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1 FUNDAMENTAL RADIATION CONCEPTS

1.1 THE RADIOACTIVE ATOM

The atom contains a nucleus consisting of protons and neutrons with electrons revolving in circular and elliptical orbits about the nucleus. Electrons carry a negative charge, protons carry positive charge, and the neutrons have no electrical charge. An atom normally has one electron for each proton in the nucleus, leaving the atom electrically neutral.

The atomic structure of an element is denoted as ${}_{Z}^{A}X$ where:

A is the **Mass Number**, defined as the sum of the number of protons and neutrons in the nucleus. Thus, A minus Z gives the number of neutrons.

X is the chemical symbol of the element.

Z is the **Atomic Number**, defined as the number of protons in the nucleus. This determines the chemical identity of the element and therfore which element the atom belongs to.

Each individual arrangement of protons and neutrons is referred to as a **Nuclide**. Nuclides which have the same number of protons are called **Isotopes**. Shown below are examples of isotopes of Hydrogen:

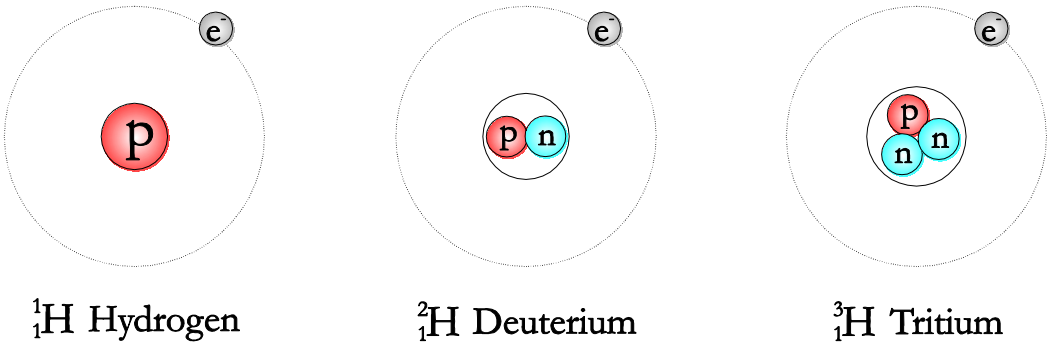

Figure 1 Three isotopes of Hydrogen.

Many nuclides, but not all, are unstable or "radioactive". In the above examples, only tritium is radioactive. Radioactivity is defined as the spontaneous disintegration of unstable that results in the formation of new nuclei. Usually such a disintegration results in emission of radiation. Stability of the nucleus is related to its ratio of neutrons to protons. For light numbered elements, approximately equal numbers of neutrons and protons in the nucleus are necessary for stability. For elements of higher atomic number, the ratio rises to approximately 1.6 to 1. As a nuclide departs from this stable ratio, changes in the nucleus occur which tend to bring the product to a more stable arrangement. This approach to stability is accomplished by one or more of five "radioactive decay modes".

1.2 BETA DECAY

When the neutron to proton ratio is too high, a neutron "transforms" into a proton and electron with the electron being ejected from the nucleus. The ejected electron is called a "beta particle". Beta particles are not emitted with a single energy but are emitted with a range of energies up to some maximum value. This is due to a division of the total energy of each disintegration between the beta particle and a neutrino. The Neutrino is a massless, chargeless particle that carries off varying amounts of the released energy. The neutrino has a negligibly small mass and no charge. It therefore travels great distances, losing little energy in nearby materials and causes no biological damage.

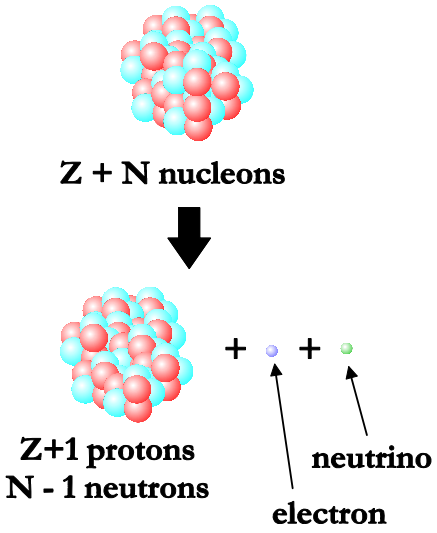

Figure 2 Beta decay.

The energy of the ejected beta particle is characteristic of each nuclide and is one criterion used for identification purposes. In general, the average energy per particle is about

1/3 of the maximum energy.

The generalized atomic equation for beta decay is as follows:

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + \beta + \upsilon$$

X = Original (parent) atom
Y = New (daughter) atom
β = Beta particle (electron)
ν = Neutrino

Examples of Beta decay

$${}^{3}_{1}H \rightarrow {}^{3}_{2}He + 0.0186\ MeV_{max}\ \beta^{-} + \upsilon$$

MeV = 1 million electron volts

max = maximum beta particle energy

$${}^{14}_{6}C \rightarrow {}^{14}_{7}N + 0.156\ MeV_{max}\ \beta^{-} + \upsilon$$

1.3 POSITRON DECAY

When the neutron to proton ratio is too low, the nucleus emits a beta particle with a positive charge (positron) resulting from the transformation of a proton into a neutron.

The positron behaves exactly as an electron except that when the positron comes in contact with a free electron, the two particles combine and are annihilated. This gives rise to two gamma rays whose energies correspond to the rest mass equivalence of the particles (0.511 MeV/gamma). See page 13 for a description of annihilation radiation.

The generalized atomic equation for positron decay is as follows:

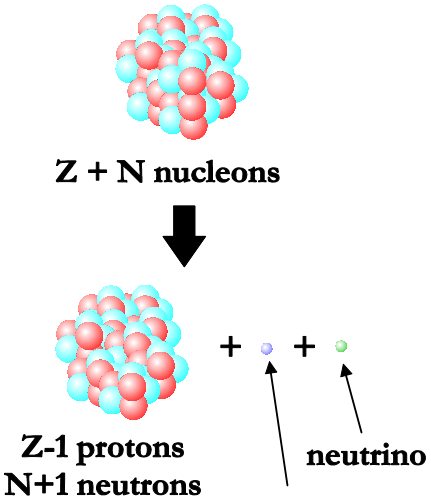

Figure 3 Positron decay

$$^{A}_{Z}X \rightarrow {}_{Z-1}{}^{A}Y + \beta^{+} + \upsilon$$

Example of Positron decay:

$$^{19}_{10}Ne \rightarrow {}^{19}_{9}F + 2.22\ MeV\ \beta^{+} + \upsilon$$

1.4 ELECTRON CAPTURE

In this decay mode, one of the orbital electrons is captured by the nucleus and combines with a proton to form a neutron. Electron capture competes with positron decay when there is a low neutron to proton ratio. If the atom is unable to meet the energy requirements of positron decay, then decay occurs by electron capture. Whenever an atom decays by electron capture, X-rays (page 15) are emitted that are characteristic of the newly formed nuclide. No particles are emitted during electron capture decay.

The generalized atomic equation for electron capture is:

$$^{A}_{Z}X + e \rightarrow {}_{Z-1}{}^{A}Y + Xray + \upsilon$$

Example of electron capture decay

$$^{54}_{25}Mn \rightarrow {}^{54}_{24}Cr + 0.835\ MeV\ Xray + \upsilon$$

1.5 ALPHA DECAY

Alpha decay occurs for those nuclides that have an atomic number greater than 82. Such heavy nuclides have no stable configuration of neutrons and protons and as a result emit an alpha particle consisting of 2 protons and 2 neutrons. Generally, a series of alpha (as well as beta) decays are required until a lighter, more stable element is reached. Unlike beta particles, alpha particles are emitted with a discrete energy.

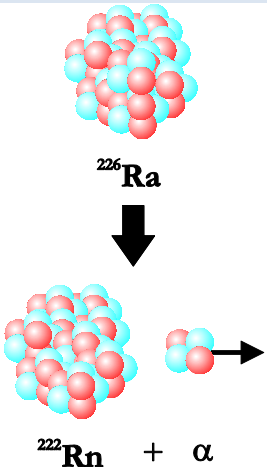

Figure 4 Alpha decay.

The generalized atomic equation for alpha decay is:

$${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + \alpha \text{ where } \alpha = {}^{4}_{2}He^{2+}$$

Example of alpha decay

$${}^{210}_{84}Po \rightarrow {}^{206}_{82}Pb + 5.3\ MeV\ \alpha$$

1.6 NUCLEAR TRANSITION - GAMMA RAY EMISSION

Gamma rays (page 13) are emitted when the emission of a particle leaves the product nucleus in a partially excited or "metastable" state. The gamma rays carry away the excess energy of the partially excited nucleus after a decay event. Such gamma rays are of discrete energy, are characteristic of the particular nuclide involved and can be used for identification purposes.

Nuclear transition can occur after beta decay, positron decay, electron capture and alpha decay.

Examples of radionuclides that undergo nuclear transition

$${}^{60}_{27}Co \rightarrow {}^{60}_{28}Ni + 0.318\ MeV\ \beta^- + 1.17\ MeV\ \gamma + 1.33\ MeV\ \gamma$$

$${}^{22}_{11}Na \rightarrow {}^{22}_{10}Ne + 0.546\ MeV\ \beta^+ + 1.27\ MeV\ \gamma$$

$${}^{125}_{53}I \rightarrow {}^{125}_{52}Te + 0.035\ MeV\ \gamma\ (6.67\ \%) + \ Xrays$$

$${}^{226}_{88}Ra \rightarrow {}^{222}_{86}Rn + 4.78\ MeV\ \alpha\ (93.4\ \%) + \ 4.59\ Mev\ \alpha\ (5.7\ \%) + \ 0.186\ MeV\ \gamma + Xrays$$

The Chart of The Nuclides list all known nuclides and is a useful reference for radioactive decay and energy data.

1.7 THE RADIOACTIVE DECAY EQUATION

A radioactive nuclide disintegrates or decays spontaneously at a rate depending on the number of original atoms present and upon its decay constant, lambda (λ). This constant is defined as the instantaneous fraction of atoms decaying per unit time. Each radioactive nuclide has its own characteristic decay constant.

The instantaneous time rate of change of the number of atoms, N, for a radionuclide is given by:

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

The solution to this equation is:

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

The e^{-t} term indicates that the radioactive atoms decay exponentially. This equation, is called the decay equation.

If we were to substitute into the decay equation the time, T, it takes for the reduction of a quantity of radioactive atoms to half of the original, we get:

$$\lambda = \frac{ln(2)}{T_{1/2}}$$

Thus, the decay constant, λ, can be calculated for any radioactive nuclide from its half-life.

1.8 RADIOACTIVITY UNITS

The instantaneous number of atoms, N, remaining at a particular instant in time is given by:

$$A = \lambda N$$

A is the activity, defined as the instantaneous number of atoms decaying per unit time. The activity determines the quantity of radioactive material in a sample.

The International System of units (SI) has defined the Becquerel (Bq) as the unit of activity, equal to 1 disintegration per second.

An older unit for activity, Curie (Ci) can still be seen in use. 1 Curie = 3.7×10^{10} Bq.

One becquerel (Bq)= 1 disintegration per second.

One curie (Ci) = 3.7×10^{10} becquerels

Since radioactive material is measured in units of activity, the decay equation now takes the form:

$$A = A_0 e^{-\lambda t}$$

A= Activity after some time t
t= Decay time
A_0= Original activity of the sample
λ= The radioactivity decay constant equal to $ln(2)/T_{1/2}$
$T_{1/2}$= Half-life of isotope

Note: The decay time and half-life must be expressed in the same units of time.

2 INTERACTIONS OF RADIATIONS WITH MATTER

Radiation interacting with matter can be either scattered or absorbed. The mechanisms of the absorption of radiation are of interest because:

- Absorption in the body tissue may result in biological injury.
- Absorption is the principle upon which detection of radiation is based.
- The degree of absorption is the primary factor in determining proper shielding requirements.
- The transfer of energy from emitted radiations to matter occurs in two major ways: Ionization and Excitation.

Ionization:

The process resulting in the removal of an electron from an atom, leaving the atom with a net positive charge.

Excitation:

Addition of energy to an atomic system, transferring it from the ground state to an excited state.

Radiation can be classified into two groups:

- Particulate radiation (charged particles) such as alpha and beta particles: or
- Electromagnetic radiation such as X or gamma rays.

2.1 INTERACTION OF CHARGED PARTICLES

All atoms are normally electrically neutral. When a charged particle strikes an orbital electron, it ejects it from the atom resulting in the formation of an ion pair. Since the removal of the electron from the atom decreases the total number of negative charges by one, it leaves the atom with a net positive charge. The ion pair consists of:

- The positively charged atom.
- The negatively charged electron.
- Such particles capable of creating ion pairs in this manner are called ionizing radiation.

The term used to compare and relate the ionizing powers of different types of charged particles is called the "specific ionization" Specific ionization is defined as the number of ion pairs per unit path length formed by ionizing radiation in a medium.

$$Spesific\ Ionization = \frac{\#\ of\ ion\ pairs\ formed}{cm\ of\ path}$$

The specific ionization is dependent on the velocity of the charged particle (and therefore its energy), and the density of the absorbing material (the number of atoms available for ionization).

2.1.1 ALPHA PARTICLES

An alpha particle is a helium nucleus stripped of its orbital electrons. It is emitted from a radioactive atom with a velocity of about 1/20 that of the speed of light and with energies ranging from 4 to 9 MeV. Alpha particles cause ionizations in matter when they are deflected by the positive charge of a nucleus and pull the orbital electrons (attracted by the alpha's positive charge) along with them. Alpha particles also cause excitation along their path by pulling inner orbital electrons to outer orbits. No ion pair is formed, but energy is lost from the alpha particle and added to the atom. The added energy is then given off by the atom as fluorescent radiation or low energy X-Rays when the electrons drop back down to the inner orbital vacancies.

Because of its relatively large mass (2 neutrons and 2 protons), high electrical charge (+2) and low velocity, the specific ionization of an alpha particle is very high. That is, it creates many ion pairs in a very short path length. Because of this, it loses all of its energy in a very short distance. The range in air is only several centimetres even for the most energetic alpha particles.

Since the alpha particle has a very limited range in matter, it presents no external radiation hazard to man. Many alpha particles cannot penetrate the protective layer of skin. However, once inside the body, surrounded by living tissue, damage will be to the local area in which the alpha emitter is deposited. Thus, alpha emitters are an internal hazard and intake to the body must be prevented. (See Chapter 7 "Internal Radiation Protection Techniques", page 51).

2.1.2 BETA PARTICLES

Beta particles are emitted from the nucleus of a radioactive atom with a wide range of energies up to some maximum value. When a beta is emitted that is below the maximum value, the neutrino carries away the rest of the energy.

Beta particles, like alpha particles, lose their energy by ionization and excitation, but because of their small mass (1/7300 of an alpha) and lower charge (1/2 of that of an alpha) the interactions take place at less frequent intervals. Therefore, the beta particles do not produce as many ion pairs per centimetre of path as alpha particles, and thus, have a greater range in matter. The beta particle's range in matter depends on the energy and the composition of the material.

Beta particles can interact with a nucleus of an element and give rise to X-rays by a method called Bremsstrahlung. Bremsstrahlung (German for "Breaking Radiation") occurs when high speed beta particles approaches the nucleus of an atom. The electrical interaction between the negative beta particle and the positively charged nucleus causes the beta particle to be deflected from its original path or stopped all together. Their stoppage or deflection results in a change in velocity of the beta particle with the emission of X-

rays of various energies. The likelihood of Bremsstrahlung production increases with increasing atomic number of the absorber. For this reason, beta shields are made from low atomic numbered material, like aluminium or plastics.

Beta particles require an energy of greater than 70 keV to penetrate the protective layer of the skin, and thus, are somewhat of an external hazard. The beta can also constitute an internal hazard. A beta particle has a greater range in tissue compared to an alpha particle due to its low specific ionization. The beta particle gives up less energy per unit volume of tissue and, therefore, is not as effective in causing damage as an alpha particle.

2.2 INTERACTION OF X-RAYS AND GAMMA-RAYS

From a practical radiation protection point of view, X-rays and gamma rays are identical, differing only in their place of origin. Gamma rays are emitted from excited nuclei with a discrete energy. X-rays are emitted when the extra-nuclear atomic structure undergoes a transition; i.e., an outer shell electron replaces a missing lower shell electron and an X-ray is produced. The energy of the X-ray is approximately equal to the difference in the electron energy levels.

Since X and γ-rays are chargeless, they do not interact by electrostatic forces as in the case of charged particles, which cause ionization of matter directly along their path of travel. However, X and γ-rays do have sufficient energy to release high energy secondary charged particles (electrons) from matter through one of three basic interactions:

- The Photoelectric Effect
- The Compton Effect
- Pair Production

The high speed electrons resulting from these interactions then cause ionization of the medium.

2.2.1 THE PHOTOELECTRIC EFFECT

The Photoelectric Effect is the interaction of X or γ-ray photons[1] as well as other photons (such as light), whereby all of the energy of the photon is transferred to an inner shell electron (usually the K shell), ejecting it from the atom and leaving the atom with an inner shell vacancy. This shell vacancy creates an excitation energy which corresponds to the Binding Energy (BE) of the ejected photoelectron.

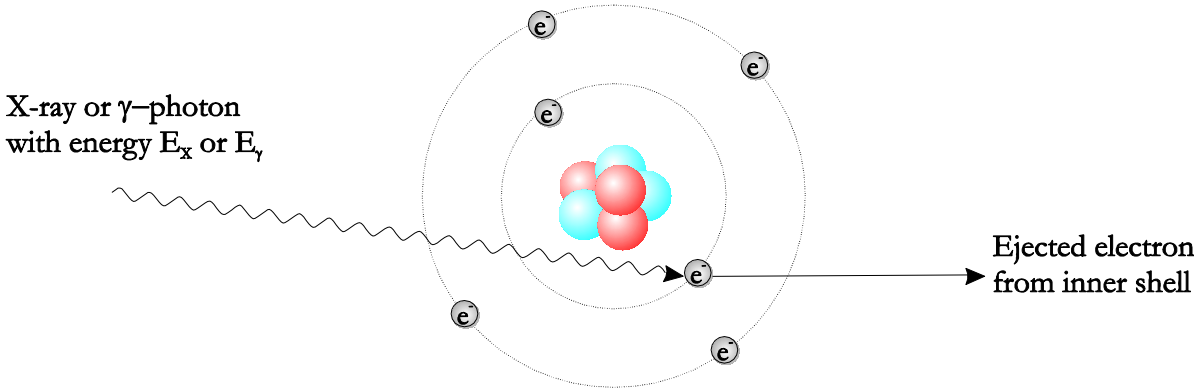

Figure 5 Photoelectric effect: An X-ray or a γ -photon ejects an electron from the inner shell. $KE_{photoelectron}=E_x$ or Eγ - BE of the inner electron.

The Kinetic Energy (KE) of the photoelectron is equal to the energy of the X or γ-ray photo minus the BE of the electron ejected.

If the X or γ -ray photon does not have sufficient energy to knock the inner shell electron loose, the reaction will not occur.

The resultant atom is now in an excited state and will decay to the ground state by emission of X-rays and fluorescent radiation with the total energy equal to the BE of the photoelectron. The energies of the secondary radiations are usually much lower than the primary X or γ-ray energies.

Application of the Photoelectric Effect

Gamma rays emitted from excited nuclei, and X-rays emitted from excited atoms, have discrete energy characteristics of the specific nuclides and elements, respectively. Thus, the energy of these γ or X-ray photons can be used as "finger prints" to identify unknown nuclides and elements.

1 A photon, as described by the Quantum Theory, is a "particle" or "quantum" that contains a discrete quantity of electromagnetic energy which travels at the speed of light, or 3×10^8 meters per second.

2.2.2 THE COMPTON EFFECT

Photons with energies much greater than the BE of the electrons in an atom may interact through essentially elastic scattering interactions in which the total KE of the system is conserved. In this interaction, the electron appears to the photon as a free electron.

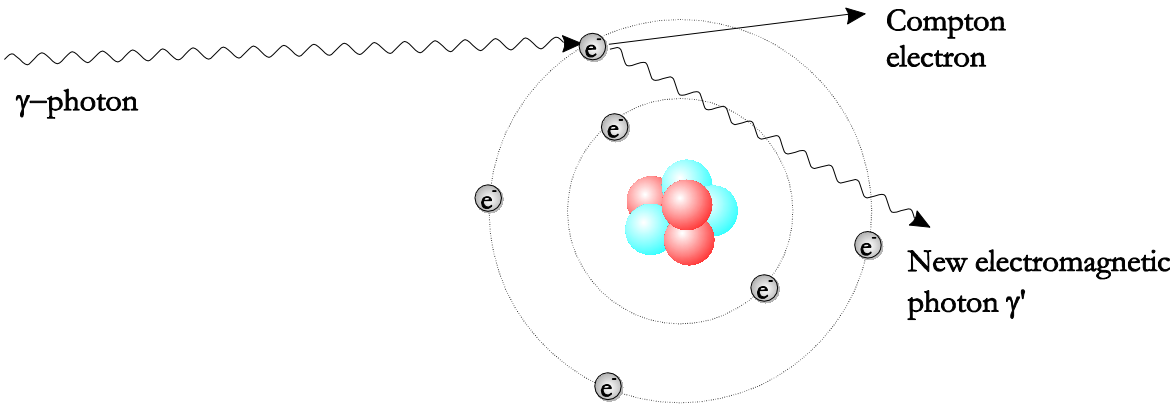

Figure 6 Compton effect: A photon interacts with an electron and transfer some of its energy.

The primary γ loses part of its energy to the Compton electron which gets scattered at an angle from the original direction of the incident , while the compton scattered γ (γ ') is scattered as an angle. In this process, the scattered photon and Compton electron share the energy of the incident γ.

The KE carried off by the Compton electron may be deposited locally (i.e., absorbed immediately by the surroundings). However, the energy carried off by the Compton scattered photon is not deposited locally. Therefore, this scattered photon can significantly contribute to the dose outside a shielding apparatus.

2.2.3 PAIR PRODUCTION

High energy gamma photons transfer their energy primarily by pair production. A high energy X or γ-ray passing close to a nucleus suddenly disappears and an electron and a positron appear in its place. This interaction must take place in the neighbourhood of a nucleus to conserve momentum.

Since both particles are created from energy supplied by the incident photon, the process is energetically possible only if E_γ or E_X is greater than 1.02 MeV.

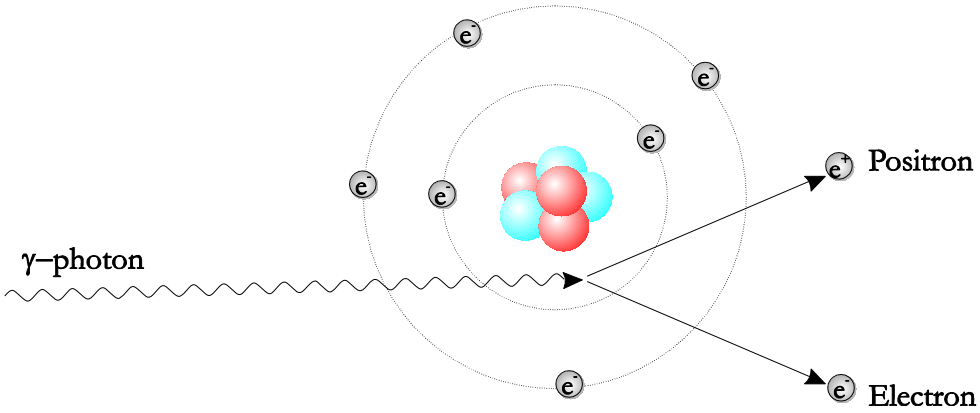

Figure 7 Pair production: A photon passing close to the nucleus disappears and a positron and an electron appear in its place.

When the positron slows down (i.e., loses its KE), it will annihilate itself by combining with an electron. This produces two photons with an energy of 0.51 MeV each. This "annihilation radiation" represents the energy equivalent of the rest mass of two electrons which is converted to pure energy according to the principles of Einstein's theories, in particular, $E = mc^2$; where

E = energy of two 0.51 MeV photons
m = the rest mass of two electrons (1/1840 amu)
c = the velocity of light (3×10^8 m/sec)

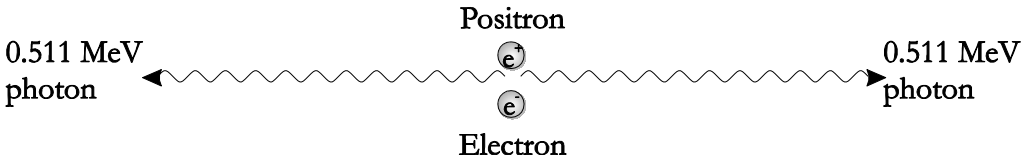

Figure 8 Annihilation: When a positron slows down it will annihiliate itself by combinig with an electron.

Applications of Pair Production

Due to characteristic peaks observed for various known nuclides, Pair Production is an aid in the identification of unknowns.

2.3 RADIATION DOSE

The effect of radiation depends on the amount you have received. The amounts of radiation received are referred to as doses, and the measurement of such doses is known as dosimetry.

2.3.1 ABSORBED DOSE

A similar approach is used in radiation protection measurements, where the unit of ABSORBED DOSE is specified in terms of the amount of energy deposited by radiation in 1 kg of material. This unit is the **gray**, abbreviated Gy. An absorbed radiation dose of 1 Gy corresponds to the deposition of 1 joule of energy in 1 kg of material. Absorbed dose is given the symbol D.

The gray is a measure of energy absorbed by 1 kg of any material, be it air, water, tissue or whatever. A person who has absorbed a whole body dose of 1 Gy has absorbed one joule of energy in each kg of body tissue.

Gray (Gy):

1 Gy = 1 J/kg

The gray is a physical unit. It describes the physical effect of the incident radiation (i.e., the amount of energy deposited per kg), but it tells us nothing about the biological consequences of such energy deposition in tissue.

2.3.2 EQUIVALENT DOSE

Studies have shown that alpha and neutron radiation cause greater biological damage for a given energy deposition per kg of tissue than gamma radiation does. In other words, equal doses of, say, alpha and gamma radiation produce unequal biological effects. This is because the body can more easily repair damage from radiation that is spread over a large area than that which is concentrated in a small area. Because more biological damage is caused for the same physical dose (i.e., the same energy deposited per unit mass of tissue), one gray of alpha or neutron radiation is more harmful than one gray of gamma radiation.

Quality factors are used to compare the biological effects from different types of radiation. For example, fast neutron radiation is considered to be 20 times as damaging as X-rays or gamma radiation. You can also think of fast neutron radiation as being of "higher quality", since you need less absorbed dose to produce equivalent biological effects. This quality is expressed in terms of the Quality Factor (QF). The **Quality Factor** of a radiation type is defined as the ratio of the biological damage produced by the absorption of 1 Gy of that radiation to the biological damage produced by 1 Gy of X or gamma radiation.

Table 1 Quality factors for various types of radiation.

Radiation	Quality Factor
200 – 250 keV X-rays	1
γ-rays, β particles and electrons	1
Thermal neutrons (< 0.8 MeV)	3
Fast neutrons (>0.8 MeV), protons	10
α-particles	20
Hevy ions	20

The absorbed radiation dose, when multiplied by the QF of the radiation delivering the dose, will give us a measure of the biological effect of the dose. This is known as the **equivalent dose**. Equivalent dose is given the symbol H. The unit of H is the sievert (Sv).

An equivalent dose of one sievert represents that quantity of radiation dose that is equivalent, in terms of specified biological damage, to one gray of X- or γ-rays. In practice, we use the millisievert (mSv) and microsievert (μSv). Equivalent dose, quality factor and absorbed dose are related by the expression:

Sievert (Sv)

$H\ (Sv) = D\ (Gy) \times QF$

The sievert is the unit that we use all the time, because it is the only one that is meaningful in terms of biological harm. In calculating the equivalent dose from several types of radiation (we call this "mixed radiation"), all measurements are converted to Sv, mSv or μSv and added. Thus, the sievert allows us to add doses of different radiation types to obtain total effective dose.

Example

What is an individual's dose equivalent from 10 mGy of gamma rays, 5 mGy of β^- particles and 10 mGy of fast neutrons?

$$Dose\ Equivalent\ (mSv) = Absorbed\ Dose(mGy) \times QF$$

Gamma dose equivalent	=	10 x 1	=	10 mSv
Beta dose equivalent	=	5 x 1	=	5 mSv
Neutron dose equiv.	=	10 x 10	=	100 mSv
Total				115 mSv

3 RADIATION INSTRUMENTATION

3.1 PORTABLE SURVEY INSTRUMENTS

The major principle for sensing and measuring radiations in survey instruments is based on the ionizations radiation produces when interacting in a gas filled detector. As described in the previous chapter, radiations passing through matter create ion pairs. In a detector, these ion pairs are collected to form an electrical signal through the use of an electric field. The signal, either a current or a pulse, is then used to register the presence or amount of radiation. There are a number of different types of radiation detectors, each operating on this basic principle, but designed for specific purposes. The two major types of portable radiation survey instruments, the Ion Chamber and Geiger Counter, are discussed below.

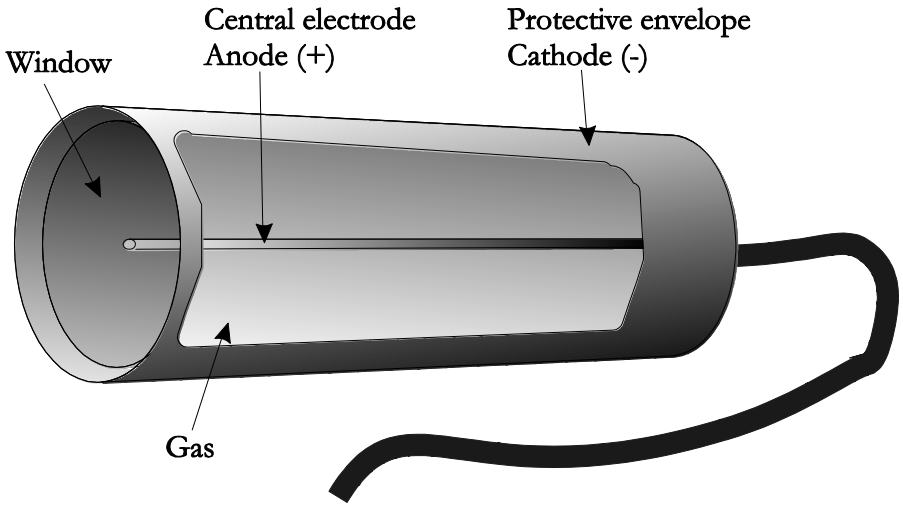

Figure 9 Geiger-Müeller Counter

Ionization produced in the gas converts neutral molecules to positive ions and electrons within the sensitive volume. This volume is contained between charged electrodes, one positive, and the other negative. The charged species are collected at the electrodes of opposite sign.

Either a photon (X or gamma ray), producing primary electrons along its path, or a particle (alpha or beta) producing secondary electrons, will create ions that will travel to the electrodes and be collected. A sufficient potential must be applied across the electrodes to prevent ion recombination and make collection possible. As the ions are collected, a current will flow. This will be measured on a sensitive measuring circuit. Alternatively, the current may be measured as a pulse by a pulse counter from the collection of each primary particle.

3.1.1 IONIZATION CHAMBERS

Ionization chamber type instruments are designed to measure exposure rates of ionizing radiation in units of mSv/hr. The detector is usually cylindrical, filled with air and fixed to the instrument. When radiation interacts with the air in the detector, ion pairs are created and collected generating a small current. The amount of ionization charge deposited in air and the measurement of this ionization current will indicate the exposure rate.

3.1.2 GEIGER-MULLER COUNTER

The most common type of portable radiation survey instrument is the Geiger Counter, also known as a Geiger-Muller (GM) Counter. The GM counter's detector consists of a tube filled with a mixture of "Q-gas", containing 98% helium and 1.3% butane; and usually can be removed from the instrument to survey an area. Instead of measuring the average current produced over many interactions, as in Ion Chambers, the output is recorded for each individual interaction in the detector. Thus, a single ionizing event causes the GM tube to produce a "pulse" or "count". Because all pulses from the tube are the same sizes, regardless of the number of original ion pairs that initiated the process, the GM counter cannot distinguish between radiation types or energies. This is why most GM counters are calibrated in "counts per second" (CPS). However, GM counters can be used to measure exposure rates in mSv/hr as long as the energy of the X or gamma radiation is known and the instrument is calibrated for this particular fixed energy. At best, for a given X or gamma ray energy, the count rate will respond linearly with the intensity of the radiation field. However, in most applications, the radioactive source will have X or gamma rays of various energies which can result in erroneous and unreliable readings. Therefore, GM counters are primarily used to detect the presence of radioactive material.

3.2 USE OF RADIATION SURVEY INSTRUMENTS

Radiation instruments are designed with specific purposes in mind. Choose the instrument depending on your particular needs. Generally, Geiger Counters are more sensitive than Ion Chambers and can monitor low **levels of contamination** in the laboratory. If you wish to measure **radiation levels** in the laboratory, the Ion Chamber is the proper instrument to use. Each instrument comes with an operating manual that describes its function and limitations such as warm up time, battery life, operating temperature range, minimum sensitivities, etc. Outlined as follows are simple instructions on the proper use of portable radiation survey instruments.

1. Read the instrument's operating manual. Gain familiarity with the controls and operating characteristics.

2. Check the batteries. Most instruments have a battery check indicator. Replace weak batteries. Turn off the instrument when not in use. When storing the instrument for extended periods, remove the batteries to prevent damage from battery acid leakage.

3. Check the operability of the detector. Pass the detector over a radioactive check source (sometimes attached to the side or end of the instrument) to verify that the detector responds to radiation in a proper way.

4. Determine the instrument's response time. By passing the detector at varying speeds over a check source, you can determine how long it takes for the detector to respond to the radiation. It is

possible to miss contamination or radiation fields if the detector is moved too rapidly over the area being surveyed.

5. Determine the operating background. Note the instrument's response in an area free of contamination or radiation levels. This is normally due to natural sources of radiation called "background" (See Chapter 0). Subtract this value from the "gross" reading to obtain the "net" results due to the sample itself: $S_{net} = S_{gross} - S_{background}$

When using portable instruments, caution should be used when extending the detector cord as this may generate electrical noise and register as "counts". Also, thin window GM tubes used to detect alpha or low energy beta particles are fragile and can easily break if dropped or punctured.

3.3 CALIBRATIONS AND EFFICIENCY

In order for the results of a survey instrument to be meaningful, the instrument must be calibrated. Calibrations should be performed at least every six month or when battery or test functions indicate a problem. Ion chambers are usually calibrated against Cs-137, Co-60, or an X-ray radiation field. The true exposure rate is determined by multiplying correction factors (if any) by the reading on the instrument. GM counters are usually calibrated against a specified reference standard at a fixed distance from the detector (usually 1 centimeter).

Efficiencies for instruments for a given source expressing results in terms of counts rates can be calculated from the following formula:

$$Efficiency = \frac{Observed\ count\ rate\ (cps)}{Known\ disintegration\ rate\ (Bq)}$$

Divide the observed sample count rate by the detector efficiency to obtain the actual disintegration rate.

Example

A Carbon-14 standard has a disintegration rate of 85,000 Bq. Your GM counter measures a count rate of 4,500 cps. If the background is 250 cps, what is the efficiency of the counter?

$$Efficiency = \frac{4500\ cps - 250\ cps}{85000\ Bq} = 0.05\ \ cps/Bq \times 100 = 5\ \%$$

3.4 COUNTING STATISTICS

Since radioactive decay is a random process, the number of disintegrations in a given time will fluctuate around an average value. The best estimation of this function is given by the standard deviation. For a single measurement,N , the standard deviation represents 68% probability that the actual value lies within the range $N \pm \sigma$. The standard deviation for a large number of measured events (i.e. counts) is given by $\sqrt{N}$:

However, it is usually the counting rate which is of interest and the standard deviation becomes:

$$\sigma = \frac{\sqrt{N}}{t}$$

Where t = counting time.

Example

What is the standard deviation of the count rate for a sample that yielded 1000 counts in two minutes and for a sample that yielded 10000 counts in twenty minutes?

$$Count\ rate = \frac{1000}{2} \pm \frac{\sqrt{1000}}{2} = 500 \pm 15.8\ cpm$$

$$Count\ rate = \frac{10000}{20} \pm \frac{\sqrt{10000}}{20} = 500 \pm 5\ cpm$$

One can see that in counting, greater statistical accuracy can be achieved by increasing the total counts which is usually accomplished by increasing the counting time of the sample. Generally, between 1000 and 10000 counts are needed for a sample to have statistical validity.

3.5 MINIMUM DETECTABLE ACTIVITY

The minimum detectable activity (MDA) is that amount of activity which in the same counting time gives a count which is different from the background by three times the standard deviation of the background counting rate:

$$MDA = Bkg_{rate} + 3 \times \frac{\sqrt{Bkg}}{t}$$

Example

What is the MDA for a counter with a background of 750 counts in ten minutes?

$MDA = 75\ cpm + 3 \times \frac{\sqrt{750}}{10} = 83\ cpm$

Thus, any gross count over 83 cpm can be considered to be due to radioactivity.

However, the MDA for a counting system must be expressed in terms of a net count so that the results can be converted to dpm or Bq. Thus, the MDA becomes:

$$MDA = 3 \times \frac{\sqrt{Bkg}}{t}$$

To calculate the MDA (in dpm) for a known nuclide, divide by the efficiency of the nuclide. Report the MDA for any nuclide for which a net count of zero is calculated or whenever the standard deviation of the sample counting rate brings the net count at or below the MDA. Note that the MDA can be reduced by increasing the counting time and lowering the background. The lower the MDA, the more accurately the activity of samples with low counting rates can be determined.

Example

What is the MDA (in Bq) for a counter with a background of 750 counts in ten minutes and an efficiency of 50% for the nuclide of interest?

$$MDA = 3 \times \frac{\sqrt{750}}{10\ min} = 8\ cpm_{net}$$

$$= 8\ cpm = 16\ Bq$$

3.6 LIQUID SCINTILLATION COUNTING

Liquid Scintillation Counting is the most common technique for the measurement of radioactivity of low energy beta emitters. Such emitters (H-3, C-14, S-35, Ca-45, etc) are difficult to detect using portable survey instruments since the beta may not be able to penetrate the thin window of the gas filled detector. In liquid scintillation counting, the sample is dissolved in a counting solution. The energy of the beta is absorbed by solvent molecules causing them to become excited. This excitation energy is transferred to a solute (known as a scintillator) resulting in a flash of light or "scintillation" when the scintillator molecules return to the ground state. The number of scintillations emitted is proportional to the energy of the beta particle. A photomultiplier tube (PMT) is used to detect and amplify the light photons from the sample. The emitted light causes the emission of photoelectrons from the PMT which are multiplied by the PMT into a measurable electrical pulse. The height (amplitude) of the pulse is proportional to the number of photons which interact in the PMT. Therefore, the pulse height at the output of the PMT is proportional to the energy of the beta particle in the sample. These pulses can be analyzed to provide the energy of the beta particle and the rate of beta emission in the sample. It is also possible to count very low energy gamma emitters by liquid scintillation since most of the gammas are absorbed in the counting solution.

3.7 GAMMA COUNTING

A common method of detecting gamma and X radiations involves the use of a scintillator coupled to a photomultiplier tube (PMT). The most popular scintillation material for this purpose is the sodium iodide (NaI) crystal. Gamma ray interactions within the crystal via the photoelectric effect, compton effect, and pair production result in light or scintillations which are amplified and converted into an electrical pulse by the photomultiplier tube.

Sodium iodide crystals can be made in various sizes, some small enough to use in portable survey instruments. Larger crystals (3 inches in diameter by 3 inches deep) are common for most radioisotope counting room applications such as isotope identification by characteristic photopeaks. Still others have a hole or "well" in the center, allowing the sample to be surrounded by the crystal, resulting in a very high detection efficiency. This type of detector is found in most laboratory "gamma counters" where a large number of samples can be counted automatically.

Unlike liquid scintillation counting, the sample does not need special preparation. The sample can be counted in any physical form. However, care must be taken to have the sample properly contained so as not to contaminate the counting equipment. Gamma emitting isotopes such as I-125, Cr-51, and those decaying by electron capture are best assayed using a NaI detector.

4 Sources and Effects of Radiation

4.1 BIOLOGICAL EFFECTS OF RADIATION

Living organisms are a collection of complex systems of many symbiotic parts arranged and packaged in a manner to allow maintenance of their internal environment and self-reproduction. The basic units are composed of cells. Cells of similar origin and structure are further grouped to form tissues. The four main groups of tissues are: muscle, nerve, connective and epithelial. Associated cells and tissues form organs which, taken collectively, function to create and control the necessary internal conditions suitable for life.

A great diversity exists among the different kinds of cells found in the body. Many have a brief lifespan, undergoing division (a process called mitosis) in a period of hours, while others (such as nerve cells) do not divide at all after birth. Mitosis represents the production of the chromosome, on which the genes containing all the genetic information necessary for cell function resides. Any alteration of the genetic information carried by the genes, or of the processes associated with mitosis can result in either a permanent change in the nature of the cell (mutation), or in the cell's death. When a cellular component is damaged by any agent (chemicals, radiation, excessive heat, etc.), a multitude of measurable effects can result. The changes may initially be restricted to a single or a few types of cells. In time, whole organs or organ systems may be affected due to the absence of a required function that upsets the equilibrium or control of the whole interrelated system. Gross physiological or morphological changes may result from an initial damage to a sufficient number of many kinds of cells. The type of cell damage will depend upon what the specific agent is that the cell is exposed to, and the amount of damage will be related to how much of the agent reaches that particular kind of cell. Biological effects from radiation are produced as a result of the transfer of energy from the radiation to the cells through ionization and excitation as described in the next section.

4.2 RADIOSENSITIVITY OF CELLS

Radiation passing through living cells causes ionization or excitation of atoms and molecules contained in the cell. This is the same process that occurs in any material, as described in Chapter I, Part 5. Since most of the human body is water, water molecules are a likely target for being hit by photons or charged particles. The reaction which occurs when this happens is an ionization to form a positive ion and an electron:

$$H_2O \xrightarrow{ionization} H_2O^+ + e^-$$

and the H_2O^+ is rapidly hydrated to form:

$$H_2O^+ + H_2O \rightarrow H_3O^+ + OH\cdot$$

Here the $OH\cdot$ is a "free radical", a species that contains an unpaired orbital electron, and is highly reactive chemically. The free electron will also react with a water molecule (after it slows down from bumping into other molecules) to yield another free radical, this time hydrogen:

$$e^- + H_2O \rightarrow OH^- + H\cdot$$

The overall reaction is thus:

$$H_2O \xrightarrow{ionization} OH\cdot + H\cdot$$

with the products separated by a considerable distance so that immediate recombination to form water are not favored. Such radicals can combine with each other and with dissolved oxygen to give a variety of potent oxidizing agents such as hydrogen peroxide, superoxide, molecular oxygen and the perhydroxy radical.

Both the initial radicals and these products can migrate to biologically important molecules (like DNA - the structural material of genes) and cause bond breakage and/or oxidation of attached groups. In this way, energy of the radiation is transferred to biologically significant molecules, changing their structure. This mode of energy-transfer is known as the **Indirect Effect** and can account for an appreciable fraction of damage. Note that the presence of oxygen can magnify this pathway due to additional radical formation.

In addition to the indirect effect, radiation may itself cause ionization in DNA or other biological molecules. The energy of ionization is far greater than the bond energy in organic molecules, thus causing bond breakage. The amount of this **Direct Effect** occurring depends on the number of a particular type of molecule in the cells, and its size. The larger a molecule is, the better target it makes. Since DNA is the largest molecule in the cell as well as the site of all the genetic information, its response has a central role in the mediation of radiation effects. Depending on how it is damaged, different results will occur. If the damage results in a strand break in its backbone (breaking the molecule in half), subsequent mitoses may fail resulting in cellular death. If the break is in one of its side groups (bases), it will then transmit different genetic data during subsequent division resulting in some kind of mutation. Both direct and indirect effects contribute to the overall number of such damaging events to the DNA and will vary for individual cell types.

The radiosensitivity of a particular cell depends on a number of factors. An early observation of this difference is reflected in the "Law of Bergonie and Tribondeau" which states "the radiosensitivity of a tissue is directly proportional to the reproductive activity and inversely proportional to the degree of differentiation". Tissues consisting of rapidly dividing stem cells (like blood or sperm cell precursors) are quite sensitive to radiation whereas cells that do not divide or only rarely divide (like nerve or muscle cells) are considerably more resistant. From microscopic examination, cells appear to get stuck in the division process and never successfully complete it after radiation exposure, which is consistent with the "Law" above. Other factors involved include metabolic rate, state of nourishment, oxygen level and presence of particular enzymes within the cell. The latter are most likely involved with the repair of some of the radiation damage.

The following table gives a summary of how various cell, tissues, organs and organ systems are affected by radiation. The doses reported are for X or gamma rays only and represent a single, acute exposure.

Table 2 Relative radiosensitivity of cells, tissue and organs.

Radiosensitivity	Organ	Biological Response
Extremely Radiosensitive	Blood-forming Organs lymph nodes, thymus, spleen, bone marrow	Exposures as low as 0.5 Gy can affect the white cell population within 15 minutes. Red cell counts fall 2 to 3 weeks later. Results in a feeling of general weakness, anemia, and a lower resistance to infection.
Moderately Radiosensitive	Reproductive Organs female, male	Exposures below 1 Gy can reduce fertility. Temporary sterility can occur lasting 12 to 15 months following 2-3 Gy. On the average, a larger exposure is needed to produce sterility in the male than in the female. Damage to the germ cells can lead to somatic and/or hereditary changes.
Radiosensitive	Digestive Organs small intestine, lower intestine, pharynx, esophagus	Degenerative changes occur as soon as 30 minutes after exposure of 5-10 Gy. Initial effects are: impaired secretion of necessary fluids: cell breakdown results in failure of food and water absorption leading to infection and dehydration from diarrhea.
Moderately Radioresistant	Vascular System arteries (lg & sm) capillaries, veins	Sensitivity varies for the vascular system. Damage is great only in the 6-15 Gy range. This damage by radiation contributes to some of the heart, changes in other tissues.
Radioresistant	Skin	Exposures between 5-10 Gy can produce skin changes. However, as little as 1 Gy can cause cell death in the germinal layer.
	Bone and Teeth	Some parts of bone can be damaged by 7-15 Gy. Regeneration can begin 2 to 6 weeks after exposure.
Relatively Radioresistant	Respiratory System	Inflammation of the lungs can occur at 10-20 Gy. Possible hemorrhaging due to changes produced in blood vessels.
	Urinary System	Secondary effects can show up years after exposure in the 5-20 Gy range due to changes in blood vessels.
Very Radioresistant	Muscle and Connective Tissues	Massive exposures (over 20 Gy) are needed to cause slight changes in these tissues.
Extremely Radioresistant	Nervous Tissue	Massive exposures are required (over 30 Gy) to bring about morphological changes in these tissues.

The most radiation-sensitive state of any individual is during embryonic development. If irradiated at a time when a particular tissue or organ is being differentiated, exposures as small as 0.25-0.5 Gy can lead to gross malformations. In humans, this corresponds to 2-6 weeks of gestation. This sensitivity is due to the presence of only a few cells at this stage which ultimately will give rise to a particular tissue or organ. If these are destroyed, other cells cannot replace them.

4.3 ACUTE LETHAL RESPONSE

Lethal effects are observed in mammals within a period of 30 days from acute exposures in the few Gy range. Acute exposure refers to a short time period of delivery of the radiation, generally within minutes. Expression of this response is known as the $LD_{50/30}$ or the dose which yields 50% lethality in an irradiated group of a particular species measured at 30 days. At doses appreciably below the $LD_{50/30}$, very little lethality occurs; whereas at doses appreciably above,100% lethality occurs.

Table 3 Acute lethal responses

Species	Dose (Gy)
guinea pig	1.75-4.09
dog	3.50
goat	3.50
man	3.50-4.50
mouse	5.50
rat	5.90-9.70
monkey	6.00
rabbit	8.00
fowl	10.00
goldfish	23.00

The ranges shown above represent an uncertainty only in the case of man, where precise experimental data does not exist. Other ranges represent a difference depending on the particular strain of the species used. The cause of death at the $LD_{50/30}$ is due to response of the blood forming organs (described previously). Death occurs when the radiation exposure has reduced the number of these cells surviving to a level below that necessary for life. Interestingly, at the tissue level, a given dose yields about the same observable damage in any species. Some species, however, are better able to cope with the damage and so survive.

When organisms are exposed at or above the acute $LD_{50/30}$ value, characteristic physiological responses are seen. These responses are known as “radiation sickness” and “acute radiation syndrome”. The following tables illustrate the symptoms and their timing from various whole-body dosages.

Table 4 Expected effects of acute whole-body radiation doses[2]

Acute Dose (Gy)	Probable Effect
0 – 0.5	No obvious effect, except possibly minor blood changes.
0.8 – 1.2	Vomiting and nausea for about 1 day in 5 to 10 percent of exposed personnel. Fatigue but no serious disability.
1.3 – 1.7	Vomiting and nausea for about 1 day, followed by other symptoms of radiation sickness in about 25 percent of personnel. No deaths anticipated.
1.8 – 2.2	Vomiting and nausea for about 1 day followed by other symptoms of radiation sickness in about 50 percent of personnel. No deaths anticipated.
2.7 – 3.3	Vomiting and nausea in nearly all personnel on first day, followed by other symptoms of radiation sickness. About 20 percent deaths within 2 to 6 weeks after exposure; survivors convalescent for about 3 months.
4.0 – 5.0	Vomiting and nausea in all personnel on first day, followed by other symptoms of radiation sickness. About 50 percent deaths within 1 month; survivors convalescent for about 6 months.
5.5 – 7.5	Vomiting and nausea in all personnel within 4 hours from exposure, followed by other symptoms of radiation sickness. Up to 100 percent deaths; few survivors convalescent for about 6 months.
10	Vomiting and nausea in all personnel within 1 to 2 hours. Probably no survivors from radiation sickness.
50	Incapacitation almost immediately. All personnel will be fatalities within 1 week.

2 The Effects of Nuclear Weapons U.S. Government Printing Office, May 1957

Table 5 Acute radiation syndromes

Response	Dose, Gy	Syndrome
Hematopoietic Death	7 – 10	Death in 10-21 days caused by blood changes resulting in infection or hemorrhaging.
Gastro-intestinal Death	10 – 100	Death in 4-7 days. Nausea, vomiting and diarrhea; food and water intake depressed. Death by severe morphological changes in gastrointestinal tract.
Central Nervous System Death	100 – 1000	Death within 2 days. Minutes after exposure disorientation, incoordination and semi-consciousness develops. Coma and death occurs from central nervous system damage.
Molecular Death	>1000	Immediate death. Death caused by inactivation of substances required for basic metabolic processes.

CHRONIC EXPOSURE RESPONSE

If a given radiation exposure is delivered over a longer time period, the effect observed is less. Experiments utilizing the "split-dose" technique have shown that radiation damage is repaired by the organism as long as any single exposure is less than the $LD_{50/30}$. For example, if animals are given one-half of the $LD_{50/30}$ (called a "conditioning dose") followed some time later by another equal dose (called the "test dose") with sufficient separation of the two doses (say, a few weeks), the animals will survive. If no time elapses between them, death occurs within 30 days. Spreading the dose over weeks or months at a low rate reduces the effect appreciably. For the induction of mutations in mice, the mutation yield for chronic exposure is about half that for acute exposure. Many other responses appear to follow this reduction in effectiveness under chronic exposure conditions.

4.4 LATE EFFECTS OF RADIATION

Radiation, given either acutely or chronically, increases the incidence of a number of conditions observable from 5-20 years after the exposure was delivered. None of these responses are unique to radiation exposure, they occur with some normal incidence in the general population, but are increased in frequency in irradiated populations. The following have been shown to be associated with radiation:

Table 6 Types of Late Effect

Effect	
Carcinogenesis	The reason for increases in certain forms of cancer by radiation (or other carcinogenic agents) is still speculative. Leukemia, skin, lung and bone cancers are radiogenic.
Tissue Effects	Of most concern are cataracts and sterility. Cataracts develop slowly, but can stop or even regress. Sterility can be either permanent or temporary.
Hereditary Effects	Since the time between generations is long, and controlled experimentation can only be performed in animals which may or may not represent the human response, the ultimate effect on us remains in question.
Lifespan Shortening	Chronic exposure results in about a 7% lifespan shortening for every dose equivalent to the LD_{50} received. A survivor of an acute LD_{50} dose has a life expectancy reduced to 50% of an unirradiated control.

The above late effects can only be predicted for large populations. For an individual in an irradiated group, death cannot be identified as to its exact cause, either natural or from one of the many environmental agents capable of producing the same effect. No amount of experimentation is expected to yield any way to identify the precise agent which may be the cause of any of these effects when several are present. That is because each agent will contribute to the risk in proportion to its amount and effectiveness, as well as factors related to the genetic resistance or sensitivity of the individual exposed.

4.5 COMPARISON OF HEALTH EFFECTS

Studies have compared the projected loss of life expectancy resulting from exposure to radiation with other health risks. Estimates are calculated by looking at large numbers of individuals, recording the age at which death occurs from apparent causes, and estimating the number of days of life lost as a result of these early deaths. The total number of days of life lost is then averaged over the total group observed.

Table 7 Estimated Loss of Life Expectancy From Health Risks[3]

Health Risk	Estimate of Days of Life Expectancy Lost
Smoking 20 cigarettes/day	2370 (6.5yr)
Overweight by 20%	985 (2.7yr)
Auto accidents	200
0,05 Gy/year for 30 years (calculated)	150
Alcohol consumption (US average)	130
Home accidents	95
Safest jobs (such as teaching)	30
0,01 Gy/year for 30 years (calculated)	30
Natural background radiation (calculated)	8
Medical X-rays (calculated from US average)	6
Natural disasters	3.5
0,01 Gy occupational dose (calculated)	1

These estimates illustrate that health risks from occupational radiation exposure are of the same order of magnitude as risks that we have historically encountered in normal day-to-day activities. Exposure to radiation should be considered in this perspective when considering its risk. As long as radiation exposure is kept at a value where its contribution to risk is a small part of the total sum of all risks, then it should not be of major concern.

4.6 RADIATION EXPOSURE LIMITS

4.6.1 BASIS FOR THE CURRENT RADIATION EXPOSURE LIMITS

Occupationally exposed individuals are allowed higher radiation exposures than the general population for the following reasons:

1. The radiation worker accepts some small risk balanced against some benefit (through employment).
2. There is a conscious selection of occupationally exposed individuals: minors are excluded, medical histories can be obtained and maintained. Fertile women may be excluded.
3. There is a limit on the percentage of radiation workers in the total population.

3 Adapted from USNRC Regulatory Guide 8. 29

4.6.2 EXTERNAL EXPOSURE

The Norwegian regulation on radiation protection and use of radiation[4] describe the radiation exposure limits to an occupational radiation worker as follows:

All radiation exposure shall be kept as low as reasonably achievable (ALARA), and the following dose limits shall not be exceeded:

a) The dose limit for workers over the age of 18 is 20 mSv per calendar year. The Norwegian RadiationProtection Authority may grant dispensation for individuals where the nature of the work makes it impracticable to set an annual limit of 20 mSv. In such cases permission may be given for a limit of 100 mSv over a continuous five-year period, on condition that the effective dose does not exceed 50 mSv in any single year.

b) The radiation dose to the lens of the eye shall not exceed 150 mSv per year.

c) The radiation dose to the skin, hands and feet shall not exceed 500 mSv per year.

d) For apprentices between the age of 16 and 18 years who use radiation sources as part of their training, doses of respectively 5, 50 and 150 mSv per year apply instead of the doses stated under a) to c).

e) For pregnant women the dose to the foetus shall not exceed 1 mSv for the remainder of the pregnancy, i.e. after pregnancy has been established.

Rescue work in emergency situations shall as far as possible be carried out within the general dose limits mentioned in a) to c). If the work may involve doses in excess of 50 mSv, the work shall only be carried out by volunteers who have been thoroughly informed of the risks and hazards involved. Women of fertile age may participate provided they are not pregnant. Exceeding this limit can only be accepted in order to save lives, avoid serious damage to health or prevent a dramatic escalation of the accident. Radiation doses in excess of 500 mSv shall as far as possible be avoided and can only be accepted in order to save lives, and only after a thorough assessment has been made and it is recognised that the benefits clearly outweigh the costs in the form of health risk to the rescue personnel.

Where there is reason to believe that an employee has exceeded the dose limit, the employer shall immediately carry out an investigation to identify the causes, and take steps to avoid repeats.

4 Regulations No. 1362 of 21 November on Radiation Protection and Use of Radiation (Radiation Protection Regulations)

5 RADIATION FROM BACKGROUND, CONSUMER PRODUCTS, AND MEDICAL EXPOSURE

The population as a whole is exposed to radiation whether it be from naturally occurring radioactivity present in the earth, from interstellar space, from medical sources, or from radio-activity contained in consumer products.

5.1 NATURALLY OCCURRING RADIATION

Naturally occurring radiation arises from three sources: cosmic rays entering the earth's atmosphere, naturally occurring radioactive materials in the earth's crust; and naturally occurring radioactive materials within the body.

5.1.1 COSMIC RADIATION

Primary cosmic rays are of galactic origin and consists of high energy protons, ^{4}He ions, electrons, and photons (X and gamma rays). When these particles enter the atmosphere, they interact with the nuclei of the atoms in the air, giving rise to neutrons, electrons, protons, gamma rays, and other particles which are responsible for most of the observed cosmic ray dose. Because of the earth's magnetic field, the cosmic ray intensity varies with latitude, the lowest value at the geomagnetic equator. The intensity also varies with elevation, the highest levels being in the upper atmosphere. Cosmic rays from solar flares consists of X-Rays, protons, and alpha particles. Because these solar cosmic rays are relatively low in energy, they usually do not contribute significantly to increases in the radiation dose a ground level.

5.1.2 TERRESTRIAL RADIATION

Naturally occurring radionuclides in the environment are classed as either cosmogonic or primordial. Cosmogonic nuclides are those nuclides produced in the atmosphere when primary and secondary cosmic rays undergo nuclear reactions with nuclei of atoms in the air. The main contributors to external exposure from cosmogonic nuclides are Be-7, Na-22, and Na-24.

Primordial nuclides are those that are long lived and have existed in the earth's crust throughout history. The main contributors to external exposure from primordial nuclides are K-40, U-238, and Th-232, and their decay products. The concentrations of primordial nuclides in soil are dependent on the process by which the soil was formed. The table below shows the typical activity of these nuclides in various types of rock:

Table 8 typical activity of these nuclides in various types of rock[5]

Type of Rock / Sedimentary	Typical Activity Concentration (mBq/g) K-40	U-238	Th-232	Absorbed dose rate in air (mGy/hr)
Acidic (e.g. granite)	1000	59	81.4	120
Intermediate (e.g. diorite)	703	23	32.5	62
Mafic (e.g. basalt)	240	11.5	11	23
Ultrabasic (e.g. durite)	148	0.37	24.4	23
Limestone	89	27.7	7	20
Carbonate	---	26.6	7.8	17
Sandstone	370	18.5	11	32
Shale	703	44.4	44.4	79

In various parts of the world, there are areas with high natural radiation levels. At the beach of the Black Sands in Guarppari, State of Espirto Santos, Brazil, it is possible to receive a radiation exposure of 50 µGy/hr due to the monazite (Thorium bearing minerals) sands. At Pocos de Caldas, State of Gerais, Brazil, the average range of radiation exposure is from 1 - 30 µGy/hr.

Naturally occurring radionuclides can give rise to external doses when contained in raw materials used to construct roads and buildings. Uranium and thorium are commonly found in cement, concrete blocks, and masonry products. For example, the possible annual dose near a granite wall at the "Redcap Stand" in Grand Central Station, New York is 2 mSv (assuming an occupancy of 8 hrs/day).

5.1.3 INTERNAL RADIATION

Naturally occurring radionuclides enter the body through inhalation and ingestion. Of the cosmogonic nuclides only H-3, C-14, and Na-22 contribute to internal exposure. The major contribution to internal exposure from primordial nuclides are K-40 and the decay products of the uranium and thorium series.

1. **Tritium**
   Tritium is produced in the atmosphere by secondary cosmic ray neutrons interacting with N-14 nuclides. The global inventory of tritium is calculated to be 1.25×10^{18} Bq*. Most (99%) of the H-3 inventory is converted to tritiated water and takes part in the normal water cycle. Approximately 65% of the inventory is in the oceans as a result of transport by rain. About 30% of the inventory is in land surfaces with the remaining in the atmosphere.

2. **Carbon-14**
   C-14 is also produced by cosmic ray neutrons. The global inventory of C-14 is about $1{,}11\times10^{19}$, with 94% distributed in the ocean, 4% in the land surface and biosphere and the remaining in the atmosphere. The natural specific activity of C-14 is 225 mBq/gm of carbon.

3. **Potassium-40**
   Potassium is an essential element of the body and enters via the food chain. The amount of potassium in the body varies with age and sex. The average whole body activity concentration of K-40 is 59 Bq/kg. K-40 emits beta and gamma radiations and is, therefore, a source of both internal and external radiation exposure.

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5 UNSCEAR 1977 Report

4. Uranium and Thorium Series

The radionuclides that contribute to internal exposure from the uranium series are: U-238, Ra-226, Rn-222, and its decay products Pb-210, Bi-210, and Po-210. The major nuclides that contribute to internal exposure from the thorium series are: Th-232, Ra-228, Ra-220, and its decay products Pb-212, Bi-212, and Po-212. The major contribution to the natural internal dose is from the decay products of Rn-222. The major source of these alpha emitting nuclides is through emanation of Rn-222 from the ground. The decay products form in clusters with water, oxygen, and other gases and attach themselves to aerosol particles. They can be inhaled, ingested, and through direct deposition on plant leaves and root absorption enter the food chain. Cigarettes are estimated to contain 22 mBq of Pb-210 and 15 mBq of Po-210. Brazil nuts and Pacific salmon have been found to contain larger concentrations (>185 mBq/kg) of radium-226. There are areas in the world in which water concentrations of uranium and radium are high due to isolated deposits. Reindeer and caribou contain elevated levels of Pb-210 and Po-210 mainly because they feed on lichens in the winter which accumulate these isotopes. The Pb-210 in fish and mollusks range between 0.74-18.5 Bq/kg.

The main source of radon indoors is from building materials such as by-product gypsum, used for internal walls and ceilings, and concrete. Increasing the ventilation of the room will significantly reduce the radon levels. The highest levels found in poorly ventilated areas, such as basements, where radon diffuses out of the concrete walls and through cracks in the floor. Sealing the walls and floors with epoxy paint can reduce the emanation rate by a factor of four. Three layers of oil paint can reduce the emanation rate by an order of magnitude.

5.1.4 SUMMARY

Table 9 summarizes the estimated annual tissue absorbed dose from natural sources:

Table 9 Estimated annual tissue absorbed dose from natural sources[6]

Source of Irradiation	Gonads (mGy)	Lungs (mGy)
External Irradiation		
Cosmic Rays:		
Ionizing component	280	280
Neutron component	3.5	3.5
Terrestrial Radiation: (γ)	320	320
Internal Irradiation		
Cosmogonic radionuclides:		
H-3 (β)	0.01	0.01
Be-7 (γ)	-----	0.02
C-14 (β)	5	6
Na-22 (β+γ)	0.2	0.2
Primordial radionuclides:		
K-40 (β+γ)	150	170
Rb-87 (β)	8	4
U-238, U-234 (a)	0.4	0.4
Th-230 (a)	0.04	0.4
Ra-226, Po-214 (a)	0.3	0.3

6 Source: UNSCEAR 1977 Report

Source of Irradiation	Gonads (mGy)	Lungs (mGy)
Pb-210, Po-210 (a+β)	6	3
Rn-222, Po-214 (a) inhalation	2	300
Th-232 (a)	0.04	0.4
Ra-228, Tl-208 (a)	0.6	0.6
Rn-220, Tl-208 (a) inhalation	0.08	40
Total (rounded)	780	1100

5.2 TECHNOLOGICALLY ENHANCED EXPOSURES TO NATURAL RADIATION

Technologically enhanced exposure to natural radiation is defined as exposure to natural radiation to which man would not be exposed if some kind of technology had not been developed. For example, travel by air, using natural gas for cooking or heating, and living near a coal fired power plant increase an individual's exposure to naturally occurring radiations.

Air travel increases the exposure due to comic rays and solar flares when flying at high altitudes. The following table shows calculated doses for various routes:

Table 10 Comparison of Calculated Cosmic-Ray Doses to a Person Flying in Subsonic and Supersonic Aircraft Average Solar Conditions[7]

Route	Subsonic Flight at 11 km		Supersonic Flight at 19 km	
	Flight duration (hr)	Dose per round trip (µGy)	Flight duration (hr)	per round trip (µGy)
Los Angles-Paris	11.1	40	3.8	37
Chicago-Paris	8.3	36	2.8	26
New York-Paris	7.4	31	2.6	24
New York-London	7.0	29	2.4	22
Los Angles-New York	5.2	19	1.9	13
Sydney-Acapulco	17.4	44	6.2	21

The table below shows the doses received by astronauts on various space missions. The largest part of the dose was received when the spacecraft passed through the earth's radiation belts. The belts contain protons, electrons, and alpha particles trapped by the earth's magnetic fields.

7 Source: UNSCEAR 1977 Report

Table 11 Absorbed Dose in Chests of Astronauts on Space Missions[8]

Mission or Mission Series	Launch Date (Yr-Mo-Dy)	Duration of Mission (Hr)	Type of Orbit	Dose(mGy)
Apollo VII	68-08-11	260	Earth Orbital	1.57
Apollo VIII	68-12-21	147	Circumlunar	1.50
Apollo IX	69-02-03	241	Earth Orbital	1.96
Apollo X	69-05-18	192	Circumlunar	4.80
Vostok 18-6			Earth Orbital	0.02-0.80
Voskhad 1,2			Earth Orbital	0.30-0.70
Soyuz 3-9			Earth Orbital	0.62-2.34

Individuals living around coal-fired power plants are exposed to enhanced levels of Ra-226, Ra-228, U-238, Th-228, Th-232, and K-40 from gaseous and particulate combustion products of coal. The major contribution to the dose is from the alpha radiation of Pb-210, Th-228, and Th-232.

Phosphate products contain high concentrations of the nuclides in the U-238 decay series. About 1/2 of the phosphate rock that is mined is converted into fertilizer, the rest goes into commodities such as phosphoric acid, gypsum, and land fills. Thus, the use of phosphate fertilizers result in radiation exposures from the following:

1. Absorption of radionuclides by food crops.
2. External radiation from fertilizer storehouses and production plants.
3. Airborne radon decay products over land reclaimed after phosphate mining.
4. Radiation from gypsum used in building products.

5.2.1 CONSUMER PRODUCTS

Radiation exposure from consumer products are considered "enhanced" since the radioactive material is deliberately incorporated into the product to serve a specific purpose.

5.2.1.1 RADIOLUMINOUS PRODUCTS

Products such as time pieces, aircraft instruments, signs, indicators, etc. contain various amounts of Ra-226, Pm-147, or H-3 to provide illumination. Light is generated when the radiations from these nuclides interact with a scintillator, usually zinc sulfide. The scintillator can be in the form of a paint (watch hands) or a coating inside of glass tubes (exit markers) to make the product "glow in the dark". With the exception of Ra-226, the low energy radiations are unable to penetrate watch crystals, glass tubes, etc. Because of the more energetic radiations from Ra-226, it is now rarely used.

8 Source: UNSCEAR 1977 Report

5.2.1.2 ELECTRONIC AND ELECTRICAL EQUIPMENT

Radioactive materials are used in lamps and electronic tubes to provide pre-ionization in gases for the purposes of passing an electrical current. This allows the equipment to respond faster and more reliably. Smoke detectors use alpha radiation from Am-241 to provide an ionization current. Smoke or combustion products entering the detection chamber cause a change in resistance (the alpha particles being stopped or absorbed by the smoke) triggering an alarm. Anti-static devices use Po-210 to ionize the air around a charged object, thereby allowing the charge to be neutralized.

5.2.1.3 MISCELLANEOUS

Porcelains used in dentistry contain uranium in combination with cerium in order to simulate the natural fluorescence of teeth. Certain glazes used in ceramics contain uranium oxides and sodium uranite as pigments. Glazes ranging from black, brown, green, and the spectrum from yellow to red are used primarily to decorate pottery and tableware. Mantles in gas lanterns and yard lights consist mainly of thorium oxides. Major radiation exposure occurs during the first few hours that a new mantle is used, primarily from the inhalation of the thorium. Color televisions generate X-rays (via Bremsstrahlung) as a result of high speed electrons striking the phosphor screen of the picture tube. Most televisions today have high voltage controls and sufficient thickness of glass to absorb most of these low energy X-rays. The following tables describes various consumer products containing radioactive materials and some annual population dose rates:

Table 12 Selected Products Containing Radioactive Material[9]

Product	Nuclides	Amount
Radioactive Material Contained in Paint or Plastic:		
Time Pieces	H-3	37-925 MBq
	Pm-147	2.4-7.4 MBqq
	Ra-226	3.7-11 kBq
Compasses	H-3	0.185-1.85 GBq
	Pm-147	370 MBq
Thermostat Dials and Pointers	H-3	925 MBq
Automobile Shift Quadrants	H-3	925 MBq
Speedometers	Pm-147	3.7 MBq
Radioactive Material Contained in Sealed Tubes:		
Time pieces, marine navigational instruments	H-3	7.4-74 GBq
Exit signs, stepmarkers, public telephone dials, light switch markers	H-3	7.4-110 GBq
Electronic and Electrical Devices:		
Fluorescent lamp starters	Ra-226	37kBq
Vacuum tubes, electric lamps, germicidal lamps	Natural Thorium	50 mg
Glow lamps	H-3	370 kBq
High voltage protection devices	Pm-147	111 kBq
Low voltage fuses	Pm-147	111 kBq
Miscellaneous:		

9 Adapted from UNSCEAR 1977 Report

Product	Nuclides	Amount
Smoke and fire detectors	Am-241	37-3700 kBq
	Ra-226	0.37-555 kBq
	Kr-85	259 MBq
Incandescent gas mantles	Natural Thorium	0.5 gm
Ceramic tableware glaze	Natural Uranium or Thorium	20% by weight of the glaze

Table 13 Average Annual Population Dose Equivalents from Selected Consumer Products and Miscellaneous Sources[10]

Product	µSv
TV Receivers	50
Airport X-Ray	0.01
Luminous Watches	0.5
Tobacco Products	20000.00
Coal Combustion	10.00
Natural Gas Combustion	50.00
Uranium in Dentures	100000.00

5.2.2 MEDICAL EXPOSURES

The population receives an exposure of radiation as part of planned medical procedures. This type of exposure is dependent on individual's health needs and is not considered as part of the individual's occupational exposure. Typical radiation exposures for various radiographic techniques are as follows:

Table 14 Patient Skin Entrance Exposure, per Film[11]

Technique	mGy
Sacral Spine	21.800
Barium Enema	13.200
Upper GI Series	7.100
Dental Bite-Wing	4.000
Skull	3.300
Chest	0.440

10 Adapted from NCRP Report No. 56

11 Source: Bureau of Radiological Health

5.2.3 SUMMARY

The table below summarizes the annual dose rates received from natural background, medical and other sources of radiation. The values indicated are averages and may vary slightly with other reported values:

Table 15 Annual Dose Rates to Population in USA BEIR III (1980)

Source		µSv/yr
Natural Background		
	Cosmic	280
	Terrestrial	260
	Internal - C-14, Ra-226, Pm-222, K-40	280
	Total Natural Background	820
Medical		
	Diagnosis	770
	Dental	14
	Radiopharmaceutical	136
	Total Medical	920
Other		
	Weapon Tests (Fallout)	50
	Power Plant and Nuclear Industry	< 10
	Building Materials (brick, masonry)	50
	TV Receivers	5
	Airline Travel	5
	Total Other	120.0
Total		1860.0

6 RADIATION PROTECTION AND LABORATORY TECHNIQUES

6.1 EXTERNAL RADIATION PROTECTION

The three basic methods used to reduce the external radiation hazard are time, distance, and shielding. Good radiation protection practices require optimization of these fundamental techniques.

6.1.1 TIME

The amount of radiation an individual accumulates will depend on how long the individual stays in the radiation field:

$$Dose = Dose\ rate\ \times time$$

Therefore, to limit a person's dose, one can restrict the time spent in the area. How long a person can stay in an area without exceeding a prescribed limit is called the "stay time" and is calculated from the simple relationship:

$$Stay\ time = \frac{Limit\ (\mu Sv)}{Dose\ Rate\ (\mu Sv/h)}$$

Example

How long can a radiation worker stay in a 50 µSv/h radiation field if we wish to limit a dose to 1 mSv?

$$Stay\ time = \frac{1000\ \mu Sv}{50\ \mu Sv/h} = 20\ h$$

6.1.2 DISTANCE

The amount of radiation an individual receives will also depend on how close the person is to the source.

6.1.2.1 THE INVERSE SQUARE LAW

Point sources of X and gamma radiation follow the inverse square law, which states that the intensity of the radiation(I) decreases in proportion to the inverse of the distance (d)squared:

$$I\ proportional\ \frac{1}{d^2}$$

To represent this in a more useful formula:

$$I_2 = \frac{I_1 \times {d_1}^2}{{d_2}^2}$$

Where:

I_1= the radiation intensity at distance d_1 from the radiation source.

d_1= the shorter distance from the source where the radiation intensity is I_1.

I_2 = the radiation intensity at distance d_2 from the radiation source.

d_2= the longer distance from the source where the radiation intensity is I_2.

Therefore, by knowing the intensity at one distance, one can find the intensity at any given distance.

Example

The exposure rate one meter from a source is 500 µSv/h. What would be the exposure rate three meter from the source?

$$I_2 = \frac{I_1 \times {d_1}^2}{{d_2}^2} = \frac{500\ \mu Sv/h \times (1\ m)^2}{(3\ m)^2} = 55.6\ \mu Sv/h$$

6.1.2.2 GAMMA CONSTANTS

Gamma radiation levels (µGy m^{-2} GBq^{-1} h^{-1}) of many radionuclides at a distance of one meter have been measured. These "gamma constants" can be used to determine the expected exposure rate at a given distance (using inverse square) for a known quantity of a radionuclide or the number of Curies of a radionuclide from a measured exposure rate. Gamma constants (Γ_δ)for selected radionuclides appear in

Table 20 in Appendix I.

Example

What is the radiation exposure rate 0.3 meter from a 100 MBq point source of Cs-137? $\Gamma_\delta = 80.10\ mGy^{-2}GBq^{-1}h^{-1}$

We have only $100\ MBq$ so the dose rate in 1 meter is:

$80.10\ mGy^{-2}GBq^{-1}h^{-1} \times 100\ MBq = 8.21\ mGy^{-1}h^{-1}$

Using the inverse square law we get:

$$I_2 = \frac{I_1 \times d_1^2}{d_2^2} = \frac{8.21\ mGy/h \times\ (1\ m)^2}{(0.5\ m)^2} = 32.8\ mGy/h$$

6.2 SHIELDING

When reducing the time or increasing the distance may not be possible, one can choose shielding material to reduce the external radiation hazard. The proper material to use depends on the type of radiation and its energy.

6.2.1 ALPHA AND BETA RADIATION

As discussed in Chapter I, alpha particles are easily shielded. A thin piece of paper or several cm of air is usually sufficient to stop them. Thus, alpha particles present no external radiation hazard. Beta particles are more penetrating than alpha particles. Beta shields are usually made of aluminum, brass, plastic, or other materials of low atomic number to reduce the production of bremsstrahlung radiation.

6.2.2 X AND GAMMA RADIATION

Monoenergetic X or gamma rays collimated into a narrow beam are attenuated exponentially through a shield according to the following equation:

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

Where:

I is the intensity outside of a shield of thickness x
I_0 is the unshielded intensity
μ is the linear attenuation coefficient
x is the thickness of shielding material

The linear attenuation coefficient is the sum of the probabilities of interaction per unit path length by each of the three scattering and absorption processes photoelectric effect, compton effect, and pair production. Note that μ has dimensions of inverse length. The reciprocal of μ is defined as the mean free path which is the average distance the photon travels in an absorber before an interaction takes place.

Because linear attenuation coefficients are proportional to the absorber density, which usually does not have a unique value but depends somewhat on the physical state of the material, it is customary to use "mass attenuation coefficients" which removes density dependence:

Mass attenuation coefficient $\mu_m = \frac{\mu}{\rho}$ where ρ = density (gm/cm^3)

For a given photon energy, μ_m does not change with the physical state of a given absorber. For example, it is the same for water whether present in liquid or vapor form. If the absorber thickness is in cm, then μ_m will have units of:

$$\frac{cm^{-1}}{g/cm^3} = \frac{cm^2}{g}$$

Values of the mass attenuation coefficient for lead are given in Table 21 in Appendix I.

Example

The intensity of an unshielded Cs-137 source is 1 mSv/hr. If the source is put into a lead shield 5 cm thick, what would be the intensity on the outside of the shield? Density of lead = 11.35 gm/cm^3

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

$I_0 = 1\ mSv/h$

$\mu = \mu_m \times \rho = 0.114\ cm^2 g^{-1} = 1.29\ cm^{-1}$

$x = 5\ cm$

$I = I_0 e^{-\mu x} = 1 \frac{mSv}{h} \times e^{-1.29\ cm^{-1} \times 5\ cm} = 1.6\ \mu Sv/h$

6.2.3 HALF VALUE LAYER

The half value layer (HVL) is the thickness of the shielding material required to reduce the intensity to one half of its original intensity and can be calculated from:

$$\frac{I}{I_0} = 0.5 = e^{-\mu x}$$

$$x_{1/2} = \frac{0.693}{\mu} = HVL$$

Example

How much lead shielding must be used to reduce the exposure rate from an I-131 source from 32 µSv/h to 2 µSv/h? HVL of lead for I-131 is 0.178 cm.

$$\frac{32\ \mu Sv/h}{2\ \mu Sv/h} = 16 = 4\ HVL$$

$$4 \times 0.178\ cm = 0.71\ cm$$

6.3 PERSONNEL MONITORING

External radiation exposure is measured by personnel monitoring devices. Three major types of monitoring devices in use today are the pocked dosimeter, the film badge, and the thermoluminescent dosimeter (TLD). Personnel monitoring is required when it is likely that an individual will be exposed during any calendar year to a dose of 1 mSv to the whole body (head and trunk, active blood forming organs, gonads) or 50 mSv to the hands. Personnel monitoring provides a permanent, legal record of an individual's occupational exposure to radiation.

6.3.1 POCKET DOSIMETERS

Pocket dosimeters are small devices (about the size of a marking pen) one can carry in a shirt or lab coat pocket to record exposure to radiation. The dosimeter is set to zero prior to use by a separate battery or AC line operated charging device. When radiation passes through the sensitive volume of the dosimeter, the charge is dissipated in proportion to the amount of radiation received. "Self reading" dosimeters have an optical system to allow the wearer to view the amount of radiation received by looking through the dosimeter like a telescope. "Indirect reading" dosimeters require a separate readout device (that also serves as the dosimeter charger). Several exposure ranges are available, the most common being from 0 to 200 µSv.

The advantage of a pocket dosimeter is that it can provide an on-the-spot result of an individual’s exposure to radiation. However, pocket dosimeters are susceptible to erroneous readings when exposed to excessive moisture, dust, or physical abuse. In each case, the dosimeter will read high. For this reason, two dosimeters are usually worn for periods of one day or less. The lower reading dosimeter is considered to be the more

accurate. Another disadvantage is the dosimeter's limited exposure range. If the dosimeter is exposed to radiation beyond its range, then the total exposure received cannot be determined.

6.3.2 FILM BADGES

A typical film badge consists of a film packet and holder. The film packet usually contains two pieces of film, one sensitive to X or gamma radiation in the energy range 15 keV to 3 MeV, and the other sensitive to beta radiation in the energy range from 200 keV to 1 MeV. Radioisotopes with energies below those values referenced above cannot be detected. This is why users of low energy beta emitters such as H-3, C-14, and S-35 are not issued film badges. Exposure to radiation causes the film to turn black upon development, the degree of film blackening is then related to the amount of radiation exposure.

The badge holder contains filters that allow different radiation types (beta, X, gamma, neutron) and energies to be distinguished on the film. An "open" window (i.e., no filter) allows all radiations of sufficient energy to pass and expose the film. A plastic filter absorbs most low energy beta radiation. Other filters such as copper or lead absorb most high energy beta radiation and all but high energy gamma radiation. Fast neutrons interact with a cadmium filter to produce film blackening. Slow neutrons interact with the nitrogen atoms in the film's gelatin layer and the resulting proton tracks are counted.

Advantages of film badges are:

1. They are relatively inexpensive compared to other dosimeter types.
2. They provide a permanent record of an individual's dose (film are kept on file).
3. Films are processed and results reported by a disinterested third party.

Disadvantages are:

1. Films are susceptible to extremes of heat, pressure and moisture.
2. Film processing and receipt of exposure results may take several weeks.

To eliminate this latter disadvantage, pocket dosimeters can be worn along with film badges. If the pocked dosimeter indicates a possible high exposure, the film badge can be evaluated on an emergency basis, usually within twenty-four hours after the receipt by the vendor.

6.3.3 THERMOLUMINESCENT DOSIMETERS (TLDS)

TLDs are small chips of lithium fluoride or calcium fluoride. The chips absorb energy from radiation which excites atoms to higher energy levels within the crystal lattice. Heating the chip releases the excitation energy as light, proportional to the amount of radiation received. Chips are placed in badge holders containing filters to distinguish between energy and type.

Advantages of TLDs are:

1. They are small and can be used as extremity monitors.
2. They can be read on-site or through a disinterested third party.
3. They are reusable.

Disadvantages are:

1. Once the chips are analyzed, the exposure information is lost and cannot be verified at a later date.
2. Chips are relatively expensive.
3. Chips are subject to physical damage such as cracking or breaking, etc.

Figure 10 TLD-dosimeter

6.3.4 PROPER USE OF PERSONNEL DOSIMETERS

1. Personnel dosimeters must be worn only by the person to whom it was issued. Any exposure information will then become a part of that person's exposure history record.
2. Dosimeters should be worn on the part of the body where exposure to radiation is likely. Usually, they are worn between the neck and waist. Care must be taken to prevent items like pens, buttons, lab benches, hood aprons, etc. from shielding the badge holder.
3. Store dosimeters along with the "control" dosimeter in a designated area, away from extremes in temperature and radiation. The purpose of the control is to record any non-occupational exposure while the badge is not being worn (i.e., during transit to and from the vendor).

6.4 POSTING AND LABELING OF RADIOACTIVE MATERIALS

Cautionary signs are required to be posted under certain conditions as described below to warn other individuals in the area that radioactive material or radiation is present:

Caution - Radioactive Materials: In areas or on items where radioactive material is used or stored. Each label shall provide sufficient information to permit individuals handling or using containers or working in the general vicinity to take precautions to avoid or minimize exposure. Such information should include:

1. The type of radioactive material;
2. The estimated activity;

3. Assay date;

4. The individual responsible for the material.

Caution – Supervised area for radiation protection: In areas where the level of radiation could cause a major portion of an individual's body to receive an exposure from external radiation that exceeds 1mSv/year but less than 6 mSv/year. ”Supervised area for radiation protection” postings should be at the point of entrance to the area.

Figure 11 Example of a sign leading into a supervised area

Caution – Controlled area for radiation protection: In areas where the level of radiation could cause a major portion of an individual's body to receive an exposure from external radiation that exceeds 6 mSv/year. ”Controlled area for radiation protection” postings should be at the point of entrance to the area.

7 INTERNAL RADIATION PROTECTION

Internal radiation exposure results when the body is contaminated internally with a radioisotope. When radioactive materials enter the body, they are metabolized and distributed to the tissues according to the chemical properties of the elements and compounds in which they are contained. For example, consider a complex molecule which can be equally satisfied with a C-12 (stable) atom or a C-14 (radioactive) atom at its regular carbon position. If the C-14 decays to nitrogen, the molecular structure is affected. If the molecule were DNA, this might be equivalent to gene mutation. Once radioactive material is in the body, little can be done to speed its removal. Thus, internal radiation protection is concerned with preventing or minimizing the deposition of radioactive substances in the body.

7.1 METHODS OF ENTRY

Radioactive substances, like other toxic agents, may gain entry into the body by four processes:

1. **Inhalation -** Breathing radioactive aerosols or dust.
2. **Ingestion -** Drinking contaminated water, or transferring radioactivity to the mouth.
3. **Absorption -** Entering through intact skin.
4. **Injection -** Entering through a puncture of the skin with an object bearing radioactive materials.

The following diagram is a summary of radionuclide entry, transfer, and exit within the body:

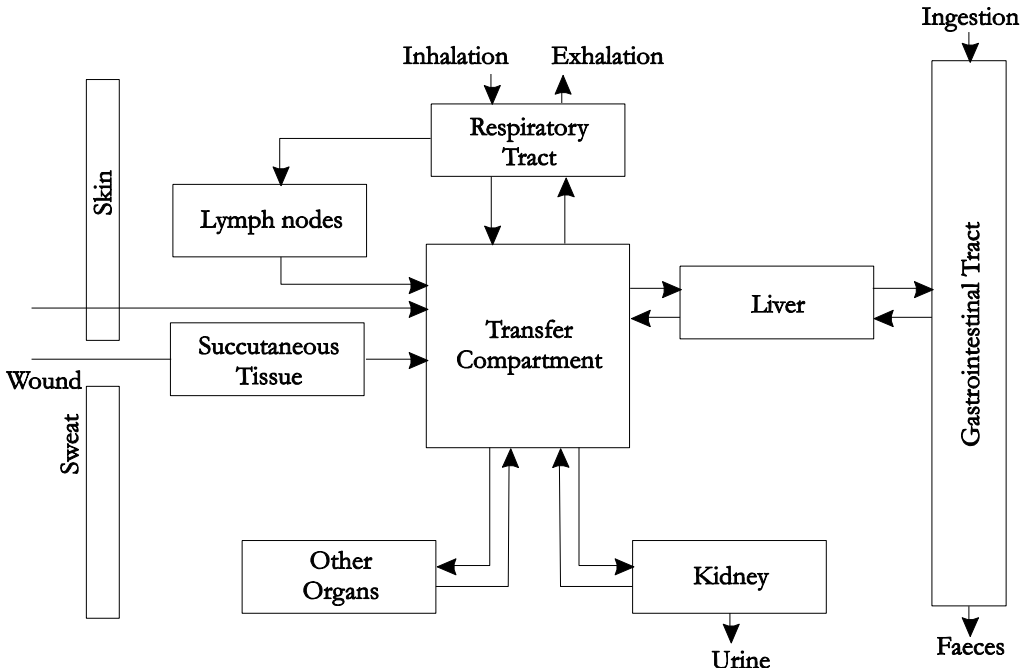

Figure 12 Routes of Intake, Transfers and Excretion

7.2 GUIDELINES

Three basic methods to control radioactive contamination which can lead to internal radiation exposures are:

1. Minimize the amount of radioactive material being handled. Use only as much activity that is needed.

2. Contain the radioactive material. Different physical states (gas, liquid, solid) require different containment techniques. Generally, two levels of containment should be provided. For example, a vial containing a stock solution of radioactive material should be properly capped and placed or transported using a drip tray or other similar device lined with absorbent paper.

Follow established laboratory procedures. Proper protective clothing, designated work areas, surface contamination monitoring, etc., are required in all laboratories that use radioactive material (see chapter 8 page 55).

7.3 INTERNAL EXPOSURE LIMITS[12]

For many radionuclides, the ICRP has calculated the relationship between intake (namely the activity taken into the body) and the dose to the target tissue resulting from that intake. In order to do this, ICRP used a "standard man" in its mathematical models. He is known as Reference Man, and is described in great detail in ICRP Publication 23, which contains a lot of interesting anatomical and physiological data. (For example, the average guy's toenails grow 0.25 mm per week, and he has 1.8 m² of skin weighing 2.6 kg.) ICRP has calculated Annual Limits on Intake for radionuclides. These differ widely for the various radionuclides that were treated by ICRP.

ICRP believes that the dose limits for stochastic effects should be based on the idea that the relative risks should be equal, regardless of whether the dose applies to the whole body (HD) or whether only some tissues are irradiated. In order to make these risks equal, the ICRP has determined weighting factors, w_T, by which doses to tissue must be multiplied to arrive at a whole-body dose that would have the same risk of fatal cancer as the tissue dose.

$$H_W = H \times W_T$$

The ANNUAL LIMIT ON INTAKE (ALI) is the activity of a radionuclide that taken in by itself would commit a person, represented by Reference Man, to 20 mSv of weighted dose, H_W.

This is an important concept. The idea behind these ALIs is that in any year, your intake must not exceed that amount that would cause you to receive a weighted dose greater than 20 mSv. Let's use an examples to be sure that you understand what this means.

---

12 J.U. Burrnham, Radiation protection, Point Lepreau Generating Station, New Brunswick Power Corporation

Example

For Sr-90, the target tissue is the lung: it has a weighting factor of 0.12. A tissue dose, H_T, of 167 mSv to the lung will correspond to a weighted dose of $H_W = 167 \times 0.12 = 20$ mSv. The ALI for Sr-90 is 6×10^4 Bq, because this intake would cause you to receive a lung dose of 167 mSv, and hence a weighted dose of 20 mSv.

Annual Limits on Intake (ALIs) are listed below for selected nuclides.

Table 16 ALI values for some selected nuclides

Nuclei	$T_{½}$	ALI (Bq)	
		Inhalation	Ingestion
^{3}H	12.3 y	1×10^9	1×10^9
^{14}C	5720 y	4×10^7	4×10^7
^{32}P	14.3 d	1×10^7	8×10^6
^{35}S	87.4 d	2×10^8	1×10^8
^{51}Cr	27.7 d	7×10^8	5×10^8
^{57}Co	270 d	3×10^7	9×10^7
^{67}Ga	3.26 d	2×10^8	8×10^7
^{99}Mo	66.0 t	5×10^7	3×10^7
^{99m}Tc	6.02 t	2×10^9	1×10^9
^{125}I	60 d	2×10^6	1×10^6
^{131}I	8.04 d	1×10^6	8×10^5
^{232}Th	1.4×10^{10} y	90	5×10^4
^{238}U	4.47×10^9 y	9×10^4	8×10^5
^{239}Pu	24065 y	300	4×10^4
^{241}Am	432 y	300	3×10^4

Table 17 Organ Dose Weighting Factors

Organ or Tissue	w_T
Gonads	0.25
Breast	0.15
Red bone marrow	0.12
Lung	0.12
Thyroid	0.03
Bone surfaces	0.03
Remainder[13]	0.30
Whole Body[14]	1.00

13 0.30 results from 0.06 for each of 5 "remainder" organs, excluding the skin and the lens of the eye, that receive the highest doses.

14 For the purposes of weighting the external whole body dose, (for adding it to the internal dose) a single weighting factor, Wt = 1.0 is specified.

7.4 INTERNAL EXPOSURE MONITORING

Internally deposited radioactive material can be monitored by measuring the radiation emitted from the body or by measuring the amount of radioactive material contained in the urine or feces. Such monitoring techniques are called "bioassays".

Bioassays are required whenever surveys or calculations indicate that an individual has been exposed to concentrations of radioactive material in excess of established limits or when required by State or Federal regulations.

8 RADIOISOTOPE LABORATORY TECHNIQUES

All laboratories authorized to use radioactive materials require special precautions to minimize the external and internal hazard from radiation and radioactive contamination. This section deals with general regulations and techniques that should be followed in the radioisotope lab.

8.1 PROTECTIVE CLOTHING

1. Lab coats should be worn when manipulating radioactive materials to prevent contamination of street clothing.
2. Disposal plastic gloves should always be worn when handeling radioactive materials. Personnel with breaks in the skin should use waterproof tape to seal such breaks or not use radioactive material.
3. Care should be exercised not to transfer contamination from the hands or lab coat by reflex actions such as wiping one's brow or scratching an itch.

8.2 THE WORKPLACE

1. Areas in which radioactive material are used should be covered with plastic backed absorbent paper to contain spills and prevent contamination of the working surface.
2. Drip trays can be used to transfer beakers, test tubes, etc. from one location to another.
3. Change absorbent paper at regular intervals to prevent cross contamination.
4. Label all containers used for radioactive materials work. Keep the work areas neat and clean to prevent accidents as well as making it easier to decontaminate if accidental spills do occur.
5. Secure all radioactive materials from unauthorized removal. Lock the lab door when materials must be left unattended. Most refrigerator/freezers can be equipped with locks and make an ideal place for storage.
6. There must be no eating, drinking, smoking, or storage of food in areas in which radioactive materials are used.

8.3 MANIPULATIONS OF RADIOACTIVE MATERIALS

1. No mouth pipetting of anything is allowed in a radio-isotope work area. Use a safety pipetting aid for dispensing with standard laboratory pipettes. Eppendorf or other precision pipettes can be used for smaller dispensing. Assume all pipettes and glassware in the work area is contaminated unless labeled otherwise. Contaminated glass pipettes can be placed in a pipette jar for washing. Contaminated Eppendorf tips and disposable pipettes should be placed in radioactive waste containers.
2. Containers used in vortexing, mixing, shaking, or centrifuging operations should be intact and sealed with parafilm or stoppers to prevent spillage.

3. Prepare samples carefully. Heating, drying, distilling, and other operations which could result in volatilization of the material should be performed in a fume hood or glove box. Do not use a heating plate (use heating lamps)
4. Provide proper shielding to reduce exposure, but not so that you hinder the safe execution of the experiment.
5. Whenever possible, rehearse operation with non-radioactive materials to ensure that the technique will be reasonably free of incidents.
6. Accurate records of radioactive material inventory on hand should be maintained. Record withdrawals from the stock vial on inventory control forms received with the isotopes.

8.4 RADIOACTIVE MATERIAL SPILLS

All spills of radioactive material must be cleaned promptly. The responsibility for cleaning up the spill rests on the individual working in the area involved and responsible for the spill. Under no circumstances should an untrained person attempt to examine or clean up a spill of radioactive material.

The following general procedures should be followed when dealing with spills of radioactive materials:

8.4.1 MAJOR SPILLS

Those involving significant radiation hazards to personnel shall be decontaminated under the direct supervision of a qualified individual.

1. Notify all personnel not involved with the spill to vacate the area at once. Have an evacuee notify the radiation protection officer of the incident.
2. Affected persons should limit their movement to confine the spread of contamination.
3. Contain the spill from further spread.
4. Remove contaminated clothing at once: flush contaminated skin areas thoroughly.
5. Shut off ventilating equipment (if possible) that may transport contaminated air from the area to other parts of the building.
6. Vacate and post or cordon off the contaminated area.
7. Assemble in a nearby safe or clean area and begin monitoring and decontamination of affected persons. Do Not Leave the Area unless adequately decontaminated or with the permission of the responsible radiation authorities.

8.4.2 MINOR SPILLS

Those involving little or no radiation hazard to personnel may be decontaminated by laboratory personnel under the direction of the laboratory supervisor.

1. Notify all personnel not involved with the spill. Then notify the radiation protection officer of the incident.

2. Contain the spill: If the material is a liquid, place an absorbent material such as paper towels, tissues, cloth, etc. over the spill to prevent its spread. If the material spilled is a powdered solid, attempt to contain its spread by covering the area with a protective barrier such as a drip tray, empty beaker, section of kraft paper, etc. If appropriate, close doors and windows, turn off room ventilation fans.

3. Inform others of the spill: Adjust your response to the seriousness of the spill. Instruct those personnel present in the room at the time of the spill to remain in an evacuation area to prevent contamination spread. Evacuated personnel should not eat, drink, or smoke until they are monitored and found free of contamination.

4. Decontaminate the area: Plan ahead. Provide adequate protection and supplies for personnel involved in the cleanup. Begin at the periphery and work toward the center of the contamination. Cover cleaned area with plastic or paper to prevent its recontamination. Place all contaminated items in the proper waste containers. The degree of decontamination arranged by the supervisor should be to the limit specified.

5. Monitor the area: Using appropriate survey techniques monitor the progress of the decontamination. Monitor all personnel and materials before releasing them to clean areas.

Other emergencies such as fire, lost or stolen radioactive material, accidental uptake of radioactive material, radiation injury, etc. require the same basic responses as described above - Containment, Notification, Corrective Action, Monitoring. The proper authorities should be notified at once of such incidents and will act with other authorities to control emergencies of this nature.

8.5 RADIOACTIVE WASTE DISPOSAL

Waste retention areas should be managed with close attention to cleanliness. Housekeeping employees should be instructed not to move or empty radioactive waste containers during the course of their duties.

Waste should be segregated according to its radiologic half-life. Short lived waste can be stored until decayed and then be disposed of as regular waste, however, all radioactive labels, markings, tapes, etc., must be removed or defaced before disposal.

Non-radioactive waste must not be mixed with the radioactive waste as this adds to the cost of disposal. A simple wipe survey or instrument survey of the item can determine if it still contains any radioactivity. If only a portion of an item (i.e., lab bench soaker) is contaminated, just that portion should be disposed of into radioactive waste.

Care should be exercised when disposing of waste in different physical or chemical forms:

1. Liquid wastes containing acids should not be mixed with liquids containing bases. Aqueous liquids should not be mixed with organic liquids.

Pipettes and other sharp objects should be bundled together in order to prevent them from puncturing the inner liner of the dry waste container.

Biological waste should contain sufficient amounts of a preservative and absorbent to prevent decomposition.

Radioactive biohazard waste must be treated in the same manner as regular biohazard waste before being placed into radioactive waste containers.

8.6 RADIOACTIVE CONTAMINATION SURVEY PROCEDURES

Surveys for radiation and removable radioactive contamination must be performed after each use of radioactive materials. The purpose of this survey is to identify any contamination present and to prevent its spread. Appropriate radiation survey equipment should be available to users for the type of surveys required for the laboratory. Such survey equipment must be properly calibrated for energy and type of radionuclide in use at least every six months.

To perform a survey, choose sites in the lab where the radioactive material has been used. Areas or equipment such as bench tops, floors near the work area, waste containers, fraction collectors, water baths, storage areas, hoods, etc. are good places to start. Each site chosen should be labeled on a diagram or floor plan of the lab for later referral in interpreting results.

8.6.1 SURVEY FOR REMOVABLE CONTAMINATION

Contamination not fixed to a surface can be transferred to hands, clothing, notebooks, pens, etc. leading to internal exposure or contamination of clean areas. The most common survey procedure to detect the presence of loose contamination is called a wipe test. In this procedure, a piece of filter paper (usually about 1 inch square or circular) is used to wipe over a surface suspected of being contaminated. The area which the wipe should cover is approximately 100 square centimeters. Depending on the surface being wiped, or the type of material being surveyed for, it may be necessary to wet the wipe material with alcohol or other solvent for better adhesion of contaminated particles to the wipe material. A single wipe can be used to determine contamination over a large surface such as a floor or bench top. If radioactivity is found a series of wipes covering smaller areas should be performed to localize the contamination. After wipes have been taken, place them in numbered scintillation vials or other carriers to organize and prevent cross contamination of the samples. Wipes should be treated as potentially contaminated until analyzed. Prepare the wipes for analysis as you would a regular sample. Analyze the wipe samples, using an appropriate instrument. For beta-emitting isotopes with energies above 100 keV, you can hold the wipe material one cm away from a GM tube and observe the count rate. Beta-emitting isotopes below 200 keV (H-3, C-14, S-35) should be analyzed using a liquid scintillation counting system. Wipe samples of gamma or x-ray emitters should be analyzed using a gamma counting system.

In most labs, a liquid scintillation counter (or gamma counter) is already optimized for the particular nuclides in use. Liquid scintillation and gamma counters should have a calibrated reference standard readily available. These standards should be counted each time samples are counted to verify efficiencies and machine settings. A control vial consisting of a "clean" wipe and counting solution must be counted with your samples to determine machine background.

Report results on your diagram in terms of bequerel (Bq) per area surveyed according to the following formula:

$$Sample\ (Bq) = \frac{Sample\ gross\ (Bq) - Background\ (cps)}{Counter\ efficency\ (cps/Bq)}$$

Any wipe indicating a gross cps greater than twice background cps should be cleaned up. Record on the survey diagrams the maximum contamination levels found as well as the final levels. Limits for removable contamination are shown in Table 18.

8.6.2 SURVEY FOR FIXED CONTAMINATION

In laboratories where high energy beta (greater than 100 keV) radioisotopes are used, a survey for fixed contamination should be performed using a GM survey instrument. Where gamma emitting radioisotopes are used, a gamma survey instrument calibrated for the particular radioisotope should be used. Scan the area suspected of being contaminated with the instrument's probe. To prevent possible contamination of the probe, do not let it touch the surface being surveyed. Sites in which the results are twice the background rate could indicate radioactive contamination (Limits for fixed contamination are shown in chapter 8.7) . Record the results of the survey on the laboratory diagram. Any fixed contamination should be tested for removable activity as described above.

8.7 RADIOACTIVE CONTAMINATION LIMITS

The following removable contamination limits can be used as a guide when working with loose radioactive material. By observing good radioisotope laboratory practices, contamination levels should be kept to less than 10 % of the limits.

Table 18 Removable contamination limits

Application	Alpha Bq/cm^2	Beta/Gamma Bq/cm^2
Basic Guide for equipment or surface in a controlled area	4	40
Skin, personal clothing	0.4	4

When contamination levels approach the values, appropriate control measures as described below should be taken. Contamination results greater than the maximum limits in any laboratory area should be reported to the laboratory supervisor and cleaned up right away. Corrective steps should be taken to prevent reoccurrences.

8.8 CONTROL MEASURES FOR RADIOACTIVE CONTAMINATION

The primary concern with radioactive contamination is to prevent its spread to other areas, and prevent its uptake into the body. Once contaminated, therefore it is important to stay in the area, alert others in the area of the problem, and request assistance.

8.8.1 PERSONNEL CONTAMINATION

1. Contamination of the skin or hair may be washed off with soap and water or commercially available decontamination solutions. Repeat washings with plenty of lather and water. Care must be taken not to break the skin when scrubbing. Stubborn fixed skin contamination on the hands may be "sweated" out by wearing a disposable glove sealed at the wrist.
2. Contaminated clothing should be removed in a suitable area while being properly monitored. Clothing may be discarded as waste, stored for decay, or washed. The area must be surveyed after cleanup.
3. If an uptake (inhalation, ingestion, etc.) is suspected contact authorities for appropriate bioassays.

8.8.2 EQUIPMENT OR AREA CONTAMINATION

Equipment or work surfaces can be cleaned using soap or commercially available decontaminating solutions. Decontaminating procedures must prevent the spread of contamination and minimize the amount of waste generated.

Plan ahead:

1. Assemble all cleaning supplies and equipment before starting, remove or cover non-contaminated items.
2. Place contaminated items in designated areas for clean-up, i.e., a fume hood if airborne activity can be generated during clean-up.
3. Wear proper protective clothing.
4. Control access to the designated work area and post appropriate cautionary signs.
5. To minimize fixation of the contaminant, perform the decontamination as soon as practical.
6. Start on the outside and work in to the most contaminated area.
7. Monitor results of clean-up -- Perform surveys regularly.
8. Fixed contamination can be sealed with paint, plastic, or covering to prevent egress.

8.9 RADIATION SURVEY PROCEDURES

Radiation exposure rates should be measured using an ion chamber type survey instrument (i.e., Ludlum, Victoreen, etc.). GM counters can be used to measure exposure rates in mr/hr or r/hr as long as the energy of the X or gamma radiation is known and the instrument is calibrated for this particular energy. Before using any instrument, become familiar with its proper operation. Be certain that the instrument has been properly calibrated usually indicated by a calibration sticker on the instrument (see chapter 3.3).

8.10 CONTROL MEASURES FOR RADIATION LEVELS

The goal of each worker should be to maintain his or her exposure to radiation as low as reasonably achievable (ALARA). When working with radioactive material yielding high radiation levels, special precautions may be necessary to limit exposure to the worker and others in the area.

1. Perform a radiation survey of the material to determine what kind of radiation levels exist. If appropriate, a survey for removable contamination should be performed.

2. Determine if the material can be safely handled without creating a hazard to yourself or others in the area. Therefore, base how long you should work in an area without exceeding this or any other specified limit by calculating your stay time:

$$Stay\ time = \frac{Limit\ (Sv)}{Dose\ rate\ (Sv/h)}$$

3. Use appropriate handling tools and shielding to reduce overall radiation exposure.

4. When finished, perform an appropriate contamination or radiation survey.

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APPENDIX I

Table 19 Mean Quality Factors, Q, And Fluence Per Unit, Dose Equivalent for Monoenergetic Neutrons

Neutron energy (MeV)	Quality factor (Q)	unit dose equivalent (neutrons/cm^2/Sv) (thermal)
2.5×10^{-8}	2	9.800×10^{6}
1×10^{-7}	2	9.80×10^{6}
1×10^{-6}	2	8.10×10^{6}
1×10^{-5}	2	8.10×10^{6}
1×10^{-4}	2	8.40×10^{6}
1×10^{-3}	2	9.80×10^{6}
1×10^{-2}	2.5	10.10×10^{6}
1×10^{-1}	7.5	1.70×10^{6}
5×10^{-1}	11	0.39×10^{6}
1	11	0.27×10^{6}
2.5	9	0.29×10^{6}
5	8	0.23×10^{6}
7	7	0.24×10^{6}
10	6.5	0.24×10^{6}
14	7.5	0.17×10^{6}
20	8	0.16×10^{6}
40	7	0.14×10^{6}
60	5.5	0.16×10^{6}
1×10^{2}	4	0.20×10^{6}
2×10^{2}	3.5	0.19×10^{6}
3×10^{2}	3.5	0.16×10^{6}
4×10^{2}	3.5	0.14×10^{6}

Table 20 Air kerma rate constant for some radionuclides considering photon energy above 20 keV[15]. Kerma is the kinetic energy released in matter. The absorbed dose equals the kerma if all the released energy is absorbed in the matter.

Radionuclide	Half-life	Energy interval (MeV)		Air kerma rate constant	
		From	To	$aGym^{-2}Bq^{-1}s^{-1}$	$\mu Gym^{-2}GBq^{-1}h^{-1}$
^{11}C	20.38 min	—	0.511	38.7	139.3
^{13}N	9.965 min	—	0.511	38.7	139.4
^{15}O	2.037 min	—	0.511	38.7	139.5
^{18}F	109.8 min	0.0005	0.511	37.5	135.1
^{24}Na	14.96 h	1.369	3.866	121.3	436.7
^{42}K	12.36 h	0.3126	2.424	9.1	32.8
^{43}K	22.3 h	0.2206	1.394	35.5	127.8
^{51}Cr	27.70 d	0.0005	0.3201	1.17	4.22
^{52}Fe	8.275 h	0.0006	1.0399	27.01	97.24
^{59}Fe	44.50 d	0.0069	1.4817	40.54	145.9
^{57}Co	271.74 d	0.0007	0.6924	3.92	14.11
^{58}Co	70.86 d	0.0007	1.6747	35.84	129
^{60}Co	5.271 a	1.1732	1.3325	85.82	309
^{67}Ga	3.261 d	0.001	0.8877	5.4	19.45
^{68}Ga	1.127 h	0.001	1.883	35.84	129
^{75}Se	119.79 d	0.0013	0.5722	13.4	48.25
^{99}Mo	65.94 h	0.0024	0.9608	5.49	19.77
^{99m}T	6.01 h	0.0024	0.1426	3.92	14.1
^{111}In	67.31 h	0.0031	0.2454	23.09	83.13
^{113m}I	99.49 min	0.0033	0.3917	12.22	44
^{123}I	13.27 h	0.0038	0.7836	10	36.1
^{125}I	59.4 d	0.0038	0.0355	10.48	37.73
131I	8.021 d	0.0041	0.7229	14.5	52.2
127Xe	36.4 d	0.0039	0.6184	14.19	51.09
133Xe	5.243 d	0.0043	0.1606	3.98	14.33
137Cs/137Ba	30.04 a	0.0045	0.6617	22.8	82.1
152Eu	13.537 a	0.0056	1.7691	41.36	148.9
154Eu	8.593 a	0.0061	1.5965	44.23	159.2
170Tm	128.6 d	0.007	0.0843	0.154	0.554
182Ta	114.43 d	0.0084	1.4531	44.45	160
192Ir	73.827 d	0.0089	1.0615	30.3	109.1
197Hg	2.672 d	0.0097	0.2687	3.159	11.37
198Au	2.695 d	0.01	1.0877	15.15	54.54
201Tl	3.038 d	0.0058	0.1674	2.84	10.22
241Am	432.2 a	0.0139	0.103	1.102	3.97

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Table 21 Mass Attenuation Coefficients for Lead, Z=82[16]

	Energy (MeV)	μ/ρ (cm^2/g)	μ_{en}/ρ (cm^2/g)		Energy (MeV)	μ/ρ (cm^2/g)	μ_{en}/ρ (cm^2/g)
	1.00E-03	5.21E+03	5.20E+03	L1	1.59E-02	1.55E+02	1.18E+02
	1.50E-03	2.36E+03	2.34E+03		2.00E-02	8.64E+01	6.90E+01
	2.00E-03	1.29E+03	1.27E+03		3.00E-02	3.03E+01	2.54E+01
	2.48E-03	8.01E+02	7.90E+02		4.00E-02	1.44E+01	1.21E+01
M5	2.48E-03	1.40E+03	1.37E+03		5.00E-02	8.04E+00	6.74E+00
	2.53E-03	1.73E+03	1.68E+03		6.00E-02	5.02E+00	4.15E+00
	2.59E-03	1.94E+03	1.90E+03		8.00E-02	2.42E+00	1.92E+00
M4	2.59E-03	2.46E+03	2.39E+03		8.80E-02	1.91E+00	1.48E+00
	3.00E-03	1.97E+03	1.91E+03	K	8.80E-02	7.68E+00	2.16E+00
	3.07E-03	1.86E+03	1.81E+03		1.00E-01	5.55E+00	1.98E+00
M3	3.07E-03	2.15E+03	2.09E+03		1.50E-01	2.01E+00	1.06E+00
	3.30E-03	1.80E+03	1.75E+03		2.00E-01	9.99E-01	5.87E-01
	3.55E-03	1.50E+03	1.46E+03		3.00E-01	4.03E-01	2.46E-01
M2	3.55E-03	1.59E+03	1.55E+03		4.00E-01	2.32E-01	1.37E-01
	3.70E-03	1.44E+03	1.41E+03		5.00E-01	1.61E-01	9.13E-02
	3.85E-03	1.31E+03	1.28E+03		6.00E-01	1.25E-01	6.82E-02
M1	3.85E-03	1.37E+03	1.34E+03		8.00E-01	8.87E-02	4.64E-02
	4.00E-03	1.25E+03	1.22E+03		1.00E+00	7.10E-02	3.65E-02
	5.00E-03	7.30E+02	7.12E+02		1.25E+00	5.88E-02	2.99E-02
	6.00E-03	4.67E+02	4.55E+02		1.50E+00	5.22E-02	2.64E-02
	8.00E-03	2.29E+02	2.21E+02		2.00E+00	4.61E-02	2.36E-02
	1.00E-02	1.31E+02	1.25E+02		3.00E+00	4.23E-02	2.32E-02
	1.30E-02	6.70E+01	6.27E+01		4.00E+00	4.20E-02	2.45E-02
L3	1.30E-02	1.62E+02	1.29E+02		5.00E+00	4.27E-02	2.60E-02
	1.50E-02	1.12E+02	9.10E+01		6.00E+00	4.39E-02	2.74E-02
	1.52E-02	1.08E+02	8.81E+01		8.00E+00	4.68E-02	2.99E-02
L2	1.52E-02	1.49E+02	1.13E+02		1.00E+01	4.97E-02	3.18E-02
	1.55E-02	1.42E+02	1.08E+02		1.50E+01	5.66E-02	3.48E-02
	1.59E-02	1.34E+02	1.03E+02		2.00E+01	6.21E-02	3.60E-02

16 Ionizing Radiation Division, Physics Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899