Aims
Studying this chapter should give you some appreciation of the variety of radiation detectors available and equip you with some practical knowledge about their characteristics and uses. This chapter also contains practical knowledge about the description and measurement of the effects of radiation on humans. You should learn how the problem of measuring doses is currently handled in terms of physical concepts, such as energy absorption, and empirical constructs, such as quality factors and equivalent dose rates. Although you should study the detailed information about the sources of radiation in the environment, there is no point in trying to memorise detailed statistics. Use the data to develop your appreciation of the problems and the precautions which need to be taken.

Minimum learning goals
When you have finished studying this chapter you should be able to do all of the following.
1. Explain, use and interpret the terms
   - gas-filled detector, gas amplification, ionisation chamber, proportional counter, Geiger counter, multi-wire detector, scintillation counter, scintillator, fluorescence, photomultiplier, image intensifier, solid state detector, semiconductor detector, film badge, stochastic process, specific ionisation (exposure), absorbed dose, gray, background, dose equivalent, sievert, quality factor (relative biological effectiveness), dose rate, annual intake, annual limits on intake (ALI), background radiation, cosmic radiation, dose limit.
2. Outline the operating principles of ionisation chambers, proportional counters, Geiger counters, scintillation counters, photomultipliers, semiconductor detectors and film badges.
3. Describe uses of various types of radiation detector.
4. (a) Describe and explain ways of specifying radiation doses.
    (b) State and apply the relation between dose equivalent and absorbed dose.
5. (a) Describe and discuss the significance of various sources of natural background radiation.
    (b) Describe how radionuclides can enter the body from the environment.
6. Describe and discuss the principles of dose limits.

5-1 RADIATION DETECTORS - INTRODUCTION
There are three aspects of radiation detection. The first aspect is the interaction of radiation with matter within the detector's sensitive volume. We have dealt with the physics of those interactions in chapter AN4. The second step is to observe the products of the interaction to get some measurable physical quantity, which is often an electrical signal. That aspect will be dealt with in this chapter. The third stage is the signal processing system, which extracts useful information from the measurements. That aspect can be summarised as a black box of electronics and computers which processes the electrical signal. You will study those topics in your laboratory course.
5.2 GAS-FILLED DETECTORS

Many radiation detectors exploit the ionisation produced by radiation as it passes through a gas. Such detectors are used mainly for detecting radiation which consist of charged particles, although photons can produce relatively small amounts of ionisation in a gas. The sensitive volume of this kind of detector is filled with a suitable gas. Radiation passing through the gas leaves a trail of ionised atoms and free electrons. Those charged particles can be made to move in electric fields. The electric fields draw the ions and electrons to electrodes where their arrival causes an electric current to flow in the signal processing system.

![Figure 5.1 General principle of gas-filled detectors](image)

The exact relationship between the number of ions produced and the current generated depends on how easy it is for the ions and electrons to move, the strength of the electric fields and the geometry of the electrodes. Strong fields accelerate the electrons and ions to energies at which they themselves can ionise the gas, thus producing more electrons and ions which in turn produce even more ionisation. This process of gas amplification is most useful in producing a measurable current from a few ions. However ions and electrons may recombine before they reach the electrodes. How quickly this happens depends on the composition of the gas and its pressure.

For a given geometry the way a gas-filled detector behaves depends on the potential difference between the electrodes. See figure 5.2. The smaller the field (or the applied voltage) the longer it takes for an ion to get to an electrode, and the greater is the probability of its recombining. If the electric field within the gas is too weak, ions and electrons can recombine before they are swept to the electrodes, so there will be only partial collection of the charge and no gas amplification. This corresponds to the part of the graph to the left of line A in figure 5.2.

Various kinds of gas-filled detectors can be classified according to the parts of the graphs (figure 5.2) where they operate.

**Ionisation chambers**

The ionisation chamber is operated with the applied voltage in the range A to B on figure 5.2. The electrodes are usually parallel plates and the electric field is weak. There is no gas amplification, but most of the ions produced by the incident radiation are collected. An ionisation chamber can be operated in one of two modes. In one mode each ionising particle produces a small output pulse which takes some time to decay. In the more usual mode, used for detecting high levels of x rays or gamma rays, a small continuous current gives a measure of the rate at which ionising particles pass through the chamber.
Curves are shown for the detection of typical alpha and beta particles. Details of the curves depend on particle energy. The lines A, B, C, D and E delineate the different operational modes of gas-filled detectors (see text). The applied voltage scale, although typical, is arbitrary since it will vary with the size and geometry of the detector.

**Proportional counters and Geiger counters**

**Proportional counters** and **Geiger counters** are often cylindrical (figure 5.3); the anode (the positive electrode) is a wire on the axis of a hollow cylindrical cathode (the negative electrode). The electric field is strongest near the central wire ($E \approx k/r$). The potential difference is chosen such that for most of the counter's volume the electric field is too low for gas amplification. When an ionising particle passes through the sensitive volume, the resulting electrons and ions are swept towards the electrodes. Substantial gas amplification takes place only near the central wire. One advantage of this design is that the signal varies little with the position of the path followed by the incident ionising particle.
A charged particle produces many ion pairs along its path; so many ions are created even in small counters. Thus every charged particle entering the sensitive volume of the counter will be counted. On the other hand photons have all-or-nothing interactions and only a small fraction will interact inside the sensitive volume of the counter. The size of that fraction depends on the energy of the photons. If the number of incident photons is large this does not matter; the incident flux can still be measured quite accurately. However if we wish to count every photon, gas-filled counters are not suitable; more substantial counters such as a scintillation counter, are needed and, even then, not every photon will be counted.

**Proportional counter**

In the region B to C on figure 5.2 some gas amplification takes place. The larger the electric field the shorter is the distance required for the electrons to gain sufficient kinetic energy to generate extra ions by collision with the surrounding gas molecules. The charge collected at the electrodes is larger than that in an ionisation chamber and it is roughly proportional to the number of ions produced by the incident radiation. Each ionising particle produces a short electrical pulse whose amplitude depends on the detected particle's energy.

**Geiger counter**

In the high voltage region D to E on figure 5.2 the gas amplification process spreads sideways, mainly through photons generated in the secondary collisions, so that ionisation can be produced over the whole sensitive volume of the counter. The gas amplification avalanche is terminated when the density of secondary ions becomes large enough so that their fields, when added to the applied field, reduce the effective field to less than that required to sustain gas amplification. The output current no longer depends on the number of original ions, but is saturated to a value determined by the detector geometry and the applied voltage. Each particle detected produces an electrical pulse whose amplitude is practically independent of the particle's energy. The pulses can be counted electronically or the pulse rate can be displayed on a meter. A detector operated in this way is known as a Geiger counter (or Geiger-Muller counter). A Geiger counter is essentially just a proportional counter operated at a higher voltage.

**Multiwire chambers**

Usually the anode of a gas-filled detector is a thin wire. The electric field near a wire is intense so most of the gas amplification takes place close to the wire. In a **multi-wire detector** the anode consists of a number of parallel wires. There are two important advantages of such a detector. Firstly, there is improved uniformity in the response of the detector to radiation entering it at different places. Secondly, by measuring the current on each wire individually, it is possible to determine the location where the ionisation was produced so information about the particle's track can be obtained.

![Multiwire detector](image)

**Figure 5.4** Multiwire detector

The sensing wires may be connected together (as shown) or each wire may have its own voltage supply, amplifier and signal processing circuits.
5.3 CLOUD CHAMBERS AND BUBBLE CHAMBERS

In cloud chambers and bubble chambers the location of the ionisation produced by the incident particles is made visible and can be photographed. In a **cloud chamber** the ionisation produced acts as a centre for condensation of a supercooled vapour. Droplets are formed which when allowed to grow can be illuminated by an electronic flash and photographed. **Bubble chambers** contain a superheated liquid which is ready to boil but does not do so because there are no centres for the bubbles to start. The ions produced by incident radiation provide such centres and the liquid starts to boil along the track followed by the incident particle. Cloud and bubble chambers have been used mostly in particle physics research and are now considered to be obsolete.

5.4 SCINTILLATION COUNTERS

Scintillation counters work by producing flashes of light - scintillations - in response to the passage of charged particles or high energy photons through specially chosen solid or liquid materials called **scintillators**. When an energetic particle enters the scintillator a large number of atoms are raised to excited states with higher energy levels. The excited atoms return to lower energy states by emitting photons in the visible or near ultraviolet regions of the spectrum. This process is called **fluorescence**. If the substance of the detector is transparent to these low energy photons, they can escape from the detecting material to be picked up by a light detector. So a charged particle or a high-energy photon penetrating the detector can be detected by the flash of light that it causes. A special kind of light detector, the photomultiplier (see below), is used to produce a voltage pulse in response to the pulse of light. These pulses can be counted and their sizes can also be analysed electronically to give information about the energies of the particles being detected.

**Inorganic and organic scintillators**

Two basic kinds of detector materials are used - organic and inorganic. The difference in their behaviour results from the different ranges of energy levels excited by the incident radiation. Organic scintillators, which usually contain aromatic hydrocarbon molecules, respond very quickly - fluorescence occurs within a few nanoseconds. But they are not very efficient, producing only a few photons for each incident particle.

Inorganic scintillators are slower, fluorescing in about 250 nanoseconds. However they are more efficient than organic materials for detecting gamma radiation because of their greater density and higher average atomic number. A very common example of an inorganic scintillator is a crystal of sodium iodide containing some thallium, NaI(Tl).

**Photomultipliers**

A photomultiplier responds to a light pulse by producing a pulse of electric current. Figure 5.5 shows the structure a typical photomultiplier. Photons enter through a window, hit the photoemitting cathode and, through the photoelectric effect, release electrons. An electric field set up between the cathode and the first of a series of electrodes called dynodes accelerates the photoelectrons. The dynodes are made of a material which, when hit by an electron, will emit more than one secondary electron by a mechanism similar to the photoelectric effect. The secondary electrons are pulled to the next dynode where the amplification process is repeated until the current is collected on the final anode. A typical twelve-dynode photomultiplier will produce a few million electrons from a single photoelectron released at the photocathode.

Not every photon will release an electron at the photocathode; on the average only one in four will do so. The ratio of the average number of photoelectrons released to the number of incident photons is called the quantum efficiency of the photocathode.
Image intensifiers

The current from a photomultiplier depends on the total amount of light falling on the photocathode; it does not depend on the positions where photons hit the photocathode. If patterns of light are to be amplified an image intensifier is used. An image intensifier works in the same way as a photomultiplier. It is not a particle detector but may be used to amplify weak light produced on x-ray screens and similar detectors. Initially an image is focused onto the photocathode. The number of photoelectrons released at a given place depends on the intensity of light at that place. The electrode structure of the image intensifier is such that electric fields produced guide the electrons from each region of the cathode along a unique path to a fluorescent scintillating screen, where they interact to produce a flash of light. On their way through the image intensifier the electrons numbers are multiplied and their energy can be increased so that the intensity of light emitted from the screen is greater than the light intensity falling on the photocathode.

5.5 SOLID STATE DETECTORS

In crystalline materials electrons in the highest energy states are not attached to individual atoms but are shared by all the atoms. The energy levels of these electrons have a broad band structure with gaps between the bands. For materials of interest here all the levels up to the top of one band are filled but the next higher band, above a gap, is nearly empty. Incident radiation can raise an electron from a level in the filled valence band to a level in the conduction band. Both the electron in the conduction band and the hole left in the valence band can now move around.

Semiconductor detectors

In semiconductors with gap widths of 1 eV to 2 eV the number of electron-hole pairs created by radiation in the vicinity of a junction between two different materials is detected directly by electrical means. Electric fields in the junction region sweep the electrons and holes to the anode and cathode respectively, producing an electric current. So semiconductor detectors work like solid ionisation chambers. They have the advantage that they can be quite small, so they can be used for accurate position measurements.

Film badges

Another kind of solid state detector is photographic emulsion. The active material is a grain of silver bromide. Incident radiation raises an electron from an energy level in the valence band to an energy level in the conduction band, leaving a hole in the valence band. Both the electron and hole diffuse through the silver bromide grain and become trapped at irregularities in the crystal structure of the grain. If a single grain accumulates more than about four electron-hole pairs it becomes possible to change the silver bromide crystal to a pure silver crystal by photographic development.
5-6 BIOLOGICAL EFFECTS OF IONISING RADIATION

The effects of radiation on living things arise from the ionisation produced by the particles. Cell damage is initiated by ions (both negative and positive) along the track of an ionising particle. The damage is magnified by free radicals generated by the ions.

It is convenient to divide up the effects of ionising radiation into two classes: those due to massive doses of radiation over a small time (less than about 14 days) and those due to much smaller doses. In this second class, the exposure time could be years and the probability of a disease depends on the dose received. The word *stochastic* is applied to these effects. For example if one is exposed to cigarette smoke or a toxic chemical, then there is a likelihood of contracting a cancer, which may be fatal. The greater the exposure, the more probable is the cancer. It is the same with radiation. Ionising radiation can induce various cancers with a probability which increases with radiation dose.

Other stochastic effects that can be caused both by poisons and radiation are of a genetic type. If the reproductive cells of an organism are affected by certain poisons or subjected to ionising radiation then the organism's descendants may suffer mutations. If, as in humans, the reproduction is sexual, then the mutation rate is greatly enhanced if both the male and female are poisoned or irradiated.

It has to be stressed that the two types of radiation induced stochastic effects: namely, genetic and non-genetic (cancers), would only slightly lift the incidence of the disorders concerned, most of the disorders being due to causes other than radiation.

5-7 MEASURES OF THE INTENSITY OF IONISING RADIATION

We are concerned here with the physical effects of radiation rather than chemical or biological effects. The first need is for a physical measure of radiation intensity which is capable of being correlated with radiation's biological effects. The measure chosen, called the *absorbed dose*, is the ratio of the energy deposited by ionisation to the mass of living tissue.

\[ D = \frac{E}{m} \]  \hspace{1cm} ... (5.1)

The SI unit for absorbed dose is the joule per kilogram, which for radiation purposes is called the *gray* (symbol Gy). The obsolete unit for dose, the rad, was defined as 100 ergs per gram. The conversion relation is 1 rad = 0.01 gray, exactly. It is, in principle, possible to measure radiation dose by the temperature rise it produces in the tissue. For 1 gray given in a short episode, the temperature rise would be only 0.000 25 K. Since 1 gray is a significant dose, measuring radiation doses this way is clearly impractical!

The obvious practical way to measure radiation dose is by recording the ionisation produced by the radiation. This can be done for gaseous media using an ionisation chamber. The chosen gas is held in a container with two electrodes which can pick up the ions of the appropriate charge: electrons or negative ions to the anode and positive ions to the cathode. The physical quantity used to describe the ionisation would be electric charge per mass of the medium, which is called *specific ionisation* or *exposure* (SI unit, coulomb per kilogram). (An obsolete unit of exposure, the roentgen is equivalent to $2.58 \times 10^{-4}$ C. kg$^{-1}$.)

We now find the relation between this measure and the absorbed dose. It takes about 35 eV to produce each pair of ions; one positive, the other negative. This figure of 35 eV varies little from one absorbing medium to another and it also depends little on the nature of ionising particle: electron, alpha particle etc. The ratio of energy deposited to the ionisation charge produced is 35 eV per electron charge or

\[ \frac{35 \times 1.6 \times 10^{-19} \text{J}}{1.6 \times 10^{-19} \text{C}} = 35 \text{ J.C}^{-1}. \]

So a specific ionisation of 1.0 C.kg$^{-1}$ is equivalent to an absorbed dose of about 35 J.kg$^{-1}$ or 35 Gy.

The ionisation chamber is the standard instrument for measuring radiation. There are problems with its sensitivity as the absorbed dose due to the "normal" background of 0.1 microgray per hour will
produce an ionisation current of less than 1 fA (10^{-15} \text{ A}) in a reasonably sized chamber. These currents are comparable with leakage currents over insulators, making measurement difficult. High pressure chambers are often used to get around this problem but they are bulky and heavy.

The Geiger and scintillation counters are more sensitive. However, as the names suggest, they count individual particles as they arrive instead of measuring the ionisation current. (The scintillation counter can also give the energies of the particles it counts). Both types of counter require calibration against an ionisation chamber.

The Geiger counter is often used to measure gamma ray doses. The scintillation counter is a better instrument although it is more expensive. Gamma rays have to interact to be registered and the probability of interaction in the sensitive volume of the counter decreases for higher gamma ray energies. One then might think that a Geiger counter exposed to high energy gamma rays would underestimate the radiation dose. There is fortunately a compensating effect because the secondary electrons have an energy commensurate with the gamma ray energy. For higher energies the electrons travel further and each produces more ions and deposits more energy into tissue. A similar thing happens with ionisation chambers as they, like the counters, are almost transparent to gamma ray photons of reasonable energy like 100 keV or so. At this energy a Geiger counter has a probability of around 1% of stopping a gamma ray photon and recording it. For higher energies the figure is smaller.

For beta particles one may also use Geiger counters where the efficiency for counting may approach 100%. One then needs to calculate the dose per count and this is not too difficult a task.

A similar method can be used with alpha particles but another problem arises. Alpha particles have a short range in tissue and other media. Gray for gray the alpha particle is observed to do much more biological damage than a particle like the electron. The density of ions along the particle's track is much higher for the alpha particle than it is for electrons. This density is proportional to the square of the charge so it is four times higher for an alpha particle than for an electron of the same speed. In addition, the speeds of alpha particles are much smaller than those of the electrons, the energy loss per track length is even higher for alpha particles. It is the high ionisation density along its track that makes an alpha particle so damaging.

To take this into account a dose unit called the sievert (symbol Sv) is used. It is a measure of the dose equivalent which is related to the absorbed dose by

\[ H = D Q N \]  

\[ \text{(5.1)} \]

\( H \) is the dose equivalent and \( D \) is the absorbed dose. \( Q \) is called the quality factor and allows for effects such as the density of ionisation described above. (The quality factor corresponds to an obsolete quantity called relative biological effectiveness or RBE.) \( N \) is a constant introduced by the International Commission on Radiological Protection (ICRP). The ICRP has assigned its value as one sievert per gray for the present. The ICRP has also proposed a definition of \( Q \) in terms of stopping power for the ionising particles in water (figure 5.6). Water has been chosen as the reference material since it is similar to living tissue as far as ionisation loss is concerned. The range of stopping powers for typical alpha and electron energies are also shown on figure 5.5. Note that electrons (beta radiation) typically have a quality factor of 1, while alpha particles, which produce heavy ionisation, can have values of \( Q \) in the range 10 to 20. Gamma rays have quality factors around 1 or less depending on the photon energy.

Some publications contain references to dose equivalent expressed in the obsolete unit, rem. The conversion is \( 1 \text{ rem} = 0.01 \text{ Sv} \).
5-8 RADIONUCLIDES IN THE BODY

It is possible to make models which describe the movement of radionuclides in the body. The models are based on measurement and take into account how particles and solutions move in the body and any possible chemical binding effects. For relatively long-lived radionuclides, the rate of excretion is clearly of great importance. The model can be used to find the annual intake of a radionuclide which would give a certain equivalent dose. Estimates of this sort are done by the ICRP. The ICRP also specifies the annual limits on intake (ALI) for various radionuclides. Varying vulnerability of various body organs is taken into account. The use of the word "limits" means that the ALI is linked to the general limits on radiation dose equivalents published by the ICRP. These general limits will be given later.

As an example of interest the ICRP give a figure of 200 Bq for the ALI of plutonium-239. This is for inhalation of most compounds of plutonium; the ALI for the oxide is 500 Bq.

5-9 NATURAL BACKGROUND RADIATION

Natural background radiation comes from many sources, including cosmic rays and various radionuclides in the environment.

Cosmic radiation

High energy charged particles come from somewhere outside the solar system and bombard the Earth's atmosphere. Many secondary particles result from collisions of the cosmic-ray particles with atoms of the atmosphere. At ground level there is a general flux of the secondary particles of about 300 particles per square metre per second. They constitute a source of ionising radiation which increases with altitude (and to a limited extent with latitude).

Carbon-14

This radionuclide is made in the high atmosphere by neutron bombardment of nitrogen-14, the most common nuclide in the earth's atmosphere. The neutrons are secondary particles from cosmic ray collisions. Carbon-14 is a beta emitter (its nuclei emit negative electrons). The half life of 5730 years gives it plenty of time to diffuse down into the biosphere where its decay electrons can irradiate all living tissue. The accounting of the various background sources must include carbon-14, because it is a universal constituent of all living organisms, including people.

Potassium-40

Potassium-40 is an electron emitter with a half life of $1.3 \times 10^9$ years. Like uranium-238 and thorium-232, it is a relic from the formation of the solar system. It is believed that the sun (and the solar system)
started to condense after a "push" from the explosion of a nearby supernova, a big star that collapsed after running out of nuclear fuel. Huge quantities of neutrons are produced in the violent event which starts like an implosion and ends as explosion. The neutrons are pushed into the lighter nuclides (like iron) one by one. This process, together with beta decay, adds neutrons and protons and builds heavy nuclei like uranium. The half life of potassium-40 is comparable with the age of the solar system.

**Uranium and thorium**

Uranium-235, uranium-238 and thorium-232 are alpha emitters; their half lives are respectively: 7.04 × 10^8 years, 4.47 × 10^9 years and 1.41 × 10^10 years. They are relic nuclides from the explosion which "blew" them into the solar system. Their decays in each case lead through a chain of radionuclides. For example for thorium-232 we have the chain of decays shown in figure 3.9.

Nearly all rocks (and it seems most other objects in our environment!) contain thorium-232 and uranium-238 at the parts per million level. As far as radiation sources are concerned; we should first look at the secondary electrons produced by gamma rays given out by the daughter nuclides. These may be either inside or outside the body when they decay and are consequently termed internal or external sources. Internal sources could also irradiate the body with alpha particles and electrons. In this respect, by far the most serious radionuclide is radon-222. It has a long enough half life (3.8 days) for significant amounts to diffuse out of the ground where it is formed by the decay of its parent radium-226. Radon-222 then decays in the air to polonium-218 which attaches on to dust particles. If the dust is inhaled, the polonium-218 is likely to go to and stay in the lungs, where its decay and the decay of its daughters will cause serious irradiation. Life outdoors is quite safe; but humans like to live indoors in shut-in rooms, and what is worse, in brick and concrete buildings. The levels of irradiation in some of these situations are given in table 5.1.

The total annual dose is a little over 2 mSv of which about half comes from being indoors. The "normal" background level of approximately 1 mSv.y^-1 (or 0.1 µSv.h^-1) is the level as assessed outdoors. Note that the cosmic radiation level increases with altitude. The figure given is probably appropriate to near sea level (where most people live in Australia).

The levels of radon-222 are given in table 5.2. These figures can be converted to dose levels through the following relation: 1 Bq.m^-3 gives an annual dose equivalent of 0.1 mSv if a subject is continuously exposed.

As well as these natural radiation levels we also expose ourselves to medical x rays and fallout. In the article cited above, these are estimated respectively at 0.2 and 0.02 milligray per year in the UK and 0.72 and 0.04 milligray per year in USA. As well as this there is occupational exposure: around 0.03 milligray per year.

**The ICRP’s recommended radiation limits**

The ICRP has set a maximum dose limit for the public of 5 millisieverts in one year and a maximum dose for occupational exposure to radiation: of 50 millisieverts in one year.

The ICRP has also enunciated a most important principle: ALARA (As Low As is Reasonably Achievable), (see ICRP publication No 26, page 14). This means that one should assess each radiation reduction proposal by using a "cost benefit" analysis. "Costs" are the sum total of all the negative aspects of an operation and include damage to health and the environment as well as monetary costs. It would be pointless, for example, to improve the shielding of a worker so as to reduce his or her radiation dose by 1% when that worker could wipe it out a hundred-fold by moving to a brick house.
<table>
<thead>
<tr>
<th>Source</th>
<th>Dose rate / mSv.y(^{-1})</th>
<th>Fraction of total %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extra-terrestrial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>External exposure</td>
<td>0.3</td>
<td>15</td>
</tr>
<tr>
<td>Internal Exposure</td>
<td>0.01</td>
<td>0.5</td>
</tr>
<tr>
<td>Terrestrial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>External exposure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outdoor</td>
<td>0.06</td>
<td>3</td>
</tr>
<tr>
<td>Indoor</td>
<td>0.29</td>
<td>14</td>
</tr>
<tr>
<td>Internal exposure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K40 &amp; Rb 87</td>
<td>0.19</td>
<td>9</td>
</tr>
<tr>
<td>U238 series</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outdoor inhalation</td>
<td>0.06</td>
<td>3</td>
</tr>
<tr>
<td>Indoor inhalation</td>
<td>0.77</td>
<td>38</td>
</tr>
<tr>
<td>Ingestion</td>
<td>0.14</td>
<td>7</td>
</tr>
<tr>
<td>Th 232 series</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outdoor inhalation</td>
<td>0.03</td>
<td>1.5</td>
</tr>
<tr>
<td>Indoor inhalation</td>
<td>0.17</td>
<td>9</td>
</tr>
<tr>
<td>Ingestion</td>
<td>0.02</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5.1  Annual doses to humans from various sources
(From ICRP publication No 39, 1984, page 2)

<table>
<thead>
<tr>
<th>Site</th>
<th>Concentration of Rn 222 / Bq.m(^{-3})</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweden: inside wood house</td>
<td>10 to 30</td>
<td>4 air changes per hour</td>
</tr>
<tr>
<td>brick house</td>
<td>10 to 80</td>
<td></td>
</tr>
<tr>
<td>concrete house</td>
<td>10 to 170</td>
<td></td>
</tr>
<tr>
<td>USSR: inside wood house</td>
<td>4 to 16</td>
<td></td>
</tr>
<tr>
<td>brick house</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>adobe house</td>
<td>10 to 400</td>
<td></td>
</tr>
<tr>
<td>slag house</td>
<td>150 to 300</td>
<td></td>
</tr>
<tr>
<td>UK: house</td>
<td>2 to 10</td>
<td>adequate ventilation</td>
</tr>
<tr>
<td>industrial premises</td>
<td>7 to 25</td>
<td>poor ventilation</td>
</tr>
<tr>
<td>office buildings</td>
<td>0.2 to 40</td>
<td>poor ventilation</td>
</tr>
<tr>
<td></td>
<td>2 to 13</td>
<td>air-conditioned</td>
</tr>
<tr>
<td>USA: inside wood house</td>
<td>0.2 to 10</td>
<td></td>
</tr>
<tr>
<td>inside basement</td>
<td>4 to 35</td>
<td>2 to 6 changes per hour</td>
</tr>
<tr>
<td>inside concrete house</td>
<td>1 to 180</td>
<td>1 to 3 changes per hour</td>
</tr>
<tr>
<td>Outdoors over land</td>
<td>0.07 to 10</td>
<td></td>
</tr>
<tr>
<td>Outdoors over sea (S. Pacific)</td>
<td>0.07 to 0.2</td>
<td></td>
</tr>
<tr>
<td>South Pole</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2  Levels of radon-222 in various situations
Adapted from *Atomic Energy in Australia*, October 1975, pp 18 -19.
A few comments are in order on the method used by the ICRP to set the limits quoted above. For
the radiation levels concerned, carcinogenesis is considered to be the greatest risk from radiation and the
ICRP assesses the risk factor for all cancers at 0.01 per sievert. The risk factor for genetic defects (in
the first two generations) is assessed at 0.004 per sievert. These figures were obtained after studying
the medical records of workers in high radiation areas and people exposed to nuclear weapon explosions.
In the above, we are considering the stochastic effects of radiation. We contrast these with the
effects of massive doses (such as 10 sievert). Death often results from exposures to such doses if they
are concentrated into a short period of time (days) so that the body's repair mechanisms do not have
sufficient time to act.

QUESTIONS

Q5.1 A fair approximation of the number of ions produced when an ionising particle travels through a gas can be made
knowing that it takes about 35 eV to produce an ion pair in most gases. Calculate the number of ion pairs
produced by an electron, kinetic energy 1.0 MeV, passing through an ionisation chamber 30 mm thick. What is
the total charge of electrons? If a hundred such particles pass through the chamber each second and all the ions are
collected at the electrodes what is the total current? The density of the gas is 1.3 kg.m⁻³.

Q5.2 Describe the process of gas amplification.

Q5.3 The total attenuation coefficient for a 300 keV photon passing through argon is 0.01 m².kg⁻¹. If 2000 such
photons enter an ionisation chamber 300 mm thick how many will interact in the chamber? The density of argon is
1.8 kg.m⁻³.

Q5.4 Draw a block diagram of the three main components of a scintillation counter.

Q5.5 A cylindrical gas-filled ionisation detector is operated as a proportional counter. Electrons are to be collected on the
central wire. What is the sign of the potential difference of the central wire with respect to the outer electrode? Draw a cross section of the counter. Identify the region in which gas amplification takes place.

Q5.6 Describe the features and operation of a proportional counter.

Q5.7 What are the similarities and the differences between ionisation chambers, proportional counters and Geiger counters?

Q5.8 What is the purpose of a photomultiplier in a scintillation counter?

Q5.9 The sensitive volume of ionisation chambers, proportional counters and Geiger counters contains gas. Why is a
denser material (a liquid or solid) not suitable for use in such detectors?

Q5.10 The sensitive volume of ionisation chambers, proportional counters and Geiger counters has to be enclosed in a gas-
tight box. How do the properties of the enclosure - material, wall thickness, geometry, etc. - affect the performance
of the detector?

Q5.11 An x-ray tube passes a current of 100 mA at 100 kV for 0.1 s. Given that it converts 0.5% of the energy to x rays
and 10% of this is absorbed by a patient whose mass is 70 kg, calculate the absorbed dose.

Q5.12 A 70 kg person accidentally ingests 1 µg of radium-226. Given that each decay of a radium nucleus gives an alpha
particle of energy 4.8 MeV (which is totally absorbed) estimate the yearly absorbed dose.

Use 1 eV = 1.6 × 10⁻¹⁹ J; activity of 1 g of radium = 3.7 × 10¹⁰ Bq.