**CHAPTER 10 – IONIZING RADIATION**

**Introduction**

Ionizing radiation is a general term used to refer to the particles (charged or uncharged) that are energetic enough to knock electrons out of the material the radiation is passing through.

Ionizing radiation uses up its energy by detaching electrons from atoms comprising the substance it passes through and, in so doing, generating ions in the substance.

** electron volts**

Throughout this lecture, the energy of radiation will be expressed in *electron volts* (*eV*).

An electron volt is the kinetic energy gained by an electron by falling through a potential difference of 1 volt.

Ex. It requires 13.6 *eV* to detach the negatively charged electron from the positively charged nucleus in a hydrogen atom.

In terms of other energy units, 1 *eV* is equivalent to 1.6 X 10-12 *ergs*.

** dose**

When used in the radiation safety context, *dose* (more appropriately, *absorbed dose*) is a measure of the amount of energy that ionizing radiation deposits in a mass of material.

Dose has units of energy per mass (e.g., *ergs/gram*).

For a person exposed to a significant amount of ionizing radiation, the health risk is generally proportional to the amount of energy that the radiation has lost in the mass of tissue the radiation has traversed.

The health risk is proportional to the dose.

**Ionizing Radiation Sources**

Producers of ionizing radiation area commonly referred to as *sources*, some of which are natural and some of which are man-made.

** cosmos**

The cosmos is a continual producer of ionizing radiation.

Much of the universe has ionizing radiation levels that would be damaging or lethal to humans if they were exposed on a continual basis.

Besides objects in deep space, our sun is also a source of ionizing radiation, emitting particularly intense burst during solar flares.

Only a fraction of cosmic radiation (whether from deep space or our sun) reaches the surface of the earth:

- the Earth’s magnetic field acts to divert much of the radiation; and

- the atmosphere absorbs much of the radiation.

Still, all life on Earth is constantly exposed to cosmic ionizing radiation; the amount is higher near the Earth’s poles and at higher elevations.

** radioactive materials**

Radioactive materials are unstable forms of the elements.

*Radioactivity* is a general term for the defining characteristic of radioactive material that it decays by emitting radiation.

These *radioisotopes* or *radionuclides* decay to stable elements, emitting ionizing radiation in the process.

Radioactive materials have made up part of the earth’s crust and its atmosphere.

Humans have always been exposed to the ionizing radiation these substances emit.

Additionally, many human activities (e.g., mining, living in houses, burning coal), cause people to receive slightly higher radiation doses from naturally occurring radioactive materials than they otherwise would.

Under certain circumstances, radioactive materials can also be created out of non-radioactive materials (e.g., when cosmic radiation interacts with the earth’s atmosphere).

** radiation-producing machines**

*Radiation-producing machines (RPMs)* produce ionizing radiation by electronic means.

Some can produce very intense beams of ionizing radiation that have the potential of resulting in extremely large radiation doses.

Radiation-producing machines must be considered when reviewing worker safety.

The ionizing radiation that is produced by machines can be turned on and off.

RPMs include machines designed to produce radiation as well as machines where the ionizing radiation is unwanted, but is an unavoidable consequence of the machines’ function.

(e.g., x ray machines used in airport security, x ray units used in dental, medical, and veterinary clinics, linear accelerators and cyclotrons, x ray diffraction units, electron microscopes, and many gauges and imaging devices used in non-destructive testing)

** nuclear reactors**

The process of *fission* involves the splitting of atoms.

When fission occurs, it releases two or more smaller atoms, several energetic neutrons, and a significant amount of energy in the form of heat.

When the fission process becomes self-sustaining, it is said that the reactor has gone *critical*.

The chain-reaction can be controlled through the use of *control rods* that absorb neutrons, preventing them from splitting other atoms.

While producing ionizing radiation is not the point of nuclear reactions, reactors necessarily generate radiation from several sources:

- fuel rods (the materials making up the rods are themselves radioactive;

- neutron production;

- activation (neutrons are absorbed by irradiated materials); and

- fission fragments (fission products are often themselves unstable isotopes).

** nuclear weapons use and testing**

Above-ground nuclear weapon testing was conducted by many countries until 1963, when it largely ceased with passage of the Limited Test Ban Treaty.

While a large fraction of the radioactive materials produced in those tests had a very short life span and is no longer present, some of the long-lived radioactive materials were distributed throughout the Earth’s atmosphere.

**Radiation v. Radioactivity**

The terms *radiation* and *radioactivity* are often used synonymously; however, they actually have different meanings.

It is important for the safety professional to be clear on the difference between the two terms.

*** radioactivity***

The term for the defining characteristics of radioactive material . . . that their nuclei are unstable and decay, emitting ionizing radiation.

*** radiation***

Energetic particles that can come from any one (or a combination) or different sources.

Note: The presence of radioactive materials always implies the presence of radiation.

However, the presence of radiation does not require the presence of radioactivity.

**Production of Radioactive Material**

There are several different processes by which non-radioactive elements or items may become radioactive.

** activation**

*Activation* means the process of producing radioactive material by bombarding something that is not radioactive.

Activation can only take place in limited circumstances involving the right materials and very large exposures to radiation of the right type and energy.

People do not become radioactive through exposure to x rays.

Note: Many hospitals have particle accelerators and create some of the radioactive materials they use in nuclear medicine through activation.

** fission and spallation**

Another physical process that can create radioactive materials from non-radioactive elements is fission, also called spallation.

The lighter atoms that are produced may be either stable or radioactive.

*Fission* is usually used to refer to the breaking up of atoms that occurs in a research or power reactor.

*Spallation* is generally reserved for non-reactor situations (e.g., breakup of atoms on the Earth’ surface by extremely energetic cosmic radiation).

** contamination**

In cases where radioactive materials are in a dispersible form (i.e., liquid, gas, powdered), *contamination* may result is the radioactive material is spilled or released.

In this case, the item with the contamination is not intrinsically radioactive . . . if the radioactive contamination can be removed, then the item will no longer be radioactive.

**Different Types of Radiation**

(see Table 10-A, p. 265, for a summary of the particles classified as ionizing radiation)

** linear energy transfer**

The amount of energy ionizing radiation deposits per unit distance is called the *linear energy transfer (LET)*.

The *range* is the distance travelled from its source by an energetic particle until essentially all the primary particles have lost their kinetic energy and are no longer capable of ionization.

The range depends on:

- the mass and charge of the particles in question;

- their energy; and

- the material the radiation is traveling through.

** directly ionizing radiation v. indirectly ionizing radiation**

Some types of radiation cause the ionization of atoms in the materials they pass through due to the interaction of their charge with the electrons in those materials.

Other types of ionizing radiation are not charged and do not interact with the electrons in the absorbing material in the same way.

** alpha particles**

Alpha particles consist of two protons and two neutrons (basically, a helium nucleus).

These particles interact very quickly with whatever substance they are passing through, creating a dense trail of ions and depositing all of their energy within a very short distance.

Alpha particles are characterized by having a high LET.

Given the quick transfer of energy, alpha radiation is easily stopped with minimal shielding (e.g., a few centimeters of air, a sheet of paper, the outer dead layer of skin).

An alpha emitter can deliver a lethal dose if it is inhaled, ingested, or otherwise introduced to the body.

Alphas are also a directly ionizing form of radiation.

Alphas are emitted by a number of natural and artificial radioisotopes.

Alpha radiation is the radiation of concern from the inhalation of naturally occurring radon, and is thus responsible for most of the natural background radiation dose received by the average person living in the U.S. (> 2/3 the annual average).

** beta particles (electrons and positrons)**

Electrons and positrons have a mass that is about 1/2000th (1/2000 *amu*) that of a proton or neutron and a charge (negative for electrons and positive for positrons) of one.

Electrons emitted by radioactive materials are called *beta particles*.

With their smaller mass and charge, electrons and positrons do not interact as much as alpha particles, and they lose less energy per unit distance traveled in a material.

Considered to be low LET radiation.

Energetic electrons and positrons moving through a material interact with the electrons in that material.

In doing so, several things occur:

- the energetic electrons and positrons gradually lose their energy;

- ionization takes place in the materials (directly ionizing); and

- secondary radiation in the form of x rays is released (*Bremsstrahlung* – from German verb *bremsen* “to brake” and noun *strahlung* “radiation”).

The degree to which electrons and positrons present a radiation hazard when their source is external to the body depends on the electron energy.

Some sources emit electrons and positrons that are energetic enough to be potentially damaging to the lens of the eye or even deeper lying internal organs.

An external source would emit electrons potentially capable of damaging skin but not energetic enough to reach the lens of the eye

At energies of about 70 *keV* and above, electrons can penetrate to the live layer of skin

At energies of about 800 *keV* and above, electrons can penetrate to the depth of the lens of the eye

Note: There are many natural and artificially produced radioactive materials that emit beta particles (medical, research, and industrial applications).

** positrons**

Positrons are the less-common anti-matter twin of electrons.

Positron-emitting radioactive materials have relatively short life spans.

Not found as a component of naturally occurring radioactive material.

However, use of positron-emitting radioactive materials has grown rapidly, and many hospitals and clinics operate on-site cyclotrons for the purpose of producing positron emitters (e.g., positron emission tomography (PET) in medicine)

** protons**

Protons are somewhat less commonly encountered, at least as a form of ionizing radiation.

Protons are an issue for those concerned with protection of astronauts and others who may be exposed to cosmic radiation (high altitude reconnaissance aircraft pilots), as well as workers at research accelerators used for radiation therapy

With a mass of 1 *amu* and a +1 charge, an energetic proton loses its energy relatively slowly as it moves through a material (low LET).

Near the end of a proton’s path through a material, it deposits a relatively large amount of energy in a short distance (high LET).

This spike in LET is known as the *Bragg Peak*.

Protons are a major component of cosmic radiation and their variable LET nature makes very energetic protons both more difficult to shield, and more hazardous.

Note: By tuning the energies of protons in a treatment beam, it is possible to produce a composite Bragg Peak that is broad and flat, and that will deliver a uniform and large radiation dose over the volume of a tumor, while delivering relatively little radiation to the surrounding healthy tissue.

** neutrons**

Neutrons are also a type of ionizing radiation encountered only under limited circumstances (e.g., reactors, high energy accelerators).

Neutrons have a mass of 1 *amu* and no charge.

Unlike charged particles, neutrons are indirectly ionizing radiation.

Depending on their energy and the composition of the material they encounter, neutrons may also cause some of the nuclei to break up and be emitted as energetic, positively charged ions (spallation) or the nuclei may undergo other types of nuclear reactions accompanied by the emission of alphas, protons, more neutrons, and the production of other stable or radioactive materials.

Because energetic neutrons generate energetic and relatively heavy charged particles that are themselves high-LET forms of radiation, neutron radiation is high LET.

***neutron shielding***

For a given neutron energy and absorbing material, it is not passible to specify the range of the neutrons.

There is no set thickness of shield that can be selected for neutrons of a particular energy that will stop 100% of the neutrons.

The types of materials particularly effective as radiation shielding (e.g., dense substances like lead), are not effective when it comes to shielding neutrons.

What does work well are materials with high hydrogen content (e.g., water, polyethylene, paraffin, concrete).

This is because energetic neutrons interact by colliding with the atomic nuclei of the material they encounter and if the nucleus is similar in mass to the neutron’s mass, the neutron will transfer more of its kinetic energy to the nucleus.

**billiard balls**

Analogy of a moving billiard ball striking a stationary billiard ball depicting what can happen when an energetic neutron strikes a hydrogen nucleus in a radiation shield.

Following the collision, it is often the case that both balls will be moving because the kinetic energy of the first ball has been shared with the originally stationary ball.

**bowling balls**

Analogy of a moving billiard ball running into a much more massive stationary bowling ball.

The billiard ball will simply bounce off the massive ball, retaining most of its original kinetic energy.

** ionizing electromagnetic radiation**

*Electromagnetic radiation (EMR)* is a form of radiation that we all encounter day in and day out.

It includes visible light (from the sun or artificial sources), radio waves, microwaves, and infrared and ultraviolet light.

All these radiations travel at the speed of light, but they are characterized by different wavelengths.

The more energetic the radiation, the shorter its wavelength and the higher its frequency.

Visible light has wavelengths ranging from about 700 *nm* (red) to 400 *nm* (violet).

At wavelengths less than 300 *nm* (and energies above 4 *eV*), electromagnetic radiation begins to be capable of producing ionization.

Historically, scientists performing experiments with electromagnetic radiation learned that radiation acted as if it had two separate personalities, depending on the type of experiment they performed.

In some cases, EMR acts strictly as if it is a wave that transmits energy.

In other situation, EMR behaves as if it is made up of particles (photons) that have kinetic energy.

As a result, there are discussions that focus on electromagnetic radiations’ wave-like nature and others that focus on its particle-like nature.

This means that energetic photons can travel through a material unaffected by the charge of the electrons in that material (e.g. radiowaves).

As a result, EMR is low LET.

Like neutrons, EMR is indirectly ionizing radiation.

Three additional terms are commonly used for types of ionizing EMR:

**- gamma rays**

Energetic photons.

**- X rays**

Arise from interactions of electrons.

**- Bremsstrahlung**

X rays that are emitted whenever an energetic charged particle is slowed down as it encounters electrons in the materials the charged particle is moving through.

By definition, Bremsstrahlung is secondary radiation.

All Bremsstrahlung is made up of x rays, but not all x rays are Bremsstrahlung.

Note: Although EMR sometimes behaves as if it was made up of particles, photons have no mass and no charge.

While photons are not slowed by electron attraction or repulsion, other interactions do take place.

The three most important processes are:

 photoelectric effect

Most important process for relatively low energy photons and materials with high atomic numbers.

The photon transfers its energy to a tightly bound electron that is ejected from its orbital.

The ejected electron proceeds to lose its energy.

 Compton scattering

Most common at intermediate photon energies and in materials with low atomic numbers.

The photon shares its energy with a loosely bound orbital electron.

The electron is ejected, while the photon appears to continue on its way, but at a lower energy and moving in a different direction.

 pair production

Requires a relatively high photon energy.

The photon’s energy is converted to mass, creating a positron and electron pair.

The positron and electron lose their energy in the absorbing material.

**Radioactivity**

Radioactive materials have some characteristics that present special safety challenges:

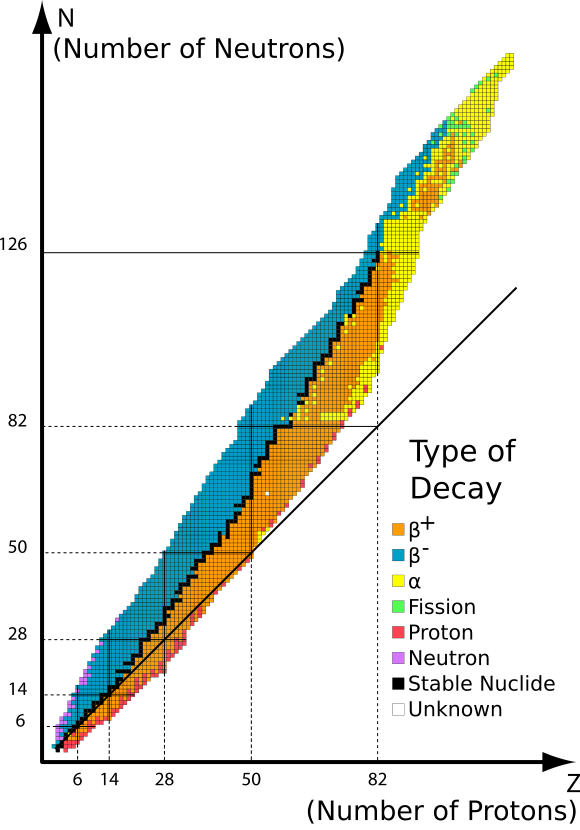
 radioactive materials cannot be switched on or off;

 each radioisotope decays at its own rate and there is nothing that can be done to slow down, stop, or accelerate that decay rate;

 radioactive materials naturally make up part of our world and they are everywhere;

 when artificially created (or concentrated), radioactive materials are in a dispersible form;

 while all life on Earth is naturally exposed to naturally occurring radioactive materials, human activities can involve exposure to much larger amounts/concentrations.



** half-life**

Different radioactive materials decay at widely different rates.

The time it takes for half of the unstable nuclei of a radioisotope to decay to a different isotope is called its *half-life*.

It is fairly common for people to be more concerned about radioactive substances that have very long half-lives than those that have a shorter half-life.

However, a long half-life goes along with a substance that is not very intensely radioactive per unit mass.

Having a long half-life does not automatically make a radioactive material more of a hazard than one with a short half-life.

In terms of hazard, what matters is the radiation dose that a person can receive from the material.

** activity and decay constant**

Another important quantity applicable to radioactive sources is activity.

The *activity* of a particular radioactive source is the number of radioactive decays that source undergoes per unit time (reported in seconds).

Note: Activity tells how many decays happen per second, but activity says nothing about the energy or type of radiation emitted.

At any point in time, the activity of a source (*A*1) is directly proportional to how many atoms of the radioactive material are present at that time (*N*1), and inversely proportional to the half-life of the material (*t*½):

where: *A*1 = activity of a source

0.693 = natural log of 2

*t*½ = half life of the material

*N*1 = number of atoms of material present

Note: The natural log of 2 (0.693) divided by the half-life is known as the *decay constant*.

An alternate representation of this equation is:

*A*1 = λ*N*1

where: λ =

If the initial activity (*A*1) is measured, then after a time (Δ*t*) the new activity (*A*2) is calculated using the formula:

or

Example: What is the activity of 1 milligram of pure C11?

The weight of 1 mole (6.022  1023) of C11 atoms is 11 grams.

Therefore, the number of C11 atoms in a milligram is:

The half-life of C11 (see Table 10-B, p. 270) is 20.4 minutes.

Note: This equates to 3.1  1016 decays/second.

Note: The *Becquerel (Bq)* is the SI unit of radioactivity.

One *Bq* is defined as the activity of a quantity of radioactive material in which one nucleus decays per second.

The *Bq* unit is, therefore, equivalent to an inverse second (s-1, or 1/s).

In the above example, it was determined that C11 had an activity of 3.1  1016 atoms/sec.

This would be the same as 3.1  1016 *Bq*.

Example: Repeat the calculation for C11’s longer-lived sibling, C14.

While it is possible to calculate the activity (*A*1) of a radioactive source at a particular moment in time, that activity is constantly changing, since the number of atoms of the radioactive material (*N*1 at time *t*1) decreases as a result of decay.

Example: In the first calculation, an activity of 3.1  1016 *Bq* was calculated for 1 *mg* of pure C11. How much of that C11 would be left after a decay time (*t*2 – *t*1) of 24 hours?

Substituting the values for the initial activity, the decay time, and the half-life into the second equation:

Example: Repeat the calculation for C11’s longer-lived sibling, C14.

**Effects of Radiation on Humans**

**Radioactive Materials in the Body**

All humans contain radioactive substances in their bodies.

For example, a small fraction of al potassium is naturally occurring K40.

K40 mainly decays by emission of an energetic beta particle and, so, contributes to the natural background radiation dose humans receive year in and year out.

** the banana dose**

People sometimes talk about the radiation dose received each time someone eats a banana, since bananas are a particularly good source of potassium.

The human body regulates the amount of potassium around a set point.

From the air and from food, different tissues in the human body accumulate a variety of materials.

Healthy thyroids tend to concentrate iodine, while bones and teeth contain about 99% of the calcium present in the human body.

The fact that a substance is radioactive does not affect how it is transported or used inside any plant or animal.

If a person breathes, drinks, or eats a substance that has a radioactive component, the radioactive substance may be:

- promptly exhaled or excreted;

- trapped in the lungs (depending on particle size);

- distributed fairly uniformly throughout body fluids; or

- concentrated in one or more particular organs.

** biological half-life**

In radiation safety, there is another half-life that is especially important when someone has an intake of radioactive material.

The *biological half-life* is the time it takes for half of any substance to be eliminated from the body as a result of natural biological processes.

** effective half-life**

The overall half-life of the substance in the body is called the *effective half-life*, and is calculated in days.

The effective half-life [*t*½*(eff)*] is shorter than the physical half-life [*t*½*(phy)*] or the biological half-life [*t*½*(bio)*].

The effective half-life is calculated:

Example: H3 (tritium) is commonly used in biomedical research. Its physical half-life is just over 12 years (4500 days). If tritium is taken into the body, it has a biological half-life that is the same as that of water (about 10 days).

Therefor, the effective half-life of tritium (H3) will be:

**Appendix A**

**Half-Lives of Various Radioisotopes**

**Element Symbol *t½ (phy)* *t½ (bio)***

Helium H3 4500 days 12 days

Carbon C14 5730 years 40 days

Sodium Na22 850 days 11 days

Phosphorus P32 14.3 days 1155 days

Sulfur S35 87.4 days 90 days

Chlorine Cl36 3.0  105 years 29 days

Potassium K40 4.6  1011 days 16 days

Calcium Ca45 165 days 18000 days

Chromium Cr51 28 days 616 days

Iron Fe59 45 days 600 days

Cobalt Co60 1930 days 10 days

Zinc Zn65 244 days 933 days

Rubidium Rb86 18.8 days 45 days

Strontium Sr89 50.6 days 18000 days

Strontium Sr90 10548 days 18000 days

Technetium Tc99m 0.25 days 1 day

Iodine I123 0.54 days 138 days

Iodine I131 8 days 138 days

Cesium Cs137 11000 days 70 days

Barium Ba140 12.8 days 65 days

Gold Au198 2.7 days 280 days

Polonium Po210 138 days 60 days

Radium Ra226 580000 days 16000 days

Uranium U235 7.1  108 years 15 days

Plutonium Pu239 2.4  104 years 73000 days

Note: This table is included as Appendix A in the homework assignment.

**Health Effects of Radiation on the Human Body**

** deterministic effects**

*Deterministic effects* are health effects that all individuals will experience, if the exposure to (dose) the potentially damaging agent is large enough.

For deterministic effects, once the threshold for the effect has been exceeded, the severity depends on the magnitude of the agent (e.g., how much heat, how much radiation, how much noise).

There is some variation between individuals when it comes to the threshold, but the effect can be avoided by staying below the threshold for the most sensitive individual.

Also in the case of deterministic effects, the damage is to the tissues that are exposed to the agent.

In the case of a very large radiation dose to the whole body, a dose of ~ 4 *Gy* (400 rad) would cause death within 60 days for about half of those exposed.

This value is sometimes expressed as LD50/60, which means the lethal dose for 50% of an exposed population within 60 days.

** stochastic effects**

*Stochastic effects* are health effects where the risk of developing a particular condition or disease increases with the increase in exposure to a particular agent, but where only a fraction of those exposed develops the health effect.

They are all-or-nothing effects . . . while the risk of coming down with the disease or injury increases with exposure to the agent, the severity of the condition for those affected is the same, regardless of the exposure (e.g., lung cancer is the stochastic effect of smoking).

Stochastic health effects associated with radiation are:

 cancer; and

 inheritable (genetic) effects.

Note: When it comes to radiation, genetic effects should not be confused with birth defects resulting from exposure of a pregnant woman.

Radiation-induced birth defects are deterministic effects from a radiation dose to the unborn.

Genetic effects are stochastic effects due to radiation doses to individuals (men or women) who later conceive children.

No direct evidence of heritable effects has been found in the children who later were conceived by these men and women.

However, given the results of studies involving animals, the various scientific organizations continue to make their recommendations assuming that heritable effects also occur in humans.

Based on the observed cancer risk from relatively high radiation doses, the International Commission on Radiological Protections (ICRP) puts the lifetime risk of developing a fatal cancer due to radiation exposure at approximately 0.05/*person-SV*.

A *Sievert (Sv)* is the basic unit for dose equivalent.

Note: The ICRP and the Health Physics Society both explicitly caution against using small individual doses (especially small doses accumulated over an extended period) in risk projections.

Studies of populations who live in areas with much higher than average natural background radiation do not find elevated cancer rates (or other health issues).

This does not prove anything because there are many factors that potentially affect cancer incidence, but it supports the idea that once should be wary of using cancer risk values to predict the impact of small radiation doses.

**Radiation Biology**

** relative biological effectiveness**

*Relative Biological Effectiveness (RBE)* is a unit-less measure of how effective a particular type of radiation is at producing a specific biological outcome relative to a standard type of radiation.

If the goal is the sterilization of syringes using radiation, it makes sense to compare the dose required to kill 100% of a certain form of bacteria using two different types of radiation:

The higher the value of the RBE for a particular type of radiation and a particular biological outcome, the more effective the radiation is at causing that specific outcome.

If the radiation of interest is less effective than the radiation used as the standard, then the RBE for that outcome will have a value less than one.

Note: The LET (e.g., in *keV/μm*) of a particular type of radiation affects its RBE for a particular biological effect.

Types of radiation that lose about 100 *keV/μm* generally have the highest RBE.

** quality factor**

The *quality factor* (related to RBE) is used in radiation protection standards and regulations.

This is a type of weighting factor that allows the use of a single set of ionizing radiation limits, regardless of the type of ionizing radiation.

The quality factor indicates the effectiveness of various types of radiation, relative to photons or electrons, in increasing the risk of stochastic effects.

**Type of Radiation Quality Factor (*Q*)**

photons (x rays, gamma rays) 1

electrons 1

alpha particles 20

fission fragments and 10

heavy particles of unknown charge

neutrons of unknown energy 10

high energy protons 10

** tissue dose weighting factor**

The *organ (or tissue) dose weighting factor* is often used in radiation safety, and takes into account that the risk of developing a stochastic effect depends on whether all of the body receives a uniform dose, or whether only certain organs are irradiated.

**Organ or Tissue Organ/Tissue Dose Weighting Factor (*W*t)**

gonads 0.25

breast 0.15

red bone marrow 0.12

lung 0.12

thyroid 0.03

bone surfaces 0.03

remainder 0.30

whole body Σ = 1

**Background**

The centimetre–gram–second system (CGS) is a variant of the metric system of physical units based on centimeter as the unit of length, gram as the unit of mass, and second as the unit of time.

All CGS mechanical units are unambigously derived from these three base units, but there are several different ways of extending the CGS system to cover electromagnetism.

The CGS system has been largely supplanted by the MKS system, based on the meter, kilogram, and second.

MKS was in turn extended and replaced by the International System of Units (SI).

The latter adopts the three base units of MKS, plus the ampere (electricity), mole (atomic weight), candela (luminosity), and kelvin (temperature).

In many fields of science and engineering, SI is the only system of units in use.

However, there remain certain subfields where CGS is prevalent, including in the U.S.

Beginning in 1986, the European Economic Community (now European Union – EU) directed that the units used for radioactivity would consist of the gray (*Gy*) for absorbed dose, Becquerel (*Bq*) for radiation activity, and Sievert (*Sv*) for equivalent dose.

Prior to this time, many other units had been used, including the curie, rad, rem, and roentgen.

Many of these units are still widely used throughout the U.S. government and industry.

** curie**

The *curie (Ci)* is a non-SI unit of radiation activity (radioactivity) defined as 1 *Ci* = 3.7  1010 decays per second.

While replaced under the SI system, the *curie* is still widely used throughout the U.S. government and industry.

Other commonly used measurements of radioactivity include the microcurie (*μCi*) – 3.7  104 decays per second or, more commonly, the picocurie (*pCi*) – 0.037 decays per second.

A radiotherapy machine may have roughly 100 *Ci* of a radioisotope such as caesium137.

This quantity of radioactivity can produce serious health effects with only a few minutes of close-range, unshielded exposure.

Ingesting even a millicurie is usually fatal (e.g., the LD50 for ingested polonium210 is 240 *μCi*, or about 5.5 *nanograms*).

The SI derived unit of radioactivity is the Becquerel (*Bq*), which equates to 1 decay per second.

1 *Ci* = 3.7  1010 *Bq* = 37,000,000,000 decays per second.

** rem**

The *roentgen equivalent in man (rem)* is an older CGS unit of equivalent dose and its derivatives, effective dose, and committed dose.

While replaced under the SI system, the *rem* is still widely used throughout the U.S. government and industry.

One *rem* carries with it a 0.055% chance of eventually developing cancer.

A *rem* is a large dose of radiation, so the *millirem* (*mrem*) which is one thousandth of a *rem*, is often used for the dosages commonly encountered, such as the amount of radiation received from medical x rays and background sources.

Doses greater than 100 *rem* received over a short period are likely to cause *acute radiation syndrome (ARS)*, possibly leading to death within weeks if left untreated.

Note: The quantities that are measured in *rem* were designed to represent the stochastic biological effects (health risks) of low levels of ionizing radiation on the human body, whether from internal or external sources.

High levels of radiation, which produce deterministic effects, are evaluated in terms of the absorbed dose measured in units of *rad* (SI unit – gray (*Gy*)).

Therefore, the absorbed dose, measured in *rad (*SI unit gray *(Gy))*, is the best indicator of ARS.

The SI derived unit of equivalent dose is the Sievert (*Sv*), which equates to the absorption of one joule of radiation energy by one kilogram of matter.

1 *rem* = 0.01 *Sv*

** rad**

The *roentgen absorbed dose (rad)* is a non-SI unit of radiation absorbed dose.

While replaced under the SI system, the *rad* is still widely used throughout the U.S. government and industry.

A dose of under 100 rad will typically produce no immediate symptoms other than blood changes.

100 to 200 rad delivered in less than a day will cause acute radiation syndrome (ARS), but are not usually fatal.

Doses of 200 to 1000 rad delivered in a few hours will cause serious illness with poor outlook at the upper end of the range.

Doses greater than 1000 rad are almost invariably fatal.

The SI derived unit of absorbed dose is the gray (*Gy*), which equates to the absorption of one joule of radiation energy by one kilogram of matter.

1 *rad* = 0.01 *Gy*

** roentgen**

The roentgen (*R*) is a legacy unit of radiation exposure of x rays and gamma rays up to 3 MeV.

Originating in 1908, this unit has been redefined and renamed over the years, but is rarely used today.

As originally defined, one roentgen deposits 9.877 *rad* in dry air, 0.96 *rad* in soft tissue, or anywhere from 1 to 4 *rad* in bone, depending on the beam energy.

In 1940, Gray, who had been studying the effect of neutron damage on human tissue, published a paper in which a new unit of measure (gray – *Gy*) for radiation exposure based on energy rather than charge was introduced.

**Quantifying Radiation**

**absorbed dose**

The radiation absorbed dose (in gray – *Gy*) is the amount of energy that ionizing radiation deposits per unit mass of tissue.

**External Radiation Sources**

**- dose equivalent**

Occupational safety personnel concerned about people possibly exposed to radiation from sources outside the body (i.e., external radiation), are primarily concerned with the *dose equivalent (DE)*.

Identical doses of two different types of radiation may cause different health impacts.

This is where the radiation *quality factor (Q)* comes into use.

*Dose Equivalent (DE)* = *Dose*  *Q*

where *Dose* = energy deposited/mass (in Sievert – *Sv*)

*Q* = radiation quality factor

Note: If the radiation dose is from a number of different types of radiation, then the dose equivalent will be the sum of the various dose and quality factors:

*DE* = *Σ* (*Dose* Q)

Example: Assume a person receives a 0.04 *Gy* (4 *rad*) absorbed dose from a 6 *MeV* photon beam and a 0.01 *Gy* (1 *rad*) absorbed dose from a 190 *MeV* proton beam.

Using the quality factors from the table (Table 10-E, p. 276), the dose equivalent would be:

*DE* = [(0.04 *Gy*)  (1)] + [(0.01 *Gy*)  (10)]

*DE* = 0.04 + 0.10

*DE* = 0.14 *Sv* (14 *rem*)

**- effective dose equivalent**

When the body is not uniformly irradiated, an additional scaling factor is applied so that the resulting quantity, the *effective dose equivalent (EDE)* is an appropriate measure of the overall health risk.

The scaling factor, the *tissue weighting factor (W)*, account for both the reduced health risk from a partial-body irradiation and the fact that the overall risk to health varies, depending on which tissues are irradiated.

*Effective Dose Equivalent* (*EDE*) = Σ (*DE*  *Wt*)

where: *DE* = dose equivalent (in Sievert – *Sv*)

*W*t = tissue weighting factor

Note: U.S. regulations also include the following additional dose quantities.

**- deep dose equivalent**

Since not all ionizing radiation is penetrating enough to affect internal tissues, it is sometimes useful to consider the *deep dose equivalent (DDE)*.

The deep dose equivalent is the dose equivalent at a tissue depth of 1 cm when the whole body has been exposed to an external radiation source.

**- lens dose equivalent**

The *lens dose equivalent* is the dose equivalent at a tissue depth of 0.3 *cm* when the eye has been exposed.

**- shallow dose equivalent**

The *shallow dose equivalent* is defined as the dose equivalent at a tissue depth of 0.007 *cm* when the skin of the whole body or the skin of an extremity has been exposed.

**Internal Radiation Sources**

Regardless of the radiation source (internal or external), in cases where a person has radioactive materials inside their body (that would not have been there naturally), some additional quantities and units are needed.

When there is an uptake of radioactive materials, the body treats the material exactly as it would the same element or chemical compound is a non-radioactive forms.

Example: This is extremely useful in medicine, since radioactive materials can be used to target a specific organ or cell type.

Thyroids need iodine for proper function.

If a researcher works with a volatile form of radioactive iodine, the researcher’s thyroid is the organ of concern.

For this reason, iodine will be given prophylactically to the researcher to ensure all available “storage sites” within their thyroid is occupied by non-radioactive iodine, thus preventing any radioactive iodine from becoming stored there.

Note: Radiation will be emitted over a period of time.

If the effective half-life of the radioactive material is short, maybe all of the radiation dose will be received within hours.

If the effective half-life is long, the radiation dose may be delivered over a period of many years.

**- committed dose equivalent**

To deal with quantifying the impact of radioactive materials inside the body in occupational health, the committed dose equivalent (CDE) and the committed effective dose equivalent (CEDE) are used.

For a given organ or tissue that contains radioactive materials, the *committed dose equivalent (CDE)* (in Sieverts – *SV*), is the total dose equivalent delivered to that organ or tissue in the 50 years following the intake of the radioactive material.

**- committed effective dose equivalent**

The *committed effective dose equivalent (CEDE)* takes into account which body tissue(s) receive the radiation.

Each tissue’s committed dose equivalent is scaled by the applicable *tissue weighting factor*, and those values are summed to determine the committed effective dose equivalent.

**Background: Radon (Rn)**

Radon is a radioactive, colorless, odorless, and tasteless noble gas, occurring naturally as the decay product of radium. It is one of the densest substances that remains a gas under normal conditions. Its most stable isotope, Rn222, has a half-life of 3.8 days and decays through alpha particle emission. Radon is often the single largest contributor to an individual’s background radiation dose (50-75%), but is highly variable from place to place. The EPA identifies radon as the 2nd leading cause of lung cancer in the U.S., responsible for 21,000 deaths per year.

Radon emanates naturally from the ground and some building materials, wherever traces of uranium or thorium are found, and particularly in regions with soils containing granite or shale, which have a higher concentration of uranium. Radon migrates freely through faults and fragmented soils, and as one of the densest gases (about 8X normal atmospheric gases), it tends to accumulate in low-lying areas, such as in caves and basements of houses. Radon is also found in some petroleum and because radon has a similar pressure and temperature curve as propane, the piping carrying freshly separated propane in oil refineries can become partially radioactive due to radon decay particles.

Although not always publicized as a tremendous public health concern, radon ranks highly among other preventable causes of death, including drunk driving, drowning, and fires. Additionally, the death risk to the average person from radon gas at home is 1000 times higher than the risk from any other carcinogen or toxin regulated by the FDA or EPA.

**Watras Incident**

Stanley Watras was a construction engineer who worked at a nuclear power plant where he triggered radiation monitors while leaving work over several days, despite the fact that the plant had yet to be fueled and despite being decontaminated and sent home “clean” each evening. This implied a source of contamination outside of the plant, which turned out to be radon levels of 100,000 *Bq/m*3 in the basement of his house. The lung cancer risk associated with living in that house was compared to the risk from smoking 135 packs of cigarettes daily.

**Background: Radium (Ra)**

Radium is an almost pure-white alkaline earth metal. All isotopes of radium are highly radioactive, with the most stable isotope being Ra226. which has a half-life of 1600 years and decays into radon gas. Because of such instability, radium is luminescent, glowing a faint blue. Radium is not necessary for living organisms, and adverse health effects are likely when it is incorpporated into biochemical processes because of its radioactivity and chemical reactivity. Ra226 is 2.7 million times more radioactive than the same molar amount of natural uranium (U238).

**Radium Girls**

Radium was formerly used in self-luminous paints for watches and instrument dials. A typical self-luminous watch that uses radium paint contains about 1 *μg* of radium. In the mid-1920s, a lawsuit was filed against the United States Radium Corporation by five dying “Radium Girl” dial painters who had painted radium-based luminous paint on the dials of watches and clocks. The dial painters routinely licked their brushes to give them a fine point, in the process ingesting radium. Their exposure to radium caused serious health effects, including sores, anemia, bone fractures, and bone cancer. This is because radium is treated as calcium by the body and deposited in the bones, where radioactivity degrades marrow and can mutate bone cells leading to bone cancers.

During the litigation, it was determined that the company’s scientists and management had taken considerable precautions to protect themselves from the effects of radiation, yet had not seen fit to protect their employees. While U.S. Radium had distributed literature to the medical community describing the “injurious effects” of radium, they told the workers that the paint was harmless and encouraging the painters to use their lips or tongues to point their brushes. For fun, the Radium Girls painted their nails, teeth, and faces with the paint. Worse, for several years the company had attempted to cover up the effects and avoid liability by insisting that the Radium Girls were instead suffering from syphilis. This complete disregard for employee welfare had a significant impact on the formulation of occupational disease labor law establishing the right of individual workers who contract occupational diseases to sue their employers.

Radium was still used in dials as late as the 1960s.

**- total effective dose equivalent**

In cases where a person receives a radiation dose from both external and internal radiation sources, the *total effective dose equivalent (TEDE)* is the sum of the deep dose equivalent resulting from the external radiation sources and the committed effective dose equivalent form internal sources.

U.S. regulations require organization using radiation sources to operate so they limit the TEDE that anyone may receive in a year.

The limits vary, depending on whether the person is:

- member of the public;

- an occupationally exposed adult;

- an occupationally exposed minor; or

- a pregnant woman.

Note: The annual limit on the TEDE treats the radiation dose from external radiation and internal radiation differently.

TEDE treats the CEDE as if the total dose from the radioactive materials uptake was received within the year that the uptake took place.

**Detection and Measurement of Radiation**

** dosimeters**

Dosimeters are used for personnel and area monitoring for radiation from external sources.

Examples include:

- film badges;

- thermo-luminescent dosimeter (TLD) badges;

- optically stimulated luminescent dosimeter (OSLD) badges; and

- pen dosimeters.

Historically, these devices have been passive monitoring in which they are used for a set period of time after which they are checked to determine the total dose accumulated during the period.

Today, passive dosimeters may contain multiple individual detectors sensitive to different types of radiation, while others are designed to determine the radiation type and energy as needed to correctly assess the dose equivalent.

Workers may be assigned multiple passive dosimeters that are worn simultaneously on different locations of the body.

Extremity monitoring is especially common.

Note: Electronic dosimeters capable of measuring radiation doses and dose rates in real time are also seeing increasing use.

These devices allow personnel to monitor the dose they receive during a particular operation, and are frequently used by emergency responders.

** portable instruments for radiation detection and measurement**

Geiger Mueller (GM) counters are useful in detecting photons and electrons.

Standard GMs are typically calibrated for a single radiation type.

For other photons and electrons, standard GMs provide qualitative rather than quantitative information.

Note: GMs are generally not useful for the detection of H3, since its beta’s range is not sufficient to penetrate the window the GM probe.

In attempting to make dose or dose rate measurements, users should be aware of two issues that may not be highlighted in instrument manuals and that can cause the dose (or dose rate) reading to be less than it should be:

1) In the case of rapidly pulsed, high-intensity radiation, the instrument may not have enough time to fully respond between pulses.

If so, the instrument may record a dose (or dose rate) that is lower than the true dose (or dose rate).

2) A more common problem is partial irradiation of the ion chamber.

Ion chamber instruments are normally calibrated using radiation that uniformly irradiates the volume of the gas-filled ion chamber.

If the instrument is used in a situation where its ion chamber is only partially irradiated (e.g., radiation escaping from narrow cracks), the dose rate it will record will be lower than the true dose rate.

Scintillation detectors and proportional counters are also used, especially to detect specific types of radiation for which other detectors are not suited.

The instruments most commonly used to measure the dose rate from neutrons have a rather striking appearance and heft, and typically include a bulky spherical (Rem Ball) or cylindrical shield.

** instruments for radiation detection, measurement, and identification**

A variety of specialized instruments can be used to detect radioactive contamination, to measure radioactive material uptakes, and to help identify which radionuclides are present.

**- liquid scintillation counters (LSCs)**

In situations where there is a possibility of radioactive contaminations (e.g., biomedical labs) workers are required to periodically confirm that there has been no unexpected spread of radioactive materials.

Checks for removable contaminations are also required upon the receipt of packages containing radioactive materials.

A common technique is to use filter paper or a cotton-tipped swab to wipe an area of a specific size and then to check the wipe for the presence of radioactive materials.

Often the material used in the wipe will be counted using a *liquid scintillation counter (LSC)*.

LSCs are especially useful for detecting contamination from radionuclides that are otherwise difficult to detect (e.g., H3, alpha emitters).

**- bioassays**

To assess the possibility that a person has inhaled or ingested radioactive material, a bioassay may be done.

*Bioassays* can involve direct measurements or radioactive materials in the body, or may involve analysis of urine, feces, nasal swabs, etc.

**- gamma spectroscopy**

In recent years, hand-held instruments for use in radionuclide identification have become increasingly available and affordable.

Units commonly rely on *gamma spectroscopy* that examines the energies of the detected photons and used that information as a fingerprint to identify the radionuclide(s) that may be present.

It is critical that the user of gamma spectroscopy instruments understand its limitations.

For example, gamma spectroscopy instruments are not useful in identifying radionuclides unless the radionuclides (or daughter radionuclides) emit photons in the process of decay.

**Radiation Regulations and Standards**

Regulatory agencies worldwide base their dose limits on the work of scientists and advisory groups.

- International Commission on Radiological Protection (ICRP)

- United nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)

- National Council on Radiation Protection and Measurements (NCRP)

- National Academy of Sciences (NAS)

Both scientific and advisory groups continue to be active in studying radiation effects on human health and in revising their recommendations for dose determination methods, appropriate weighting factors, and dose limits.

**U.S. Regulatory Agencies**

The U.S. has a rather complicated regulatory framework for occupational radiations safety.

The worker will be subject to different regulations depending on location, facility type; and kinds of radiation sources present.

- Nuclear Regulatory Commission (NRC)

Has ultimate authority.

NRC has granted over half the states (Agreement States) permission to regulate radiation safety for radioactive materials uses.

In the remaining states (Non-Agreement States) the NRC continues to regulate.

- Environmental Protection Agency (EPA)

- Occupational Safety and Health Administration (OSHA)

- Department of Transportation (DOT)

- other agencies

**U.S. Occupational Doses**

There is consistency about the values of the occupational (and public) radiation dose limits within the U.S.

U.S. radiation safety regulations address many topics beyond dose limits, and include requirements for:

- registration or licensing of radiation sources;

- radiation monitoring;

- testing of safety features on devices that contain radiation sources;

- incident reporting;

- shipment and disposal of radioactive material;

- training;

- security;

- labeling; and

- record-keeping.

**Protective Measures in Radiation Safety**

Safety professionals involved in radiation safety will find it necessary to carefully consider the sections of the regulations that apply to their radiation source uses and to develop a program that addresses those requirements.

**ALARA**

U.S. regulations and radiation safety professionals stress the goal of keeping radiation doses *as low as reasonably achievable (ALARA)*.

Three factors are critical to reducing dose levels from external sources:

** time**

For a person in a particular location, halving the exposure time halves the amount of radiation.

Workers planning operations involving manipulation of radiation sources sometimes carry out practice runs to test their techniques and make them as efficient as possible

** distance**

Increasing the distance between a person and a radiation source can dramatically decrease the radiation dose rate.

The dose rate decreased with increased distance according to the *Inverse Square Law*:

where: *DR*1 = dose rate at distance *r*1 from source (in *Sv/h*)

*DR*2 = dose rate at distance *r*2 from source (in *Sv/h*)

Example: If the dose rate at 10 *cm* from a small-sized Cs137 source is 1 *Sv/h* (100 *rem/h*), the dose rate at 20 *cm* is calculated:

The Inverse Square Law can also be used to estimate the dose rate closer to a source, if the dose rate at a longer distance is known.

Example: If the dose rate at 100 *cm* from the Cs137 source is known to be 0.01 *Sv/h* (1 *rem/h*), the dose rate at 10 *cm* is calculated:

Note: While the Inverse Square Law is useful, it is important to recognize its limitations:

- ignores shielding by air

Assumes no shielding in the space between the source and recipient.

- not for charged particles

Because it ignores for shielding by air, should not be used to predict dose rates from charged particles.

- point source

Not useful unless the distance from the source to the recipient are at least 3x larger than the largest dimension of the source.

If the source is a 0.5 *cm* × 2.0 *cm* cylinder, the distances used in the equation must be at least 6 *cm*.

** shielding**

Earlier, the ways in which alpha particles, beta particles (electrons), protons, neutrons, and photons interact with the material in the radiation’s path were discussed.

The interactions that take place are what make certain materials and amounts of material effective as radiation shields.

- electrons

The fact that electrons of a particular energy have a specific range in materials makes their shielding somewhat simpler than is the case for photons.

Electrons emitted by radioactive materials (betas) have a distribution of energies up to a maximum energy that is specific to the radionuclide.

There are more at the lower end of the energy distribution than close to the maximum beta energy.

These lower energy betas have shorter ranges and are more easily shielded.

While it makes sense to select beta shielding thick enough to stop the most energetic betas, lesser amounts of shielding (such as typical personal protective equipment – gloves, lab coats, glasses) are highly effective in dose reduction.

Energetic electrons produce more secondary photon radiation (Bremsstrahlung) when shielded by dense, high atomic number materials (e.g., lead) than when shielded by a plastic.

For this reason, it is common to prefer a plastic as shielding for electrons.

The best material for shielding electrons should be evaluated on a case-by-case basis.

In some situations, composite shields, such as a layer of acrylic glass backed by a layer of lead, will be the best of both worlds for shielding electrons.

Note: If a composite shield is used, it must be oriented so the low-atomic number material is nearest the electron source.

An appropriately chosen thickness of plastic will slow or stop most of the electrons without generating too much Bremsstrahlung, while the lead will be quite effective in attenuating any Bremsstrahlung that is produced.

- photons

Unlike charged particles, energetic photons do not have a set range in a particular type of materials.

However, for a particular photon energy and a specific material, it is possible to determine the thickness of the materials that will stop half or one tenth of the radiation.

These thicknesses are known as the *half value layers (HVL)* or *tenth value layers (TVL)*.

Note: The attenuation of photons by shielding is exponential and the amount of radiation that passes through shielding depends on the shielding material’s half value layer (see Table 10-K p. 283) and the shielding thickness.

The photon dose rates through a shield (*DR*S) can be calculated:

where: *DR*U = unshielded dose rate at a particular location

*DR*S = shielded dose rate at same location

Δx = shield thickness

HVL = half value layer for the photon energy and

shielding material

Example: There is an unshielded dose rate (*DR*U) of 0.01 *Sv/h* (1 *rem/h*) at a particular location as a result of 0.4 *MeV* photons. If a 1 *cm*-thick (Δx) lead shield is placed between the photon source and the location, the shielded dose rate (*DR*S) at that location (using the appropriate HVL from Table 10-K) is calculated:

Note: This equation underestimates the shielded dose rate (and the amount of shielding required) since it assumes that all photons that interact are removed and ignores forward scattering.

**Unsealed Radioactive Materials**

For most workers using unsealed radioactive materials, time, distance, and shielding considerations remain important in minimizing radiation dose.

Additional precautions are necessary to minimize the possible uptake of radioactive material.

These measures are the same that are used to prevent uptakes of other hazardous materials:

- use of proper personal protective equipment (e.g., gloves, glasses, lab coats);

- use of fume hoods for volatile substances; and

- measures to prevent, contain, and promptly clean up any spills.