2} \text{ J kg}^{-1}$ )
Radiation Dose Equivalent	Sievert (Sv) = Gray x Quality Factor	Rem = Rad x Quality Factor
Radioactivity	Becquerel (Bq) = 1 disintegration per second	Curie (Ci) = $3.7 \times 10^{10}$ disintegrations per second

Thus:

$$\begin{aligned} 1 \text{ Gray} &= 100 \text{ Rads} \\ 1 \text{ Sievert} &= 100 \text{ Rems} \\ 1 \text{ Becquerel} &= 2.7 \times 10^{-11} \text{ Curies} \end{aligned}$$

The SI radiation dose unit is large and in radiation protection radiation doses are expressed in milli or micro units. For example,

Annual Exposure limit is 20 mSv

Dose rates are expressed in  $\mu\text{Sv}$  per hour

The Becquerel is such a small unit that it requires the use of Kilo (k), Mega (M) or even Giga (G) prefixes. For example

$$\begin{aligned} 1 \text{ MBq} &= 27 \mu\text{Curies} \\ 37 \text{ kBq} &= 1 \mu\text{Ci} \\ 100 \text{ MBq} &= 2.7 \text{ mCi} \\ 37 \text{ MBq} &= 1 \text{ mCi} \end{aligned}$$

In Universities radioactive materials are generally ordered in quantities of 10s or 100s of MBq, dispensed in fume cupboards at these levels and used on the bench in 10s of kBq activities.

## APPENDIX 2

### Dose Limits

The dose quantities given in the table below are the sum of internal and external exposure to ionising radiation in any calendar year and are the summary of Schedule 4 of the Ionising Radiations Regulations 1999.

Part of the body	Dose to Employees 18 Years or Over	Dose to Trainees Under 18 Years	Dose to Any Other Person
Whole Body	20 mSV / year	6 mSv / year	1 mSv / year
Individual Organs or Tissues	500 mSV / year	150 mSv / year	50 mSv / year
Lens of the Eye	150 mSv / year	50 mSv / year	15 mSv / year

### **Dose Limits for the Abdomen of Women of Reproductive Capacity**

- In any consecutive three month interval 13 mSv / 3 months
- In the case of a woman who is pregnant during the declared term of pregnancy 1 mSv / Term of Pregnancy

### **Annual Dose Equivalent Limit for Undergraduate Students**

The dose limits for undergraduates are the same as 'Other Persons, that is:

- Effective dose equivalent to whole body of 1 mSv / year
- Dose equivalent to a single organ 50 mSv / year
- Dose equivalent to the lens of the eye 15 mSv / year

**NOTE:** *The dose equivalents given in the tables above do NOT include doses from natural background radiation or medical procedures.*

## APPENDIX 3

### Annual Limits of Intake (ALI)

Annual Limits of Intake (ALIs) are allocated for each radionuclide and each has two ALI, one for ingestion and one for inhalation. ALIs are defined in units of Bq per year. Their values are such that intake of one ALI will result in a committed dose equivalent of one annual exposure limit.

ALIs for radionuclides used in the University are:

#### ALI (MBq / Year)

Radionuclide	Ingestion	Inhalation
H-3	1111	1111
C-14 (CO <sub>2</sub> )	-	3077
C-14 (Organics)	35	
Na-22	6.2	10
Na-24	47	38
P-32	8.3	18
S-35	26	166
Cl-36	22	41
K-42	47	100
Ca-45	26	9
Sc-46	13	4.2
Cr-51	526	667
Fe-55	61	22
Ni-63	133	39
Cu-64	167	294
Zn-65	5	7
Se-75	8	14
Rb-86	7	15
Mo-99	27	56
Tc-99	26	50
I-125	1.3	2.7
W-185	45	91
Hg-203 (Organic)	11	27

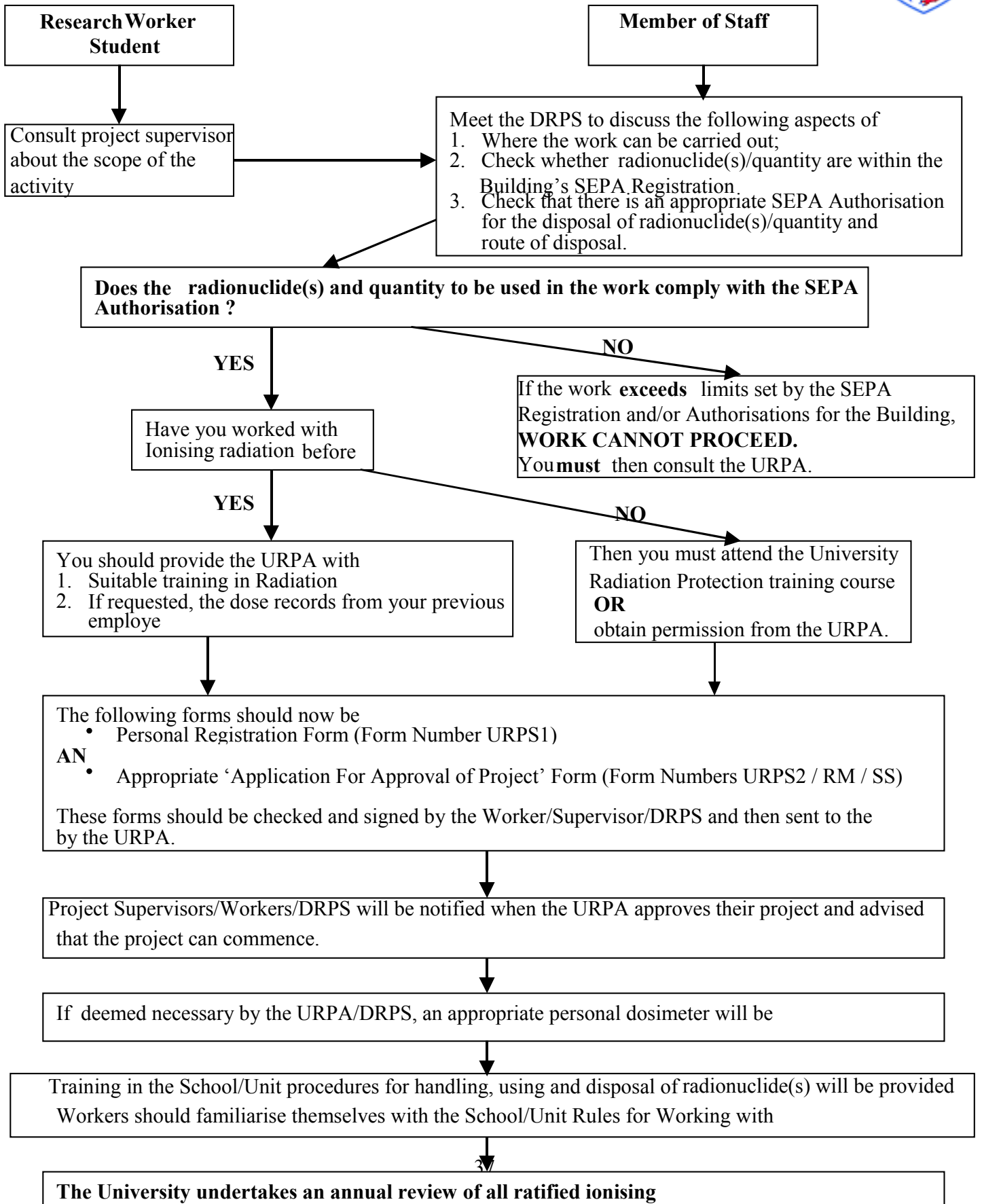
The ALI can depend on the labeled compound. For example the ALI for H-3 refers to tritiated water. The ALI for tritiated thymidine is not definitely laid down but is at least 10 times smaller than that for tritiated water because of the different way the thymidine is metabolised and because of its longer biological half life. Similar variations occur among the organic compounds referred to under 14-C.

APPENDIX 4

**Designation of Work Areas**

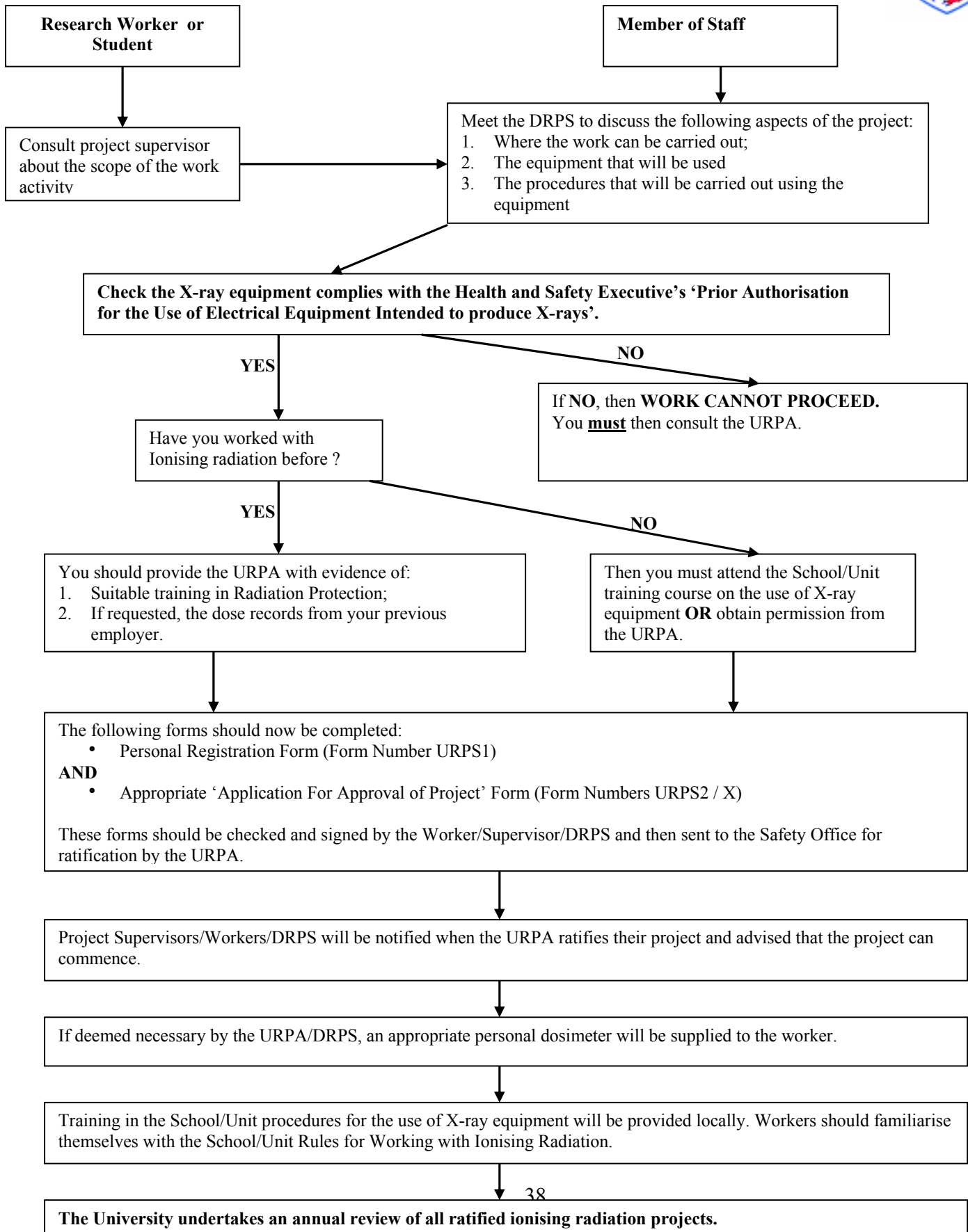
Area Designation	Worker Designation	Area Classification In Relation to External / Internal Radiation Hazard
<p><b>CONTROLLED</b></p> <p>e.g. Radioisotope room, dispensing area, fume cupboard, fridge etc.</p>	<p><b>CLASSIFIED WORKER</b></p> <p>Classified workers, workers under an Approved Scheme of Work etc.</p> <p><b>No Undergraduates</b></p>	<p><b>Dose Rate:</b></p> <p>&gt; <b>7.5 <math>\mu\text{Sv hr}^{-1}</math></b> Instantaneous or liable to receive an effective dose of 6 mSv or more over a year.</p> <p><b>Usage Quantity at Any One Time</b></p> <p>Fume Cupboard - &lt; <b>100 ALI</b> Open Bench - &lt; <b>10 ALI</b></p> <p><b>Storage Quantity</b></p> <p>See SEPA Registration Certificate</p>
<p><b>SUPERVISED</b></p> <p>e.g. Research laboratory, Fume Cupboard, Fridge etc.</p>	<p><b>All radiation workers</b></p> <p><b>Undergraduates 18 years and over.</b></p>	<p><b>Dose Rate:</b></p> <p><b>2.5 - 7.5 <math>\mu\text{Sv hr}^{-1}</math></b> Instantaneous or likely to receive an effective dose of greater than 1 mSv in a year (but less than 6 mSv).</p> <p><b>Usage Quantity at Any One Time</b></p> <p>Open Bench (See table in Appendix 9)</p> <p><b>Storage Quantity</b></p> <p>Upper limits are given in the table in Appendix 9.</p>
<p><b>GENERAL LABORATORY AREA</b></p> <p>e.g. Teaching laboratory</p>	<p><b>All radiation workers, non-radiation workers, all undergraduates.</b></p>	<p><b>Dose Rate:</b></p> <p>&lt; <b>2.5 <math>\mu\text{Sv hr}^{-1}</math></b> Instantaneous or is likely to receive an effective dose of less than 1 mSv in a year.</p> <p><b>Usage Quantity at Any One Time</b></p> <p>Open bench (See table in Appendix 9)</p> <p><b>Storage Quantity</b></p> <p>No storage is permitted.</p>

**Guidelines For Commencing Work With Ionising Radiation**





## Guidelines For Commencing Work With X-ray Generators





### Application for Approval of Project Involving the Use of Sealed Sources

**NOTE:** This document serves as a risk assessment for radiation hazards only. All non-radiological with the project should be assessed on the

School / Unit	
Title Of Project	
Justification for the Use of Ionising Radiation	

Project Number	
Date	
Name Of Supervisor	
Name of DRPS	

#### Declaration to be Signed by the Workers and Countersigned

I/We have received relevant training in the safe handling and use of radioactive materials.  
 I/We shall follow and comply strictly with the current edition of the University of St Andrews Local Rules and School/Unit Codes  
 I/We undertake to follow and comply strictly with Certificates issued by the Scottish Environment Protection Agency (SEPA) so far as is relevant to my /our work

TLD	Name of Worker(s)	Signature(s)
<input type="checkbox"/> YES <input type="checkbox"/> NO		
<input type="checkbox"/> YES <input type="checkbox"/> NO		
<input type="checkbox"/> YES <input type="checkbox"/> NO		
<input type="checkbox"/> YES <input type="checkbox"/> NO		
<input type="checkbox"/> YES <input type="checkbox"/> NO		
<input type="checkbox"/> YES <input type="checkbox"/> NO		
<input type="checkbox"/> YES <input type="checkbox"/> NO		

Experimental Procedure	Radio-Nuclide	Activity of Source ( Bq)	Frequency of Procedure	Location of Work ( Room Number)	Designation of Work Area*	Location of Source when NOT in use	Disposal Route when Source is 'Spent' and Estimated Cost (If Known).

\*\* = There are four designations of work area: General (1) ; Supervised (2); : Supervised Area with Additional Control Measures (3); Controlled Area (4). Identify the work area using (i) The maximum permitted activity Table (see Appendix 20 - University Local Rules) and Area Classification Table (see Appendix 19 - University Local Rules).

Person(s) other than named workers who may be at risk \_\_\_\_\_

Additional Control Measures (if any) \_\_\_\_\_

Signature of \_\_\_\_\_ Date.....

I hereby approve this (Signature of School/Unit \_\_\_\_\_ Date.....

I hereby ratify this (Signature of \_\_\_\_\_ Date.....



## Application for Approval of Project Involving the Use of X-Ray Generating and Ancillary Equipment

**NOTE:** This document serves as a risk assessment for radiation hazards only. All non-radiological hazards associated with the project should be assessed on the appropriate form.

<b>School / Unit</b>	
<b>Title Of Project</b>	
<b>Justification for the Use of Ionising Radiation</b>	

<b>Project Number</b>	
<b>Date</b>	
<b>Name Of Supervisor</b>	
<b>Name of DRPS</b>	

**Declaration to be Signed by the Worker(s) and Countersigned**

I/We have received relevant training in the use of the generating equipment.

I/We shall follow and comply strictly with the current edition of the University of St Andrews Local Rules and School/Unit Codes.

TLD	Name of Worker(s)	Signature(s)
<input type="checkbox"/> YES <input type="checkbox"/> NO		
<input type="checkbox"/> YES <input type="checkbox"/> NO		
<input type="checkbox"/> YES <input type="checkbox"/> NO		
<input type="checkbox"/> YES <input type="checkbox"/> NO		
<input type="checkbox"/> YES <input type="checkbox"/> NO		
<input type="checkbox"/> YES <input type="checkbox"/> NO		
<input type="checkbox"/> YES <input type="checkbox"/> NO		

Person(s) other than named workers who may be at risk

Experimental Procedure

**Description of Equipment:**

Model Number .....	Serial Number .....	Maximum Operating Voltage (kV) .....	Maximum Operating Current (mA) .....
--------------------	---------------------	--------------------------------------	--------------------------------------

**Control Measures**

Room Number

Designation of Work Area  There are four designations of work area: General Laboratory (1); Supervised Area (2); Supervised Area with Additional Control Measures (3); Controlled Area (4). Identify the work area using the Area Classification table (see Appendix 19 - University Local Rules).

- (i) Does the X-ray equipment comply with the conditions set out in HSE Document 'Prior Authorisation for the Use of Electrical Equipment Intended to Produce X-Rays'? (If **NO**, then contact the URPA as a **matter of urgency**). Yes  No
- (ii) A written 'Safe System of Work' is required for alignment and any other activities which may give rise to foreseeable radiation risks been produced. Has this been produced? (If **NO**, then contact the URPA). Yes  No
- (iii) Have relevant workers had appropriate training for (ii)? (If **NO**, then contact the URPA). Yes  No

Additional Control Measures (if any) \_\_\_\_\_

Signature of Supervisor \_\_\_\_\_ Date.....

I hereby approve this application  
(Signature of School/Unit DRPS) \_\_\_\_\_ Date.....

I hereby ratify this application  
(Signature of URPA) \_\_\_\_\_ Date.....

Appendix 9

**The Maximum Permitted Activity of Unsealed Radionuclides which may be Stored/Used at One Time.**

**NOTE:** All radioactivity must be stored in a locked cabinet or room.

The activity of a radionuclide given under STORAGE is the cumulative total and must never be exceeded. The maximum activity of a radionuclide stored in an individual vial must never exceed the activity for that nuclide given under USAGE.

Where more than one radionuclide is involved, the Quantity Ratio must be used. This ratio is derived from the equation

$$\frac{\text{Sum of } Q_p}{Q_{lim}}$$

$Q_p$  = Quantity of radionuclide present

$Q_{lim}$  = Quantity of the radionuclide specified in this table

**NOTE:** The quantity ratio must **NOT** exceed 1

Storage		Usage	
Radionuclide	Supervised Area (MBq)	Supervised Area (MBq)	Teaching Laboratory (MBq)
<b>3H</b>	1000	100	20
<b>14C</b>	500	50	10
<b>22Na</b>	50	5	1
<b>24Na</b>	50	5	1
<b>32P</b>	50	5	1
<b>33P</b>	500	50	10
<b>35S</b>	500	50	10
<b>36Cl</b>	50	5	1
<b>45Ca</b>	50	5	1
<b>51Cr</b>	500	50	10
<b>59Fe</b>	50	5	1
<b>63Ni</b>	50	5	1
<b>65Zn</b>	50	5	1
<b>86Rb</b>	50	5	1
<b>125I</b>	10	5	0.1

## APPENDIX 10

### Calculation of Dose Rates

#### *Gamma ( $\gamma$ ) Dose Rates*

The dose rate from a  $\gamma$  emitter can be calculated using the equation:

$$\frac{1}{7} \cdot \frac{AEF}{d^2} \quad \mu\text{Sv hr}^{-1}$$

Where    A = The activity of the source in MBq  
          E = Is the  $\gamma$  energy in MeV  
          F = Is the fraction of disintegrations in which the  $\gamma$  of energy E is emitted  
          d = The distance from the source in metres

The equation applies to a 'Point Source' which is one whose dimensions are small compared to the distance d, say 1/10 of d. The equation assumes no attenuation of the  $\gamma$  radiation, the decrease in dose rate with distance falling only for geometric reasons and following the inverse square law ( $1/d^2$ ).

For example the unshielded  $\gamma$  dose rate at 0.1 metres from a 50 MBq Na-22 source in a vial of diameter 1.5 cm could be reasonably represented by a point source formula. The  $\gamma$  radiations given off by Na-22 are:

- 1  $\gamma$  = 1.28 MeV in 100% of disintegrations (F = 1.0)
- 2  $\gamma$  = each of 0.51 MeV in 89% of the disintegrations where a positron is emitted and produces a  $\gamma$  via annihilation radiations (F = 0.89)

$$\frac{1}{7} \frac{AEF}{d^2} = \frac{1}{7} \frac{(50 \times 1.28 \times 1.0)}{(0.1)^2} + \frac{2}{7} \frac{(50 \times 0.51 \times 0.89)}{(0.1)^2} = 1600 \mu\text{Sv hr}^{-1}$$

The inverse square law can be used directly to calculate the dose rate at other distances; for example at 1 metre the unshielded  $\gamma$  dose rate is 16  $\mu\text{Sv hr}^{-1}$ .

In 89% of its disintegrations Na-22 emits a positron and in the remaining 11 % it decays by electron capture. Both positrons and the X-rays produced by electron capture are potential contributors to the dose rate but it is easier to reduce both of these by shielding.

The electron capture X-ray dose rates can be estimated using the above formula if the X-ray energies and corresponding F values are available. An idea of the  $\beta^-$  and  $\beta^+$  dose rates can be obtained from the formula given below.

#### *Beta ( $\beta$ ) Dose Rates*

The approximate  $\beta$  dose rate at 0.1 metres from a point source is given by the following equation:

$$1000 \cdot A = \text{Dose Rate } (\mu\text{Sv hr}^{-1}) \text{ at 0.1 metres}$$

Where A = Activity in MBq

This assumes no absorption of the  $\beta$  's but in practice this will be complete and appreciable, depending on the  $\beta$  energy. Glassware 1 mm thick will completely absorb  $\beta$  particles of energy up to about 0.5 MeV.

A feel for the  $\beta$  doses which might be involved can be obtained from considering the dose rate to the hands from handling 50 MBq of  $^{32}\text{P}$ .

$^{32}\text{P}$  is a high energy  $\beta$  emitter of  $E_{\text{MAX}}$  1.7 MeV. The dose rate at 0.1 metres is :

$$1000 \cdot 50 = 50\,000 \mu\text{Sv hr}^{-1} \text{ (assuming no absorption).}$$

If the  $^{32}\text{P}$  is in a 1mm thick glass vessel approximately 0.7 of the  $\beta$  s will be absorbed but any subsequent absorption in 0.1 metre of air will be negligible. The dose at 0.1 metres will therefore be approximately:

$$0.3 \times 50\,000 = 15\,000 \mu\text{Sv hr}^{-1} = 15 \text{ mSv hr}^{-1}.$$

If the container was handled with tongs and the average distance from the hands was 0.1 metres and if the operation took 5 minutes, the dose to the hands would be:

$$15 \times (5/60) = 1.25 \text{ mSv}$$

and if the operation was carried out once a day for 200 working days per year, the annual dose to the hands would be

$$200 \times 1.25 = 250 \text{ mSv}$$

This can be compared with the annual dose limit for hands which is 500 mSv per year.

In practice it is easy to decrease the  $\beta$  dose markedly by using appropriate shapes of Perspex shielding.

Bremsstrahlung radiation could contribute to the exposure to  $\beta$  emitters of  $E_{\text{MAX}}$  greater than about 1 MeV. It is more difficult to calculate dose rates from Bremsstrahlung radiation but they are likely to be significant only for  $\beta$  sources of activity greater than those normally used in Universities.

The sensitivity of Optically Stimulated Luminescence dosimeters issued at this University is about 0.01 mSv.

APPENDIX 11

Properties of Some Commonly Used Radionuclides

Radionuclide	Half Life	Type of Radiation	MeV and % of Disintegrations		Range ( $\beta^-$ or $\beta^+$ ) ( $\text{mg cm}^{-2}$ )	Approx $\gamma$ Half Value Thickness in Lead (cm)
H-3	12.3 yrs	$\beta^-$	0.018	100%	0.5	-----
C-14	5730 yrs	$\beta^-$	0.156	100%	30	-----
Na-22	2.6 yrs	$\beta^+$ ( $\beta^+$ EC $\gamma$ $\gamma$	0.54 1.83 X-rays 2 $\gamma$ of 0.51 1.28	89% 0.06% 11% 89% 89%	200 - - - -	----- ----- See Notes 0.4 1.0
Na-24	15.0 hrs	$\beta^-$ $\gamma$ $\gamma$	1.39 1.37 2.75	100% 100% 100%	600 - -	----- 1.2 1.6
P-32	14.2 days	$\beta^-$	1.71	100%	800	-----
S-35	87 days	$\beta^-$	0.167	100%	33	-----
Cl-36	$3 \times 10^5$ yrs	$\beta^-$ EC	0.714 X-rays	98.3% 1.7%	270 -	----- See Notes
K-42	12.45 hrs	$\beta^-$ $\beta^-$ $\gamma$ $\gamma$	2.0 3.6 0.32 1.52	18% 82% Very low 18%	900 1800 - -	----- ----- 0.2 1.3
Ca-45	165 days	$\beta^-$	0.25	100%	60	-----
Sc-46	84 days	$\beta^-$ ( $\beta^-$ $\gamma$ $\gamma$	0.36 1.48 0.89 1.12	100% 0.004% 100% 100%		
Cr-51	27.8 days	EC $\gamma$	X-rays 0.32	100% 9%	- -	See Notes 0.2
Ni-63	125 years	$\beta^-$	0.067	100%	1	-----
Rb-86	18.7 days	$\beta^-$ $\beta^-$ $\gamma$	0.68 1.77 1.08	8.5% 91.5% 8.5%	250 800 -	----- ----- 1.0
I-125	60 days	EC $\gamma$	X-rays 0.035	100% 7%	- -	See Notes -

NOTES:

- The range in cm in a given material is obtained by dividing the range in  $\text{mg cm}^{-2}$  by the density of the material in  $\text{mg cm}^{-3}$ .  
Density of :      *Tissue is approx*       $1000 \text{ mg cm}^{-3}$   
                         *Glassware is approx.*       $2000 \text{ mg cm}^{-3}$   
                         *Perspex is approx.*       $1000 \text{ mg cm}^{-3}$   
                         *Air is approx.*       $1.3 \text{ mg cm}^{-3}$
- The X-rays emitted by electron capture radionuclides in the above table cover an energy range such that a few millimetres of lead sheet provides sufficient attenuation for the activities normally handled in Universities.

## APPENDIX 12

### Derived Levels for Surface Contamination

From Guidance Notes for the Protection of Persons against Ionising Radiations Arising from Medical and Dental Care (National Radiological Protection Board) as amended by the Medical and Dental Guidance Notes published by the Institute of Physics and Engineering in Medicine (IPEM) (2002).

#### Derived Limits for Surface Contamination

Category	Surfaces	Levels of Contamination That Should Not be Exceeded (Bq cm <sup>-2</sup> )		
		Class III	Class IV	Class V
A	Surfaces of the interiors and contents Of glove boxes and fume cupboards	The minimum reasonably achievable		
B	Surfaces in controlled areas including any equipment therein (other than those in Category A)	30	300	300
C	Surfaces of the Body	3*	30	300
D	Supervised and Public Areas, Personal Clothing, Hospital Bedding	3	30	300

Derived levels for Class I and Class II radionuclides may be taken as 10<sup>-2</sup> and 10<sup>-3</sup> respectively of Class III levels.

\* For alpha emitters, use one tenth of this value.

#### **Classification of Radionuclides** (For the purpose of assigning derived levels)

Class	Radionuclides
I	Ac-227, Th-228, Th-230, Th-232, Th-nat, Pa-231, U-232, U-233, U-234, U-236, Alpha emitters with Z > 92.
II	Sm-147, Pb-210, Th-227, U-235, U-238, U-depleted, U-nat, U-enr, Pu-241.
III	All radionuclides which are not in the other classes.
IV	C-14, S-35, Mn-54, Co-57, Zn-65, Ga-67, Se-75, Br-77, Sr-85, Tc <sup>m</sup> -99, Cd-109, I-123, I-125, Cs-129, Hg-197, Tl-201.
V	H-3, Cr-51, Fe-55, Ni-63, Cs-131.

**NOTE:** - Measurements of the contamination of surfaces of the body should be averaged over the most appropriate area which in any case should not exceed 100 cm<sup>2</sup>. For floors, walls and ceilings measurements may be averaged over an area not exceeding 1000 cm<sup>2</sup>; for other surfaces, over an area not exceeding 300 cm<sup>2</sup>. If there is reason to believe that discrete specks of a β emitter may be embedded in clothing, the latter should be monitored with an average area of 1 cm<sup>2</sup>.

## APPENDIX 13

### Safe Handling of P-32

P-32 is a common radionuclide used in Universities. It is a pure  $\beta$  emitter with a maximum  $\beta$  energy of 1.7 MeV and a mean energy of about 0.7 MeV. The  $\beta$  energies are among the highest encountered in  $\beta$  decay and can lead to high external radiation doses if the P-32 labelled materials are not handled properly.

The range of P-32 is  $800 \text{ mg cm}^{-2}$ . The linear ranges in air and biological tissues are therefore approximately:

Air	6 metres
Tissues	8 mm

Significant proportions of the  $\beta$  spectrum are absorbed at much lower thicknesses however, and the thickness at which half the  $\beta$ 's are absorbed is about  $100 \text{ mg cm}^{-2}$  corresponding to the linear ranges of approximately:

Air	80 cm
Tissues	1 mm

The P-32 labelled compounds which are in common use are generally not volatile and the risk of internal irradiation because of inhalation is small provided the appropriate precautions are taken against inhalation of aerosols. Procedures such as centrifuge blending or the use of syringes can **produce** fine aerosols. The use of capped centrifuge tubes usually provides sufficient protection and this can be checked by monitoring the inside of the centrifuge before and after each period of use. Other operations capable of producing aerosols of high activity can be carried out in a fume cupboard.

Exposure resulting from the ingestion of P-32 compounds will not be a problem if basic rules for radioactive laboratories are followed and backed by routine contamination monitoring.

#### **The greatest hazard in handling P-32 is that of external irradiation**

The possibility of irradiation of the eyes should also be considered. The annual exposure limit for skin and extremities for employees is 500 mSv per year but the corresponding exposure limit for eyes is 150 mSv per year.

The main aim of radiation protection in handling P-32 is therefore to keep external irradiation of skin and eyes as far below these limits as possible. This is achieved by a combination of:

### **Distance and Shielding**

The rate of change of  $\beta$  dose rate with distance is high at distances close to the source. There is therefore a large decrease in dose rate when simple handling tools such as forceps or tongs are used instead of fingers for picking up a tube containing P-32.

Containers of P-32 must not be picked up by hand if the activity exceeds about 0.5 MBq. Handling tools which increase the finger to source distance to 10-30 cm should be used provided they are of a design which provides a good grip of the container.

The protection provided produced by distance should be supplemented by appropriate shielding. This is usually provided by Perspex, 8 mm of which will completely absorb P-32  $\beta$ 's. Perspex shielding can take the form of screens (to protect body and eyes), of boxes or bored blocks to hold tubes and other containers and of bored cylinders (to shield the bodies of syringes or chromatography columns)\*\*.

#### Procedures for Opening and Dispensing Packages of P-32.

These procedures will vary slightly depending on the type of vial in which the P-32 is packed.

1. Put the package in a BenchKote- lined tray behind a Perspex screen;
2. Put on disposable gloves;
3. Have a monitor standing by and switched on in readiness to monitor gloves, wipes and equipment;
4. Open the can;
5. Remove the top layer of polystyrene packing and monitor it. If it is contaminated a significant leakage of P-32 has occurred in the package during transit;
6. Pick up the lead pot by hand and remove the adhesive tape securing it;
7. Put the lead pot back into the can. Remove the lid with tongs and monitor it.

The operations beyond this stage should be carried out with the vial either in the lead pot or in a suitable vial shield made of Perspex. When it is necessary to handle the vial this must be done only with tongs or suitable handling tools. It may be easier to reach the vial with tongs if a piece of tissue is placed inside the lead pot to lift the top of the vial slightly above the edge of the pot.

Gloves must be monitored frequently and replaced if they are contaminated. Heavily contaminated gloves will irradiate the skin at high dose rates through the glove.

8. Steady the vial with one set of handling tools and remove any screw cap with another. In a similar way use forceps to bend upwards the metal ring protecting the serum seal; if the vial cap and serum seal are to be removed altogether at this stage remember that they will be contaminated with P-32;
9. If the vial cap and serum seal have been removed prior to using a pipette to dispense P-32 use a pipette which allows the hands to remain as large a distance as possible from the P-32 solution.
10. If the vial cap is to be left in place and the P-32 extracted with a syringe, choose a syringe which does not need to be handled by its barrel and/or shield the barrel with a bored out cylinder of Perspex securely fitted to the barrel.

If the P-32 in the vial is to be diluted before removal it may be useful to place a needle in the serum cap beforehand to release any pressure caused by the addition of the diluting material. The syringe needle should be removed slowly and carefully to minimise the spread of contamination from the tip of the needle.

The top of the vial should be wipe tested with a moist tissue held in forceps and then presented to the monitor probe. If it has been contaminated wipe the top with moist tissues held in forceps until it is clear.

A significant activity of P-32 will remain in the needles and syringes and care will be required in their treatment and disposal.

\*\* = The book by Ballance et al cited in Appendix 14 provides useful information about various perspex shields which can be easily built for handling P-32

## APPENDIX 14

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