RADIATION PROTECTION MANUAL

Contents

UNIVERSITY OF WATERLOO

1.0 What is Radiation

Before beginning its important to understand a few definitions:

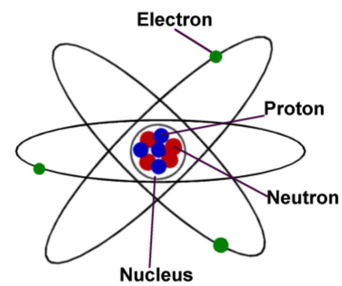
Matter
Anything that takes up space and has mass.

Element
An element represents the purest form of matter. Generally speaking, heating, freezing, or separating an element into segments.

Atom
An atom is the smallest quantity of an element which still retains the chemical properties of that element.

1.1 Structure of Matter

Ernest Rutherford suggested that the atom consists of a positively charged nucleus surrounded by a "cloud" of negatively charged electrons. In actuality, experimental results suggested that the nucleus contains two types of particles, the positively charged proton, and the neutral neutron. Furthermore, the electrons in the "cloud" are actually found following specific pathways around the nucleus. This could visually be described as a simple solar system model.



An atom is also described as a cloud. This is because the nucleus makes up 99.9% of the weight of the atom.

Finally, the following table provides a summary of the properties of protons, neutrons and electrons.

	Proton	Neutron	Electron
Charge	+1	0	-1
Mass	1.6726 x 10^{-27} kg	1.6750 x 10^{-27} kg	9.1095 x 10^{-31} kg
Location	Nucleus	Nucleus	Specific orbit around nucleus
Description	Mass same as neutron, with magnitude of charge as the electron	No charge, but mass same as proton	2000 times lighter than proton or neutron, but same magnitude of charge as proton

1.1.1 Atom Nomenclature

The atomic mass number of an atom is an important term that is utilized in chemistry and physics to identify and differentiate between various types of atoms. The atomic mass number of an atom is a representation of the weight of an atom, and its unit of the measure is the atomic mass unit (amu). An atomic mass unit (amu) is a unit of measure approximately equal to 1.67 x 10^{-27} kg. Both a proton and a neutron are equal in weight to 1 amu. An electron on the other hand is only equal to 0.00055 amu, or almost nothing.

The atomic mass number of an atom is equal to the sum total of protons and neutrons in an atom and is given the symbol "A". The atomic number is the number of protons in an atom and is given the symbol "Z".

Elements are atoms that contain specific numbers of protons and electrons and its unique nature is defined by these numbers. The chemical symbol for an atom containing 3 protons (atomic number 3) is Li for Lithium and for an atom containing 3 protons (atomic number 4) is Be for Beryllium.

Therefore, by using these definitions, an element can be uniquely identified. For example:

- Lithium has the following symbol: ${}^{A}_{Z}Li = {}^{6}_{3}Li$
  - The mass number = Protons (3) + Neutrons (3) = 6
  - Therefore, Lithium has 3 proton and 3 neutrons
  - Lithium is an electrically neutral atom therefore number of protons (3) = number of electrons (3)
- Beryllium has the following symbol: ${}^{A}_{Z}Be = {}^{9}_{4}Be$
  - The mass number = (4) Protons + (5) Neutrons.
  - Therefore, Beryllium has 4 protons and 5 neutrons
  - Beryllium is an electrically neutral atom therefore number of protons (4) = number of electrons (4)

All atoms of the same element will have the same number of protons. If an atom has a different number of protons from another atom the atoms are considered to belong to different elements. This means that the number of protons an atom has determines its chemical characteristics. On the other hand, if two atoms have the same number of protons, but differ in the number of neutrons, we differentiate them by calling them isotopes of the same element.

Example:

Hydrogen has 3 commonly known isotopes:

Hydrogen 1 – ${}^{A}_{Z}H = {}^{1}_{1}H$

Hydrogen 2 or Deuterium - ${}^{A}_{Z}H = {}^{2}_{1}H$

Hydrogen 3 or Tritium - ${}^{A}_{Z}H = {}^{3}_{1}H$

A nuclide is a specific type of atom that is differentiated by the number of protons, number of neutrons, or both. Therefore, atoms of different isotopes, and atoms of different elements are both referred to as nuclides.

1.1.2 Energy and Radiation

All matter has energy. This energy is related to mass and movement. The faster something moves, the more energy it will have (kinetic energy). Similarly, the more mass something has, the greater will be the energy it possesses. Energy can be changed into different forms, but it is never destroyed. This is Einstein’s basic theory of relativity:

$E=mc^2$

Where:

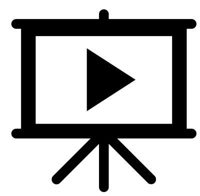
E = Energy

m = Mass

C = Speed of light in a vacuum

Radiation is the transfer of energy in the form of waves or particles through a medium or through space. Radioactive decay is when an unstable atom releases energy to become more stable. Energy emitted during radioactive decay, like all other matter, is related to mass and speed. However, with such small masses the energy emitted is also quite small. For this reason, the use of traditional units of energy for these types of materials is not practical. In this realm, the unit of energy used is called the electron volt (eV).

The definition of an electron volt is the amount of energy gained by an electron as it passes through an electric potential difference of one volt.



$1\ eV = 1.602 \times 10^{-19}$ joules

1 thousand electron volts=1 keV

1 million electron volts=1 MeV

Click the video icon to watch a video from the CNSC on what radiation is.

1.1.3 Electromagnetic Radiation

Electromagnetic radiation consists of oscillating electric and magnetic fields which are propagated in matter or free space. Electromagnetic radiation may be described as either a wave or a particle depending on the phenomena described.

When electromagnetic radiation is defined as a wave, it can be arranged in a spectrum according to frequency or wavelength as shown in the electromagnetic spectrum, where the wavelength is inversely proportional to frequency as defined by the formula:

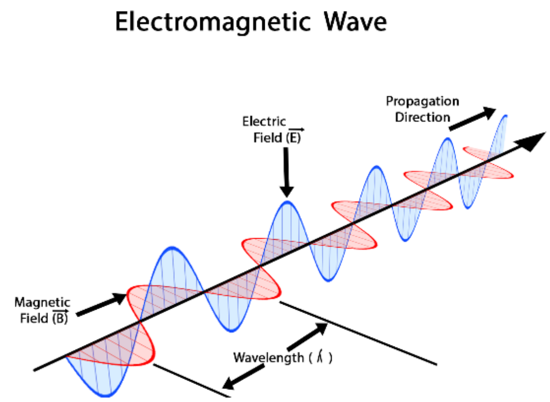
$l=c/v$

Where:

l= wave length in meters

v = frequency in Hz

c= the speed of light (3 X 108 m/s)



Electromagnetic radiation may also be described as a particle or a discrete bundle of energy called a photon. The energy of any photon is proportional to frequency as described by the following formula:

E = hv

Where:

E= energy (electron Volts =1.602 X 10-19 Joule)

h = Plank's constant (6.6 X 10 -34 J second)

v = frequency in Hz (cycles/second)

1.1.4 Ionizing and Non-ionizing Radiation

As radiation penetrates matter it deposits energy through collisions and other interactions in the absorbing medium. The atoms that absorb this energy can become excited and ionized. When the radiation absorbed is capable of producing electrically charged atoms (ions) in the absorber atoms, the radiation is called Ionizing Radiation. The process actually results in the removal of electrons in the absorber atoms.

On the other hand, non-ionizing radiation does not have sufficient energy to remove electrons from the absorber atoms.

Examples:

- **Ionizing radiation:** Radiation from radioisotopes, cosmic radiation, radiation from x-ray machines and accelerators
- **Non-ionizing radiation:** Visible light, microwaves, radio waves

1.1.5 Stable and Radioactive Nuclides

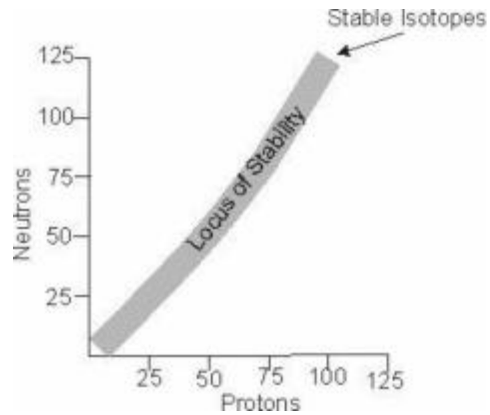
The forces that hold an atom together include nuclear forces and electrostatic forces:

Electrostatic forces: There are two electrostatic forces working simultaneously within an atom and are based upon the electrical charge of the components within the atom (proton and electron). Opposite charges attract one another – like what happens with electrons and protons. They attract one another and work to keep the electrons in their orbits.

Like charges repel each other, like electrons against one another, and protons against one another. In the nucleus, the protons situated close to one another will repel one another. The greater the number of protons (atomic number), the greater the electrostatic force working to the break apart the nucleus.

Nuclear forces: are the cohesive forces that work against the electrostatic forces of the protons to keep the nucleus together. As the number of neutrons (mass number) in an atom increase so will the nuclear forces acting on that atom.

Atoms are stable when the nuclear forces and electrostatic forces balance one another. As the ratio of neutrons and protons in an atom change, so will its stability. This ratio is called the locus of stability. If the ratio of neutrons to protons increases or decreases too far past this locus of stability the (see figure nuclear stability to the right) electrostatic and nuclear forces become unbalanced and the nucleus attempts to rearrange itself into a more stable configuration.



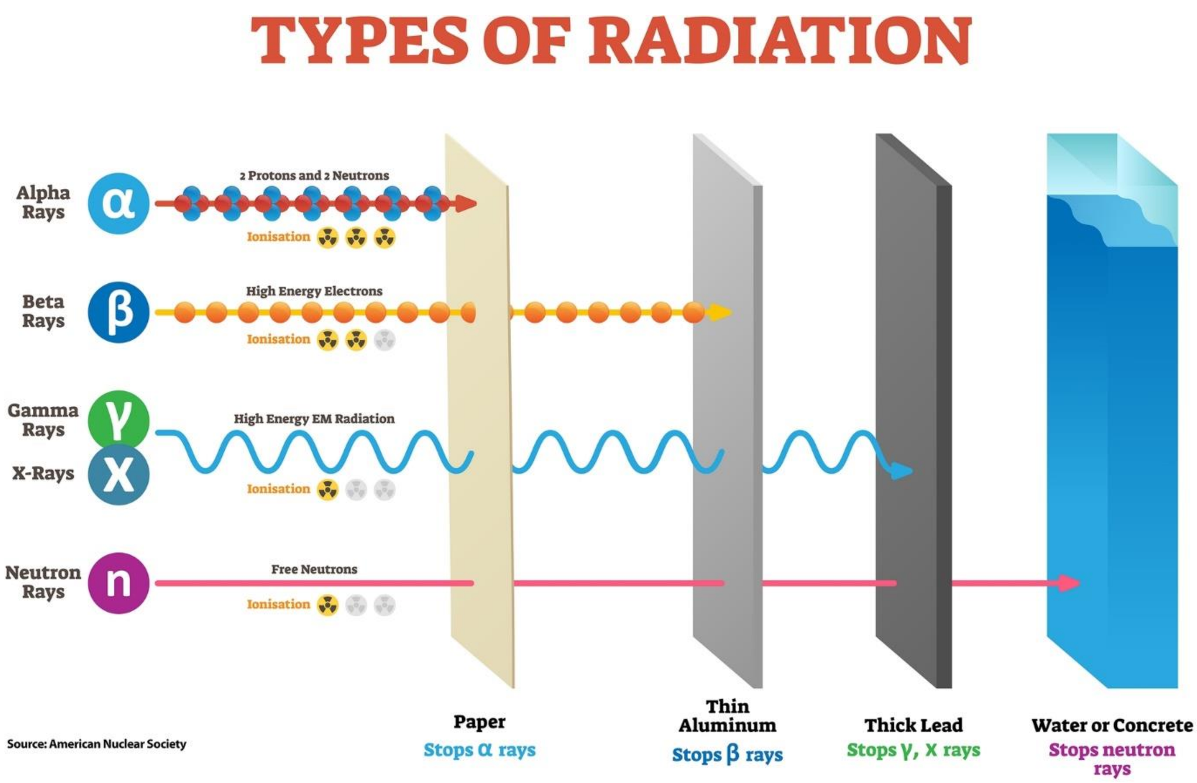
Elements which spontaneously rearrange their nucleus by emitting particles or energy are called radioactive isotopes. There are over 100 elements having about 1,300 isotopes of which about 1,100 are radioactive isotopes.

The exact mode of radioactive transformation depends on two factors:

1. The particular type of nuclear instability (too high or too low neutron to proton ratio)
2. The mass-energy relationships between the parent nucleus, progeny nucleus, and the emitted particle

1.2 Types of Ionizing Radiation

Six main types of ionizing radiation will be discussed here (alpha, beta, positron, gamma, x-ray, and neutron). What makes radiation dangerous is its ability to interact with human cells, and in some cases, the ability to travel.



1.2.1 Ionization by Alpha Particles

When an atom has greater than 82 protons (Z > 82), and has a neutron to proton ratio that is too low, the electrostatic forces are strong enough to overcome the nuclear forces in keeping the nucleus together. In order to become more stable, the atom can emit an alpha particle, which is a nuclear fragment consisting of 2 neutrons and 2 protons (this is the structure of a Helium nucleus).

Formula for emission	Neutron to Proton Ratio for Radium	Neutron to Proton Ratio for Radon
${}^{226}_{88}Ra \rightarrow {}^{222}_{86}Rn + {}^{4}_{2}\propto$	136:88 = 1.568	134:86 = 1.581

In the alpha decay summarized in Table 2, the ${}^{226}_{88}Ra$ atom is referred to as the parent atom. The ${}^{222}_{86}Rn$ atom is referred to as the progeny, decay product, or daughter product. When emitted, an alpha particle is considered mono-energetic. This means that each alpha particle emitted from a particular isotope will have the same energy.

When dealing in atomic size ranges, alpha particles are considered quite large and with quite a bit of energy. Their size and strong charge makes them highly ionizing, and in comparison, to other radiation alpha particles will produce more ions per unit distance as it passes through matter. However, because of this tendency to be highly ionizing, they do not travel far in air (a few centimeters) and they can easily be stopped by something as benign as a sheet of paper or the dead outer most layer of skin on humans. This means that alpha sources of radiation originating outside the body pose little risk of harm. However, if an alpha particle emitter is able to enter the body (through injection, ingestion or inhalation) the risk of damage to cells will be significant.

1.2.2 Ionization by Beta Particles

When an atom has too many neutrons it can internally change neutron ($^{1}_{0}n$) into a proton ($^{1}_{1}p$). When this process occurs, the nucleus will eject a particle with the same mass and charge as an electron called a beta particle ($^{0}_{-1}e$).

The process can be summarized by the following equation:

$$^{1}_{0}n \rightarrow \; ^{1}_{1}p + \; ^{0}_{-1}e$$

In the case of a pure beta emitter, this is the only process that happens and no other radiation is emitted. Radionuclides considered to be pure beta emitters include: $^{32}_{15}P$, $^{3}_{1}H$, $^{14}_{6}C$, and $^{90}_{38}Sr$.

For many other atoms, after beta emission occurs the daughter nucleus is left in an excited condition and rids itself of the energy of excitation by the emission of a gamma ray. This is similar to when an alpha particle is emitted leaving the daughter in an excited state and emits a gamma ray with the beta particle.

Like alpha radiation, beta radiation is ionizing, but because of the smaller size and smaller charge (-1), it is less ionizing and can penetrate deeper into matter. Depending on its energy, it can travel several hundred centimeters in air. In tissue, beta radiation will penetrate only millimeters, but because of this penetrating ability it is considered both an internal and external radiation hazard.

Beta radiation can also form x-ray radiation (sometimes referred to as bremsstrahlung – or braking radiation). Fast moving beta particles can be slowed down, change direction, or stopped by an absorbing medium. When this happens, energy is emitted in the form of x-rays. In order to minimize this radiation, shielding must be selected carefully. A general rule of thumb is that the higher the atomic number of a shielding material, the higher will be the bremsstrahlung. In practice, radiation shields with Z > 13 (aluminum) are rarely used.

When an atom undergoes beta decay the progeny nuclei will have a mass number (A) which is the same as the parent nuclei, but the atomic number (Z) will be one unit higher.

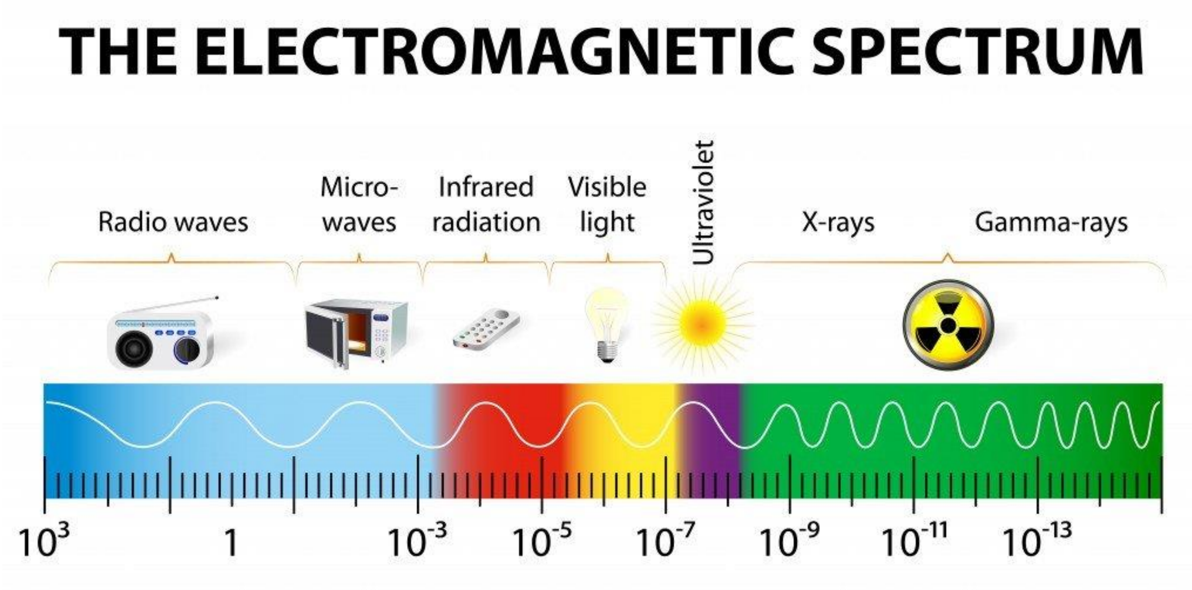
1.2.3 Positron Decay

When a particle has too many protons, and it is not feasible to emit an alpha particle, the nucleus can convert a proton into a neutron. When this happens, a particle called a positron is emitted from the nucleus. In essence, a positron is a positively-charged electron. It also can be thought of as a beta particle ((_1^0)e) with a positive charge. Other than the charge, the difference between an electron and a positron is that electrons occur freely in nature whereas positrons are only formed during positron emission and remain in existence for a very short period of time. When a positron collides with an electron it annihilates both yielding gamma ray photons with an energy equivalent to the mass of both the positron and the electron.

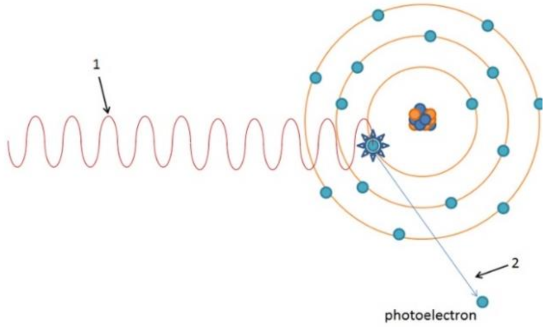
When positron emission occurs, the progeny or daughter nuclei will have the same mass number (A) as the parent, but its atomic number (Z) will be one less than the parent nuclei.

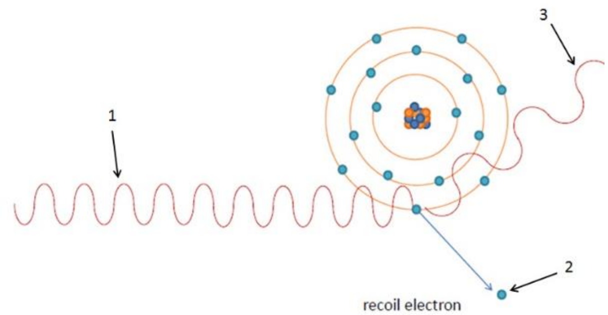
1.2.4 Ionization by Gamma and X-ray Particles

Gamma particles occur through radioactive decay while x-rays are created through high voltage x-ray machines. Yet, both forms of radiation that are photons and are very similar once they are created.



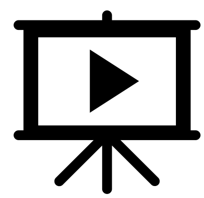
X-rays and gamma rays are high-energy photons that can travel indefinitely yet have very little ability to ionize atoms. Despite their lack of ionization potential, x-rays have different ways of creating damage in the cells, these being the photoelectric effect and compton scatting effect.

<table>
<tr><th>Photoelectric Effect</th><th>Compton Scattering Effect</th></tr>
<tr><td>

A photon (either an X-Ray or a gamma ray) hits an electron. Through this collision, the photon uses ALL its energy and disappears, the electron is knocked out of the atom.</td><td>

A photon (either an X-Ray or a gamma ray) hits an electron. Through this collision, the photon uses SOME of its energy and continues, although in a different direction. The electron that was hit is knocked out of the atom.</td></tr>
</table>

The ejected electron (often called a photo electron) will then produce secondary ionization events with its surrounding atoms in a similar manner to beta particles. The photoelectric effect has the highest probability with lower energy photons and atoms having a high atomic number.



For more information on alpha, beta, and gamma ionization, click the video icon.

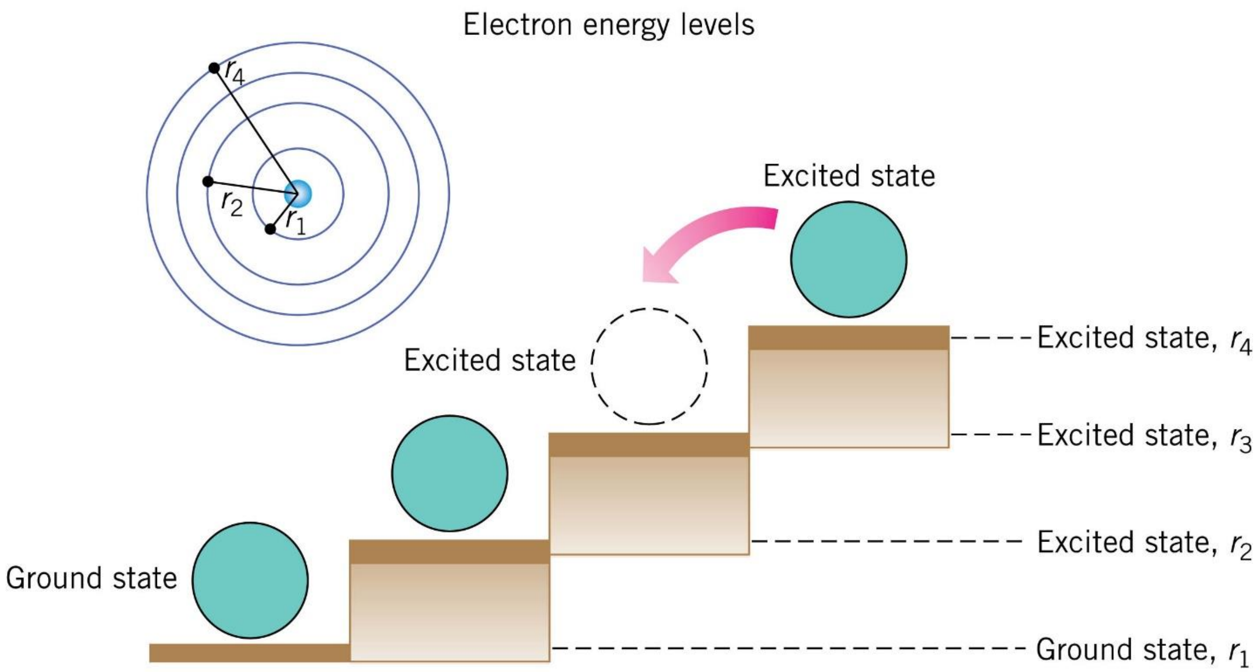
1.2.5 Ionization by Neutron Radiation

Neutron radiation refers to the emission of neutron particles. There are no known naturally occurring radioisotopes that emit neutrons. The only way to produce neutrons is to bombard a nucleus with alpha particles or high energy gamma rays.

Neutron radiation behaves similarly to photons as they ionize atoms by passing through matter. Unfortunately, while neutron radiation does have much ionizing potential, it is exceptionally dangerous to human bodies at is a non-charged particle that reacts very strongly to water, particularly the hydrogen nuclei. This reaction to hydrogen nuclei is what makes neutron radiation part of the nuclear fission process and a great energy producer, yet it also makes it very dangerous for the human body. Additionally, neutron radiation travels very far, and think layers of water or concrete are needed to stop it.

1.2.6 Excitation

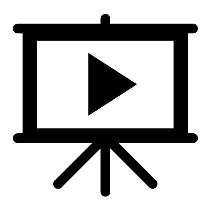
If the energy transfer is not sufficient to cause ionization, excitation occurs. Excitation is brought about by the transfer of energy to an orbital electron and raising the electron to a higher orbital or energy level (see figure below). Electrons in an excited state may form or break molecular bonds or simply revert to their original energy level by the emission of electromagnetic radiation.



2.0 Radiation Dose

Since the effects of ionizing radiation are directly proportional to the amount received, a system had to be set up to measure the quantity of ionizing radiation. This section will cover units of measure for ionizing radiation, conversion from SI units, and the dosimetry requirements for persons using x-rays at UW.

2.1 Dose Limits



The term "radiation dose" is a somewhat general term applied to the amount of ionizing radiation and its effects on any given material. To avoid ambiguity, it is necessary to distinguish between exposure, absorbed dose, and dose equivalent.

Click the video icon to watch a video from the IAEA introducing the four main radiation units.

2.1.1 Exposure (Roentgen)

The roentgen (R), a unit adopted in 1928 as a unit of exposure, is defined as the ability of photons to produce ionization in air. More specifically, it is the amount of photon energy required to produce 1.610 x 1012 ion pairs in one cubic centimeter of dry air at 0 degrees Celsius. The roentgen applies only to photons (gamma and x-rays) less than 3.0 MeV and their ionization of air. The roentgen was however preferable to the previous unit the "erythema dose", which was measured by the quantity of gamma or x-radiation required to produce visible reddening on the skin of the hand or arm.

2.1.2 Absorbed Dose (Gray)

To overcome the shortfalls of the roentgen, a unit of absorbed dose was adopted in 1953 which was defined as the amount of energy absorbed in a given mass and is called a "gray". 1 gray (Gy) = 1 joule per kg of mass and it is necessary to define the absorbing material when using gray as a unit for absorbed dose. One gray will produce various levels of tissue damage depending on the type of radiation.

2.1.3 Equivalent Dose (Sievert)

To develop a unit of dose that reflects the biological effects of radiation, it was necessary to modify the absorbed dose by using a "Radiation Weighting Factor" The equivalent dose or sievert (Sv) is the amount of energy absorbed in a given mass multiplied by a "Radiation Weighting Factor" (WR) which is specific for each type of radiation.

1 Sv = 1 Gy x WR where "x-rays have a WR of 1"

"Radiation weighting factor" for various types of ionizing radiation reflect how the absorbed energy produces tissue damage are listed below:

Item	Type of radiation and energy range	Weighting factor (WR)
1	Photons, all energies (x-rays)	1
2	[1]Electrons and muons, all energies	1
3	[2] Neutrons of energy < 10 keV	5
4	[2] Neutrons of energy 10 keV2 to 100 keV	10
5	[2] Neutrons of energy > 100 keV2 to 2 MeV	20
6	[2] Neutrons of energy > 2 MeV2 to 20 MeV	10
7	[2] Neutrons of energy > 20 MeV	5
8	Protons, other than recoil protons, of energy > 2 MeV	5
9	Alpha particles, fission fragments, and heavy nuclei	20

[1] Excluding Auger electrons emitted from nuclei bound to DNA.

[2] Radiation weighting factors for these neutrons may also be obtained by referring to the continuous curve shown in Figure 1 on page 7 of the *1990 Recommendations of the International Commission on Radiological Protection*, ICRP Publication 60, published in 1991.

2.1.4 Effective Dose (Sievert)

Effective dose is a reflection of the difference in radiation sensitivity of various organs. A weighting factor is applied to the equivalent dose for organs or tissues that are more sensitive to radiation.

X-Ray workers have maximum effective doses that employers must comply with. These can be found on our Information Memo to X-Ray Workers. These workers fall under the University of Waterloo X-Ray safety program. Under the X-Ray program, most workers fall under the maximum whole body max dose of 5 mSv/year.

For workers that work with Radioisotopes, the effective dose limits are listed in the Radiation Protection Regulations. As none of our workers qualify as nuclear energy workers, the max effective dose under the Radiation Safety Program is 1 mSv/year.

2.1.5 Dose Conversions

Canada and most of the world use the SI units of measurement, all regulatory documents and reports are required to have values in SI units. However, one of our closest trading partners, the USA, does not. To assist in conversion to SI units the following table has been supplied.

Quantity	SI Unit	Customary units	Relation
Absorbed dose	Gray (Gy)	rad	1 Gy = 100 rad
Equivalent, effective dose	Sievert (Sv)	rem	1 Sv = 100 rem
Dose rate	Sv/h	rem/h	1 Sv/hr = 100 rem/h
Exposure	C/kg	R	1 C/kg = 3876 R
Exposure rate	C/kg/h	R/h	1 C/kh/h = 3876 R/h

3.0 Biological Effects of Radiation

This next section will discuss the relationship between exposure (dose) and response as well as describe various effects of ionizing radiation.

For radiation, health effects if directly related to dose, or as Paracelsus says (16th Century): "It's the dose that makes the poison".

3.1 Exposure

Radiation exposure can be either chronic, acute, or a mix of both.

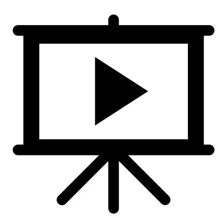
Chronic exposure is continuous or intermittent exposure to low levels of radiation over a long period.

Acute exposure is exposure to a large, single dose of radiation, or a series of doses, for a short period. Large acute doses can result from accidental or emergency exposures or special medical procedures.

The type of exposure received can impact the biological effect, for example, radiation burns only occur after acute exposures.

3.2 Response

Click on the video icon to see how cells respond to ionizing radiation.



No cell responds well to ionizing radiation, yet time has shown that some cells respond worse than others. This is the idea behind the tissue weighting factors used in effective dose calculations. For example, breast tissue is more sensitive to radiation (weighting factor of 0.12) than bone surfaces (weighting factor of 0.01). All tissue weighting factors can be found in the [Radiation Protection Regulations.]

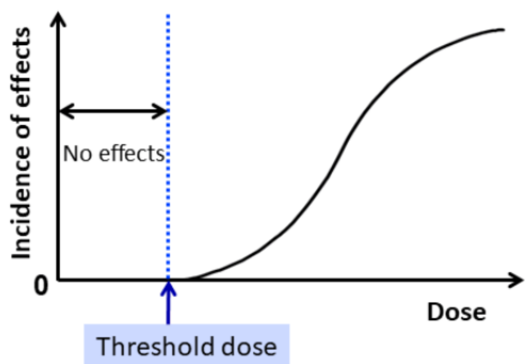
3.2.1 Dose-response Relationship

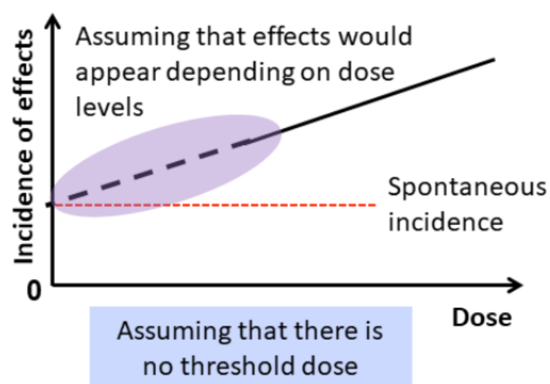
In general, radiation can affect people in one of two ways:

- Deterministic effects
- Stochastic effects

<table>
<tr><th>Deterministic Effects</th><th>Stochastic Effects</th></tr>
<tr><td>Deterministic effects are those effects that appear after meeting some threshold value of exposure. Once below that threshold of exposure, no effect is observed. In this case, the severity of the effect is dependent upon dose.

Generally speaking, legislative limits are far lower than threshold doses of radiation.


</td><td>Stochastic effects do not have a threshold value, meaning that the probability that effect will appear increases as dose increases, but the severity of the effect is independent of dose.


</td></tr>
<tr><td>E.g., Hair loss, cataract, skin injury</td><td>E.g., Cancer, leukemia, hereditary effects</td></tr>
</table>

Once the realization that radiation exposures could cause stochastic effects evolved, the principle of ALARA (As Low As Reasonably Achievable) was recognized as being important in the protection of workers, the public, and the environment from radiation exposure.

ALARA is a concept that seeks to keep all doses of radiation as low as possible. Controls are expected to be implemented by taking into account social and economic factors.

3.3 Types of Effects

In earlier sections, we have learned how ionizing radiation interacts with matter. However, in radiation protection what matters is the effect of ionizing radiation on the human body.

3.3.1 Stochastic Effects

Biological effects of radiation may occur in the unexposed as well as the exposed population. These effects are termed "Stochastic effects" and are not unequivocally linked to the exposure. The response is proportional to the dose, but exposure does not guarantee an effect. For example, lung cancer is a disease that both smokers and nonsmokers get, but the more cigarettes a person smokes the higher the likelihood of lung cancer. However, even heavy smokers are not guaranteed to get lung cancer.

Biological effects may be grouped into three major classes:

- Somatic
- Fetal
- Genetic

3.3.2 Somatic Effects

The affected cells are somatic or non-reproductive cells such as skin, liver, or lung cells.

Acute effects result from a large, single dose of radiation, or a series of doses, for a short time. Large acute doses can result from accidental or emergency exposures or special medical procedures. Listed below are some of the major acute biological effects of ionizing radiation.

Blood

Blood consists of three major cell types:

- Red blood cells to transport oxygen and carbon dioxide
- White blood cells for fighting infections
- Platelets to assist in blood clotting

Reduction in the levels of the various cell types may happen at exposure levels as low as 140 milligrays (mGy) and will almost certainly appear above 500 mGy.

The various types of blood cells are produced in bone marrow which replaces damaged cells over some time. If the bone marrow receives a dose greater than 2 gray (Gy), the rate of production is lowered. Production stops if the marrow is subjected to a dose of 5-6 Gy.

Gastrointestinal system

Cells embedded in the stomach produce glandular secretions which aid in digestion and are sensitive to doses of a few sieverts (Sv). These cells will reduce or cease to function, but they will resume after a recovery period. The most radiation-sensitive organ in the gastrointestinal tract is the small intestine. At the present, this is the organ that will determine if a person survives an acute massive whole-body attack of radiation. In a healthy individual, the cells lining the small intestine are constantly worn away and are replaced by crypt cells. With an acute dose of more than 10 Sv, the crypt cells are killed, and the lining of the small intestine ruptures and death follows.

Reproductive system

An acute dose of 2.5 Sv to the gonads will produce temporary sterility in males and doses above 5 Sv will cause permanent sterility. Females experience a 1 to 3 year sterile period with an acute dose of 1.70 Sv, while permanent sterilization may occur with a dose above 3 Sv, depending upon the age at the time of exposure.

Skin

After an acute overexposure to radiation, erythema may occur. This is a reddening of the skin, which may be accompanied by changes in pigmentation, blistering, and ulceration.

Central nervous system

50 Sv to the central nervous system will damage it, resulting in unconsciousness within minutes of exposure and death occurring shortly after.

3.3.3 Fetal Effects

In the previous section we found that the most radio-sensitive cells were those that fit the following criteria:

- High division rate
- High metabolic rate
- Non-specialized type
- Well-nourished

The cells of the fetus meet all four of these criteria and special care must be taken by the mother and co-workers to reduce exposure of the fetus to ionizing radiation.

Radiation effects on the developing fetus vary with time. For example, there is a much larger effect during the time of organ development (fourth to eighth weeks).

Congenital abnormalities

The process of development of an embryo is highly complex and in many cases unsuccessful. Congenital abnormalities are responsible for the loss of 40% of human embryos in the first 20 weeks. About 6% of live-born children have abnormalities.

Evidence for prenatal or neonatal death caused by radiation in humans is sparse, and estimates of the relevant LD50 have been extrapolated from rodent data.

Severe mental retardation

Data from the atomic bomb survivors in a study of 1600 children exposed in utero has shown about 30 cases of severe mental retardation (normal rate 0.8%). The most sensitive gestational period was 8-15 weeks, and in this period the fraction of those retarded increased by 0.4 per Sv. For the period 16-25 weeks, the rate was 0.1 per Sv. There appeared to be a threshold of around 0.2 Sv.

Mental impairment of lower severity is also apparent in children exposed in utero. There is a dose-related decrease in IQ of about 30 units per Sv again in the 8-15 week period.

Cancer induction

Irradiated fetuses seem to be more sensitive to the induction of cancer before the age of 10. There is a disagreement between the Japanese data and that derived from prenatal irradiation for medical purposes. The current best estimates are 2.5 X 10-2 per Sv for leukemia and 3.5 X 10-2 per Sv for other cancers.

3.3.4 Genetic Effects

Genetic effects of radiation show up in the offspring of the exposed person. Mutations occur due to an alteration in the DNA passed to the offspring. These genes may be altered in three ways:

- The omission of needed DNA
- The addition of extra DNA
- The rearrangement of genes within a DNA strand

It has been shown that larger radiation doses produce an increase in offspring mutation. However, at lower doses, the risk of mutation is more difficult to predict. It is not clear whether the risk of mutation at lower doses is linear (proportional to dose) or threshold (no effect at a lower dose).

3.4 Hazard Perspective

Radiation exposure may come from either natural or artificial (person-made) sources.

It is important to be aware of the effects of radiation exposure, but it is also important to have some perspective as to the expected dose received from the use of radioisotopes compared to that received from the environment.

Ionizing radiation is simply a form of energy derived from nuclear interaction and is always around us.

Natural radiation comes from soil and rocks, the food we eat, the houses we live in, cosmic rays, and even our bodies. Potassium-40, a naturally occurring radioisotope in fruits and vegetables is the most significant contributor to our dose from internal radiation emitters.

Your physical location on earth affects your annual radiation dose. Radiation exposure increases with altitudes (electromagnetic radiation from cosmic rays increases with altitude) or you may live in an area with the bedrock close to the surface (uranium and thorium concentrations would be higher).

Person-made sources of radiation include television, smoking, and x-rays for medical reasons.

Approximated average dose from natural and manmade sources as provided by the IAEA include:

Source	Dose (mSv)
Natural	
Cosmic	0.4
Gamma rays	0.5
Internal	0.3
Radon	1.2
Artificial	
Medical	0.4
Atmospheric nuclear testing	0.005
Chernobyl	0.002
Nuclear power	0.0002
Total	**2.8 mSv**

3.5 ALARA

In the workplace, the concept of ALARA is used for radiation exposure. ALARA refers to As Low Aa Reasonably Achievable. Workplaces are expected to implement any control possible within the bounds of social and economic factors.

The "social and economic factors" to be taken into account include the costs of reducing the doses from a given level to a lower level, bearing in mind the expenditures that are generally made for reducing a unit of occupational or public risk associated with other industrial and social activities. Factors such as the possible loss of employment if the dose had to be reduced to such low levels that an operation had to be discontinued should also be considered. Regardless of economic and social considerations, however, no person must be exposed to more than the regulatory dose limits.

In practice, both individual and collective doses should be considered when deciding what levels of dose are as low as reasonably achievable for a given operation. Efforts devoted solely to minimizing collective dose could result in some workers approaching dose limits early in the dosimetry year, whereas operational needs and manpower planning considerations might require that the doses of all workers be kept well below the limits early in the year so that additional dose could be received during necessary work with radiation during the remainder of the year.

4.0 Detection

To ensure that x-ray radiation dose rates are not exceeded, various ionizing radiation detectors have been developed and sold commercially.

This section deals with the most common types of radiation detectors used at the University of Waterloo.

4.1 Personal Dosimetry

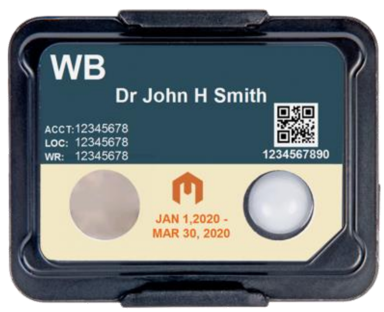
4.1.1 Thermoluminescent Dosimetry (TLD)

Thermoluminescent materials such as lithium fluoride (LiF) provide a simple inexpensive method of measuring radiation dose over an extended time. Normally when energy is applied to an electron, it will move up to a higher energy state (orbital), then drop back to its ground state releasing the excess energy.

Crystals of LiF have met a stable energy state in which excited electrons may be trapped for periods up to 80 years. Heat applied to the crystal will raise the electron out of the meta-stable trap, allowing it to revert to its ground state by emitting the excess energy as photons.

The amount of light emitted is proportional to the amount of radiation absorbed and can be quantified using a photo-multiplier tube.

Whole Body Badge



Construction of a TLD Whole Body Badge consists of two lithium fluoride (LiF) crystals of different thicknesses mounted on a metal plaque. These crystals are shielded by either a metal foil or an aluminum planchet. The difference in the shielding and thickness of the crystals allows the differentiation between whole body dose and skin dose.

Use:

- TLD badges should be worn at the chest position (if worn at the waist benchtops will shield the badge from radiation giving low results).
- The TLD badge should be stored away from light, radiation, and dust when it is not used.
- TLDs are changed every three months except for badges worn by pregnant women. These badges change every two weeks.

Response:

- Lithium fluoride (LiF) is considered to be approximately tissue equivalent, with little energy dependence for photon energy above 100 keV.
- LiF over responds by 40% relative to the 20- to 70 keV range.
- Lithium fluoride TLDs will detect a minimum of 0.2 mSv dose for the wearing period (usually 3 months).

Ring Badge

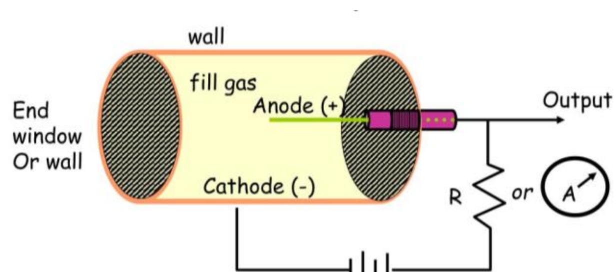
Ring badges consist of a single lithium fluoride crystal inside a plastic holder. This type of badge is used to measure extremity dose and is required when working closely with the x-ray beam.

Use:

- Ring badges should be worn on the dominant hand.
- Ring badges should be stored away from light, radiation, and dust when it is used.

Ring badges are changed every three months.

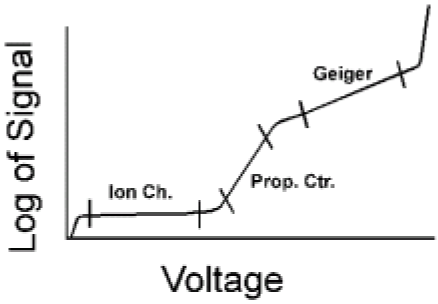
4.2 Gas Filled Detectors



The most common type of radiation detector is the gas filled detector (see picture to the right). These detectors consist of a gas filled tube, a positive electrode (cathode) and a negative electrode (anode). Ionizing radiation enters the tube, atoms of gas are ionized, producing positive and negative ions. If a potential is applied across the tube, the positive ions will migrate towards the anode and the negative ions towards the cathode (Coulomb attraction). The migration of ions to the electrodes results in a current flow that can be measured; thus, reflecting the amount of ionizing radiation striking the tube.

Ionization Chambers

When the potential applied across the tube is very low, ion pairs produced by ionizing radiation will not move fast enough towards their respective electrodes, the ion pairs will then reform into neutral gas molecules and produce little or no current flow. Increasing the voltage potential to a level in which electrostatic attraction accelerates 100% of the ions to their respective electrodes (Ionization chamber plateau) producing a current flow proportional to the radiation striking the tube (**see figure below on signal vs. voltage)**. The number of ion pairs produced is dependent on the amount of ionizing radiation entering the tube. This type of detector can be used to **measure dose rate**.



Ionizing chamber detectors produce a very small current requiring high signal amplification.

Proportional Counters

As the voltage potential across the gas-filled chamber is increased past the ionization chamber plateau, it enters into the proportional counter region. The voltage potential is now high enough to accelerate the ion pairs to a speed that causes secondary ionization (**see figure Signal vs. Voltage)**. Secondary ionizations themselves produce more ionizations; this avalanche process multiplies the signal as high as 106 times for each original ionizing event. Proportional counters must wait for the avalanche process to finish and count before counting the next event which is described as dead time (about ½ microsecond).

The output of proportional counters is proportional to the primary ionizing energy, the higher the energy of the ionizing radiation the higher the output of the detector.

Proportional counters can be used to discriminate between various types and energies of ionizing radiation.

Geiger-Mueller Counters

Geiger-Mueller counters are the most common detectors at UW and operate at the last voltage plateau of the gas-filled detectors **(see figure to the right on signal vs voltage)**.

The increased voltage potential not only causes an avalanche of secondary ionizations as in proportional counters but also UV photons are produced when electrons strike the collecting anode. These UV photons produce another avalanche of ionization, which would be self-perpetuating except that a quenching gas is added to ensure the process ceases.

Geiger-Mueller Counters produce a very large signal for each ionizing event that is the same for all energies of ionizing radiation. A detector of this type is extremely sensitive and is normally **used for leakage surveys** (They must not be used to measure dose rate as they give the same response no matter what the energy level of the ionizing radiation).

4.3 Scintillation Detectors

When an ionizing particle interacts with an atomic electron, it may fail to completely detach the electron from its atom (ionization), but merely transfer sufficient energy to raise the electron to a higher energy state (excitation). When the electron subsequently falls to a lower level, the excess energy is emitted as electromagnetic radiation, often in the visible energy range. If the light is not absorbed by the scintillation medium it may be observed as a glow such as produced by a luminous radium watch dial.

Crystal Scintillators

Pure sodium iodide mixed with a small amount of thallium becomes one of the most commonly used scintillation detectors. The addition of thallium atoms into the structure of a sodium iodide crystal produces energy levels to which electrons are more easily excited, and on de-excitation, produce visible light of a wavelength not readily absorbed by the sodium iodide. The NaI crystal is sealed in a cylindrical aluminum container with a face of beryllium or Mylar to prevent it from absorbing atmospheric moisture and to permit low-energy radiation entry.

A photo-multiplier tube collects the photons emitted by the NaI crystal, converts them to an electric signal which can be counted.

The sequence of events:

1. The ionizing photon enters the crystal and imparts some or all of its energy to an atomic electron.
2. The excited electron dissipates its energy by emitting light.
3. The light strikes the photo-multiplier tube. The light is amplified and converted to a signal proportional to the energy deposited in the NaI(TI) crystal.

NaI(TI) detectors were widely used for x-ray energy measurements, and because of their higher detection efficiency and lower cost, they are still common for such applications where energy resolution is not paramount.

4.4 Calibration

These meters are to be sent away annually for calibration. A calibrated gamma dose rate meter is available at the Safety Office.

5.0 Controlling Exposures

Radiation safety when working with both radioisotopes and x-rays uses the three principles of time, distance, and shielding.

5.1 Time

Radiation dose is directly proportional to the exposure time. Therefore, one of the simplest methods of reducing exposure is the reduction of the time spent exposed to the radiation.

For example, if you were to work in a radiation field of 25 mSv/hr for one hour your dose received will be 25 mSv. If you were to spend 6 hours in a 25 mSv/hr field your dose received would total 25 X 6 = 150 mSv.

When working with radioisotopes, you could theoretically also wait for the half-life to drop before working with the isotope.

Activity equation	Half-life equation
$A_t = A_0 e^{-\lambda}$	$t_{\frac{1}{2}} = \frac{\ln(2)}{\lambda}$

Variable	Definition	Units
A_t	Activity at time t	Bq
A_0	Initial Activity (t=0)	Bq
$t_{(1/2)}$	Time to decay to ½ of the starting amount	Time
λ	Decay constant	Time(-1)

From the equations above, the following general relationships hold:

- Waiting for one half-life will decrease the activity by a factor of 2.
- Waiting for seven (7) half-lives will drop the activity to 1% of the original activity.
- Waiting for ten (10) half-lives will drop the activity to 0.1% of the original activity.

Therefore, waiting for a few half-lives before commencing work with short-lived sources (on the order of minutes or hours), is an effective and practical way of reducing potential exposure.

Another way to reduce exposure is by performing dry runs of any new procedure. Dry runs will identify any missing equipment, improper layout, and potential spill problems. It will also allow one to become familiar and competent with the procedure, which allows for the identification of potential errors and problems overlooked while creating the processes; and, it improves the efficiency of operators.

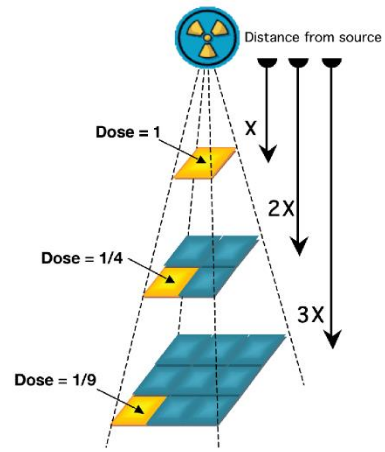
5.2 Distance

The intensity of x-ray or isotope radiation emitted from a point source is inversely proportional to the distance (follows the inverse square law).

To calculate a dose at a given working distance uses the following formula derived from the inverse square law:

The mathematical relationship of Figure 2 is:

$$\frac{D_1}{D_2} = \frac{(d_2)^2}{(d_1)^2}$$



Variable	Definition	Units
D_1	Radiation dose rate at d1	μSv/hr
D_2	Radiation dose rate at d_2	μSv/hr
d_1	Distance at point 1	Same units as d_2
d_2	Decay constant	Same units as d_1

Example: Consider a source in which the dose rate at 10 cm is 12 uSv/h. If a worker were to move the source from 10 cm to 20 cm, what would the new dose rate be?

Summary of Variables:

I_1 = 12 uSv/hr Given

Therefore, in this example, the intensity at distance of 20 cm will equal:

= 12 uSv/hr * [10(~~cm~~)^2/20(~~cm~~)^2]

= 3 uSv/hr

In this example, doubling the distance will decrease the intensity by a factor of 4. In practical terms, tools such as forceps and tongs can help increase the personal distance to a source, thus reducing exposure. This relationship only works for a point source, and only for x-rays and gamma rays.

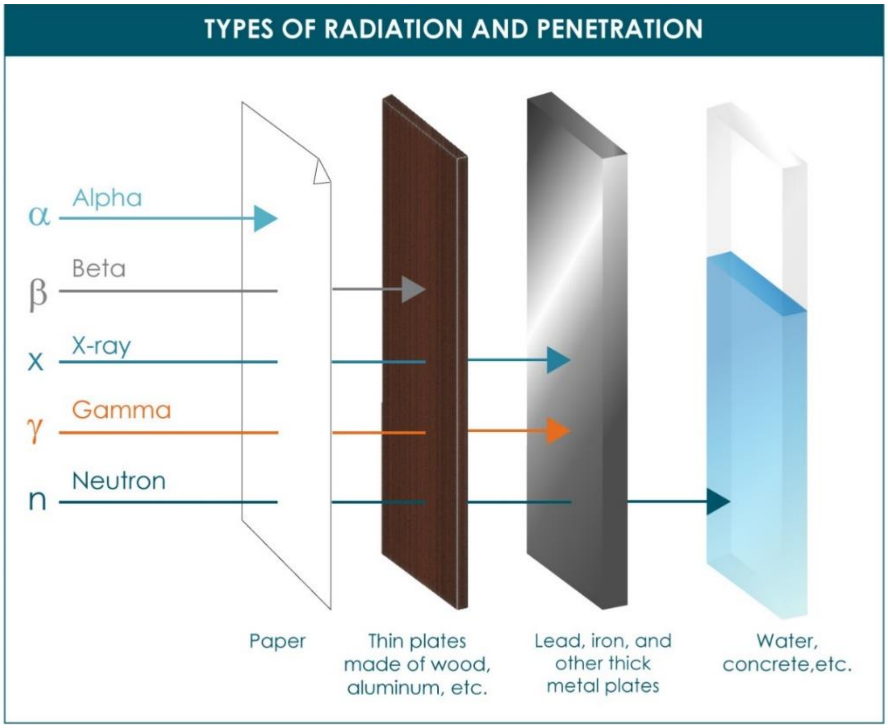
5.3 Shielding

Shielding is used to separate the person from the source.

- Alpha emitters do not require shielding as they can easily be stopped by the skin.
- Beta emitters require shielding, but if shielded improperly, using the wrong shielding they create x-rays called bremsstrahlung. Beta shielding must be completed with materials of a low atomic number for example plexiglass, lucite, or glass.
- Gamma emitters require thick, dense shielding. Materials composed of lead tend to be best. However, in many cases, atoms that emit alpha or beta radiation will also emit gamma radiation, thus both emissions require consideration. Shielding these materials requires layers, with the first layer composed of a beta shield (glass/plexiglass), and the second layer composed of a gamma shield (lead).

- For non-medical x-rays, shielding is the best way to control radiation. Lead shielding is typically used.

The most convenient way to calculate the amount of shielding necessary is to use the concept of Half Value Layer (HVL), which is the amount of material that is able to reduce the incident radiation by one half. Similarly, the tenth value layer (TVL) is the thickness of material required to reduce the incident radiation to 1/10th of its initial value.



The following table shows the half value layers for different materials at different photon energies.

Absorber	100 keV	200 keV	500 keV
Air	3555 cm	4359 cm	6189 cm
Water	4.15 cm	5.1 cm	7.15 cm
Carbon	2.07 cm	2.53 cm	3.54 cm
Aluminum	1.59 cm	2.14 cm	3.05 cm
Iron	0.26 cm	0.64 cm	1.06 cm
Copper	0.18 cm	0.53 cm	0.95 cm
Lead	0.012 cm	0.068 cm	0.42 cm

Absorber	F-18	Co-57	Cr-51
Lead	7 mm	0.4 mm	2.8 mm
Steel	36 mm	7.4 mm	30 mm
Concrete	121 mm	87 mm	119

When working with radioisotopes, the half value layer is determined by the isotope. More information on isotope Half Value Layers can be found in the CNSC Radionuclide Information Booklet.

6.0 Summary of Radiation

Type of Radiation	Description	Ionization	Comments
Alpha particles	▪ Heavy particle that resembles a Helium atom ▪ Double positive charge ▪ Travels only 7 cm in air ▪ Only emitted by large atoms (atomic # > 82)	Direct or indirect	These have low penetrating power and are not considered an external radiation hazard. If ingested or taken into the body they can cause significant internal damage.
Beta particles	▪ Small particle with little mass ▪ Negative charge ▪ Travels 200 cm in air ▪ Negative beta decay (neutron -> proton) emits electrons (more common) ▪ Positive beta decay (proton -> neutron) emits positrons (rare)	Direct or indirect	Low to moderate energy beta particles will penetrate about 0.2 cm into the skin but no farther. High-energy particles can penetrate further but are rare. When beta particles pass through matter they can form x-rays (called bremsstrahlung), therefore shielding considerations are more complex for beta radiation.
Gamma-rays	▪ Made up of photons ▪ Shorter wavelength then x-rays ▪ Gamma-rays come from nuclei of a radioactive atom after an alpha or beta decay.	Indirect	These rays can theoretically travel forever, but as they pass through matter, they lose their intensity. Click the video icon to watch this video summarizing alpha, beta and, gamma radiation.
Neutrons	▪ Heavy particle ▪ Manmade in nuclear fission and fusion reactions ▪ No charge	Direct	High-speed nuclear particles have an exceptional ability to penetrate other materials. Neutrons are the only type of radiation that can make other objects radioactive. This is called neutron activation.
X-rays	▪ Made up of photons ▪ Formed when high-speed electrons are slowed down or change direction because of atoms in the target material	Indirect	These rays can theoretically travel forever, but as they pass through matter they lose their intensity. Click the video icon to watch this video on a summary of x-ray cabinets.

7.0 Record of Revisions

Date	Author/Editor	Change	Version
July 2022	Katelyn Versteeg	▪ Document release	Radiation Protection Manual v.1.0 JUL2022