Radiation Safety

Safety Resources

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University of Saskatchewan

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1 RADIATION PHYSICS

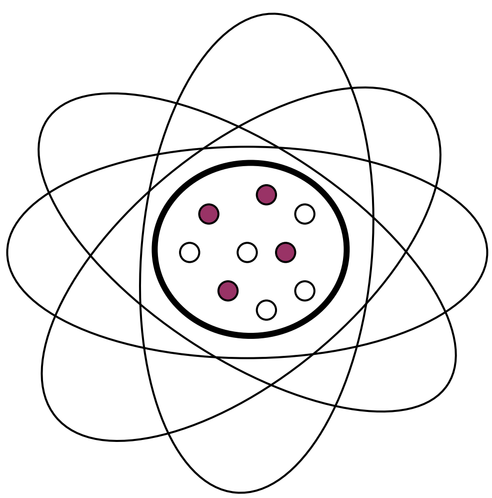
In order to appreciate the origins, characteristics and relative risks associated with nuclear radiation, a few introductory remarks are necessary about the nature of matter.

1.1 The Atom

The atom is the smallest quantity of an element, still retaining the chemical properties of that element. Atoms are made up of protons, neutrons and electrons, all of which are elementary particles. Atoms consist of a nucleus of protons and neutrons, surrounded by a “cloud” of electrons. The nucleus of an atom is positively charged and the electrons are negatively charged. The force that keeps the electrons revolving around the nucleus in elliptical orbits is the electrical attraction of the nucleus, which varies inversely as the square of the distance from the nucleus. The nucleus has a positive electric charge and a definite size. The nucleus constitutes approximately 99.9% of the mass of the atom. The electrons are all alike: each carries the same negative charge and has no determinable size, although each electron has intrinsic angular momentum. An atom has the same number of electrons as protons so that the net electrical charge of the atom is zero. The number of protons in the nucleus determines which element the atom belongs to.

The *atomic number* (Z) represents the number of protons in the atom. The *mass number* (A) of an atom represents the total number of protons and neutrons in the nucleus. Hence, $A = Z + N$, where N represents the number of neutrons in the nucleus.

Example: ${}^{9}_{4}Be$ or ${}^{9}Be$ represents an atom of beryllium.



1.2 Radioisotopes

Each element is characterized by its unique atomic number. Atoms composed of nuclei with the same number of protons but different number of neutrons are called isotopes. Since isotopes have the same number of electrons, they have the same chemical properties and cannot be separated from one another by chemical means. Since they have different masses, they may be separated by physical devices.

Elements often occur naturally with a stable nucleus. In a stable nucleus, the protons and neutrons are bound together by nuclear forces so strong that no particles can escape. If this is the case, the nucleus structure will not change (disintegrate) with the passage of time. For example, an atom of iron may become iron oxide, but even in its combined state with oxygen it has not changed its identity.

Not all isotopes of an element are stable. Unstable isotopes consist of a nucleus which has some unbalance in the number of protons and neutrons. This unbalance will eventually create the ejection of energy (particle) which changes the nucleus from one form to another. The ejection of such energy is known as disintegration and the nucleus will continue to eject particles until a stable isotope is reached. This event during which an unstable atom emits its excess energy and transforms into an entirely different isotope is called *radioactive decay*. These unstable isotopes are referred to as *radioisotopes.* For example, ^{11}C and ^{14}C are radioisotopes of carbon, where as ^{12}C and ^{13}C are stable isotopes of carbon.

Light nuclei, with a few protons and neutrons, become stable after one decay. When a heavy nucleus such as radium or uranium decays, the resulting nucleus may still be unstable and the final stable state is reached only after several decays.

The radioactive decay process accounts for the existence of many radioactive nuclides in the environment.

In general, more than one type of radiation is emitted from each radioisotope. The *yield* (fraction emitted per disintegration) and energy are unique to that radioisotope.

1.3 Activity

Uranium-238 and its daughter Thorim-234 each contain about the same number of atoms per gram; approximately 2.5×10^{21} Radioactivity refers to the capability of a given substance to emit radiation. It does not give an idea of the intensity of radiation emitted. The intensity is provided by the unit *Becquerel,* named after the French physicist, Henri Becquerel. The *activity* of a radionuclide refers to the number of nuclear transformations occurring in a given amount of radionuclide per unit time. The activity is the rate of disintegration (decay) of a nuclear substance. Radioactive and radioactive properties of nuclides are determined by nuclear considerations only, and are independent of the chemical and physical states of the radioisotope. The International System of Units (SI) unit, for activity is called the Becquerel (Bq). A *Becquerel* is defined as one disintegration per second.

1 Becquerel (Bq) = 1 disintegration/sec.

Another unit of activity is the C*urie* (Ci). A Curie is defined as 37 000 000 000 (billion) disintegrations per second.

1.4 Half-life

The time required for any given radioisotope to decrease to one-half of its original activity is a measure of the speed with which the isotope undergoes radioactive transformation. This period of time is called the *half-life*, and is characteristic of the particular radioisotope. Each radioisotope has its own unique rate of transformation, and no operation, either chemical or physical, is known that will change the transformation rate; the half-life of a radioisotope is an unalterable property of the isotope. Half-lives of radioisotopes range from microseconds to billions of years.

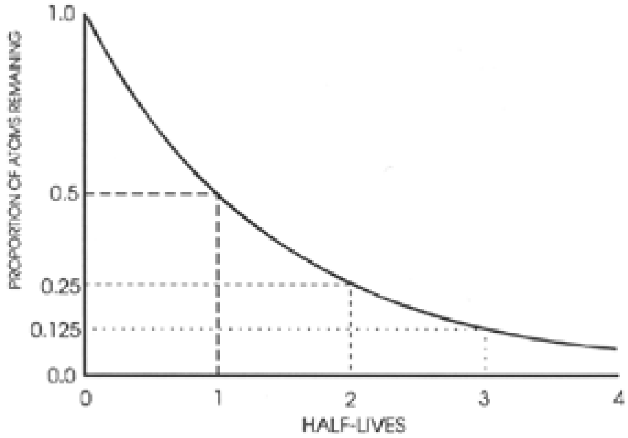
Radioactive decay occurs when an unstable nucleus rearranges its structure to achieve stability and emits particles or photons in the process. Not all of these particles or photons come from the nucleus. Some may originate in or between electron shells as the electrons themselves are ejected from an atom or as they drop into lower energy levels to fill the gaps left by ejected or absorbed electrons.

Because radioactive decay is a random process, we can only say that there is a probability it will occur within a specified interval. For a population of atoms of the same element and mass number, this probability is called the *decay constant*, lambda (λ). Lambda is equal to the natural logarithm of two divided by the half-life.

$$\lambda = \frac{0.693}{T_{1/2}}$$

where $T_{1/2}$ = half-life.

The formula of this curve (an exponential function) enables us to determine, among other things, the number of radioactive atoms remaining at any time, provided we know how many were present to begin with.



$$N = N_o e^{-\lambda t}$$

N = number of atoms at time *t*
N_o = number of atoms at start (time *t* = 0)
e = base of natural logarithms
t = the elapsed time

* Note that the units of time for the decay constant and the elapsed time must be the same.

The rate at which radioactive decay takes place is measured by the half-life of that radioactive substance.

This relationship in the equation above can be simplified to the following:

$$A = A_o (0.5)^{\frac{t}{T_{1/2}}}$$

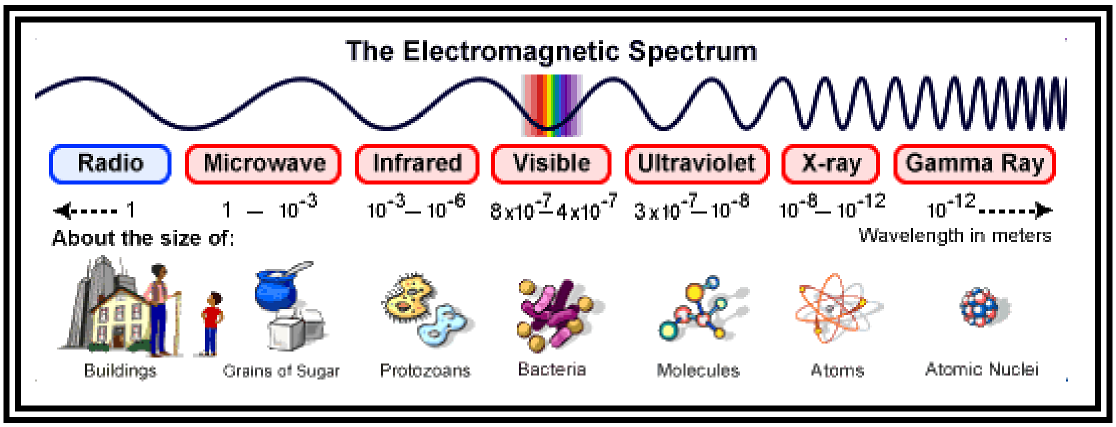
Example: Given: 10 mCi of ^{32}P with a $T_{1/2}$ of 14 days.
Find the activity remaining after 49 days.

Solution:

1.5 Radiation

Radiation is energy travelling in the form of waves or subatomic particles.

Radiation is the emission and propagation of energy in the form of waves or particles. Radiation *waves* vary in frequency and wavelength and may be described according to their position on the electromagnetic spectrum. The electromagnetic spectrum includes gamma and x-rays, ultraviolet radiation, visible light, infrared radiation, and radio waves.



Courtesy of Space Telescope Science Institute operated by NASA for AURA.

All forms of radiation are capable of travelling through a medium or space, depending on the type of radiation and the medium. Furthermore, when radiation travels through a medium it deposits (loses) some of its energy to the medium.

Radiation exists in several physical forms, each with unique characteristics that define how and to what extent, it interacts with matter. There are two types of radiation: electromagnetic and particulate. The radiation type, size, electric charge and rate of activity all impact the level of hazard posed by radiation and the protective measures required to work with it safely. Summarized below, are some of the fundamental characteristics of the most common types of radiation; alpha particles, beta particles, neutrons and gamma/X-rays.

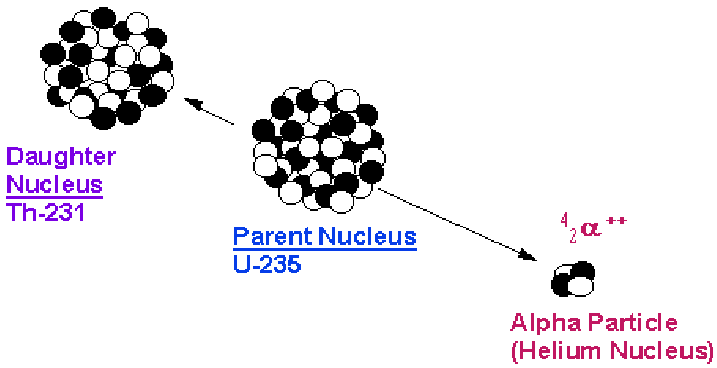
1.5.1 Alpha Particle

An alpha particle is a highly energetic helium nucleus that is emitted from the nucleus of the radioactive isotope when the neutron to proton ratio is too low. Alpha decay is a radioactive process in which a particle with 2 neutrons and 2 protons is ejected from the nucleus of a radioactive atom. With one exception, samarium-62, naturally occurring alpha emitters are found only among elements of atomic number greater than 82. The nuclei of these atoms are very “neutron rich” (i.e. have more neutrons than protons in nucleus) which makes emission of alpha particles possible.

An alpha particle (α):

- originates from a disintegrating nucleus;

- is composed of two neutrons and two protons thus carrying a positive charge of two (+2);
- is a powerful ionizer because particle is a heavy subatomic particle (roughly 2,000 time heavier than an electron);
- is essentially a monoenergetic particle with an energy range between 4 to 8 MeV;
- can travel in air between 1 to 2 cm;
- is effectively stopped by a sheet of paper;
- cannot penetrate the 0.07 mm outer-layer of skin (dead skin).



1.5.2 Beta Particle

The beta particle is a highly energetic electron as is its antimatter counterpart, the positron. Thus, beta particles can take either a negative (for the electrons) or positive (for the positrons) charge. There are two main conditions that spur the release of beta particles from radioactive nuclei: (1) when there is just too many neutrons compared to protons and (2) when there is just too many protons compared to neutrons.

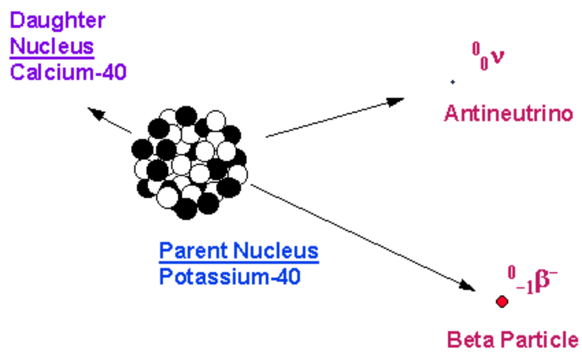
Beta particle emission occurs when the ratio of neutrons to protons in the nucleus is too high. In this case, an excess neutron transforms into a proton and an electron. The proton stays in the nucleus and the electron is ejected energetically as the beta particle along with an unusual particle called an antineutrino. The neutrino is an almost massless particle that carries away some of the energy from the decay process. Because this electron is from the nucleus of the atom, it is called a beta particle to distinguish it from the electrons which orbit the atom.

In positron emission, a proton in the parent nucleus decays into a neutron that remains in the daughter nucleus, and the nucleus emits a neutrino and a positron, which is a positive particle like an ordinary electron in mass but of opposite charge.

A beta particle (β):

- originates from a disintegrating nucleus;
- is either in the form of a negatron (electron) or positron (similar to an electron but positive in charge);
- can travel in air between 0 to 10 meters;

- is not monoenergetic, but is emitted with a continuous spectrum of energy between 0.02 and 4.8 MeV. Average energy approximately 1/3 of its maximum energy.
- absorbed by matter is a function of the distance travelled by the particle through the absorbing material and the density of the absorber;
- can penetrate several grams per cm^{-2} of tissue depending upon its energy;
- is effectively stopped by low atomic weight material (i.e. plexiglass, lucite). Other materials are also effective, such as glass and paper.



When fast moving beta particles (electrons) are suddenly stopped by the absorbing medium the quick change in energy is emitted as photon (x-ray) radiation and is known as *Bremsstrahlung* radiation. The percentage of bremsstrahlung production increases with the atomic number of the absorbing material and also with the energy of the beta particle. Hence, for protective shielding against beta radiation, it is customary to use material of low atomic number, such as plastic. Similarly, high energetic beta radioisotopes of significant activity should be treated as gamma radioisotopes regarding your protection.

1.5.3 Neutron Particle

Neutrons are not emitted by pure nuclear substances. The emission of neutrons is accomplished by bombarding some suitable target material with either alpha particles or high-energy gamma rays. The neutrons are literally knocked out of the target atom nucleus. For example, radium mixed with beryllium will produce neutrons. By the interaction of alphas with the nucleus of beryllium a neutron particle is ejected from the nucleus.

A neutron particle:

- carries no charge; therefore, is not influenced by electrostatic or magnetic fields;
- has great penetrating power;
- is effectively stopped by hydrogen rich materials or thick barriers (i.e. wax, water, concrete).

Neutron sources require special handling.

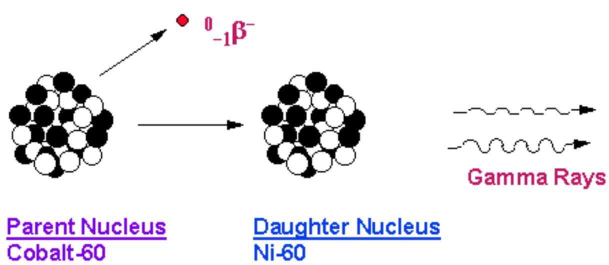
1.5.4 Gamma and X-rays

Gamma rays are monochromatic electromagnetic radiations that are emitted from nuclei of excited atoms following a radioactive transformation; they provide a mechanism for ridding excited nuclei of their excitation energy. This means that the radioactive transformation has resulted in producing a nucleus which still has excess energy to get rid of. Rather than emitting another beta or alpha particle this energy is lost by emitting a pulse of electromagnetic radiation called a *gamma ray*. The gamma ray is identical in nature to light, but of very high energy. Gamma rays interact with material by colliding with the electrons in the shells of atoms. It is important to note there is no such thing as a "pure" gamma emitter.

X-rays are similar to gamma rays except in two major areas. X-rays are produced external to the nucleus of the atom, where gamma rays originate from within the nucleus and x-rays are characteristic of low energy.

Gamma and X-rays (γ):

- are electromagnetic waves;
- travel with a velocity of light (3.0×10^{10}cm/s);
- penetration of matter is governed statistically by a probability of its interaction per unit distance travelled;
- are monoenergetic with the energy between 10 keV and 3 MeV.
- are effectively stopped by lead or concrete.



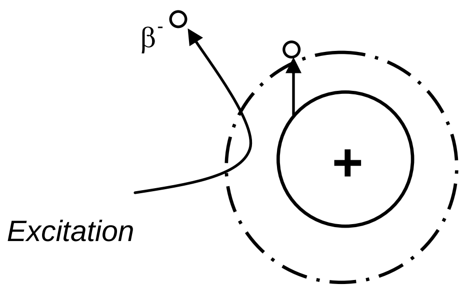
1.6 Radiation Interactions with Matter

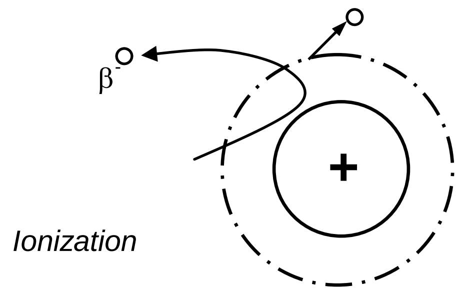
The electron orbits of an atom account for most of its size. The diameter of the "electron cloud" is approximately 10^{-10}m, while the nucleus is about 10^{-15}m. Incoming particles therefore, interact mainly with the electrons surrounding the nucleus. Although we often talk of particles "hitting" electrons, it is the electric field generated by an incoming charged particle that collides with the extensive electric field generated by the electron. The outcome is that the incoming particle transfers some of its energy to a target electron. The amount of energy transferred depends on whether the incoming particle happens to hit the electron "head on" (large energy transfer) or off to one side.

Depending on how much energy is transferred, basically, one of three things will happen:

Nothing: If the amount of energy available for transfer is less than that needed to raise the target electron to the next available energy level, no energy is transferred.

Excitation: The target electron receives enough energy to raise it to a higher energy level, but not knocked out of the shell.
Ionization: The target electron receives so much energy that it is excited beyond the highest level (i.e. it pops out of the orbit and leaves the atom altogether).





1.7 Ionization

Understanding the *ionization* concept is fundamental to understanding how radiation causes changes and damage to the material with which it interacts and how radiation may be detected. *Ionizing radiation*, whether electromagnetic or particulate, differs from other kinds of radiation in that it may add enough energy to atoms to eject electrons from their orbits. The atoms is said to be ionized, and the negative electron together with the remaining positively charged atom is called an ion pair. This mechanism is of great importance in health physics because it is the avenue through which energy is transferred from radiation to matter. One consequence is the formation of highly reactive free radicals in biological substances.

The ability to create ions is the main difference between nuclear radiation and other forms of radiation known as non-ionizing radiation.

There are two main categories of ionizing radiation:

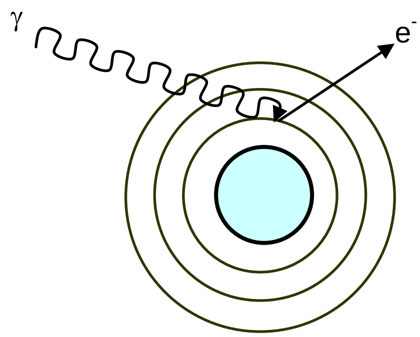
Directly ionizing radiation - this consist of charged particles such as alpha or beta particles, which interact with the target electrons via the coulomb electric force. When a charged particle moves through matter it interacts with hundreds and hundreds of atoms.

Indirectly ionizing radiation - this includes neutral particles such as neutrons and high-energy photons such as X and gamma rays. The interactions will not involve the coulombic forces. This means they can travel some distance before interacting with an atom. When the photon interacts, it might be absorbed and disappear or it might be scattered, changing its direction of travel, with or without loss of energy. The principal mechanisms of energy deposition by photons in matter are photoelectric absorption, compton scattering and pair production.

Photoelectric Effect

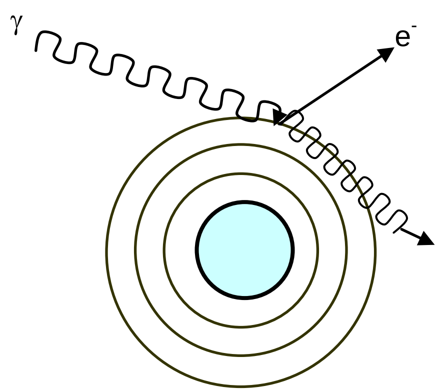
When a low energy photon strikes an electron, the resultant photoelectron is ejected from the atom. Its new energy will be the same as the photon's, less the amount of energy required to remove it from its shell. All of the photon's energy is expended in this interaction, so the photon no longer exits.

The photoelectric effect is more probable with low gamma ray energies and in matter with a high atomic number.



Compton Scattering

The incoming gamma ray transfers a portion of its energy to an outer electron and scatters off in a different direction than before. This scattered photon may subsequently interact with another target electron. The energy given to the electron is the difference in the energy of the gamma ray before and after the interaction.

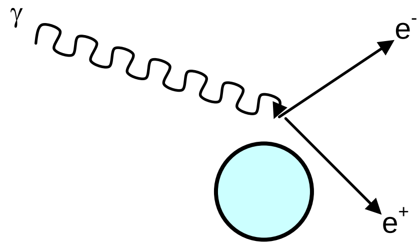


Pair Production

Pair production occurs in the electric field around the nucleus and is sometimes considered a collision. In this interaction the gamma ray completely disappears. The gamma ray energy is used to produce two oppositely charged particles: an electron and a positron. The remaining energy is distributed equally between the two particles as kinetic energy. Both charged particles then cause ionizations.

This interaction is only possible for gamma rays above 1022 keV. The 1022 keV is the energy used to produce the mass of the electron (511 keV) and positron (511 keV).

The probability of pair production increases with the energy of the gamma ray and the atomic number of the material.



1.8 Radiation Energy

The *electron volt* a convenient energy unit, particularly for atomic and nuclear processes, is the energy given to an electron by accelerating it through 1 volt of electric potential difference. The work done on the charge is given by the charge times the voltage difference, which in this case is:

$$1 \text{ eV} = 1.692 \times 10^{-19} \text{ joule}$$

Radioisotopes commonly used on campus emit radiation with energies in the range from 18 keV (betas from tritium) to less than 2 MeV (betas from phosphorus 32).

1.9 Energy Transfer

Stopping Power

A charged particle comes to a stop when it has lost its kinetic energy. The *stopping power* of a target material is the energy loss per unit path length in the material, often expressed in MeV per cm. (*Path length* of an individual charged particle is the total distance it travels irrespective of direction).

Linear Energy Transfer (LET)

The *linear energy transfer* of a material, for charged particles, is the energy lost by the primary charged particle in collisions with electrons, along a track segment, minus energy carried away by secondary electrons having kinetic energies greater than a specific energy. The reason for this specific energy "cut off" is that high energy transfers produce fast moving target electrons which carry off energy beyond the local area of interest. Thus, LET is an indication of how much energy the particle deposits locally, an indication of the ionization density.

High LET particles, such as alpha particles, produce a higher ionization density than low LET particles, such as beta particles. This is important because the amount of irreparable biological damage produced increases with ionization density.

1.10 Specific Activity

The *specific activity* (SPA) is the activity, A per unit mass of a radioisotope. The specific activity is related to the half-life $T_{1/2}$ through the decay constant λ, Avogadro's number N and the gram atomic weight M.

$$
\begin{aligned}
SPA &= \frac{A}{M} = \frac{\lambda N}{M} \\
&= \frac{0.693 \times 6.023x10^{23}}{T_{1/2} \times \ atomic\ weight} \\
&= s^{-1}g^{-1}
\end{aligned}
$$

Since the becquerel (Bq) is defined as one disintegration per second, the answer above is equivalent to the specific activity in units of Bq/g.

Example: Determine the specific activity of radioisotope Iodine - 125 in sodium iodide (NaI)

Given: Atomic weight of Na = 23
Atomic weight of I = 125
Half life of I-125 = 60.2 days
Fraction of iodine in NaI = $\frac{125}{125 + 23} = 0.84$

$\therefore$ If you have 1 gram of NaI it will contain 0.84 grams of iodine.

SPA of Iodine = $\frac{0.693 \text{ x } 6.023 \text{ x } 10^{23}}{8.64 \text{ x } 10^{4} \text{ s / day x } 60.2 \text{ days x } 125\text{g}}$

= $6.42x10^{14}$ Bq/gram or 642 TBq/gram

or $\frac{6.42x10^{14}\,Bq}{gram} \times \frac{1Ci}{3.7x10^{10}\,s^{-1}} = 1.735x10^{4}\ Ci / gram$

SPA of sodium iodine = 0.84 x 642 TBq/gram = 539.3 TBq/gram

Specific activity can also be designated as MBq/mmole or MBq/litre.

Table 1.0 Radioactive Properties of Selected Radioisotopes

Radioisotope	Half-life	Decay Mode	Energy (MeV)
^{3}H	12.26 y	Beta	0.018 (max)
^{14}C	5730 y	Beta	0.156 (max)
^{32}P	14.28 d	Beta	1.71 (max)
^{33}P	25.3 d	Beta	0.250 (max)
^{35}S	87.9 d	Beta	0.167 (max)
^{45}Ca	165 d	Beta	0.252 (max)
^{51}Cr	27.8 d	Electron capture, x-rays	0.320 (9%)
^{59}Fe	45.6 d	Beta Gamma	0.475 (max) 1.173 (100%) 1.332 (100%)
^{65}Zn	245 d	Electron capture, x-rays	1.115 (59%) 0.511 (3.4%)
^{125}I	60.2 d	x-rays Gamma	0.027 (114%) 0.031 (26%) 0.036 (7%)
^{131}I	8.05	Beta Gamma	0.514 (max) 0.662 (85%)
^{226}Ra	1620 y	Alpha Numerous β and γ radiations from progeny	4.78 (95%), 4.60 (5%)
^{241}Am	458 y	Alpha	5.49 (85%), 5.44 (13%)

2 UNITS OF MEASURE

Radiation dosimetry is the branch of science that attempts to quantitatively relate specific measurements made in a radiation field to chemical and/or biological changes that the radiation would produce in a target. Dosimetry is essential for quantifying the incidence of various biological changes as a function of the amount of radiation received (dose-effect relationships), for comparing different experiments, for monitoring the radiation exposure of individuals, and for surveillance of the environment.

2.1 Radiation Exposure (Coulombs/kg)

Exposure is defined for gamma and x-rays in terms of the amount of ionization they produce in the air. The unit of exposure is called the *roentgen* (R) and was named after W.C. Roentgen, who discovered x-rays in 1895. The SI unit for radiation exposure is *coulombs/kg*. Since 1962, exposure has been defined by the International Commission on Radiological Units and Measurements (ICRU) as the quotient $\Delta Q/\Delta m$, where ΔQ is the sum of all charges of one sign produced in the air when all the electrons liberated by photons is a mass Δm of air are completely stopped in air. The unit roentgen is now defined as:

$$2.58 \times 10^{-4} \text{ coulombs/kg.}$$

This radiation exposure applies only for x and gamma radiation measured in the air.

Radiation exposure is not an effective measurement for radiation protection because it does not describe the amount of radiation actually being absorbed by the biological system. Only radiation that is absorbed can have an effect on a living system; therefore, it is necessary to know the amount of radiation that is absorbed.

2.2 Radiation Absorbed Dose (Gray)

Measurement of the energy deposited in matter by radiation is fundamental in health physics. The primary physical quantity used in dosimetry is the *absorbed dose*. It is defined as the energy absorbed per unit mass from any kind of ionizing radiation in any target. The SI unit for absorbed dose is joule per kilogram (J/kg) and its special name is *gray* (Gy). The imperial unit for the absorbed dose is the *rad* - *r*adiation *a*bsorbed *d*ose.

$$1 \text{ gray} = 1 \text{ joules/kilogram} = 100 \text{ rad}$$

This unit depends on neither the type of radiation nor the material in which the energy is absorbed.

2.3 Equivalent Dose (Sievert)

Unfortunately, the problems of radiation protection are not that simple, since different types of radiation are known to have different biological effects for the same given absorbed dose. For example, one gray of alpha radiation will cause twenty times as much biological damage than one gray of gamma radiation. The probability of stochastic effects is found to depend, not only on the absorbed dose, but also on the type and energy of the radiation causing the dose. Therefore, this is taken into account by weighting the absorbed dose by a factor related to the quality of the radiation. The term *radiation weighting factor,* (w_R) is selected for the type and energy of the radiation incident on the body or, in the case of sources within the body, emitted by the source. Table 2.0 lists the radiation weighting factors for various types of radiation.

Table 2.0 Radiation Weighting Factors

Type of Radiation		w_R
Beta, gamma, x-rays		1
Neutrons, energy	< 10 keV	5
	10 keV to 100 keV	10
	>100 keV to 2 MeV	20
	> 2 MeV to 20 MeV	10
	> 20 MeV	5
Alpha particles		20

This weighted absorbed dose is referred to as the *equivalent dose* in tissue T and is given by the expression

$$H_T = \sum_R w_R \times D_{T,R}$$

where $D_{T,R}$ is the absorbed dose averaged over the tissue or organ T, because of radiation R. The unit of equivalent dose is the joule per kilogram with the special name *sievert* (Sv). The imperial unit for the equivalent dose is the *Rem -R*oentgen *E*quivalent *M*an*.*

2.4 Effective Dose

The relationship between the probability of stochastic effects and equivalent dose is found also to depend on the organ or tissue irradiated. It is therefore appropriate to define a further quantity, derived from the equivalent dose, to indicate the combination of different doses to several different tissues in a way that is likely to correlate well with the total of the stochastic effects. The factor by which the equivalent dose in tissue is weighted is called the *tissue weighting factor*, (w_T) which represents the relative contribution of that tissue to the total detriment because of these effects resulting from uniform irradiation of the whole body. Table 2.1 lists the tissue weighting factors for various tissues or organs.

Table 2.1 Tissue Weighting Factors (ICRP publ. 60, 1990)

Tissue or Organ	w_T
Reproductive organs	0.20
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Breast	0.05
Liver	0.05
Bladder	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05
Whole body total	1.00

This doubly weighted absorbed dose is referred to as the *effective dose* and is the sum of the weighted equivalent doses in all the tissues of the body. It is given by the expression

$$E = \sum_T w_T \times H_T$$

where H_T is the equivalent dose in tissue T and w_T is the weighting factor for tissue T. The unit of equivalent dose is the joule per kilogram with the special name *sievert* (Sv).

2.5 Dose Rate

Dose is a measure of radiation energy actually deposited in an object, material or individual that has been exposed to ionizing radiation. *Dose Rate* is the rate at which a radiation dose is delivered. Radiation monitoring equipment is usually calibrated in Sv/hour or Gy/hour to describe the rate at which radiation is received. For example, the total dose received by a woman working in a gamma radiation field of 300 mSv/h for 20 minutes is

$$\frac{300\,\text{mSv}}{1\text{h}} \times 20\,\text{min} \times \frac{1\text{h}}{60\,\text{min}} = 100\,\text{mSv}\,.$$

Table 2.2 SI Units for Radiation Activity

37 Bq	1 kBq	37 kBq	1 MBq
1 nCi	27 nCi	1 uCi	27 uCi

37 MBq	1GBq	37GBq	1TBq
1 mCi	27 mCi	1 Ci	27 Ci

Table 2.3 Common Prefixes for SI Units

Sub multiples

10^{-3}	milli	m
10^{-6}	micro	µ
10^{-9}	nano	n
10^{-12}	pico	p

Multiples

10^{3}	kilo	k
10^{6}	mega	M
10^{9}	giga	G
10^{12}	tera	T

3 BIOLOGICAL EFFECTS OF RADIATION

Shortly after the discovery of radiation in the late 1890's, it became apparent that exposure to ionizing radiation could cause harmful effects. This was first recognized among early radiology technicians who held the x-ray film under the patient during the x-ray exposure. The hands of the technicians were severely affected by the radiation that they received.

In 1928, the International Commission on Radiological Protection (ICRP) developed, maintained, and elaborated the *International System of Radiological Protection* used world-wide as the common basis for radiological protection standards, legislation, guidelines, programs, and practice. The *International System of Radiological Protection* has been developed by ICRP based on (i) the current understanding of the science of radiation exposures and effects and (ii) value judgements. These value judgements take into account societal expectations, ethics, and experience gained in application of the system.

In Canada, the Canadian Nuclear Safety Commission (CNSC) is the federal agency, which sets radiation standards. It bases its regulations on accepted international practices and the recommendations of the ICRP.

Radiation, whether from natural or artificial sources, is an integral part of life on the planet. The primary goal of radiation protection is to protect people and the environment from the detrimental effects of radiation during occupational uses of nuclear substances while still allowing its use for beneficial purposes.

3.1 Dose-Response Characteristics

Radiation ranks among the most thoroughly investigated etiologic agents associated with disease. Although much still remains to be learned about the interaction between ionizing radiation and living matter, more is known about the mechanism of radiation damage on the molecular, cellular, and organ system levels than is known for most other environmental stressing agents. Observed radiation affects may be broadly classified into two categories, stochastic and non-stochastic effects. Most biological effects fall into the category of non-stochastic effects.

Non-stochastic effects are characterized by three qualities:

- A certain minimum dose must be exceeded before the particular effect is observed;
- The magnitude of the effect increases with the size of the dose;
- There is a clear causal relationship between exposure to the noxious agent and the observed effect.

For example, a person must exceed a certain amount of alcohol before he shows signs of drinking. After that, the effect of the alcohol depends on how much he drank. Finally, if he exhibits drunken behaviour, there is no doubt that his behaviour is the result of his drinking. Because of the minimum-dose that must be exceeded before an individual shows the effect, non-stochastic effects are also called *threshold effects*.

Stochastic effects are those effects that occur by chance; and they occur among unexposed as well as among exposed individuals. Stochastic effects are therefore not unequivocally related to exposure to a noxious agent, as drunkenness is to alcohol ingestion. In the context of radiation protection, the main stochastic effects are cancer and genetic effects. The result of exposure to a carcinogen or to a mutagen is an increase in the probability of occurrence of the effect, with the increase in probability being directly proportional to the size of the dose. Thus, people develop cancer whether or not they are exposed to carcinogenic agents. However, exposure to a carcinogen increases the likelihood of cancer; and the greater the exposure the greater is the increased likelihood. At no time, however, regardless of the size of the exposure, is it certain that cancer will result from exposure to a carcinogen. If cancer des develop after exposure to a carcinogen, we cannot be absolutely certain as we are in the case of the causal relationship between alcohol and drunkenness – that the cancer was caused by the carcinogen. The best that we can do is to estimate the probability that the cancer was caused by the carcinogen.

Stochastic effects are often called *linear, zero-threshold dose-response effects*. According to the linear, zero-threshold model, every increment of radiation, no matter how small, carries with it a corresponding increase in risk of stochastic effect.

The gross biological effects resulting from overexposure to radiation are the sequelea to a long and complex series of events that are initiated by ionization or excitation of relatively few molecules in the organism. Direct effects of radiation, ionization and excitation, are non-specific and may occur anywhere in the body. When the directly affected atom is in a protein molecule, or in a molecule of nucleic acid, then certain specific effects due to the damaged molecule may ensue. However, most of the body is water, and most of the direct action of radiation therefore is on water. The result of this energy absorption by water is the production, in the water, of highly reactive free radicals that are chemically toxic (a free radical is a fragment of a compound or an element that contains an unpaired electron) and which may exert their toxicity on other molecules.

There is evidence that cells may benefit from the radiation received, and actually lengthen its life span or make it more robust. Studies of the simple paramecia, of animals and of radiation workers have all indicated this effect. This is referred to as radiation *hormesis*.

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3.2 Tissue Sensitivity

In general, the radiation sensitivity of a tissue is:

- proportional to the rate of proliferation of its cells;
- inversely proportional to the degree of cell differentiation.

For example, the following tissues and organs are listed from most radiosensitive to least radiosensitive:

Most Sensitive:	Blood-forming organs
	Reproductive organs
	Skin
	Bone and teeth
	Muscle
Least Sensitive:	Nervous system

This also means that a developing embryo is most sensitive to radiation during the early stages of differentiation, and an embryo/fetus is more sensitive to radiation exposure in the *first* trimester than in later trimesters.

Additional factors that determine the cell's response to radiation are:

Nature or type and energy of radiation:
The damage that is caused by the radiation is a function of the energy of the radiation and whether or not the radiation is penetrating or non-penetrating.

α	cannot penetrate the dead skin level
β	a few millimeters
γ	very penetrating
neutron	very, very penetrating

Time distribution:
A dose, which would be lethal if given in a short time, may not be lethal if it were given over a long period of time.

Absorbed dose:
The higher the dose the greater the dose response. It takes extraordinary large doses of ionizing radiation delivered in a short time to kill a significant number of cells.

Dose distribution:
A dose received by the whole body is more detrimental than a dose received by the partial body.

Age at irradiation:
Response is altered during growth in some organs. For example bone and cartilage show a definite response during growth (childhood) but are relatively radioresistant when mature.

3.3 Acute and Chronic Effects

In health physics, as in other areas of environmental control of harmful agents, we are concerned with two types of exposure:

- a single accidental exposure to a high dose of radiation during a short period of time, which is commonly called *acute exposure*, and which may produce biological effects within a short time after exposure;
- long-term, low level overexposure, commonly called continuous or *chronic exposure*, where the results of the overexposure may not be apparent for years, and which is likely to be the result of improper or inadequate protective measures.

Acute whole body radiation overexposure affects all the organs and systems of the body. However, since not all organs and organ systems are equally sensitive to radiation, the pattern of response, or disease syndrome, in an overexposed individual depends on the magnitude of the dose.

The effects on high dosage irradiation are present in Table 3.0. It must be stressed that this is presented for information purposes only and such doses are <u>extremely</u> unlikely in the event of an accident at this University.

Table 3.0 Effects of High Whole Body Dosage Irradiation on Humans

Dose (Sv)	Effects
0 - 0.25	No obvious injury
0.25 - 1	Temporary nausea, temporary sterility in males and temporary blood cell changes are all possible; no early deaths.
1-3	Nausea, fatigue and vomiting, blood cell changes, loss of appetite, diarrhea; temporary sterility in males; death possible.
3-6	Nausea and vomiting, diarrhea, marked blood cell changes, loss of weight, general malaise; early death of 50% of those exposed; permanent sterility and eye cataract development in survivors.

Source: Canada: Living with Radiation, Atomic Energy Control Board, 1995

Delayed effects may be caused by a single, large over-exposure (acute) or by a continuous long-term low-level exposure (chronic). Delayed health effects are manifested long after the relevant exposure. The majority of delayed effects are cataract formation, cancer induction, genetic effects, and life shortening.

3.4 Somatic and Hereditary Effects

Somatic effects are those health effects, which act on the person who has been exposed to radiation.

Hereditary effects are transmitted to offspring due to the irradiation of the parent egg or sperm cells. It has been estimated that the chance of a severe hereditary effect is between 0 and 0.00006 per 10 mSv. The frequency of serious genetic disorders that are induced by radiation would be highest in the first generation of children of exposed parents and gradually decrease in subsequent generations. To estimate genetic risks associated with radiation, data from the following is needed: normal incidence of genetic disorders; natural rate of genetic mutations; rate of induced mutations per sievert.

3.4.1 Prenatal Radiation Exposure

The developing child in the womb is believed to be particularly susceptible to the effects of high doses of radiation. It is now known that any effects of low level radiation on the developing child should be very close to zero during the first four weeks after conception. [1]Exposure of the developing child in the womb to high doses of radiation may produce a variety of health effects, including cancer induction, mental retardation, or reduced intelligence in live-born children. However, no detectable effects of these kinds are produced by low radiation doses below 100 mSv.

3.5 Risk Due to Radiation Exposure

A risk is the mathematical probability that an injury, damage, or other detrimental event will occur. Risks are usually calculated by observing a group of people and counting the number of times a detrimental effect occurs. The risk of the detrimental effect occurring is the number of events divided by the number of people in the group.

Calculating the risk of contracting cancer as a result of working with nuclear substances, cannot be done in such a simple way. At the low levels associated with medical and research applications, no link between cancer and occupational exposure has been observed. In other words, people who work with radiopharmaceuticals and comparable materials show about the same rate of cancer as the population in general. That is not to say no risk is present. It means that the risk from occupational radiation exposure is so small that it cannot be measured directly. Instead the risk is estimated from observations of people who have been exposed to high doses of radiation, primarily the survivors of the atomic bomb in Hiroshima and Nagasaki. Other groups that have been exposed to elevated levels of radiation (i.e. radium dial painters, cancer therapy patients) have also been studied for their response to the exposures received.

The BEIR-V Report states, [2]In this report it is estimated that if 100 000 persons of all ages received a whole-body dose of 100 mGy of gamma radiation in a single brief exposure, about 800 extra cancer deaths would be expected to occur *during their remaining lifetimes* in addition to the nearly 20 000 cancer deaths that would occur in the absence of radiation.

[1] Canada, Atomic Energy Control Board, Canada: Living with Radiation (Ottawa: Ministry of Supply and Services Canada, 1995) 29.
[2] United States, National Research Council, Health Effects of Exposure to Low Levels of Ionizing Radiation, BEIR V (Washington, DC: National Academy of Sciences, 1990) 162

In summary, the risk of cancer death is 0.08% per mSv for doses received rapidly (acute) and might be 2 – 4 times (0.04% per mSv) less than that for doses received over a long period of time (chronic). These risk estimates are an average for all ages, sex, and all forms of cancer. There is a great deal of uncertainty associated with the estimate.

There are many job situations, which lead to accidental deaths during employment. Focusing on a single source of risk is misleading unless one compares risks in other professions. The following table gives the probability of job related fatal injuries for different occupations.

Table 3.1 Average Annual Risk of Death in Canada from Fatal Accidents at Work and from Radiation Exposure

Occupation	Risk of Death per Year
Finance	1 in 60 000
Service	1 in 40 000
Trade	1 in 20 000
2 mSv radiation per year	1 in 12 000
Government (police and firefighters)	1 in 11 000
Manufacturing	1 in 11 000
Transportation	1 in 4 000
Construction	1 in 3 000
Mining	1 in 1 100
Forestry	1 in 900
Fishing and Hunting	1 in 500

Note: Includes deaths arising out of occupational illnesses, but does not include deaths among the 20% of all workers who were not covered by workers compensation. Data based on compilations by the Occupational Safety and Health Branch of Labour Canada.

3.6 Risk Models

We know a great deal about the cancer risk of high radiation doses from studies of Japanese A-bomb survivors, patients exposed for medical therapy, occupational exposures, etc. But the vast majority of important applications deal with much lower doses, usually accumulated at much lower dose rates, referred to as "low level radiation" (LLR).

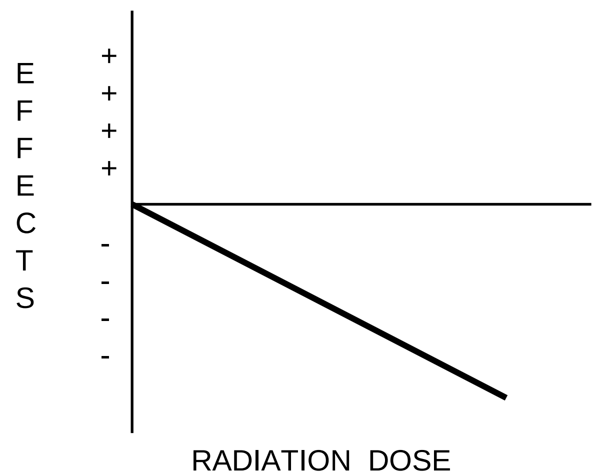
3.6.1 Linear No-Threshold Model (LNT)

The principal basis for the LNT is theoretical, and very simple. A single particle of radiation hitting a single DNA molecule in a single cell nucleus of a human body can initiate cancer. The probability of a cancer initiation is therefore proportional to the number of such hits, which is proportional to the number of particles of radiation, which is proportional to the dose. Thus, the risk is linearly dependent on the dose; this is the LNT.

The problem with this very simple argument is that factors other than initiating events affect the cancer risk. Our bodies have biological defense mechanisms that prevent the vast majority of initiating events from developing into a fatal cancer.

Another way of stating this risk model is a dose of 0.1 mSv creates a risk of death from cancer of approximately 1 in 1 000 000.

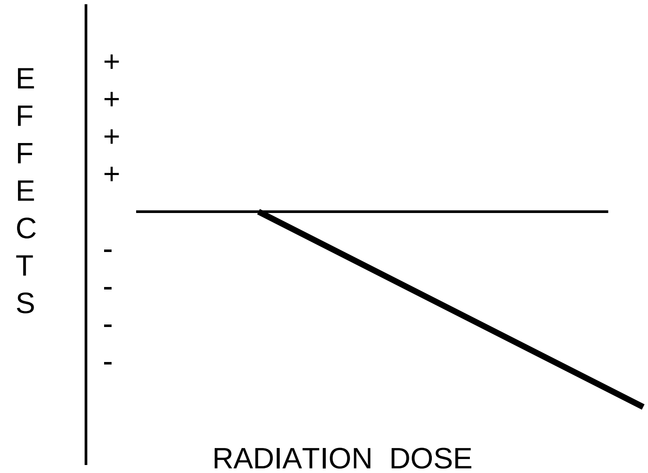
Figure 3.0 Linear No Threshold model



3.6.2 Threshold Model

Some researchers go a step further and argue that the risk from small doses is practically zero. According to the threshold risk model, only doses exceeding a specific tolerance limit would be harmful. One of their arguments is that cancer is no more common in areas where background radiation is many times higher than average. Supporters of that model have a strong faith in the recuperative powers of the body.

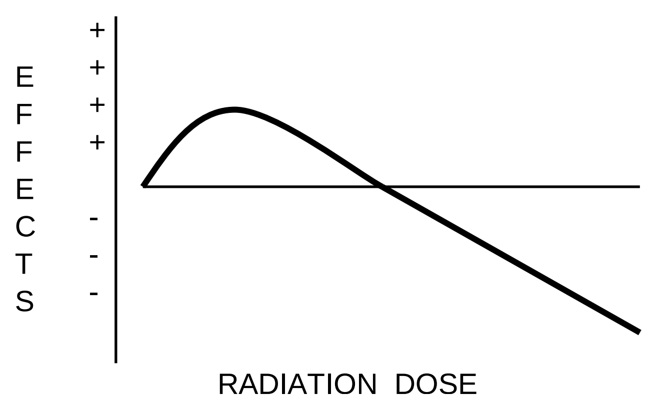
Figure 4.1 Threshold model



3.6.3 Hormesis Model

"Radiation hormesis" is the name given to the putative stimulatory effects of low level ionizing radiation (generally in the range of 1 – 50 cGy of low-LET radiation). Most of these effects are generally ascribed to protective feedback systems that, upon exposure to low concentrations of toxins, proceed to stimulate metabolic detoxification and repair networks. The activation of these networks may then result in net beneficial effects on the cell, organism or species. For instance, a massive dose of ultra-violet light would burn a person to death, but our health suffers if we get no sun at all. The data in support of the hormesis postulate is intriguing but inconclusive.

Figure 4.2 Hormesis model



4 RADIATION EXPOSURE

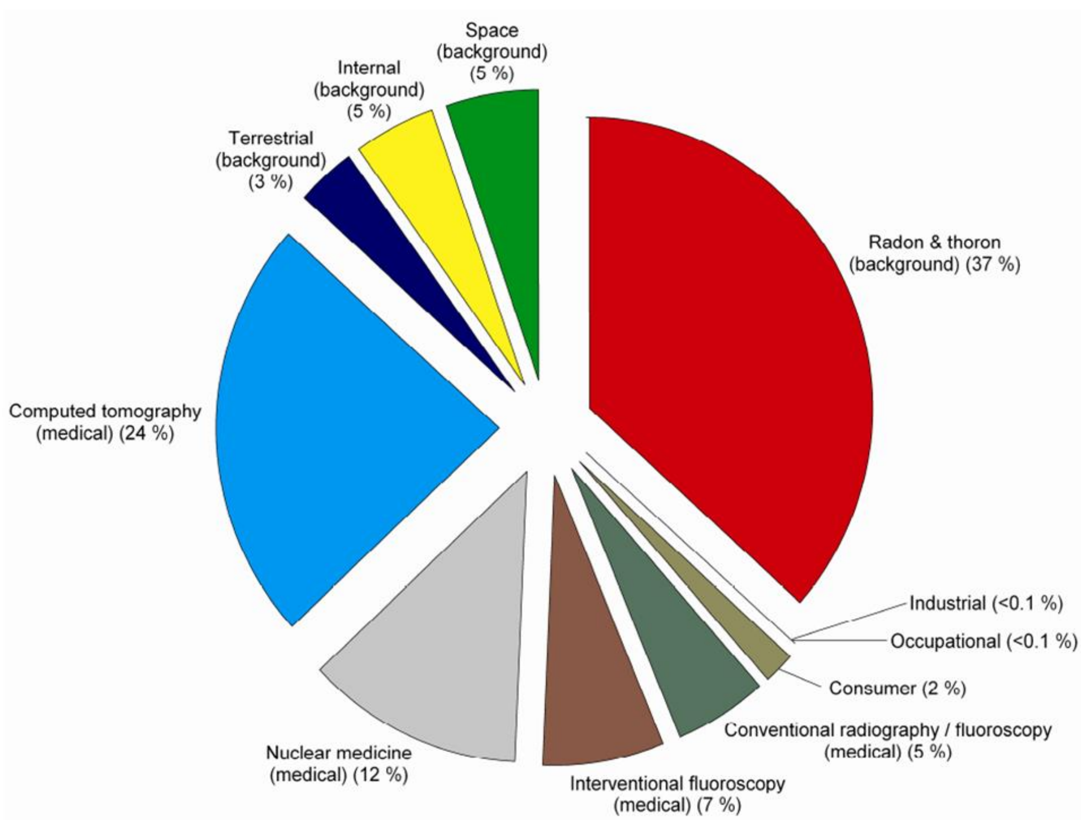
4.1 Background Radiation

Radiation is a natural part of life. It has existed since the beginning of time and is an integral part of the universe in which we live. Mankind has always been exposed to background radiation from naturally occurring sources, such as radium in drinking water, potassium 40 in living tissues, heavy radioactive elements in rock and stone, and cosmic rays. Radiation arising from these natural sources in the environment is referred to as *background radiation*. After 1895, man-made sources were added to those that occur naturally.

The primary source of man-made radiation is medical diagnostic x-rays and treatments. Although an average amount has been determined, this too will vary depending on the individual's needs.

Figure 4 shows the sources of radiation and their relative contribution to the radiation dose received by the average person each year. The average worldwide background radiation dose rate is 2.4 mSv/year.

Figure 4.0 Sources of Global Background Radiation



Source: Courtesy of NCRP Report 160 (2009)

4.2 Regulatory Limits

Radiation protection guidelines have been established for two fundamental groups in society, *Nuclear Energy Workers (NEW)* and *members of the public*. Both groups may receive a radiation dose from the occupational use of nuclear substance but the dose limitations are different for each group.

Table 4.0 CNSC Annual Dose Limits

Person	***Period***	***Effective Dose***	***Equivalent Dose***
Nuclear Energy Worker	One-year dosimetry	50 mSv	
	Five-year dosimetry	100 mSv	
Lens of an eye	One-year dosimetry		150 mSv
Skin	One-year dosimetry		500 mSv
Hands and feet	One-year dosimetry		500 mSv
Pregnant NEW	Balance of pregnancy	4 mSv	
General Public	One calendar year	1 mSv	
Lens of an eye	One calendar year		15 mSv
Skin	One calendar year		50 mSv
Hands and feet	One calendar year		50 mSv

Note that these limits are maximum values, the expected normal value is much lower.

To put these values in perspective, it is interesting to note that the average Canadian whole-body dose rate from background radiation is approximately 1.8 mSv per year. A passenger taking a return flight from Toronto to Vancouver would receive a whole body dose of about 50 µSv from the increased cosmic radiation at high altitudes.

4.3 ALARA Concept

It is not sufficient for a person to simply respect the maximum dose limits identified above; efforts must be made to reduce doses further. Management of radiation doses places emphasis on keeping the radiation exposure *as low as reasonably achievable*.

The concept of ALARA is to keep all exposures as low as reasonably achievable, social and economic factors must be taken into consideration. It is incumbent on persons working with nuclear substances and all levels of management be committed to a policy of safety and good radiation protection in order to keep all exposures as low as reasonably achievable.

4.4 Controlling Exposure to Radiation

If you are in the vicinity of nuclear substances, the radiation from it may penetrate your body, this is called *External Exposure*. Hence, external exposure is the irradiation of live tissue from sources outside the body. However, if nuclear substance is accidentally taken into the body, the radiation will be irradiating from within your body, this is referred to as *Internal Exposure*.

4.4.1 External Exposure Control

All measures taken in radiation protection are designed to reduce exposures consistent with the ALARA concept. There are three general methods: *time, distance*, and *shielding* that may be carried out for protection from external sources of radiation. Time, distance, and shielding should always be used in appropriate combinations to suit each operation.

4.4.1.1 Time

Radiation is emitted from a source at a constant dose rate. The effective dose may be reduced by reducing the dose rate or the time of exposure. The time of exposure to radiation can be reduced by preplanning experiments or by procedures in experiments.

- Review the safety aspects of the experiment in detail.
- Carry out trial runs with no radioactivity.
- Design experiments to be a sequence of simple steps that can easily be accomplished quickly and safely.
- Equipment should be assembled before introducing the radiation source.
- The dose rate at various steps in the experiment should be monitored to identify high radiation fields. Efforts should be made to reduce the time of working in these fields.
- Experiments that do not require proximity to nuclear substances, for example, paperwork should be carried out away from the radiation area.
- Regularly monitor and promptly remove contaminated gloves.

4.4.1.2 Distance

Distance is the most useful aid in protection when handling small concentrated sources of nuclear substances. The dose rate from a source is inversely proportional to the square of the distance from the source. This "inverse square law" means, for example, that if the distance from the source is doubled, the dose rate will be one-fourth.

$$\text{Exposure rate} = \frac{\tau A}{d^2}$$

where

A = the activity of the source (mCi).
d = the distance from source to dose point (cm).
τ = the specific gamma constant $\frac{(\mathrm{Rcm}^2)}{(\mathrm{hr} \times \mathrm{mCi})}$.

* Note: The above formula applies only for gamma exposure.

The following methods can reduce exposure by increasing the distance between the worker and source.

- Avoid direct handling of nuclear substances as much as possible.
- Use forceps, tongs, or holders to maintain distance between the hand and the source.
- Store sources at the back of benches when in use.
- Work with radioisotopes at arm’s length to minimize the radiation field to the trunk of the body.

4.4.1.3 Shielding

There are a variety of shielding materials that can be placed between a person and the source to absorb most of the radiation that would otherwise reach a person. Choice of shielding material depends on the type of radiation and other functions served by the shield(s). It may also be necessary to shield the nuclear substance in storage or in the waste.

Alpha sources, because of the limited range of the particle, can be shielded by a piece of paper. Beta radiation can be shielded using any suitable substance such as plastics. Since gamma radiation is very penetrating shields are usually constructed of lead, concrete or other high atomic number (Z) materials.

When planning an experiment, it may be necessary to calculate the shielding thickness. The concept of *half value layer (HVL)* is useful. The half value layer is the thickness of the absorbing material required to decrease the intensity of the gamma radiation by one half. The decrease in intensity of the radiation is expressed as

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

where

I_0 = the intensity of the incident radiation.
I = the intensity after traversing thickness x.
μ = the linear attenuation coefficient (which corresponds to the decay constant (λ).

Table 4.1 Half Value Layer Thicknesses

Energy	**Shielding Thickness HVL (cm)**		
	Lead	**Aluminum**	**Water**
at 20 keV	0.0007	0.0747	0.975
at 140 keV	0.0256	1.796	4.530
at 364 keV	0.2190	2.646	6.245

4.4.2 Internal Exposure Control

The main objective of controlling radioactive contamination is to prevent internal doses to workers. Nuclear substances can enter the body by *ingestion, inhalation,* or *absorption* through intact or damaged skin. To prevent internal exposure, it is necessary to intercept each of these routes.

4.4.2.1 Preventing Ingestion

Intake through ingestion can be minimized by ensuring that potentially contaminated objects are not placed in the mouth. In radiation work areas there should be:

- no eating, drinking, or smoking;
- no applying of cosmetics;
- no mouth pipetting;
- nothing placed in the mouth like fingers, pens or pencils.

4.4.2.2 Preventing Inhalation

Inhalation intakes can be prevented by ensuring that volatile nuclear substances are handled in well-vented areas.

- Fume hoods should be checked for proper function before use.
- Minimize the area of the fume hood window opening to maintain an air flow velocity of about 100 linear fpm. Avoid excessive velocities at the face of the fume hood in order to prevent turbulence.
- Keep your head out of the fume hood and keep the sash as low as possible when processing nuclear substances.
- Keep equipment and operations toward the rear of the fume hood to avoid impeding the flow of air through the window.
- Avoid sudden movements at the fume hood face, which could draw contaminated air into the laboratory.
- Use a glove box when the risk or airborne contamination is too high for the use of a fume hood.

4.4.2.3 Preventing Skin Absorption

Skin contamination is best prevented by using personal protective equipment to avoid direct contact with nuclear substances.

- Wear gloves.
- Wear a lab coat (which is buttoned up).
- Handle sharp objects and syringes carefully.
- Regularly monitor the skin for quick recognition of contamination.
- Wash hands upon completing radioactive work.

4.5 Critical Organ

When radioisotopes are internally deposited some activities are distributed throughout the body (i.e. tritium) while others concentrate in specific organs or tissues (i.e. thyroid).

The organ of the body, which received the greatest damage resulting from the intake of radiation from a particular radioisotope, is referred to as the *critical organ.* This organ accumulates the greatest concentration of the radioactive element. The importance of the organ to the well being of the body and the radio sensitivity of the organ are important criteria for the critical organ. Example: the critical organ for iodine isotopes is the thyroid, for phosphorous isotopes it is the bone.

4.5.1 Biological Half Life

The characteristic time required for the activity of a radioisotope to be reduced to one half its initial value due to elimination by biological processes alone. The biological half life is not dependent on the radioisotope, but does depend on the organ or body system in which the radioisotope is deposited and the chemical properties of it.

4.5.2 Effective Half Life

The characteristic time required for a nuclear substance to be 50% eliminated from the biological system through the combination of the physical and biological removal processes. The effective half life is a mathematical combination of the physical and biological half lives of the particular radioisotope.

$$T_{eff} = \frac{(T_{1/2})(T_b)}{T_{1/2} + T_b}$$

where T_{eff} = the effective half life.
$T_{1/2}$ = the physical half life.
T_b = the biological half life.

4.6 Radiotoxicity

Radiotoxicity of a radioisotope refers to its potential capacity to cause damage to living tissue as a result of being deposited inside the body. This potential of damage is governed by the:

- energy of the radiation;
- physical half life;
- biological half life;
- radio sensitivity of the critical organ; and
- decay mode.

4.7 Annual Limit on Intake (ALI)

[3]For occupational exposures, the ICRP 1990 recommendations limit the effective dose to 100 mSv in a five-year period (average annual value of 20 mSv) with a limit of 50 mSv in any single year. Thus, the annual limit of intake for any radioisotope is obtained by dividing the annual average effective dose limit (20 mSv) by the committed effective dose, *E*(50), resulting from the intake of 1 Bq of that radioisotope.

Table 4.2 Annual Limits of Intake

Radioisotope	[4]Inhalation (Bq)	[5]Ingestion (Bq)	CNSC Reg. limit
Hydrogen-3	1×10^9	1×10^9	1×10^9
Carbon-14	3×10^9	4×10^7	3.4×10^7
Phosphorus-32	5×10^6	8×10^6	8×10^6
Phosphorus-33	3×10^7	8×10^7	8×10^7
Sulphur-35	3×10^7	7×10^7	2.6×10^7
Chromium-51	2×10^8	4×10^8	5.30×10^8
Iodine-125	2×10^6	1×10^6	1×10^6
Iodine-131	1×10^6	8×10^5	1×10^6

[3] ICRP 61, Annual Limits on Intake of Radionuclides by Workers Based on the 1990 Recommendations, (New York: Pergamon Press Inc., 1991) 3.
[4] ICRP 61, Annual Limits on Intake of Radionuclides by Workers Based on the 1990 Recommendations, (New York: Pergamon Press Inc., 1991).
[5] ICRP 61, Annual Limits on Intake of Radionuclides by Workers Based on the 1990 Recommendations, (New York: Pergamon Press Inc., 1991).

5 SAFETY PRECAUTIONS

The basic framework of the University of Saskatchewan's radiation safety program has to include social, as well as, scientific judgements, because the primary aim of radiological protection is to provide an appropriate standard of protection for workers without unduly limiting the beneficial practices that include the use of nuclear substances. Furthermore, it must be presumed that even small radiation doses may produce some deleterious health effects. Since there are thresholds for deterministic effects, it is possible to avoid them by restricting doses to individuals. On the other hand, stochastic effects cannot be completely avoided because no threshold can be invoked for them. The University's radiation safety program is intended to prevent the occurrence of deterministic and stochastic effects by keeping doses as low as reasonably achievable with social and economical factors taken into consideration.

5.1 General Nuclear Substances Safety Precautions

Every worker shall comply with the measures established by the University to protect the environment, the health and safety of persons, maintain security, and control the levels and doses of radiation. A poster listing some of these precautions is posted in every laboratory designated as a radioactive work area.

1. Only persons properly trained to work with nuclear substances and informed of the hazards involved are permitted to work with nuclear substances or operate devices containing nuclear substances.
2. Keep external radiation exposure as low as reasonably achievable.
3. Comply with CNSC and University regulatory requirements.
4. Restrict access to nuclear substances and work areas to authorized staff only. Never leave nuclear substances including waste unattended, unless in a locked room or enclosure.
5. Do not eat, drink, or store food in laboratories.
6. No nuclear substances shall be used in or on human beings.
7. If required by the permit, wear a dosimeter at all times while in the radioactive work area. Dosimeters shall be stored away from sources of radiation.
8. In case of a radioactive spill or incident involving a nuclear substance follow emergency procedures and notify the Radiation Safety Officer.
9. Wear appropriate personal protective equipment (PPE) (i.e. gloves, safety glasses, lab coat) when working with nuclear substances.
10. All containers used to contain nuclear substances shall be labelled with the radiation warning symbol, radioisotope, activity and date. This does not apply to containers that are:
    - used to hold nuclear substances for current or immediate use and are under the continuous direct observation;
    - used to hold nuclear substances in quantities less than 10 kBq (0.27 uCi);
    - used exclusively for transporting nuclear substances and labelled in accordance with the *Packaging and Transport of Nuclear Substances Regulations*.
11. Clearly identify and mark working surfaces used for handling nuclear substances.
12. Place radiation warning symbols on access doors to storage locations (cold rooms, fridges, freezers, cupboards, etc.)

13. All equipment and other items used during a procedure with nuclear substances shall be labelled with the appropriate radiation warning labels. Keeping in mind to avoid frivolous use.
14. Prior to using a meter for contamination monitoring, workers shall ensure they have read the operator's manual and understand how to use the meter. Workers shall ensure the meter used to monitor for radiation contamination is function tested every 12 months.
15. Work in a fume hood when handling radioactive dry powders or volatile substances.
16. Cover radioactive work surfaces with disposable absorbent materials (i.e. bench coat). Disposable absorbent material should be replaced on a regular basis.
17. To minimize internal exposure, monitor the laboratory for removable contamination following radioactive work or at least weekly. Decontaminate any surface where contamination was found as soon as possible. Keep a record of all monitoring and decontamination results.
18. Monitor equipment used for radioactive work to ensure that it is not contaminated prior to being used for non-radioactive work.
19. Radioactive work shall be conducted only in a laboratory or area authorized as a radioactive work area.
20. No worker shall transfer any nuclear substances to any person not listed on their permit without the approval of the Radiation Safety Officer.
21. Maintain up-to-date inventory, usage and disposal records of all nuclear substances.
22. Dispose of radioactive waste on a regular basis and in accordance with the Hazardous Waste Disposal Standard.
23. Wash hands thoroughly before leaving the laboratory. When possible, monitor the hands for contamination.
24. Prior to leaving the University ensure all radioactive substances are disposed of properly.

In the use of nuclear substances for teaching or research, consideration must be given to other physical, chemical and biological hazards, which may arise during the procedure.

5.2 Good Work Practices for the Use of Nuclear Substances

Proper handling precautions serve as the primary barrier to prevent the spread and subsequent adverse effects of contamination. The following tips will aid in handling nuclear substances safely.

1. Ensure the internal authorization (permit) is posted near the entrance of the radioactive work area and the information is current.
2. Keep laboratory neat and tidy.
3. Prior to conducting a new procedure involving nuclear substances, a dry run using non-radioactive material should be performed to test the procedure.
4. Use the minimum quantity of nuclear substance necessary to satisfy the objective of the procedure.
5. If a radiation monitor is available in the laboratory, it should be kept on during the procedure to monitor for radiation.

6. If heating is necessary, nuclear solutions should never be heated directly over a flame. If it is necessary to look into a beaker containing nuclear substances during this procedure, safety glasses or a face shield shall be worn.
7. A radioactive solution shall not be poured from one container to another, but shall be transferred carefully with a pipette or funnel.
8. Upon completion of a radioisotope experiment, all materials shall be properly labelled, stored or prepared for disposal.
9. All radioactive waste shall be disposed in the waste container labelled with the correct waste type and radioisotope.
10. All equipment or devices, which are to be sent for repair or maintenance, must be decontaminated before being released from the radioisotope laboratory. Complete the appropriate paperwork (i.e. Equipment/Area Release Form)
11. Radioactive work should be confined to an area or bench in the laboratory with minimal traffic. If possible, activities requiring the handling of nuclear substance should be grouped in one area of the laboratory.
12. Radioisotope work areas should be kept free of any articles that are not relevant to the work carried out during the procedure. Laboratory books for recording results should be kept away to prevent possible contamination.
13. Due to the volatile nature of iodine, all iodinations shall be performed in a fume hood.
14. Where possible, only one sink should be used for the washing of contaminated glassware and equipment.
15. Select comfortable, sturdy footwear that will protect against contamination or injury due to broken glass or corrosive materials. No open toe or heel shoes.
16. Laboratory clothing shall be removed when leaving the laboratory or designated lab coat area.
17. No person shall post a radiation sign or symbol where a nuclear substance is not present.
18. No animals (i.e. dogs, cats, fish) are allowed in radioactive work areas, except those that are part of the research or the patient.

5.3 General Nuclear Substances Safety Precautions for Radiation Devices

In addition to the general safety precautions and handling precautions for nuclear substances the additional precautions apply to all workers handling radiation devices.

1. Any worker transporting a radiation device must be certified to transport Class 7 dangerous goods.
2. Appropriate documentation shall accompany the radiation device when transported.
3. No worker shall use a radiation device in field operation unless the device has securely attached to it a legible label that identifies the name or job title and contact number of Protective Services (306-966-5555) who can initiate the accident procedure and who can be contacted 24 hours a day. Protective Services will contact the Radiation Safety Officer.
4. When working with a radiation device written emergency procedures shall be available at all times and accompany the device to the work site.
5. Prior to using a radiation device the worker shall ensure the device was leak tested within the 12 months preceding its use. Copies of the leak test certificates are kept in the Radiation Safety Office.

6. When a radiation device is involved in an accident or is subject to conditions other than those in which it is designed to operate, the worker shall discontinue using it until the Radiation Safety Officer has inspected it and established that it is safe to use.

5.4 Storage of Nuclear Substances

1. All nuclear substances shall be stored in a **secure** location to prevent unauthorized access to the substance. If the storage room, cabinet, refrigerator or freezer can be easily accessed by unauthorized persons it must be <u>locked</u> at all times (i.e. freezer in a hallway).
2. All storage rooms, cabinets, refrigerators or freezers used for the storage of nuclear substances must be clearly labelled with a radiation warning sign, indicate the job title and telephone number of Protective Services (306-966-5555) who can initiate the accident procedure and who can be contacted 24 hours a day. Protective Services will contact the Radiation Safety Officer.
3. No food or drink shall be stored in the same enclosure with any hazardous substance.
4. All stored nuclear substances shall be labelled with the radiation warning sign, indicate the amount of activity, date and name of the radioisotope unless there is less than 10 kBq (0.27 µCi) of activity in the container.
5. Every location where nuclear substances are stored shall not have at any occupied area outside the area, room or enclosure a dose rate that exceeds 2.5 µSv/h.
6. Fume hoods shall not be used for the storage of materials except where those materials may produce hazardous discharges.
7. For storage of waste containers refer to the Hazardous Waste Disposal Standard.

6 RADIATION MONITORING

Personnel should regularly monitor themselves and their work area for fixed and removable contamination in order to:

- ensure that contamination is not transferred to non-radioactive areas;
- provide feedback as to the effectiveness of contamination control measures;
- prevent unnecessary personnel exposure resulting from intake of contamination.

6.1 Contamination

Radioactive contamination is the presence of nuclear substances in any place where it is not desired (or don’t know it is there). Contamination can be described as removable or fixed.

6.1.1 Removable Surface Contamination

Removable surface contamination is nuclear substances in a form that is easy to spread. There are three potential problems with loose contamination. First, the possibility that it might be inadvertently ingested if not quickly discovered and removed. Second, it might be spread beyond the boundaries of the licensed area and cause undue stress. Third, loose surface contamination might become airborne and be made available for inhalation. Radioactive surface contamination is primarily caused by poor handling techniques and housekeeping. Accidental spills or leaks of nuclear substances are another source of surface contamination.

6.1.2 Fixed Contamination

Fixed contamination is that which cannot be readily removed. Depending on the radioisotope and activity, fixed contamination may pose an external radiation hazard. When contamination is significant, the surface or equipment may have to be disposed of or if the radionuclide has a short half life it may be stored until the radiation field is no longer a problem.

6.2 Standard Procedures for Contamination Monitoring

All radioisotope facilities must be monitored for contamination control as specified by the Canadian Nuclear Safety Commission regulations. CSNC stipulated that all radioactive work areas must be monitored for contamination; at least once a week providing work was done that week.

6.2.1 Indirect Monitoring Method

Indirect monitoring means surveying an area for contamination using a method that does not provide immediate results. A wipe test is an example of an indirect method of monitoring.

The following instructions have been designed to assist laboratory personnel in the correct procedure for monitoring their laboratory(s) for contamination. It may be necessary to adapt some of the procedure to the equipment being used for monitoring.

1. Draw a map of the floor plan of each laboratory designated as a radioactive work area. On your map identify areas that are potential locations for contamination. Add a couple of less likely areas.
2. Create a 12-month log book to record the monitoring results in. A hard copy shall be readily available in the laboratory. (Contact Safety Resources for a sample copy.)
3. If no nuclear substance has been used that week, a simple notation of this fact should be documented in the log book. Otherwise, there must be monitoring results recorded.
4. A background wipe shall always be taken to compare the results with. (May or may not wipe a clean surface.)
5. Number the holding container for the wipe (liquid scintillation vials or test tubes) to correspond to the numbered location on the map of the laboratory where the wipe shall be taken.
6. If monitoring for beta emitters select filter paper for the wipe. If monitoring for gamma emitters select cotton tipped application swabs.
7. Wearing gloves, wipe each of the locations shown on the map. Try to avoid touching the surface with your fingers.
8. Wipe an area of approximately 100 cm^2. This is equivalent to the area of a square, 10 centimeters on each side. However, the preferred method is to perform the wipe in an S-shaped pattern over a distance of 30-35 centimeters or a straight line 70 cm long.
9. Use uniform and constant pressure, when taking a wipe.
10. Most wipe surveys are performed with dry wipes. However, if you wet the wipe with water or alcohol, allow for the wipe to thoroughly dry before counting. Otherwise, water or alcohol will shield the beta particles especially those of low energy.
11. Place the wipe in the holding container. Proceed to count the wipes. For liquid scintillation wipes the filter paper should dissolve prior to counting to prevent erroneous results. (This might take several hours.)
12. Record the results.
13. If contamination is detected, clean the area, re-monitor. Repeat cleaning until all contamination had been removed. Refer to section 8.6 for cleaning procedures.
14. Record results after decontamination.

6.2.2 Direct Monitoring Method

Direct monitoring means surveying an area for contamination using a method that provides immediate results. Direct monitoring may be used when background radiation levels are negligible. A portable radiation detection monitor is an example of a direct method of monitoring.

1. Read the instrument's operating manual to gain familiarity with the controls and operating characteristics.
2. Check for proper instrument function including recent function test date, battery strength and response to a check source (if possible).
3. Follow the same first three steps outlined in section 6.2.1.

4. Determine the background reading at a surface that is known to be uncontaminated. Record this result.
5. To directly monitor a surface for contamination, bring the detector to within one centimeter of the surface, being careful not to damage or contaminate the detector.
6. Move the detector slowly over the surface.
7. Adjust the meter range selector if necessary and observe the reading from a point directly above the meter face to ensure proper alignment of needle and scale.
8. Since the readout will fluctuate, look for the average value.
9. Record the results. Any contamination monitoring result greater than double the background level is considered to be contamination.
10. If contamination is detected, clean the area, re-monitor. Repeat cleaning until all contamination had been removed. Refer to section 8.6 for cleaning procedures.
11. Record results after decontamination.

6.2.3 Leak Tests of Sealed Sources

All sealed sources with an activity greater than 37 MBq (1 mCi) shall be tested for radioactivity leak. Safety Resources staff carries out this procedure on a yearly basis. Permit Holders will be notified if a leak is found. The frequency of testing is as follows:

- Sealed sources in storage are leak tested every 24 months.
- Sealed sources in a radiation device are leak tested every 12 months.
- When an event that may have damaged the sealed source or shielding has occurred, the sealed source shall immediately be leak tested.
- Any other source is leak tested every 6 months.

Copies of the leak test certificates can be obtained from Safety Resources.

6.2.4 Contamination Limit

Radioactive decay is a random process; one never knows exactly when a particular radioisotope will decay. We can only deal with the average behaviour of billions of such unstable nuclei. As a result, the counts per minute from a radiation detector are subject to statistical variation. When reviewing the results from contamination monitoring, one must consider the uncertainty associated with a single measurement and account for the effects of statistical fluctuations. Radiation decay follows what is known as the Poisson distribution (bell curve). In the Poisson distribution, the mean is equal to the measured number of counts x. The uncertainty in the measured counts is called the variance of the mean. The best estimate of the variance from the true mean value is $\sqrt{x}$, and is referred to as one standard deviation σ. Thus, a standard deviation is a measure of the dispersion of randomly occurring events around the mean. This range of values $x \pm \sqrt{x}$ will contain the true mean value x with 68% probability. However, to achieve a 99.75% probability that the true mean value is included, multiply x by 3σ.

For example, if the background measurement is 100 cpm = x, then one can say with 99.75% confidence any location with a measurement result greater than

$x \pm 3\sigma = 100 + 3\sqrt{100} = 130$ cpm there is contamination.

However, it is practiced, any location monitored for contamination with a result greater than **TRIPLE** the background is considered to be contaminated and shall be cleaned.

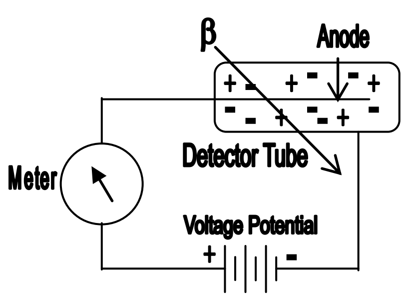
6.3 Radiation Detectors

Because humans cannot see or feel radiation, it is necessary to rely on monitoring instruments to measure the amount of radioactivity present. Almost all radiation detectors are based on the collection of ion pairs produced by ionizing radiation. A few of the more common types are described below.

6.3.1 Gas Filled Detectors

The figure below illustrates the basic principle used by portable instruments in the detection and measurement of ionizing radiation. The detector tube is simply a gas filled tube with a central wire that has a positive charge applied to it (anode) and is then connected, through a meter, to the wall of the tube (cathode). Radiation enters the tube and produces ion pairs in the gas. The electron part (negative charge) of the ion pair is attracted to the anode where it enters the electric circuit. The meter then shows this flow of electrons (i.e. the number of ionizing events) in counts per minute (cpm).

The only prerequisite for the detection of radiation with a survey meter is that the radiation must have sufficient energy to penetrate the window of the detector tube and create ionization in the gas. The most common type of survey meter used in research laboratories is the Geiger-Mueller (GM) survey meter.



6.3.1.1 Ionization Chambers

In the ionization chamber region, the range of the electric field (voltage) is great enough to collect the ions before a significant fraction of them can recombine yet not great enough to accelerate the ions sufficiently to produce secondary ionization by collision with other gas molecules. In this region, the number of electrons collected by the anode will be equal to the number produced by the primary ionizing particle; the gas amplification factor is equal to one. The pulse size, accordingly, will be independent of the detector operating voltage, and will depend only on the number of ions produced by the primary ionization particle during its passage through the detector.

6.3.1.2 Proportional Counters

The electric field is increased enough to accelerate the ion pairs to cause secondary ionization. The electron liberated by this secondary ionization process will also be accelerated by the electric field. During its subsequent drift, it undergoes collisions with other neutral gas molecules and thus can create additional ionization. This gas multiplication process therefore takes the form of a cascade, known as a *Townsend avalanche*. Over a specific region of the electric field, the gas multiplication will be linear and the collected charge will be proportional to the number of original ion pairs created by the incident radiation. Under constant operating conditions, the observed pulse amplitude will indicate the number the ion pairs created within the counter, although its charge has been greatly amplified.

6.3.1.3 Geiger-Mueller Counters

In the GM tube, substantially higher electric fields than proportional tube electric fields are created that enhance the intensity of each avalanche. Under proper conditions, a situation is created in which one avalanche itself can trigger a second avalanche at a different position within the tube. At a critical value of the electric field, each avalanche can create, on the average, at least one more avalanche, and a self-propagation chain reaction results. At still greater values of the electric field, the process becomes rapidly divergent and, in principle, an exponentially growing number of avalanches could be created within a very short time. Once this *Geiger discharge* reaches a certain size, however, collective effects of all the individual avalanches come into play and ultimately terminate the chain reaction. Because this limiting point is always reached after about the same number of avalanches have been created all pulses from a Geiger tube are of the same amplitude regardless of the number of original ion pairs that initiated the process.

Figure 6.0 Gas Filled Detector Regions of Interest

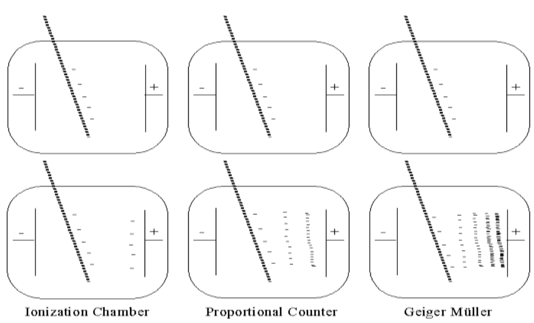
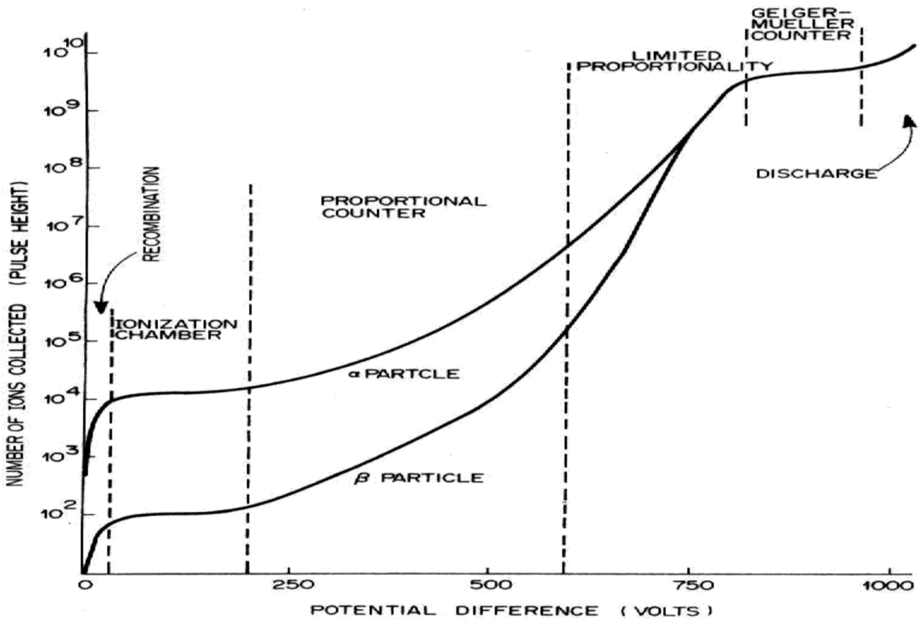


Figure 6.1 Regions of Operation of Gas Filled Detectors



6.3.2 Personal Dosimeters (Thermoluminescent Dosimeter)

In working with nuclear substances, monitoring of the amount of ionizing radiation delivered to a person's body allows one to verify that safe practices are being followed and engineered and procedural controls are effective.

TLDs (Thermoluminescent Dosimeter) are small inorganic crystals ($CaSO_4$, CaF_2, LiF) which exhibit high concentrations of "trapping centers" for electrons excited to certain energy levels. These lattice inorganic crystals house energy bands for electrons to exist. The energy of any electron within the crystal material must be confined to one of these energy bands, which are separated by band gaps. The lower band called the balance band, corresponds to those out-shell electrons that are bound to specific lattice sites within the crystal. The next higher-lying band is called the conduction band and represents electrons that are free to migrate through the crystal. The process is one in which electrons are elevated from the valence to the conduction band by the incident radiation and then captured at various trapping centers.

To read the TLD, the TLD is heated to a temperature determined by the energy level of the trap. The electrons get re-excited and release an amount of light that is viewed by a photomultiplier tube. The light released is proportional to the amount of radiation the TLD crystal absorbed. So the system can be calibrated to give radiation dose as a function of light output. If the TLD is raised to a relatively high temperature, all the traps are depleted and the exposure record is "erased" and the TLD can be reused.

Personnel dosimeters are required for anyone working with high-energy beta emitters or gamma emitters and where it's possible for a person to receive 1 mSv in a year.

TLD badges cannot pick up a dose from ^{3}H, ^{14}C, or ^{35}S radioisotopes.

6.3.2.1 Proper Care and Use of TLD

- Do not expose the TLD to high temperature, water, direct sunlight or fluorescent light.
- Clip the whole body TLD firmly to your clothing between your waist and neck.
- Extremity TLD's should be worn facing the source of radiation.
- Store your dosimeter in a low radiation background area and away from direct light and heat.
- If you lose or damage your TLD contact the Radiation Safety Office as soon as possible.

6.4 Detector Efficiency

The efficiency of a detector is a measure of how well it detects radiation. By definition, the efficiency is the percentage of the total number of radiation disintegrations occurring in a source that are actually measured by the detector. To understand the concept of efficiency, one has to ask two questions:

1. Does the radiation intercept the detector?
2. Is the radiation intercepting the detector measured?

The percentage of the total number of radiation disintegrations occurring in a source that intercept the detector is referred to as the geometric efficiency. The geometric efficiency is governed solely by the source-detector geometry. The percentage of the total number of radiation particles intercepting the detector that are actually registered is referred to as the intrinsic efficiency. The intrinsic efficiency of a detector depends on the detector design and construction and the type of radiation being measured.

$$\text{Det. Efficiency} = \text{Eff.}_{\text{geometric}} \times \text{Eff.}_{\text{intrinsic}}$$

6.4.1 Source – Detector Geometry

The source-detector geometry is affected by the detector size, geometric relationship between the radiation source and the detector and presence of material which may absorb or scatter radiation.

- The detector size and shape will influence the monitoring results. The larger the "window" and volume, the more sensitive the detector.
- Charged particles like beta particles are readily absorbed or scattered by air. Hence, the distance from the detector to the nuclear substance is very influential. Double the distance and it reduces the count rate by four. Therefore, accurate measurement requires that the detector be close to the source.

- If the background field is too high then measurements will be less accurate.

6.4.2 Detector Construction

- Radioactive decay is a random process. Consequently, any measurement based on observing the radiation emitted in nuclear decay is subject to some degree of statistical fluctuation. Refer to section for more information in this area.
- The absorption of radiation by the detector window will have an effect on the detector efficiency. For example: with a window thickness of 1.5 $mgcm^{-2}$.

Radioisotope	Absorption by window
H-3	99.9%
C-14	32%
S-35	29%
P-32	1%

- For alpha and beta particles, interaction in the form of ionization will take place immediately upon entry of the particle into the detector. After travelling a small fraction of its range, a typical particle will form enough ion pairs along its path to ensure that the resulting pulse is large enough to be recorded. Therefore, the detector is said to have a counting efficiency of 100 percent.
- For gamma rays and neutrons, they must first undergo a significant interaction in the detector before detection is possible. Because these radiations can travel large distances between interactions, detectors are considerably less 1 – 2% efficient.
- In nearly all detector systems, there will be a minimum amount of time that must separate two events in order to be recorded as two separate pulses. Because of the random nature of radioactive decay, there is always some probability that a true event will be lost because it occurs too quickly following a preceding event. These "dead time losses" can become rather severe when high counting rates are encountered.

6.4.3 Determination of Detector Efficiency

The detector efficiency can be determined by counting a standard source of known activity with your detector.

$$\text{Efficiency} = \frac{(\text{measured counts/minute} - \text{background counts/minute})}{\text{expected counts/minutes (known activity of source)}} \times 100\%$$

The efficiency can be calculated using units such as counter per second (cps) or counts per minute (cpm). However, it is important that the units be consistent (do not mix cps with dpm or visa-versa).

Detector efficiencies are often quoted in units of percent. However, the fractional form must be used when applied to actual calculations.

The efficiency can be applied to measured count rates to calculate activity using the expression:

$$Activity = \frac{cps}{efficiency}$$

Similarly, the following equation can be used to calculate removable activity (Bqcm^{-2}) during the monitoring for surface contamination.

$$Bqcm^{-2} = \frac{N - NB}{E \times 60 \times A \times F}$$

where:

N	=	total count rate in counts per minute (cpm) measured.
NB	=	normal background count rate from the survey instrument.
60	=	seconds/minute
E	=	instrument efficiency factor expressed as a decimal for the radioisotope being measured.
A	=	area wiped in cm^2 (100cm^2)
F	=	collection factor for the wipe (F = 0.1 or 10%)

7 TRANSPORTATION REQUIREMENTS

7.1 Classifying of Nuclear Substance Packages

The packaging and labelling of nuclear substances is regulated by the Canadian Nuclear Safety Commission's *Packaging and Transport of Nuclear Substances Regulations*. Nuclear substances may be shipped as "Excepted Packages", "Low Specific Activity (LSA)", "Type A", or "Type B" packages. It is the package design that makes nuclear substances safe for transportation and ensures only an acceptable amount of radiation is released. Therefore, the design and construction of the packaging is very strictly controlled.

On Excepted Packages, the safety mark "Radioactive" must be visible upon opening the package and the radiation level at any point on the external surface of the package must not exceed 5 µSv/h. All other packages must be categorized by radiation level and display the corresponding radiation warning labels as follows:

<u>Category I - White</u>

Does not exceed 5 µSv/h at any location on the external surface of the package.

<u>Category II - Yellow</u>

Does not exceed 500 µSv/h at any location on the external surface of the package and the transport index does not exceed 1.

Category III - Yellow

Does not exceed 2 mSv/h at any location on the external surface of the package and the transport index does not exceed 10.

The transport index for a package is the maximum radiation level in microsieverts per hour at one meter from the external surface of the package, divided by 10.
Example: 1 µSv/h at 1 m equals a TI = 0.1.

7.2 Receiving Nuclear Substance Packages

Packages containing nuclear substances or radiation devices shall be delivered to the Radiation Safety Office. The package will be wipe tested, the received good number entered into the system, and the package delivered to the end user in a timely manner.

In keeping with good radiation safety practices, the following procedures should be performed when opening packages which contain unsealed nuclear substances:

- Wear a lab coat and disposable gloves while handling the package.
- Upon receiving, the recipient shall examine it for damage or leakage. If the package is found damaged or leaking, contain and isolate the package and *immediately* contact the Radiation Safety Officer.
- If no damage is evident, remove the shipping vial holder and wipe test the vial. If contamination is detected, monitor the rest of the package and any areas that have come in contact with the vial. Contain the contamination and contact the Radiation Safety Officer.
- Avoid unnecessary direct contact with unshielded containers.
- Verify the radioisotope, the activity, and other details with the information on the packing slip and the purchase order.
- Log the reference date, activity on reference date and any other anomalies on the inventory sheet.
- Write the requisition number on the shipping vial holder.
- Store the nuclear substance according to the requirements of the manufacturer.

7.3 Transporting Nuclear Substances

The transportation of nuclear substances within Canada is done in accordance with performance safety standards set by the CNSC. These standards are based on international safety standards developed by the International Atomic Energy Agency (IAEA) of the United Nations.

7.3.1 Between Laboratories

When transporting nuclear substances between laboratories in the same building the instructions listed below shall be followed:

- Unsealed nuclear substances shall be transported in a two-container package. The primary container shall be securely sealed and labelled with the radioactive warning symbol.
- Enough absorbent material shall be placed between the primary and secondary container to contain a spill. Glass containers are prohibited.
- Sealed nuclear substances shall be transported in their original transport containers, which are labelled and marked accordingly. If no original shipping container is available a holding container with the radiation warning symbol label shall be used.
- Walk or use a cart to transport the nuclear substance.
- Select a route that is the shortest and has the least amount of risk for an accident to occur.

7.3.2 Between Buildings

When transporting nuclear substances between buildings:

- Unsealed nuclear substances shall be transported in a two-container package. The primary container shall be labelled with the radioactive warning symbol.
- Enough absorbent material shall be placed between the primary and secondary container to contain a spill.
- Sealed nuclear substances shall be transported in their original transport containers, which are labelled and marked accordingly. If no original shipping container is available a holding container with the radiation warning symbol label shall be used.
- Walk or use a cart to transport the nuclear substance.
- Select a route that is the shortest and has the least amount of risk for an accident to occur.
- If a vehicle is required to transport the nuclear substance contact the Radiation Safety Officer.

7.3.3 Off Campus

- Any person packaging and transporting a nuclear substance off campus must hold a valid Transportation of Dangerous Goods certificate.
- The amount of activity shipped determines the classification of the package.

- Contact the Radiation Safety Officer for assistance with the packaging, marking, labelling and documentation.

8 EMERGENCY PROCEDURES

In case of an Emergency involving Nuclear Substances

Contact:
Weekdays: Mon. - Fri. 8:00 - 4:30

Safety Resources	**306-966-4675**
Waste Management Facility	**306-966-8497**

After Hours, weekends and holidays

Protective Services	**306-966-5555**

8.1 Precautionary Measures

There are several measures that can be taken to enhance the remediation of an accident with nuclear substances.

1. All work should be carried out according to some prearranged plan. Any departure from the plan should be followed by a reassessment of the radiation hazards involved.
2. All workers should familiarize themselves with the clean up procedures.
3. Priority shall be given to human safety according to need and urgency. Responsibility for protecting the public should take precedence.
4. Workers should be thoroughly familiar with the location and method of use of the protection and first-aid equipment for emergencies.
5. No person should undertake dangerous work without someone standing by who can assist in case of trouble.

8.2 Emergency Procedures

There are a number of procedures that are common to all types of accidents involving hazardous substances. These procedures should be followed in the initial stages of any incident.

1. *Assess the situation.*
   Take your time to assess the situation for any potential hazards and then determine your plan of action. The protection of personnel and the containment of the hazardous substance should be given primary consideration.

2. *Alert everyone in the area.*
   Ensure that everyone in the vicinity of the accident has been alerted. Be sure to make an effective warning, especially in large laboratories or areas.

3. *Confine the accident.*
   Restrict access to the area. Confine the problem (contain the hazardous substance) to minimize the exposure to personnel or release to the environment.

4. *Clear the area.*
   Evacuate all persons from the immediate vicinity of the incident. Ensure a sufficient separation such that persons near the incident cannot become exposed to the problem.

5. *Summon aid.*
   In any emergency situation, it is vital to notify the appropriate personnel (Protective Services, Ambulance, and/or Fire Department). It is important to contact Safety Resources so they can ensure proper clean up of the area and personnel.

6. *Report Incident/Accident.*
   Report the incident/accident to Safety Resources through the online reporting system (http://safetyresources.usask.ca). A telephone call would also be appropriate at the time of the incident.

8.3 Theft or Loss of Nuclear Substances

Theft or loss of nuclear substances is a serious offense and shall immediately be reported to the Radiation Safety Officer. It is important to know the amount of nuclear substance that is missing. An investigation will follow. If a significant quantity of substance is involved, the CNSC may have to be notified by the Radiation Safety Officer.

8.4 Fire or Explosion Involving Nuclear Substances

In the event of a fire or explosion, where nuclear substances are known to be present, the Radiation Safety Officer shall immediately be notified. Emergency personnel responding to the scene should be advised that nuclear substances are present. If chemicals are involved, the concern with their toxicity should also be addressed.

8.5 Classification of a Radioactive Spill

For the purpose of cleaning spills, a nuclear substance spill is classified as:

Classification	Activity Spilled
Minor	< 1 mCi
Major	≥ 1 mCi

8.6 Cleaning Procedures in the Event of a Minor Spill

In the event of any spill of nuclear substance, it is important that the correct steps be taken promptly to avoid exposure and the spread of contamination.

The most important immediate action is to prevent the spreading of the nuclear substance (provided that it can be accomplished without creating any additional hazard).

The following steps shall be taken in the following order:

1. If possible, using the appropriate detector, monitor clothing and hands to determine if any skin or clothing contamination has occurred. If personal contamination has occurred treat it according to Section 8.8.
2. Alert everyone in the area that a spill has occurred and restrict access to the area involved in the incident.
3. Do not allow anyone to leave the contaminated area without first being monitored for contamination.
4. Contain the spill. If the substance is a liquid, use absorbent material to prevent it from spreading. If the substance is dry, use damp absorbent material to prevent it from becoming airborne.
5. Ask a trained co-worker to assist you in cleaning up the area. Ensure that one person cleans the spill while the secondary person remains "clean". This will ensure no further spreading of contamination.
6. Wear two pairs of gloves. This will protect the hands during the changing of the first pair.
7. Ensure that a lab coat is worn and properly buttoned up to prevent contamination of personal clothing.
8. Outline the location and probable extent of the contamination with an erasable marker. Radiation warning tape may also be used. Do not use felt tip or other permanent markers.
9. Avoid entering this outlined area. This prevents the spreading of contamination.
10. Begin decontamination procedures as soon as possible.
11. Ensure that sufficient materials are available to properly clean the area prior to beginning the cleaning procedure. If you need something ask your co-worker (who should remain free from contamination) to pass it to you.
12. First **blot** the spill to pick up all of the substance. Do not wipe the area.
13. Apply any normal cleansing agent or commercial decontamination agent to the contaminated area.
14. Then working from the outside of the spill towards the center, wipe the spilled area. Repeat three to four times.
15. Finally, gently wash the affected area while remaining inside the outlined area.
16. Discard all cleaning materials as radioactive waste.
17. Monitor (indirectly or directly) the area for residual contamination and count the samples.
18. Repeat the cleaning procedure until the contamination is removed. If cleaning is ineffective at removing the contamination, contact the Radiation Safety Officer for assistance.
19. Wash hands thoroughly.

20. Monitor hands, clothing and shoes for contamination.
21. Notify the Radiation Safety Officer. Complete a University of Saskatchewan Incident Report online at http://safetyresources.usask.ca.
22. If the spilt substance is volatile or may become air borne, secure the laboratory to prevent entry. Post warning signs and immediately contact Safety Resources or the Waste Management Facility for cleanup.

8.7 Cleaning Procedures in the Event of a Major Spill

The following steps should be taken:

1. Alert everyone in the area that a spill has occurred and restrict access to the area involved in the incident.
2. Do not attempt to clean the spill, but do take actions to prevent it from spreading. If the substance is a liquid, use absorbent material to prevent it from spreading. If the substance is dry, use damp absorbent material to prevent it from becoming airborne.
3. If personal contamination has occurred, treat it according to Section 8.8 and contact the Radiation Safety Officer.
4. Contact the Waste Management Facility or Safety Resources to clean the spill.

8.8 Treatment of Personal Contamination

When contamination of the skin is known or suspected, the steps listed below should be followed. It is very important that skin contamination be cleaned immediately. Early, effective removal of the contamination can help to reduce radiation exposure.

During skin decontamination, it is important to proceed from mild treatments to harsher ones only if necessary. Abrasion or any other breaks of the skin must be avoided, as these will allow rapid penetration of nuclear substances. Therefore, hard scrubbing is discouraged.

8.8.1 Treatment of Skin Contamination

1. Contact the Radiation Safety Officer.
2. Flush contaminated area with copious amounts of warm water.
3. Apply mild soap or detergent. Lather well with plenty of water.
4. Work lather into contaminated area by rubbing gently for two to three minutes.
5. Exercise caution to prevent contamination from spreading to other areas of the body.
6. Pay special attention to a variety of areas where contamination might settle, such as fingernails, folds, creases, inner-finger spaces and jewellery.
7. Rinse thoroughly with tepid water.
8. Monitor contaminated area. (direct or indirect)
9. Repeat wash/rinse procedure several times using a soft brush, if necessary.
10. Discontinue before skin becomes abraded or sensitive.

Only after several attempts with soap and water should harsher decontamination methods and cleaning agents be considered. These methods should be under the direction of the Radiation Safety Officer.

8.8.2 Treatment of Contaminated Wounds

1. Contact the Radiation Safety Officer.
2. Dry clean the affected area with swabs.
3. Using a wet swab wipe the contamination away from the wound taking care not to spread the contamination over the body or into the wound.
4. Wash the contaminated wound with copious amounts of warm water. Encourage minor bleeding.
5. In the case of contaminated facial wounds, ensure that contamination does not spread to mouth, ears, eyes or nasal passages.
6. Wash wound with mild soap and water as noted above.
7. After decontamination, apply first aid dressing.

In the case of serious injuries:
1. Call 9-911 and Protective Services at 306-966-5555.
2. Call Safety Resources to report the nature of the hazard, the amount of nuclear substance, the chemical form of the substance and any other pertinent information such as location.
3. Direct someone to meet the emergency medical personnel.
4. Ensure that nuclear substances cannot further contaminate the victim.

NOTE: Seriously injured persons should not be delayed medical attention because of concerns relating to radiation contamination.

8.8.3 Internal Contamination

If internal contamination is suspected, the Radiation Safety Officer shall immediately be notified.
- Personnel working with nuclear substances should understand its chemical and radioactive properties such that a prompt response to a suspected intake of substance can be carried out.
- If the material is chemically toxic as well as radioactive, treat for chemical toxicity first. It is important for a quick response to internal contamination to prevent or reduce the nuclear substance uptake into the bloodstream and tissues. The contaminated person should be taken to the hospital for proper medical attention.

8.9 Treatment of Clothing Contamination

In the event that nuclear substances contaminate personal clothing or lab coat, it is important that it be removed quickly to reduce your exposure to the radiation. Collect the clothing in a plastic bag labelled with the estimated amount of activity and radioisotope. Contact the Radiation Safety Officer for further information.

INTERPRETATION OF TERMS

(Taken from the Radiological Health Handbook,
The Health Physics and Radiological Health Handbook
and ICRP 60)

Absorbed Dose

Energy absorbed per unit mass (1 Joule per kg). The energy imparted to matter by ionizing radiation per unit mass of irradiated material.

$$1\ \text{Gy} = \frac{1\ \text{Joule}}{\text{kg}} \qquad 1\ \text{rad} = 0.01\ \text{Joule/kg}.$$

Absorption

The process by which radiation transfers some or all of its energy to any material through which it passes.

Absorption Coefficient, Linear (μ)

A factor expressing the fraction of a beam of x or gamma radiation absorbed in unit thickness of material. In the expression $I = I_0e^{-\mu x}$, I_0 is the initial intensity, I the intensity of the beam after passage through a thickness of the material x and μ is the linear absorption coefficient.

Activity

The rate of disintegration (transformation) or decay of nuclear substances. The SI unit of activity is the Becquerel (Bq).

ALARA

(acronym for “as low as reasonably achievable”) Making every reasonable effort to maintain exposures to radiation as far below the dose limits as is practical, taking into account the state of technology, the economics of improvements in relation to state of technology, the economics of improvements in relation to benefits to the public health and safety, and other societal and socioeconomic considerations, and in relation to utilization of nuclear energy and licensed materials in the public interest.

Alpha Particle

A positively charged particle emitted from the nucleus of an atom having a mass and charge equal in magnitude of a helium nucleus; i.e. two protons and two neutrons.

Annual Limit of Intake (ALI)

The derived limit for the amount of nuclear substance taken into the body of an adult worker by inhalation or ingestion in a year. ALI is the smaller value of intake of a given radionuclide in a year by the reference man that would result in a *committed effective dose equivalent* of 50 mSv or a *committed equivalent dose* of 50 mSv to any individual organ or tissue.

Atom

Smallest particle of an element that cannot be divided or broken up by chemical means. It consists of a nucleus, which contains protons and neutrons and electrons orbiting the nucleus.

Atomic Number (Z)

The number of protons in the nucleus of a neutral atom. The atomic number determines the chemical properties of the element.

Atomic Weight (A)

Expressed in terms of “atomic mass units”. The number of neutrons and protons in the nucleus of an atom.

Attenuation

The process by which a beam of radiation is reduced in intensity when passing through some material.

Avogadro’s Number

Number of atoms in a gram atomic weight of any element. It is numerically equal to 6.023×10^{23} on the unified mass scale.

Background Radiation

Radiation from cosmic sources, naturally occurring nuclear substances, radon and global fallout as it exits in the environment from the testing of nuclear explosive devices.

Basic Level Laboratory

A room where nuclear substances are used and where the total quantity of each nuclear substance used at one time does not exceed five (5) times its corresponding Annual Limit of Intake (ALI).

Becquerel

A unit, in the International System of Units (SI), of measurement of radioactivity. It is equivalent to 1 disintegration per second.

Beta Particle

A negatively charged particle emitted from the nucleus of an atom, with a mass and charge equal in magnitude to that of the electron.

Bremsstrahlung

Secondary photon radiation produced by sudden deceleration of charged particles passing through matter.

Contamination (fixed)

Contamination that can not be readily removed from the surface. Depending on the radioisotope and activity, fixed contamination may pose an external radiation hazard.

Contamination (removable)

Contamination that can be readily removed from the surface. Removable surface contamination is of the greatest concern as it is transferable to other surfaces. This can result in widespread surface contamination and lead to internal contamination due to the intake of nuclear substances into the body.

Contamination (Radioactive)

Deposition of nuclear substances in any place where it is not desired.

Critical Organ

That part of the body that is most susceptible to radiation damage resulting from the specific exposure conditions under consideration, taking into account the dose the various parts of the body receive under the exposure conditions. For example, ^{125}I and ^{131}I, the critical is the thyroid due to the preferential uptake of iodine by that gland and its susceptibility to radiation damage.

Curie (Ci)

A unit of activity. One Curie equals 3.70×10^{10} nuclear transformations per second, which is approximately the rate of decay of 1 gram of radium.

Decay Constant (λ)

The fraction of the number of atoms of a radioisotope which decay in unit time. It is expressed as the reciprocal of time (*i.e. seconds*$^{-1}$) and is related to the half life by the following equation: $\lambda = 0.693/T_{1/2}$.

Decay, Radioactive

The decrease in the activity of any nuclear substance with the passage of time, due to the spontaneous emission from the atomic nuclei of either alpha, beta particles, or gamma radiation.

Deterministic Effects

Effects characterized by a severity that increases with dose above some clinical threshold. The severity of the syndrome that occurs following the administration of the radiation will depend on the number of cells damaged and the total equivalent dose received by the individual.

Dose

A generic term denoting the quantity of radiation or energy absorbed.

Dose Rate

The absorbed dose delivered per unit time.

Dosimeter

A portable device used to measure and record the total exposure to ionizing radiation.

Effective Dose

Effective Dose is the sum of the doubly weighted absorbed dose in all the tissues and organs of the body. The weighting factors for this purpose are called the radiation weighting factor and tissue weighting factor. This unit is in joules per kilogram with the special name sievert.

1 Sv = 100 Rem

Equivalent Dose

Equivalent Dose is the absorbed dose averaged over a tissue or organ and weighted for the radiation quality that is of interest. The weighting factor for this purpose is called the radiation weighting factor. This unit is in joules per kilogram with the special name sievert.

Electromagnetic Radiation

Travelling waves of radiation resulting from changing electric and magnetic fields.

Electron Volt (eV)

A unit of energy equivalent to the energy gained by an electron in passing through a potential difference by one volt.

Energy

Capacity for doing work. “Potential energy” is the energy inherent in a mass because of its spatial relation to other masses.

Exposure

A measure of ionization produced in air by gamma or x-radiation. The unit of exposure is coulombs per kilogram of air.

Gamma Ray (γ)

High energy, short wavelength, electromagnetic photon emitted from the nucleus.

Genetic Effect

An effect in a descendant resulting from the modification of genetic material in a parent.

Geometry Factor

The fraction of the total solid angle about the source of radiation that is subtended by the face of the sensitive volume of a detector.

Gray

The International Systems of Units (SI) unit of absorbed dose. This is the energy absorbed per unit mass. 1 Gy = 1 J/kg = 100 Rad

Half Life, Biological

The time required for the body to eliminate half of the nuclear substance taken in by natural biological means.

Half Life, Effective

Time required for a radionuclide in a body to reduce its activity by half as a result of the combined action of radioactive decay and biological elimination. The effective half life is a mathematical combination of the physical and biological half lives of the particular radionuclide.

Half Life, Radioactive

Time required for a nuclear substance to lose 50 percent of its activity by decay. The time in which half the atoms of a nuclear substance disintegrate to another nuclear form. Each radionuclide has a unique half life.

Half Value Layer

The thickness of a specified substance which, when introduced into the path of a given beam of radiation, reduces the exposure rate by one half.

Hormesis

Hormesis is a theory that some radiation is beneficial to health.

Ion

An atom that has too many or too few electrons, causing it to be chemically active.

Ionization

The process by which a neutral atom or molecule acquires a positive or negative charge. The process of adding one or more electrons to, or removing one or more electrons from, atoms or molecules, thereby creating ions.

Intermediate Level Lab

A room where the total quantity of a nuclear substance used at one time does not exceed 50 times its corresponding ALI.

Isotopes

Nuclides having the same number of protons in the nuclei, and hence the same atomic number but differing in the number of neutrons; therefore, in the mass number.

Linear Energy Transfer (LET)

A measure of the ability of biological material to absorb ionizing radiation; specifically, for charged particles traversing a medium. The energy lost per unit length of path as a result of those collisions with electrons in which the energy loss is less than a specified maximum value. A similar quantity may be defined for photons.

Neutron

A nuclear particle having a mass similar to a proton but having no electrical charge.

Nuclear Energy Worker (NEW)

A person who is required, in the course of the person's business or occupation in connection with a nuclear substance, to perform duties in such circumstance that there is a reasonable probability that the person may receive, a dose of radiation that is greater than the prescribed limit (1 mSv) for the general public.

Nuclide

A general term referring to all known isotopes, both stable and unstable of the chemical elements.

Open Source

An open source is any unsealed nuclear substance. This could be in the form of a liquid, gas, or solid. Such a source is most likely to cause contamination.

Photon

A quantum of energy emitted in the form of electromagnetic energy. Gamma rays and x rays are examples of photons.

Radiation

Energy in motion in the form of a wave or particle.

Radiation, External

Radiation from a source outside the body--the radiation must penetrate the skin.

Radiation, Internal

Radiation from a source within the body (as a result of deposition of radionuclides in body tissues).

Radiation Weighting Factor (RWF)

A modifying factor used in the derivation of equivalent dose. This factor if selected for the type and energy of the radiation incident on the body. Used to allow comparison of different types of radiation.

Radioactive Decay

The decrease in the amount of any nuclear substance with the passage of time, due to the spontaneous emission from the atomic nuclei of either alpha, beta particles, or gamma radiation.

Radioactivity

Spontaneous emission of radiation, generally particles or gamma radiation from the nucleus of an unstable isotope.

Radioisotope

An unstable isotope of an element that decays or disintegrates spontaneously, emitting radiation. Approximately 5000 natural and artificial radioisotopes have been identified.

Radionuclide

A radioisotope.

Radiotoxicity

The term referring to the potential of a radioisotope to cause damage to living tissue by the absorption of energy from the disintegration of the nuclear substance that is within the body.

Radon

A radioactive element that is one of the heaviest gases known. Its atomic number is 86, and its mass number is 222. It is a daughter of radium.

Roentgen

The amount of x or gamma radiation required to produce a specific amount of ionization in 1 cc of air. One roentgen equals 2.58×10^{-4} coulomb per kilogram of air.

Sealed Source

A nuclear substance in a capsule that is sealed or in a cover to which the nuclear substance is bonded, where the capsule or cover is strong enough to prevent contact with and dispersion of the nuclear substance under the conditions of use.

Sievert (Sv)

The (SI) unit for equivalent dose. See equivalent dose. 1 Sv = 100 Rem

Somatic Effect

Effects of radiation limited to the exposed individual. Somatic injury affects the current generation but is not passed on to future generations.

Specific Activity

Total activity of a given nuclide per gram of a compound, element or radioactive nuclide.

Stochastic Effects

Health effects that occur randomly and for which the probability of the effect occurring, rather that its severity, is assumed to be a linear function of dose without a threshold. Hereditary effects and cancer incidences are examples of stochastic effects.

Tissue Weighting Factor

Tissue Weighting Factor represents the relative contribution of that organ or tissue to the total detriment due to the effects resulting from uniform irradiation of the whole body.

Yield

The percentage of radiation emitted from a radioisotope with a particular energy. Example for Iodine-125 35% of the radiation is 35 keV gammas. 93% is internally converted.