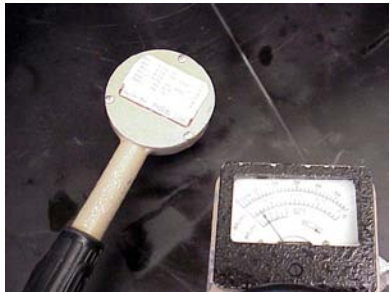


# ***Radiation Worker Manual***

Radiation Safety Office



# Table of Contents

Introduction.....	1
Review of Scientific Notation and Unit Prefixes.....	3
Sources of Ionizing Radiation.....	5
Interaction of Radiation with Matter.....	13
Radiation Shielding.....	19
Detection and Measurement of Radiation.....	21
Radiation Exposure and Dose.....	27
Biological Effects of Low Level Radiation.....	33
Operational Radiation Safety.....	37
Glossary.....	45

## **INTRODUCTION**

The keys to working safely and efficiently are basic knowledge, a respect for safety and experience. This training manual provides the basic information applicable for an individual who wants to become a radioactive material (RAM) radiation worker. A RAM radiation worker is an individual who will be handling radioactive material or using a radiation source in research or development, in a clinical laboratory, or for a medical application. A respect for safety comes from within. Working safely should be a goal for everyone. The individual worker has the ultimate responsibility to ensure they work safely and it is the individual RAM radiation worker who has the primary responsibility to ensure that any work they perform using radioactive material is performed using good radiation safety practices. The final key, experience, is gained with time. Performing a dry run prior to utilizing radioactive material helps an individual gain experience and thus improves safety.

Even if you have used or worked with radioactive materials in the past it is recommended that you review the information in this manual prior to applying to become a RAM radiation worker under the University of Cincinnati Radiation Control and Safety Program (RCSP). Refresher training enhances knowledge and thus enhances safety practices.

In addition to reviewing this manual, all RAM radiation workers will receive additional site-specific training from the Radiation Safety Office (RSOf) staff and should receive additional laboratory specific training from their authorized user. Any questions about information provided in this manual should be directed to the technical staff of the RSOf.

This page intentionally left blank

## REVIEW OF SCIENTIFIC NOTATION AND UNIT PREFIXES

Numbers can be very large or very small when measuring and explaining radiation and radioactivity. Therefore, before beginning a discussion of radiation and radioactivity it is necessary to review some basic mathematical concepts.

In **scientific notation**, integral powers of ten are used with the decimal point placed just to the right of the first significant digit. The power of ten is obtained by counting the number of places the decimal point was moved. When the decimal point is moved to the left the power of ten is a positive value. When the decimal point is moved to the right, the power of ten is given a negative value.

$$1400 = 1.4 \times 10^3 \quad 0.0014 = 1.4 \times 10^{-3}$$

NOTE: Another common method of writing a number in scientific notation that may be encountered is to substitute the "x 10" with an E.

$$1400 = 1.4E3 \quad 0.0014 = 1.4E-3$$

Further simplification and standardization is gained through the use of measurement prefixes that are given names and one-letter symbols to designate multiples and sub-multiples of ten. These prefixes are used in conjunction with *International System of Units* (SI units). There are many SI units and prefixes; however, only prefixes that may be realistically used by a radiation worker at the University of Cincinnati are listed in Table 1. Other references are available with the complete listing.

Table 1 Commonly Used Prefixes

PREFIX	FACTOR	SYMBOL	PREFIX	FACTOR	SYMBOL
tera	$10^{12}$	T	centi	$10^{-2}$	c
giga	$10^9$	G	milli	$10^{-3}$	m
mega	$10^6$	M	micro	$10^{-6}$	$\mu$
kilo	$10^3$	k	nano	$10^{-9}$	n

Examples of the use of prefixes and scientific notation:

$$\begin{aligned}
 1 \text{ inch} &= 0.0254 \text{ meters (m)} = 2.54 \text{ cm} \\
 1 \text{ curie (Ci)} &= 3.7 \times 10^{10} \text{ becquerels (Bq)} = 3.7 \times 10^1 \text{ GBq} = 37 \text{ GBq} \\
 1 \text{ millicurie (mCi)} &= 3.7 \times 10^7 \text{ Bq} = 3.7 \times 10^1 \text{ MBq} = 37 \text{ MBq} \\
 0.001 \text{ rem} &= 1 \text{ mrem} = 1,000 \text{ } \mu\text{rem} \\
 1 \times 10^6 \text{ electron Volts (eV)} &= 1 \text{ MeV} = 1,000 \text{ keV}
 \end{aligned}$$

This page intentionally left blank

## SOURCES OF IONIZING RADIATION

Radiation with sufficient energy to cause an electron to be removed from an electrically neutral atom or molecule is called **ionizing radiation**. Ionizing radiation may be a particle or an electromagnetic ray. All further use of the word radiation in this manual means ionizing radiation.

Natural background radiation is continuously present and is constantly being absorbed by human beings. Natural background radiation comes from numerous sources in the environment and from within our bodies. Sources of natural background radiation include: cosmic radiation, terrestrial radiation and natural radionuclides within the body. Cosmic radiation comes from the sun and outer space. Cosmic radiation exposure increases at higher altitudes, where there is a lower atmospheric density; therefore, people

living in Denver receive more cosmic radiation than people living in Washington, DC. Individuals flying at high altitudes and into outer space also receive increased amounts of cosmic radiation.

Terrestrial radiation is a natural source of radiation in the ground, rocks,

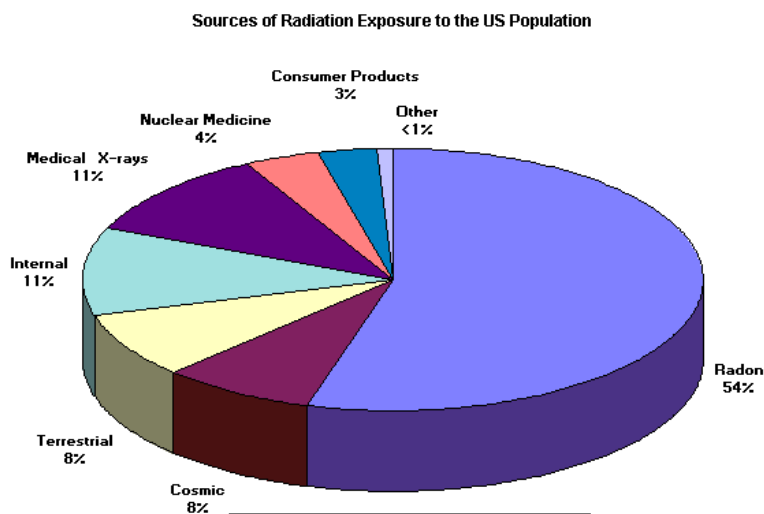


Fig 1: Source Chart

building materials and drinking water supplies. Many areas have elevated levels of terrestrial radiation due to increased concentrations of uranium or thorium in the soil. Finally, there are natural radionuclides that are within the human body. They include radioisotopes of carbon ( $^{14}\text{C}$ ) and potassium ( $^{40}\text{K}$ ).

In 1895 Wilhelm Roentgen discovered X-rays and in 1896 Henri Becquerel discovered radioactivity. These two discoveries were the beginning of the quest to use radiation and radioactivity for the good of mankind. New, man-made or technically enhanced sources of radiation were now added to the existing natural background sources.

The largest source of exposure from man-made radiation in the United States is due to machine produced x-rays and radioactive materials used in medical procedures. Radiation is used extensively in medicine to diagnose the condition of the human body and to treat diseases, primarily cancer. Other man-made sources of radiation include consumer products such as some luminous dial watches, self-illuminating emergency signs (i.e., where no electrical power is needed), smoke detectors, and static eliminators. Nuclear

reactors, which provide steam to generate electricity in commercial power plants, submarines and ships; and nuclear weapons, are more examples of man-made radiation sources. The dose from man-made radiation sources is relatively small as compared to naturally occurring background sources of radiation .

Radioactive isotopes, by definition, are unstable. Through a process called **radioactive decay** these materials seek a stable state through transformation. Transformation may or may not result in a stable isotope, so the process may continue in what is called a **decay chain**. The radiation emitted from radioactive materials comes from these transformations, which release excess energy. In order to understand how radiation is produced and how it interacts with matter, a basic knowledge of atomic structure is required.

## The Atom

All matter is made of atoms. In a simple picture we can imagine an atom as a heavy, compact, positively charged nucleus surrounded by light, negatively charged electrons orbiting in distinct electron shells. The size of the atomic nucleus is about 10,000 times smaller than the atom as a whole.

The nucleus of an atom consists of protons and neutrons held together by nuclear forces. Protons and neutrons have about the same mass and each are approximately 2000 times heavier than an electron. A proton carries a positive electrical charge equal in magnitude to the negative electrical charge carried by an electron. A neutron is electrically neutral.

The number of protons in a nucleus determines the chemical element of the atom and its atomic number, designated as  $Z$ . The total number of protons and neutrons in a nucleus is the mass number of the atom, designated as  $A$ . The standard notation used to represent a nuclide is  ${}^A_Z\text{X}$ , where

$X$  is the chemical symbol of the element (Note: general practice is to drop the atomic number  $Z$  since each chemical element has a unique number of protons).

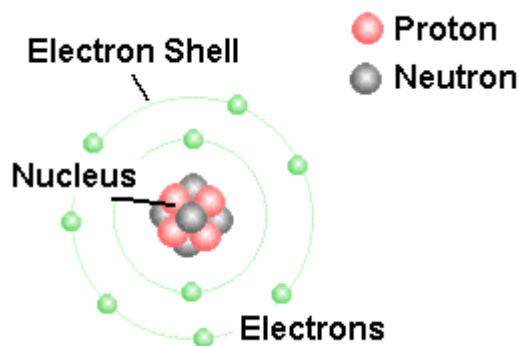


Fig 2: The Atom

Elements with the same atomic number, but different mass numbers are referred to as isotopes. Isotopes that are unstable are called radioisotopes. Radioactive phosphorus is commonly used in research and is written as the chemical symbol P, implying an atomic number of 15. The atomic mass numbers are indicated as either  ${}^{32}\text{P}$  or  ${}^{33}\text{P}$  for its radioisotopes (Note: when discussing like elements the reference is to “isotopes.” When



discussing different elements the reference is to “nuclides.” Therefore  $^{32}\text{P}$  or  $^{33}\text{P}$  are *radioisotopes* of phosphorus and  $^{32}\text{P}$  or  $^{14}\text{C}$  two different *radionuclides*).

Electrons are particles carrying a negative electrical charge equal to the positive electrical charge of a proton. In an electrically neutral atom the number of negatively charged electrons is equal to the number of positively charged protons in the nucleus. Electrons circle the nucleus in distinct orbits or shells and occupy the inner most shells of an atom first. The innermost shell is called the K shell, followed by L shell, M shell, out to the outermost Q shell. Energy is required to move an electron to a higher shell (excitation) or to completely remove an electron from an atom (ionization). Conversely, energy can be released as a characteristic x-ray when an electron from an outer shell fills a vacancy in an inner shell.

## **Radioactivity and Radioactive Decay**

Radioactivity may be defined as a spontaneous process in which an atom with an unstable nucleus undergoes transformation to a more stable atom by energy emission in the form of radiation. The released energy can be in the form of a particle with kinetic energy, a photon of electromagnetic energy, or a combination of both. The original nucleus prior to the transformation is called the “parent” and the resulting nucleus after transformation is called the “progeny”. A given transformation, i.e., one parent/progeny transition, is termed a “radioactive decay” or disintegration.

Stability of a given nucleus depends on the number and ratio of its neutrons to protons (n:p). The two main forces that act upon the nucleus are electrostatic forces caused by the strong repulsion of the positive charges of the protons and the strong nuclear attraction forces that affect all of the neutrons and protons in a nucleus. In a stable atom the nuclear and electrostatic forces are in balance because the n:p ratio allows the forces to balance. The range of the electrostatic force from a proton is greater than the range of the nuclear force of a neutron or proton. As the number of protons increases in a nucleus more neutrons than a 1:1 ratio are needed to keep the atom stable. As elements increase above an atomic number of 20 the n:p ratio range to remain stable gradually increases until Bismuth, atomic number 83, where the n:p ratio exceeds 1.5:1. Above  $^{209}\text{Bi}$  there are no completely stable nuclei.

An atom that is in an unstable range will transform (disintegrate or decay) to move its n:p ratio towards a stable configuration. It does this by transforming a neutron to a proton or vice versa, and then ejecting excess mass or energy from the nucleus in the form of radiation.

## **Alpha decay**

Relatively heavy radionuclides decay by alpha emission. An alpha particle is essentially an energetic helium nucleus consisting of two protons and two neutrons with an electrical

charge of +2. An alpha particle is designated by the symbol  $\alpha$ . A nucleus emitting an alpha particle reduces its atomic number  $Z$  by 2 and mass number  $A$  by 4.

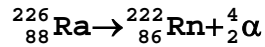


Fig 3: Alpha Decay

## Beta decay

Beta decay will result in the emission of a particle from the nucleus that has the same charge and mass as an electron. Nuclei with an excess of neutrons decay by emission of a beta particle. The result is a neutron transforming into a proton, and the atomic number  $Z$  increasing by 1 while the mass number  $A$  remains the same (An antineutrino  $\bar{\nu}$  is also given off, but is of no concern to the radiation worker since it is electrically neutral with negligible rest mass and radiation dose effect). The beta particle is designated by the symbol  $\beta^-$ . Common research radionuclides that undergo beta decay include  ${}^{32}\text{P}$ ,  ${}^{35}\text{S}$ ,  ${}^3\text{H}$  and  ${}^{14}\text{C}$ .

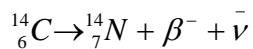
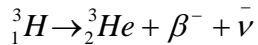
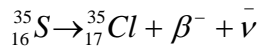
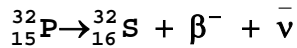


Fig 4: Beta Decay

Beta decay results in a continuous spectrum of energy from the emitted particles up to a maximum energy level for any given radionuclide. The average energy emitted,  $E_{\text{avg}}$  is equal to  $1/3 E_{\text{max}}$ .

## Positron decay

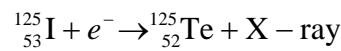
Positron decay will result in the emission of a particle from the nucleus that has a positive electrical charge equal to an electron's negative charge. A positron has a rest mass equal to an electron and is the anti-particle of an electron. Nuclei with an excess of protons decay by emission of a positron. The result is a proton transforming into a neutron which lowers the atomic number  $Z$  by 1 and the mass number  $A$  remains the same (a neutrino  $\nu$  is given off, but is of no concern to the radiation worker since it is electrically neutral with negligible rest mass and radiation dose effect).

The positron is designated by the symbol  $\beta^+$ . A common research radionuclide that undergoes positron decay is  $^{22}\text{Na}$ .



## Electron Capture

A decay mode with a similar result to positron emission is electron capture. In electron capture a nucleus captures an orbital electron, usually from the K shell, and changes a proton into a neutron. Characteristic x-rays are emitted as electrons from higher shells move down to replace vacancies left in the lower shells. An example of a radionuclide that decays by electron capture is  $^{125}\text{I}$ .



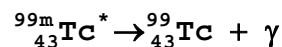
## Photon Emission

A **gamma ray** is a type of electromagnetic radiation that travels at the speed of light and acts like small packets of energy called photons. A gamma ray is the same as an **x-ray** except for two distinguishing characteristics: 1) Gamma rays originate in the nucleus while x-rays originate in the electron shells of an atom, and 2) Gamma rays are usually of a higher energy (MeV range) than x-rays (keV range). Gamma rays are emitted from a nucleus that is in an excited state, usually after a decay reaction has taken place. Many, but not all, nuclear decay reactions result in a gamma ray emission. The gamma ray is designated by the symbol  $\gamma$ .



Fig 5: Gamma Emission

**Isomeric transition** commonly occurs immediately after particle emission. If a nucleus remains in an excited state for a measurable period of time, it is known as an **isomer** because it is in a metastable state. The metastable state is represented by a small m following the atomic mass number. A widely used isomer in medicine is  $^{99\text{m}}\text{Tc}$ , which decays to  $^{99}\text{Tc}$  with the emission of a 140.5 keV gamma.



## Rate of Radioactive Decay

The rate of radioactive decay of a substance is its **activity**, defined as the number of transformations or disintegrations per unit time. The standard international (SI) unit of

activity is the becquerel (Bq), equal to 1 disintegration per second. The historical unit of activity is the curie (Ci), equal to  $3.7 \times 10^{10}$  disintegrations per second.

Originally, the curie unit applied only to radium and was based on the disintegrations per second (dps) occurring in the radon gas being produced in equilibrium from one gram of radium. If permitted to attain equilibrium, the atoms in this quantity of radon gas undergo about  $3.7 \times 10^{10}$  disintegrations per second. In 1950, the International Joint Commission on Standards, Units, and Constants of Radioactivity defined the curie unit by accepting  $3.7 \times 10^{10}$  dps as a curie of radioactivity regardless of its source or characteristics.

Because the becquerel is very small and the curie is very large it is common practice to express activity using measurement prefixes discussed earlier. Also, activity is often converted to disintegrations per minute (dpm) by multiplying by 60. Table 2 shows a summary of activity units.

Table 2 Summary of Activity Units

Units	dps	dpm	Abbreviation
curie	$3.7 \times 10^{10}$	$2.22 \times 10^{12}$	Ci
millicurie	$3.7 \times 10^7$	$2.22 \times 10^9$	mCi
microcurie	$3.7 \times 10^4$	$2.22 \times 10^6$	uCi
nanocurie	$3.7 \times 10^1$	$2.22 \times 10^3$	nCi
picocurie	$3.7 \times 10^{-2}$	2.22	pCi
becquerel	1	60	Bq
kilobecquerel	$1 \times 10^3$	$6 \times 10^4$	kBq
megabecquerel	$1 \times 10^6$	$6 \times 10^7$	MBq
gigabecquerel	$1 \times 10^9$	$6 \times 10^{10}$	GBq
terabecquerel	$1 \times 10^{12}$	$6 \times 10^{13}$	TBq

Increasingly, throughout the world the becquerel is becoming the industry standard. Currently, however, both activity units are still used (with the older units mostly used in the United States) and the radiation worker must be able to convert between them.

### Half-life

An individual unstable atom in a radioactive material sample decays in a seemingly random fashion; however, projected over a period of time, unstable atoms in a radioactive material sample decay at a fixed rate characteristic of its particular radionuclide. One way to describe this phenomenon for a particular radionuclide is to determine how long it takes for  $\frac{1}{2}$  of the radioactive atoms to decay, defined as the half-life ( $T_{1/2}$ ). The decay continues at an exponential rate, i.e. the fraction of activity remaining after any number of half-lives will be  $(\frac{1}{2})^n$ , where n is the number of half-lives that have elapsed. For example after one half-life there is  $\frac{1}{2}$  the original and after two half-lives there is  $(\frac{1}{2})^2$  or  $\frac{1}{4}$  the original amount.

The decay curve is demonstrated graphically below.

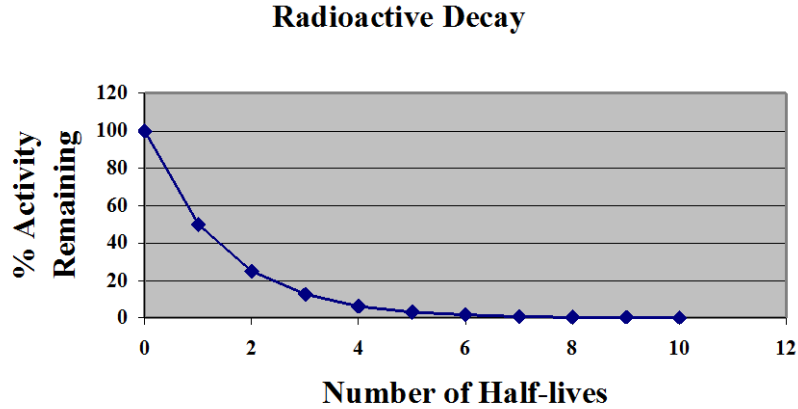


Fig 6: Exponential decay of any radionuclide.

Calculations can be made using the **decay law** equation to determine activity levels at various times if the activity level is known at some specific time. It is defined as:

$$A_t = A_o e^{-\lambda t}$$

Where  $A_t$  = the activity at the time of interest

$A_o$  = the original activity

$t$  = time elapsed since the original activity was known

$\lambda$  = the decay constant for a particular radionuclide =  $(0.693/T_{1/2})$

$T_{1/2}$  = characteristic half-life

**Example:** A researcher receives 10 mCi of  $^{32}\text{P}$  ( $T_{1/2} = 14.3$  days) on June 1<sup>st</sup> for an experiment that begins on June 10<sup>th</sup>. The amount of activity that will be available on June 10<sup>th</sup> can be calculated using the decay law equation:

$$A_t = A_o e^{-\lambda t}$$

$$\lambda = (0.693/T_{1/2}) = (0.693/14.3 \text{ days}) = (0.0485)$$

$$A_t = (10\text{mCi}) (e^{-(0.0485)(10)})$$

$$A_t = (10\text{mCi}) (0.616)$$

$$A_t = 6.16\text{mCi}$$

(It is important that the time units used for the half-life ( $T_{1/2}$ ) and the elapsed time ( $t$ ) be the same when using the decay law equation. If  $T_{1/2}$  is in hours and  $t$  is in days, then one of the times must be converted to the other's units. It is also possible to calculate what the activity was in the past by changing  $-\lambda t$  to  $+\lambda t$ .)

Table 3 contains a list of commonly used radionuclides and their half-lives.

Table 3 Half-lives of Commonly Used Radionuclides

<b>Radionuclide</b>	<b>Half-life</b>
Hydrogen-3 ( $^3\text{H}$ , tritium)	12.3 years
Carbon-14 ( $^{14}\text{C}$ )	5730 years
Phosphorus-32 ( $^{32}\text{P}$ )	14.3 days
Phosphorus-33 ( $^{33}\text{P}$ )	25.4 days
Sulfur-35 ( $^{35}\text{S}$ )	87.4 days
Chromium-51 ( $^{51}\text{Cr}$ )	28 days
Iodine-125 ( $^{125}\text{I}$ )	60.1 days
Iodine-131 ( $^{131}\text{I}$ )	8.0 days
Calcium-45 ( $^{45}\text{Ca}$ )	162.7 days
Sodium-22 ( $^{22}\text{Na}$ )	2.6 years
Technetium-99m ( $^{99\text{m}}\text{Tc}$ )	6.0 hours

# INTERACTION OF RADIATION WITH MATTER

Radiation possesses energy that it transfers to matter as it interacts with the atoms within it. This interaction results in the radiation being scattered or absorbed through three basic mechanisms: ionization, excitation and bremsstrahlung. The interaction of radiation with matter has three major impacts in the area of radiation safety: 1) it makes radiation easily detectable and measurable; 2) it is absorbed in body tissues and can cause physiological harm; and 3) it can be blocked or shielded by placing material between a source of radiation and an area where it is not wanted.

## Ionization

Radiation with sufficient energy to overcome an electron's **binding energy**, with the result being the removal of an electron from an atom or molecule is called ionizing radiation. The removed negatively charged electron and the positively charged nucleus and its remaining electrons form an **ion pair**. This ionization process makes it easy to detect radiation. Ions can simply be collected on surfaces energized with an electrical charge where they can be routed through circuitry and counted. Ionization chambers and Geiger-Mueller (GM) detectors are two common radiation detection instruments that work on this principle.

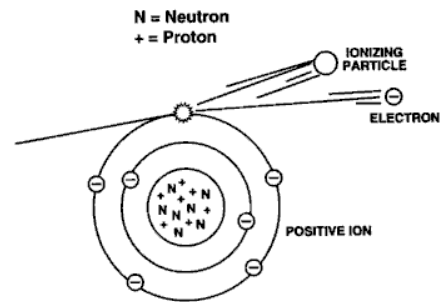


Fig 7: Ionization

## Excitation

At energies insufficient to ionize an atom the electron can be raised to a higher, or excited state, without leaving the atom. The atom will remain in this excited state for a short period of time until an electron in a higher energy level moves to fill the vacancy in the lower shell. The excess energy is then released as an x-ray.

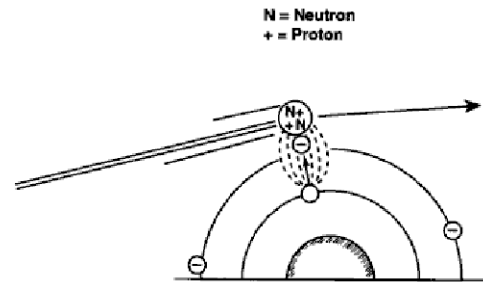


Fig 8: Excitation

## Bremsstrahlung

The X-rays emitted when a charged particle, especially a fast electron, is rapidly slowed down is defined as the Bremsstrahlung, or “braking” radiation. This happens when, for example, a negatively charged beta particle passes through the positively charged electric field around an atomic nucleus. The kinetic energy lost by the

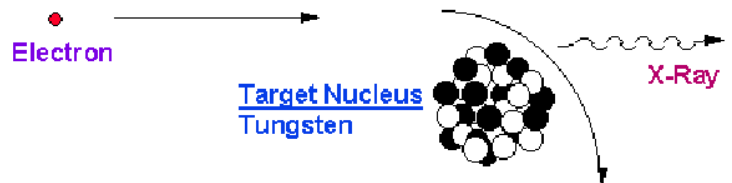


Fig 9: Bremsstrahlung

particle in this process is emitted as an X-ray photon. Subsequently, the x-ray must undergo further interaction to be absorbed.

## Directly Ionizing Radiation

Radiation can interact with matter through one of two mechanisms: 1) the radiation can physically contact a target particle or 2) if the radiation is in the form of a charged particle, the *electric fields* of both the radiation particle and the target particle can interact. Both result in an energy transfer between the radiation and the target particle. Since electric field ranges extend much farther than the physical dimensions of atoms in matter, charged particle radiation continuously loses energy as it passes through matter. Charged particle radiation is also called *directly ionizing* radiation.

The **range** of a charged particle is the depth of penetration the charged particle will travel in a specific type of matter (an absorber) before it loses all of its kinetic energy. The range varies with the mass, magnitude of charge, and energy of the charged particle along with the density of the absorber. The absorber may be air, shielding material or a person. This concept is important when considering the distance a charged particle travels in air or in a particular shielding material. The range of an alpha particle in air is very short and usually expressed in cm of air. An alpha particle's range is so short that it will not make it through a sheet of paper or the dead layer of skin on the human body. The approximate range in air of an alpha particle of known energy may be calculated using the following formula.

$$R_a = 0.318 E^{3/2}$$

where:  $R_a$  = Range in cm of air at 1 atmosphere and 15° C  
E = Energy in MeV

Because an electron or beta particle has a smaller mass and electrical charge than an alpha particle, it will have fewer interactions in a given medium than an alpha particle of equal energy. This causes the range of a beta particle to be much longer than an alpha particle of the same energy. The approximate range of a beta particle in air may be calculated using the following formula.

$$R_a \approx 12 \text{ ft} / \text{MeV}$$

The maximum range in air of the  $^{32}\text{P}$  beta is approximately 20 feet. ( $E_{\text{max}} \text{ } ^{32}\text{P} = 1.71 \text{ MeV}$ )

## Specific Ionization

As a charged particle passes through an absorber, it causes a number of ion pairs to be formed along its path. The average number of ion pairs formed per unit distance traveled is called its **specific ionization**. The specific ionization is dependent on the absorber material's stopping power and the type of particle and its energy. As the specific ionization increases, the range decreases.



## Stopping Power

Stopping power is the ability of an absorbing material to remove energy from a beam of charged particles. It is defined as the average energy lost by a charged particle per unit distance traveled and is measured in keV/cm units. Materials having higher stopping power values cause the particle to lose its energy over shorter distances thereby shortening the range of the radiation in that material.

## Linear Energy Transfer (LET)

The **LET** is the average energy deposited locally in an absorber material by a charged particle per unit distance traveled. The unit for LET is keV/cm, the same as for stopping power; however, the difference between LET and stopping power is the term "locally". Some of the energy removed from a charged particle does not get deposited locally because some electrons interact via bremsstrahlung or excitation and the resulting photons escape the local area. The LET is used to calculate quality factors for comparing various types of radiation and the relative biological damage each cause in the body. The higher the LET for a particular radiation, the more biological damage expected.

## W-Value

The previous concepts under directly ionizing radiation can all be related to each other if the **W-Value** of the absorbing material is known. The W-Value is the average amount of energy needed to create an ion pair in a given material, given in units of eV/ion pair. The W-Value is particularly useful in radiation detection systems where ions in a gas or semiconductor are measured to determine the amount of radiation energy that was deposited. Some common W-Values are listed below in Table 4.

Table 4 W-Values,  $W_\alpha$  and  $W_\beta$  for Alpha and Beta Particles

Material	$W_\alpha$ (eV/ip)	$W_\beta$ (eV/ip)
Air	36	34
CO <sub>2</sub>	36	33
O <sub>2</sub>	33	31
He	43	42
Si	3.7	3.7
Ge	3.0	3.0

## Indirectly Ionizing Radiation (Electromagnetic)

Electromagnetic radiation, i.e. gamma and x-rays, is pure energy with no charge to interact over some distance with the atoms of an absorbing material. They physically contact particles to interact. Because the atom is primarily empty space and a photon is much smaller than an atom, photons move freely through matter with a small probability of interacting. They do not continuously lose energy to the absorbing material as charged particles do so there is no range concept. Instead, electromagnetic radiation loses energy

to the absorbing material through the **photoelectric effect**, **Compton scattering** and **pair production**.

### Photoelectric Effect

In the photoelectric effect, the photon is completely absorbed by an orbital electron and vanishes. The kinetic energy imparted to the electron causes it to overcome the attractive force of the nucleus (binding energy) and results in the electron, now called a photoelectron, leaving the atom. The photoelectron travels through the absorbing material causing other ion pairs to be formed until all of its energy is expended. The probability of photoelectric effect is greatest when the energy of the photon is equal to the binding energy of the electron. These are relatively low energy photons. The probability of the photoelectric effect varies directly with the atomic number of the absorber and inversely by the cube of photon energy. That is why high atomic number materials such as lead are excellent shielding materials for gamma and x-rays of typical energies used in biomedical research.

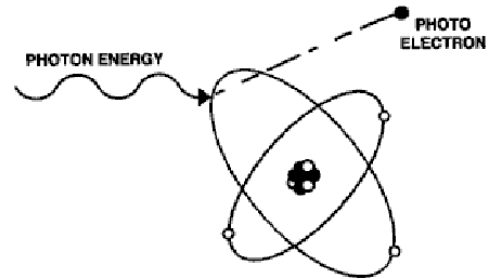


Fig 9: Photoelectric Effect

### Compton Scattering

In Compton scattering, a photon with relatively medium energy is partially absorbed by an orbital electron, usually one that is loosely bound. The electron leaves the atom and is called a Compton electron, which travels through the absorbing material causing other ion pairs to be formed until all of its energy is expended. The photon continues on with less energy and in a different direction from which it entered until it is completely absorbed through other photon interactions.

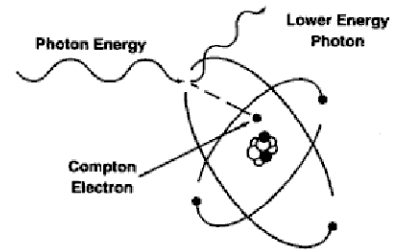


Fig 10: Compton Scattering

### Pair Production

Pair production occurs when all of the energy of the photon is converted to mass. The interaction must take place in the presence of the strong electric field that exists near the nucleus of an atom. Essentially, a photon disappears near the nucleus of an atom and two anti-particles; a positron and an electron appear, formed from the energy of the photon. To undergo pair production the photon must have greater than 1.022 MeV of energy to make up the rest mass of the particles.

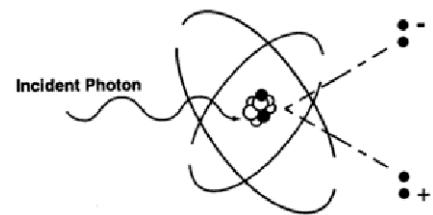


Fig 11: Pair Production

The two particles travel through the absorbing material causing ionizations until their kinetic energy is expended. At this time the positron will be attracted to the opposite charge of an available free electron in the absorbing material. When the two anti-particles come together they annihilate each other and convert their mass into pure energy in the form of two 0.511 MeV photons. These annihilation photons continue through the material undergoing interactions by photoelectric effect and/or Compton scattering until they are completely absorbed.

This page intentionally left blank

## **RADIATION SHIELDING**

Having explained how radiation interacts with all matter it is now possible to discuss shielding principles and concepts. Any matter can act as a radiation shield as all matter has the ability to absorb particles and/or photons. Even air, as was previously discussed, can stop alpha and beta particles. Plastic, glass, aluminum, steel, lead, concrete and water are some of the common shielding materials that may be encountered while using radioactive materials under the University of Cincinnati RCSP. All of these materials interact to some extent with the different types of radiation; however, some shielding material works better for specific types of radiation.

### **Shielding for Alpha Radiation**

Due to their large mass and charge alpha particles are easily shielded by: a piece of paper, the dead layer of skin on the body, or a few inches of air. As long as radioactive material that emits alpha particles is kept out of contact with living cells, i.e. it is not deposited internally, it poses little threat to the health and safety of a radiation worker (Note: only rare radiation workers under the University of Cincinnati RCSP work with alpha-emitting radionuclides).

### **Shielding for Beta Radiation**

Beta particles, having less mass and charge than an alpha particle, will travel farther in the same material before being completely absorbed. However, since Beta particles have mass and charge, they still have a limited range (i.e. distance they travel). The range increases with the energy of the Beta and decreases with the density of the shielding material. Beta particles are easily shielded by plastic, glass, or aluminum; however, bremsstrahlung radiation will increase as the atomic number ( $Z$ ) of the shielding material increases. Using low  $Z$  number materials next to the beta radiation source then following the low  $Z$  material with high  $Z$  number material, like lead, can shield photons produced by bremsstrahlung radiation. In the research environment, plastic (e.g. "Plexiglas") shields are commonly used to shield a worker from a beta source while working on an experiment. Plastic sheets can be placed over fixed contamination from a beta emitting radionuclide while the radionuclide decays. Waste containers storing  $^{32}\text{P}$  may be placed inside specially constructed boxes or behind sheets of plastic. Aluminum foil may also be wrapped around a beta source to provide shielding.

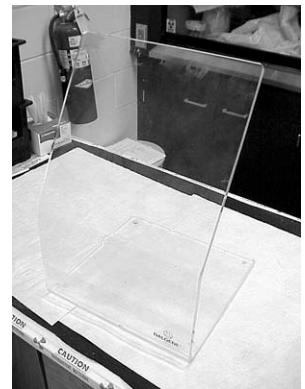


Fig 12: Beta Shield

### **Shielding for Photon Radiation**

Since photons have no mass or charge, Gamma rays and X-rays are absorbed in a material on a probability basis. Unlike alpha and beta particles, there is no distance in a material where it can be said that all of the incoming photons will have been absorbed.

Theoretically, some will always make it through so there is no “range” concept. Photon sources are shielded to reduce their intensity to a reasonable level based on the work to be performed in the radiation field.

Photon radiation entering a material is reduced exponentially with thickness. The amount of energy absorption, or “attenuation,” varies with photon energy and the density of the material and is described using the linear attenuation coefficient. The linear attenuation coefficient is the probability of an interaction as a photon passes through a certain path length, usually per cm. Linear attenuation coefficients are known for many materials and can be found in various references.

The formula for calculating the effectiveness of a photon shielding material follows.

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

where: I = Radiation intensity exiting a shield

$I_0$  = Radiation intensity entering the shield

e = Base of natural logarithms

$\mu$  = Linear attenuation coefficient in  $\text{cm}^{-1}$

x = Thickness of material in cm

The half-value layer (HVL) of a shielding material is a useful concept. It is the thickness of a material needed to attenuate an incoming photon radiation beam to 1/2 of its original intensity. For instance, if the photon intensity is 300 from a given source, adding an HVL of shielding will reduce it to 150 (50% of the original value), a second HVL reduces it to 75, and so on. HVLs have been determined for common shielding materials and various photon energies, and can be found in various references. The equation for half value layer ( $x_{1/2}$ ) is:

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

where  $\mu$  = linear attenuation coefficient for the gamma energy of the beam for the shielding material of interest. Lead is often the shielding material of choice for photon emitting radionuclides used in research and medicine at the University of Cincinnati.

## DETECTION AND MEASUREMENT OF RADIATION

Radiation itself cannot be directly detected by the human body. It cannot be detected by sight, smell or touch. However, its effect on the material it interacts with can be easily detected. All atoms contain protons and electrons that have opposite and equal electrical charges. When an electron is detached from an atom it is free to move and will continue to move if a supply of energy is available to keep it moving. This flow of electrons is electric current and it can be amplified to drive indicators for the human eye to see and interpret. The flow of electrical current can be initiated by directly ionizing radiation causing free electrons, created in an irradiated substance, to be converted into an electrical current.

Radiation can also be detected when it causes a material to give off light that can be measured or when it causes chemical changes in a material. The phenomena utilized in radiation detection are gas ionization, thermoluminescence, and scintillation.

### Rate Meters and Counters

Radiation detection and measurement equipment comes under two basic categories depending on what function is desired.

Rate meters are simple instruments that only give an indication of the amount of radiation that is present at a specific time. Rate meters are usually portable and allow immediate radiation protection decisions to be made on location; i.e. contamination can be found and cleaned up before it is spread. The readout is in terms of counts per minute (cpm), milliRoentgen per hour (mR/hr) or mrem/hr.

Counters, as their name suggests, count and total the number of radiation interactions over a specified period of time. Counters can also determine the dose an individual receives, e.g. pocket dosimeters, film badges or thermoluminescent dosimeters (TLDs). Counters can be used to measure and/or analyze small amounts of radioactivity or radiation that is not energetic enough to enter the detector on common portable rate meters. Liquid Scintillation Counters (LSC) are commonly used in the research environment to detect and measure radioactivity. Circuitry that reveals information on the type and energy of radiation being detected can be added to counter systems. (This manual will not go into detail on the many complicated circuits that are used in radiation detection and counting.)

### Ionization Chambers

Ionization chambers are simple devices used to measure the dose rate of a radiation field. A detection chamber is filled with air at atmospheric temperature and pressure. Two electrodes, one usually the outer wall of the detector and a second internal electrode, with opposite electrical charges are used to collect ion pairs formed from



Fig 13: Ion Chamber

the interaction of the radiation with the air in the chamber. The negatively charged electrons are collected at the positive electrode (anode) and the positively charged nuclei are collected at the negative electrode (cathode). A battery supplies the relatively low 12 volts needed for the detector to function and the power needed to amplify the current to drive a meter indicator. Ion chambers can accurately determine dose rate; however, their lack of sensitivity to very low levels of radiation make it necessary to develop more sensitive detection methods.

## Gas-Filled Chambers

A gaseous mixture will absorb radiation and form ion pairs. Under normal conditions the ion pairs will be attracted to other ion pairs of opposite electrical charge and recombine. In order to observe and measure ionization taking place, an electrical potential must be induced across the detector volume. The ion pairs are then attracted to their oppositely charged electrodes and a current flow, induced by the applied electrical potential, is amplified and a visual readout is provided on a meter. The commonly used Geiger-Mueller (GM) tube will be discussed; however, the principles apply to other gas-filled detectors.

The type of radiation that can be detected is limited by its probability of interaction (specific ionization) in the detector media. Gamma and x-rays have a very low specific ionization in a gas compared to alpha and beta particles. Because of this a large majority of the gamma and x-rays that enter the GM tube never interact with a gas atom and are not detected. Alpha particles on the other hand have an extremely high specific ionization, but the problem is most alpha particles cannot make it through the detector housing (Remember that a sheet of paper or the dead layer of skin on the human body shields an alpha particle). Beta particles have a medium specific ionization factor when compared to gamma and alpha radiation. Beta particles are generally capable of entering the detector to produce ion pairs in the gas; therefore, the GM tube is well suited to detect beta radiation. However low energy beta emitters such as  $^{14}\text{C}$  and  $^{35}\text{S}$  can be shielded by the outer surface and walls of the detector. Tritium ( $^3\text{H}$ ) cannot penetrate a GM window at all.

The size of the detector determines how many gas atoms are available for interaction. Making a larger volume increases the probability of an ionizing event; however, the volume of a GM tube is limited especially if it is attached to a portable survey meter with a probe that an individual will carry in the hand. One way of increasing the probability of an interaction with a gas atom is to put more gas atoms into an existing volume. This results in increased pressure inside the gas-filled tube.



Fig 14: GM Counter

The applied voltage (electrical potential) is very important when considering the operation of a gas-filled detector. There are six regions that a gas-filled tube can operate in as determined by the applied voltage. The region of operation selected is determined by



the measuring system in which the detector is located. The extreme regions of the operating curve are useless for detecting ionizing radiation.

The GM tube operates in the GM region with a typical applied voltage of 900 volts. An ionizing event results in the ion pair being rapidly moved toward opposite electrodes in the detector. The rapid movement causes secondary ionization of gas atoms resulting in an avalanche effect that eventually causes the entire tube to "flash". A single large pulse is detected and counted for each ionizing event regardless of the energy of the radiation that entered the tube. This makes the tube very sensitive to any radiation, but it cannot discriminate between different types and energies of absorbed radiation. The GM tube is very useful for performing surveys to detect the existence of radiation where the type and energy is not important.

Since all gas-filled detectors require narrow voltage ranges for proper operation it is imperative that battery checks be performed prior to use. Should the batteries in a detector register below the recommended voltage during a check the batteries should be replaced. Some survey instruments have an adjustment knob for high voltage that can be used to raise the high voltage setting. If the batteries are low such levels are unlikely to last very long.

## **Scintillation Detectors**

Wilhelm Roentgen first noticed scintillation, caused by ionizing radiation, when he saw fluorescence that was induced by x-rays. When radiation deposits energy in a scintillator or phosphor, it causes transitions to excited energy states. The molecules stay in an excited state for a very short time period before releasing the excess energy in the form of a photon of light.

A light-detecting device must be employed with a scintillator to change the photons of light into an electrical signal that can be amplified and used to drive an indicating meter. A photomultiplier tube (PMT) is an electronic device that serves this function. A PMT has a photosensitive cathode that converts light photons into photoelectrons. The photoelectrons are accelerated toward a second electrode called a dynode. When a photoelectron impacts the dynode it causes several secondary electrons to be emitted. By accelerating these electrons through more dynodes, the original photoelectron numbers are greatly amplified to a usable electrical signal. The output of the PMT is proportional to the original light emitted from the scintillator, which is proportional to the radiation energy absorbed.

Scintillation detectors are made of either organic or inorganic materials. The luminescence mechanism is different in the two. Organic scintillators (like anthracene) have interactions occurring at the molecular level while inorganic scintillators have interactions occurring at the atomic level over a crystal lattice structure. Organic scintillators may exist in a solid, liquid or vapor state while an inorganic scintillator must be in a crystalline solid or powder.

Liquid scintillators are widely used for counting radiation samples. Liquid scintillation counting involves the use of a scintillation “cocktail” made up of a scintillating chemical and a solvent (usually toluene or xylene). The sample may be mixed with the liquid scintillation cocktail or, as in the case of wipe samples, be placed directly into the cocktail. The solvent makes for better contact between the radioactive substance and the scintillant. Radiation interacts with the scintillant molecules causing them to reach an excited state. The scintillant molecules emit light photons as they return to a ground energy state. Liquid scintillation counting is highly efficient and can easily detect the low energy beta particles emitted by  $^{14}\text{C}$  and  $^3\text{H}$ .

Sodium iodide doped with thallium [NaI(Tl)] is a common inorganic crystal used for gamma radiation detection. The NaI crystal is highly sensitive to beta radiation; however, because it has to be hermetically sealed to prevent deterioration of the crystal, its beta response is limited. A gamma interacts with an atom of the NaI crystal causing an excited electron to move into the conduction band and leaves a hole in the valence band. The free electron and hole drift in the crystal until captured by a Tl impurity center. This capture raises the impurity center to an excited state, which results in a photon being emitted when the impurity center returns to the ground energy state.

## Thermoluminescent Dosimeters

A *thermoluminescent dosimeter* (TLD) is an inorganic crystal with impurities that trap excited, free electrons that have absorbed energy from radiation impacting the crystal. Without the impurity “traps” the free electrons would quickly reunite with crystal atoms missing an electron and would give off their excess energy in the form of a visible light photon. The impurities hold the electrons in an excited state as long as the TLD crystal remains at room temperature. In order to determine how much radiation the TLD crystal absorbed, it is heated to a preset temperature inside a light-detecting chamber. The amount of visible light given off is a direct indication of the total amount of radiation energy absorbed. The crystal is then heated to a higher temperature to insure any remaining excited electrons are freed from the impurity traps so it can be returned to service as a dosimeter. TLD crystals are in the finger ring dosimeters utilized under the University of Cincinnati RCSP.

When using finger ring dosimeters the user must keep in mind the fact that the hand is more than sufficient to significantly attenuate (e.g., shield) or eliminate radiation levels. As such, the label of the ring dosimeter should be turned toward where the user is most likely to receive radiation. If the user expects most of the exposure to be toward the palm, as when handling radioactive material, the label should be turned to the inside of the hand. Conversely, if the user expects most of the exposure to be toward the top of hand, as when working in the area of a radiation source (e.g., a fluoroscopic x-ray) the label should be turned likewise (see figure 15).

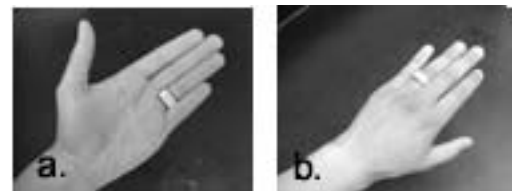


Fig 15: Wearing Ring Badge when a) handling RAM and b) with exposure to top of hand.

In addition, the user should always wear the ring dosimeter underneath gloves when using unsealed RAM to prevent contamination of the dosimeter.

## Film Badge Dosimeters

A small piece of photographic film can be used to quantify the amount of radiation dose received by an individual. The film is sealed in a light proof covering and placed in a holder. The holder has areas of different thickness or metallic shields to "filter" radiation.

The filters help in assessing the amount and type of radiation absorbed (Photons go through and interact with the film while beta particles are entirely shielded from some areas of the film. Low and higher energy photons are differentiated by an image pattern). The different patterns are used to determine the shallow dose given by beta radiation and the deep dose given by gamma or x-ray radiation. The holder has an alligator clip to attach the dosimeter to clothing in the area that will most likely receive the highest exposure.

Radiation interacts with crystalline atoms on the photographic film causing ionizing events that free electrons. The electrons move through the crystal until they are trapped by silver ions that form elemental silver. A chemical developing process results in the silver atoms darkening the film proportionally to the amount of radiation that was absorbed. The developed film is passed through a light reader that determines the dose to assign by the amount of light that is blocked by the film.

## Luxel® Dosimeters

The Luxel® dosimeter is the latest technology in personnel dosimetry. The dosimeter measures radiation through a thin layer of aluminum oxide. A laser light stimulates the aluminum oxide after use, causing it to become luminescent in proportion to the amount of radiation exposure.



(**Note:** This manual cannot specifically cover the myriad of different survey meters, counters and analyzers that are in use in the various laboratories. It is your responsibility as a radiation worker to learn how to properly operate the specific equipment in your laboratory as part of lab-specific training that is provided by your Authorized User.)

Fig 16: Luxel Dosimeters

This page intentionally left blank

## **RADIATION EXPOSURE AND DOSE**

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

### **Roentgen (R)**

The roentgen (R) is a unit adopted in 1928 as a unit of exposure and is defined as a measure of the ionization produced in air by x-ray or gamma radiation. (1 roentgen =  $2.58 \times 10^4$  coulombs/kilogram of air). More specifically, it is also defined as the quantity of x-ray or gamma radiation that will produce ions carrying 1.0 electrostatic unit (esu) of electrical charge in 1 cubic centimeter of dry air under standard conditions. The roentgen is no longer used in radiation protection, as it applies only to photons (gammas and x-rays), is related only to their effect in air and can only be measured for radiation with energies less than 3.0 MeV (The roentgen was preferable to the previous unit "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).

### **Rad or Gray (Gy)**

The definition of the roentgen places severe limitations on the interpretation of radiation measurements since it describes only the amount of ionization caused by x-ray or gamma radiation in air. Another unit must be used to describe the amount of ionization caused by any radiation in any material. The historical unit of absorbed dose is the rad, (Radiation-Absorbed-Dose) and is equivalent to the amount of any radiation that deposits 100 ergs in 1 gram of material. The SI unit is the gray (Gy) and is equivalent to the deposition of one Joule of energy per kilogram of a material.

$$1 \text{ Gy} = 100 \text{ rad}$$

Although the rad and gray are measures of ion pairs produced, they do not provide information about the biological effects of the radiation that is absorbed.

### **Rem or Sievert (Sv)**

The historical unit rem (Radiation-Equivalent-Man) and the SI unit sievert (Sv) are used to equate the biological effects of different radiation on humans. The dose equivalent (H) is the absorbed dose (D) multiplied by a Quality Factor (Q), which is specific for each type of radiation. Q is related to the LET of the deposited particle radiation. The Q for gamma and x-rays is related to the secondary particles produced and their LET.

Standard Q values from federal regulations are listed in Table 5.

$$1 \text{ rem} = 1 \text{ rad} \times Q$$

$$1 \text{ Sv} = 1 \text{ Gy} \times Q$$

$$1 \text{ Sv} = 100 \text{ rem}$$

Table 5 - Q Values from 10 CFR 20.1004

<b>RADIATION TYPE</b>	<b>QUALITY FACTOR</b>
X-, gamma, or beta radiation	1
Alpha particles, multiple-charged particles, fission fragments and heavy particles of unknown charge	20
Neutrons of unknown energy	10
High-energy protons	10

A higher quality factor indicates that type of radiation has a greater biological risk or greater effect than radiation with a lower quality factor for the same absorbed dose. Use of dose equivalent units for recording personnel radiation exposure permits us to add exposures from various types of radiation to get a total dose equivalent which is proportional to the risk. Annual exposure limits set by regulatory agencies are based on dose equivalents. By knowing what type of radiation is present, the quality factor can be determined and relate the absorbed dose converted to the dose equivalent.

### **Internal and External Radiation Sources**

Radiation energy can enter the cells of the body from internal or external sources.

An external source does not touch the body. An individual can move away from it. Shielding can be placed between an individual and an external source to reduce or eliminate the exposure.

Internal sources are radioactive materials that have entered the body through inhalation, ingestion or absorption through the skin or open wounds. Because an individual cannot simply walk away from or shield an internal source, it is important to prevent the intake of radioactive materials. Proper wearing of personal protective equipment (PPE) is critical in preventing internal contamination. Many of the other good practices used while handling radioactive material are used to prevent the ingestion, inhalation or absorption of radioactive material.

## **External Dose, Internal Dose and Total Effective Dose Equivalent (TEDE)**

External dose is that portion of the total dose equivalent received from radiation sources outside the body. Internal dose is that portion received from radioactive material taken into the body. TEDE is the sum of the deep-dose equivalent (of the total external sources) and the committed effective dose equivalent (of the total internal exposure).

Deep-dose equivalent is the whole-body exposure from an external source at a tissue depth of 1 cm. This dose is from penetrating radiation and would not apply to alpha or beta radiation, which give a shallow-dose equivalent to skin or an extremity.

Committed dose equivalent is the dose equivalent to organs or tissues of reference that will be received from an intake of radioactive material by an individual during the 50-year period following the intake. The committed effective dose equivalent is the sum of the products of the weighting factors applicable to each of the body organs or tissues that are irradiated and the committed dose equivalents to these organs or tissues. Weighting factors for each organ or tissue were developed based on the risk of stochastic effects (i.e., probable effect determined from statistical data) from the irradiation of that organ or tissue when compared to the whole-body being irradiated uniformly. The organ dose weighting factors are listed within the general radiation safety regulations.

## **Biological and Effective Half-life**

The body can eliminate radionuclides through urine, feces, sweat and respiration. The time it takes the body to eliminate one-half of the activity through normal body excretory functions is called the biological half-life. This can vary from hours to years. Radioactive decay is also occurring at the same time as the biological elimination. Taking the radioactive half-life and biological half-life into consideration results in the effective half-life. The effective half-life is calculated by the product over the sum as shown in the following formula:

$$T_{1/2 \text{ eff}} = \frac{T_{1/2 \text{ bio}} * T_{1/2}}{T_{1/2 \text{ bio}} + T_{1/2}}$$

where:  $T_{1/2 \text{ bio}}$  = biological half-life  
 $T_{1/2}$  = radioactive half-life

When radioactive material is taken into the body, the body responds to it based upon its chemical properties. This response is used effectively when radiopharmaceuticals are administered to diagnose or treat disease. For example, radioactive iodine ( $^{131}\text{I}$ ) is concentrated in thyroid tissue and thallium ( $^{201}\text{Tl}$ ) is concentrated in heart muscle. Other radionuclides seek bone tissue while tritium ( $^3\text{H}$ ) disperses throughout the body.

## **Determining Internal Contamination and Dose Levels**

Once a radionuclide enters the body it can be measured by two methods, *in-vivo* (meaning inside the body) or *in-vitro* (meaning outside the body). In-vivo counting is generally only performed when the radionuclide is a gamma emitter since alpha or beta particles are absorbed by body tissue. A beta emitter could be indirectly measured if enough bremsstrahlung radiation was produced to make a meaningful measurement. Specifically, in-vivo counting is used when the radionuclide involved becomes naturally concentrated in an organ or type of tissue (for example, users of radioactive iodine could be screened in-vivo because iodine chemically seeks the thyroid). In-vitro counting is utilized when the radionuclide involved cannot be easily detected through external surveys (i.e. the radionuclide involved is of insufficient energy to penetrate through the person's tissue, for example, internal tritium contamination is determined through analysis of urine samples).

### **Bioassay**

Bioassay means the determination of kinds, quantities or concentrations, and, in some cases, the locations of radioactive material in the human body. A bioassay may be required routinely if larger amounts of a given radionuclide are used and after an incident when radioactive material may have been deposited on an individual's skin, ingested, or inhaled.

One type of bioassay is a thyroid count. A thyroid count is performed on individuals having potential for an uptake of radioactive iodine. Individuals who work with volatile or large quantities of radioactive iodine are required to have their thyroids counted to determine if radioactive iodine is being taken into their bodies.

Urinalysis, as the name suggests, is a form of bioassay that analyzes the amount of activity being excreted by urine from an individual. This bioassay is commonly used for tritium, <sup>35</sup>S, <sup>32</sup>P, and any other radionuclides that after being distributed throughout the body is excreted in the urine. It involves getting urine samples from the individual being monitored.

Fecal analyses, nasal swabs, and sputum samples are other types of in-vitro bioassay procedures. They are normally used for accident situations when a large amount of radioactive material is taken up by the body.

Because bioassays can only give an approximate estimate of the amount of radioactivity in the body, the need to avoid any uptake cannot be emphasized enough. Always protect the skin from contact by wearing proper protective equipment, use fume hoods when necessary, and keep contamination levels under allowable limits.



## Regulatory Dose Limits

Regulatory dose limits are set by regulatory agencies such as the United States Nuclear Regulatory Commission and/or the State of Ohio Department of Health. These agencies set occupational dose limits as well as limits for the general public, minors, and the embryo/fetus. The regulatory dose limits were established with the ALARA concept in mind and are well below doses where detrimental effects have been observed.

The following annual occupational limits apply to the dose received by an individual in the course of employment when assigned duties involve exposure to radiation and radioactive material:

- 5 rem** (0.05 Sv) total effective dose equivalent (commonly called "whole-body")  
or
- 50 rem** (0.5 Sv) sum of the deep-dose equivalent and the committed dose equivalent to any individual organ or tissue, other than the lens of the eye.
- 15 rem** (0.15 Sv) dose equivalent to the lens of the eye.
- 50 rem** (0.5 Sv) shallow-dose equivalent to the skin or to any extremity.

Dose to a minor is 10 percent of the adult occupational dose.

0.5 rem (5 mSv) dose equivalent to the embryo/fetus of a declared pregnant woman during the entire pregnancy.

The annual total effective dose equivalent to a member of the public is limited to 0.1 rem (1 mSv). Public dose is the dose received by a member of the public from exposure to radiation or radioactive material released by a licensee, or to any other source of radiation under the control of the licensee.

This page intentionally left blank

## **BIOLOGICAL EFFECTS OF LOW LEVEL RADIATION**

The biological effects of low level radiation, i.e. acute whole body doses of 10 rem or less, or substantially larger doses if received over an extended period of time, are not directly known. The biological effects are assumed using the "linear no threshold" theory. This theory proposes that a linear relationship exists from high dose levels all the way down to a zero dose level and that even very small amounts of radiation can cause biological damage detrimental to the individual. Other theories hold that below some threshold value, possibly 10 rem, there is no biological damage the human body cannot repair. Finally, some individuals believe there is a positive (hormetic) effect at low dose levels that may help the body fight cancer. However, until more positive proof is provided, government agencies will continue to regulate worker and public doses based on the conservative linear-no threshold theory.

Before explaining the details of the biological effects of radiation, methods to reduce the amount of radiation exposure received will be discussed.

### **ALARA**

The ALARA acronym stands for "as low as is reasonably achievable". ALARA means that every radiation worker shall make an effort to keep doses as low as possible even if their annual dose is well below regulatory limits. All these efforts shall be "reasonable" efforts.

The three primary methods to reduce or avoid radiation exposure relate to the appropriate application of time, distance and shielding.

#### **Time**

Reducing the amount of time an individual is in a radiation field decreases the radiation dose. This can be accomplished by removing the individual from the radiation field and by performing procedures around a radiation field quickly and accurately. Methods to reduce the amount of exposure time is to become more efficient by first doing a walk-through, practice procedures without radioactive material, and to avoid loitering, socializing or doing something unrelated to the work in progress while in a radiation field.

#### **Distance**

Increasing the distance from a radiation source can greatly reduce the exposure. Moving outside the range of a beta emitter (e.g., moving 20 feet away from a  $^{32}\text{P}$  source) will eliminate all radiation exposure because of the shielding provided by the air. For photon emitters (gamma or x-ray) the air provides essentially no effective shielding; however, because photon radiation travels out of the radiation source in primarily straight lines, the density of photons from a point source will drop by a square function as the distance increases. What this means is if a person is 1 foot from a point source and is receiving a

dose of 100 mrem/hr, by simply moving to 2 feet away the dose is lowered by a factor of 4 ( $2^2$ ) to 25 mrem/hr. Subsequently, moving to 3 feet away the dose is lowered by a factor of 9 ( $3^2$ ) to almost 11 mrem/hr. This is known as the "inverse square law" and is shown mathematically below.

$$\frac{I_1}{I_2} = \frac{(R_2)^2}{(R_1)^2}$$

where  $I_1$  = radiation intensity at distance  $R_1$  from the source  
 $I_2$  = radiation intensity at distance  $R_2$  from the source

A method to reduce dose by increasing distance when a worker cannot walk away is to use an automatic pipette, forceps, or other remote handling tool.

### Shielding

It is often not possible to increase the distance from or significantly reduce the work time with a radiation source when working with radioactive material. In these cases shielding is used to reduce the dose received from the radiation source (Shielding principles were previously discussed in this manual in detail).

Through the use of the principles of time, distance and shielding, the radiation worker can keep his or her radiation dose ALARA.

### Effect on Living Cells

Radiation interacts with human cells primarily by secondary charged particles causing direct and indirect effects. A direct effect is when a particle causes a break in a DNA molecule through direct ionization. An indirect effect is when highly reactive free radicals (i.e. chemical species with unpaired electrons) interact with a DNA molecule at a later time and cause damage. The free radicals are produced when radiation interacts with water molecules in a human cell. Many of these free radicals are removed by competing reactions and produce no further damage; however, if too much damage occurs the cell will be unable to repair itself and will no longer function.

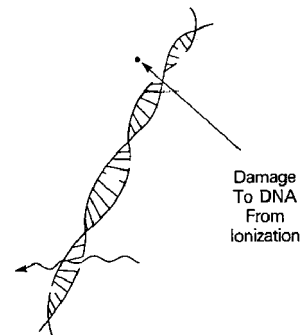


Fig 17: Radiation Damage to DNA

For further reference see National Council on Radiation Protection and Measurements(NCRP) Report No. 93 or International Atomic Energy Agency (IAEA) Report No. 5.

## **Stochastic and non-Stochastic Effects**

The effects of radiation on the body can be classified under two broad categories: *stochastic* and *non-stochastic* effects. Stochastic effects are those that occur randomly and are assumed to have no threshold value. The severity of stochastic effects does not increase with the dose, only the probability that they will occur. Non-stochastic effects have a threshold value below which they do not occur and their severity increases as the dose increases.

The stochastic effects of radiation are cancer and genetic defects. An increase in genetic defects has been too small to observe in populations exposed to high doses of radiation and are assumed to be eliminated when exposures are kept below regulatory limits. Cancer occurs in individuals from many causes; however, it cannot be proven at low dose levels (below 10 rem) that radiation causes or does not cause an increase in cancer. Because of this the dose-response curve at higher radiation levels where there is a known relationship is projected to a zero dose level. This projected curve known as the *Linear No-Threshold* (LNT) model is used to estimate the number of cancers that may be induced from low-level radiation exposure. Regulatory agencies use this projected dose-response line to set limits for occupational workers and members of the public.

A non-stochastic effect has two basic qualities; 1) the effect is not seen until a certain dose level is exceeded and 2) the effect is more severe as the dose increases. Examples of non-stochastic effects are cataracts, blood changes, radiation sickness, skin reddening, and temporary sterility.

## **Risks**

What risks may be involved in working with radioactive material under the University of Cincinnati RCSP? Exposure to radiation may create a health risk. A health risk is the statistical probability or mathematical chance that a personal injury, illness, or death may result from some action. Since it is impossible to completely eliminate health risks from our lives, a statistical level of risk is determined for most human activities. Individuals then make "cost versus benefit" choices as to whether to participate in a particular activity.

Regulatory agencies set radiation dose limits based upon acceptable risk estimates. A 1 rem lifetime radiation dose is estimated to increase the chances of dying from cancer by  $4 \times 10^{-4}$ . Twenty percent of adults in the United States will die from cancer from smoking, food, alcohol, drugs, air pollutants, and inherited traits. To put this into a proper perspective, in any group of 10,000 workers, it can be estimated that 2,000 will die from cancer without any occupational radiation exposure. If each of these 10,000 workers receives 1 rem of occupational radiation dose, using the LNT model it is estimated that an additional 4 will die from delayed cancer. Put another way, the chances of getting cancer from 1 rem of radiation exposure is the same as drawing any ace from a full deck of cards three times in a row. These odds are extremely low when compared to odds in other

occupational fields and most individuals feel the benefits of working with radiation outweigh the risks involved.

The 1-rem figure is used because the majority of radiation workers receive 1 rem or less of occupational radiation dose in their lifetimes. Radiation workers within the University of Cincinnati RCSP average well below 100 mrem/year of exposure. As noted earlier 100 mrem is the exposure limit for a member of the general public. A detailed explanation of risks from occupational radiation exposure can be found in U.S. Nuclear Regulatory Commission REGULATORY GUIDE 8.29 INSTRUCTION CONCERNING RISKS FROM OCCUPATIONAL RADIATION EXPOSURE.

### **Prenatal Radiation Exposure**

Because the embryo/fetus is more radiosensitive the total effective dose equivalent limit for the embryo/fetus during a declared pregnancy is set at 1/10<sup>th</sup> the normal adult occupational limit. Please note that this limit is only in effect if the female chooses to "declare" her pregnancy in writing. Detailed information is found in U.S. Nuclear Regulatory Commission REGULATORY GUIDE 8.13 INSTRUCTION CONCERNING PRENATAL RADIATION EXPOSURE.

## **OPERATIONAL RADIATION SAFETY**

This section of the training manual discusses ways that a radiation worker can convert general knowledge into good practices when using radioactive material on a day-to-day basis. The information provided in this manual and the radiation safety classes is wasted if an individual does not apply good practices each time radioactive material is used.

### **Categories of Radiation Surveys**

Radiation surveys are a very important safety practice as it informs of the presence of radiation and radioactive contamination. There are three general categories of radiation surveys: 1) operational, 2) routine, and 3) special.

The most important surveys, by far for the radiation worker are the operational surveys. Operational surveys are performed during and after each use of radioactive material. A radiation worker must survey his or her hands, clothing, feet, and all work areas at the end of each procedure involving the use of radioactive material. A good after-use survey will identify any radioactive material that was spread outside the work area. Throughout a procedure or experiment where radioactive materials were used surveys should be performed of the work area and the worker's hands. Good practices have surveys being performed each time the work area is moved or changed and/or each time there is a significant change in radioactivity amount or concentration. Operational surveys are very important because contamination that is identified early is much less likely to become widespread and if it is on the radiation worker, the amount of dose from the contamination can be greatly reduced by quick removal.

Routine surveys are performed on a regular basis as a quality control check to ensure the laboratory is meeting the safety standards for control of radioactive materials. Routine surveys may be performed daily, weekly, monthly, quarterly or at some longer frequency. The most common routine survey frequencies are monthly, performed by laboratory staff and quarterly surveys performed by RSO staff.

Special surveys are required for emergency situations, such as when a spill of radioactive material occurs. Special surveys may also be performed for situations requiring an assessment of radiological conditions under normal circumstances, e.g. release of a room or piece of equipment or prior to repair of equipment or facilities. RSO staff should be contacted anytime a special survey is required.

### **Direct and Indirect Surveys**

A very important factor to consider when surveying for radioactive contamination is if it can be spread, exacerbating the potential problem. Merely surveying for contamination with a meter only reveals if there is significant radioactive material present in an area. It does not reveal whether said contamination is *fixed* to a surface or *removable*.

Fixed contamination is often of less concern than removable because it is not easily removed by normal contact and will not readily spread. Fixed contamination is detected by a *direct survey*, using a portable survey meter with its detector placed in close proximity to the surface being monitored. A general rule is to place the detector as close as possible without touching the contaminated surface. The probe should never be more than 1/4 of an inch away from the surface and it should be moved horizontally at about 1-2 inches per second. Sensitive detection meters generally readout in counts per minute (cpm). CPM is a qualitative assessment and is not a true indication of the activity present or of radiation dose. The detector will have its efficiency marked on the probe. The efficiency for the radionuclide of interest is used to calculate the disintegrations per minute (dpm). DPM is an actual quantitative measurement of the activity. All regulatory information must be entered as dpm (or cpm with an efficiency that can be later used to calculate dpm). The formula follows:

$$\text{dpm} = \frac{\text{cpm} - \text{background cpm}}{\% \text{ efficiency}}$$

Removable contamination is detected through an *indirect survey*, a wipe test using an absorbent material. A large area wipe, such as a mop cover, is often used in a spill area to determine if contamination still exists. The mop cover is read directly with a portable survey meter to assess the progress of a cleanup. A more accurate method is needed to quantify the amount of contamination on a surface for release purposes and for documentation. The most common wipe test materials used in laboratories are commercially available, absorbent grade, filter material in circular patches that are 1.5 - 2.0 inches in diameter. Alternatively, one can also use 2.54 cm Whatman #1 filter papers. The wipes are "wiped" across at least 100 cm<sup>2</sup> of a surface using uniform and constant pressure provided by the tips of the pointer and index fingers. An area 4 x 4 inches square or a sweeping "S" curve 16 inches long will equal approximately 100 cm<sup>2</sup>. The 100 cm<sup>2</sup> area is a standard reference area for reporting a wipe's activity, i.e. dpm/100 cm<sup>2</sup>. If the object being monitored has less than 100 cm<sup>2</sup> of surface area, the activity is recorded as dpm/wipe with the area wiped also noted. It is also a standard practice to ignore a wipe or a direct reading result of less than 100 cpm.



Fig 18: Wipe Testing

Wipe tests and direct surveys should both be performed to verify that no contamination exists in the area being surveyed. Areas immediately outside a radioactive material work area should be surveyed when work is completed. Surveys should check floor areas, workbench tops, doorknobs, refrigerator and drawer handles, water faucets, telephones, waste containers, and any other areas where contamination may have spread.

Before using a battery-powered portable survey meter, perform the following preoperational checks. Check the battery condition and replace weak or dead batteries before proceeding. Check the calibration date on the calibration sticker. If the end of the



month of the calibration due date has passed, do not use the meter before having it calibrated, *except in the case of an emergency*. Check the general condition of the meter to ensure there are no physically damaged parts, e.g. frayed cables, broken switches. Check the correction chart to determine if any corrections to the indicated readings must be made. If no check source is provided with the meter, it is a good practice to check a known source of radiation to verify the meter is responding to radiation.

A wipe may be monitored directly with a portable survey meter to determine if radioactivity is present. However, because of their superior efficiencies, wipes are generally counted in Liquid Scintillation (for beta emitters) and/or Gamma Counters (for gamma emitters). The wipes are placed into empty vials in a Gamma Counter for gamma counting and have a cocktail added for counting in a Liquid Scintillation Counter. (Different counters have different operating procedures and should be covered during lab-specific training conducted by the Authorized User.)

### **Personal Protective Equipment (PPE)**

Gloves and a lab coat are the minimum PPE required to be worn when handling unsealed radioactive material. The purpose of the minimum PPE is to protect the radiation worker from skin contamination. If the possibility of airborne exposure exists, respiratory protection PPE is required. Safety goggles, face shields, aprons, plastic arm sleeves and full Tyvek suits are additional PPE that may be required in various situations to prevent skin contamination.

Keeping in mind that the purpose of PPE is to prevent skin contamination, it is not appropriate to wear sandals, shorts, or dresses that leave exposed skin on the legs when working with radioactive material. Any radioactive material that is accidentally dropped could splash on the exposed skin. It is also important to ensure that PPE fits properly. A common problem to avoid is a lab coat with sleeves that are too short, which causes skin to be exposed between the gloves and the coat sleeves when reaching.

Even when PPE is worn and a survey is completed, a radiation worker should always wash their hands before leaving the laboratory.

### **Dosimetry**

Dosimetry must be worn on that part of the body where it is likely to receive the highest dose. Finger rings are to be worn on the hand that will most likely receive the higher exposure with the detector facing the area of greatest exposure. The finger ring should be worn under the glove to avoid contamination. Whole body dosimetry badges are normally worn in the front of the body at waist to shoulder level.

Dosimetry, if assigned, should be worn at all times when working with radioactive material and should be turned in for processing as scheduled by the RSO. An individual should never wear another person's dosimetry nor should one store dosimetry in a

radiation field. Care should also be taken not to damage a dosimeter by allowing it to be exposed to heat or accidentally putting it through an automatic clothes-washing cycle. A lost or damaged dosimeter should be reported to the RSO immediately so a replacement can be obtained.

## Labeling Radioactive Items and Areas of Use

The trefoil is an international symbol for radiation and/or radioactivity. It is a hazard communication used to warn people that a possible radiation hazard exists. Under the University of Cincinnati RCSP, areas where radioactive material is used or stored must



Fig 19: Work Area Labeling

have this symbol displayed with the amplifying information "Caution - Radioactive Material".

The entrance doors to laboratory rooms approved for radioactive material usage are marked to warn that radioactive material may be inside. Since the entire laboratory room is not used for radioactive work, smaller areas of use are marked inside, e.g. cabinets, fume hoods, drawers, waste containers, equipment, refrigerators, bench top work areas. Work areas where open sources of radioactive materials are manipulated should be covered with absorbent material to catch any inadvertent spillage of the radioactive material. This area should be completely labeled on its boundaries with tape designating it a radioactive use area so there is no doubt the area is potentially contaminated.

Radioactive material (waste and stock) must be clearly labeled with the trefoil symbol, the radionuclide, the activity, the date of assay, and the Authorized User's name or number. Equipment that is used for radioactive work, e.g. a centrifuge, should be marked with a radioactive label to warn that radioactive work is performed with the equipment and that a thorough survey is required before the equipment is used for non-RAM procedures.

## Inventory Control and Waste Management

All radioactive material used under the University of Cincinnati RCSP must be closely controlled and inventoried. Radioactive material is ordered, stored, used and disposed. It is closely tracked and inventoried through each of these phases. Specifics of the inventory and waste management systems are covered during the Advanced radiation worker training course. The following is a summary of the programs.

## **Purchasing Radioactive Material**

All radioactive material purchases must be approved by the RSO of before an order is made. A Form 14 Radioactive Material Request form is submitted to the RSO of where approval is given if the AU is authorized by the Radiation Safety Committee to have the radioactive material. Never order radioactive material before having an approved Form 14. Never change the order once the Form 14 is approved without first obtaining further approval (initiated by submitting a revised Form 14) from the RSO of.

All radioactive material, with the exception of certain routine clinical human-use radiopharmaceuticals, is received in the RSO of (If an order is mistakenly shipped directly to a laboratory, immediately inform the RSO of and bring the material to the RSO of for receipt processing). RSO of personnel perform regulatory required receipt surveys on incoming packages and enter the radioactive material into the University-wide inventory system for tracking. Laboratory personnel are informed when an order is received and a person, authorized by the AU, picks up the radioactive material package at the RSO of and takes it to the laboratory.

## **Storing Radioactive Material**

Radioactive material must be stored and used in such a manner that an unauthorized individual cannot gain access to it. This means it must be locked up or in the line of sight of someone who can stop an unauthorized individual from gaining access to it. Access simply means touching or handling the radioactive material, or being exposed to its radiation field if the exposure rate is above regulatory limits. Some individuals mistakenly believed that security of radioactive material only involves preventing stock solution from being stolen; however, non-compliance to proper security of RAM requirements include radioactive waste and RAM in experimental procedures (since their use places the RAM out in the open). Their thinking may have been that the waste or RAM already incorporated into an experiment had no value and no one would want to steal it; however, the radioactive waste and RAM in experimental procedures accessible to unauthorized individuals can result in them receiving radiation exposure.

Radiation workers using or disposing of RAM are responsible for the security of the radioactive material they are using. This means they must be able to see the area of use or they must lock the radioactive material up if they leave the area, even for a very short period of time. It is a security violation if a radiation worker leaves even momentarily. Some examples of violations to avoid are making a quick trip to the restroom or going around the corner to get a drink of water without securing the radioactive material. In these cases security can be maintained by locking the lab door when leaving or locking up the RAM in a cabinet or refrigerator.

As radioactive material is used, records are kept of its disposition. All of the radioactive material, unless it is used in a human medical procedure, will end up in a waste stream managed by the RSO of. Only the RSO of is authorized to dispose of radioactive waste, including liquid disposals. Never dispose of radioactive material into a sink. When

radioactive waste is ready for disposal, a pickup request is made to the RSO. The waste is checked against inventory control cards and liquid waste is verified to have a pH of 6.0-8.0. If the pH is not in the acceptable range, due to hazardous waste regulation, it must be readjusted by laboratory personnel and the pickup rescheduled. Radioactive waste must be segregated by its half-life classification, and its physical and chemical form.

When radioactive material is transferred to the RSO it is declared radioactive waste and removed from the AU's inventory and then disposed of by decay-in-storage, incineration, sewer disposal or shipment offsite. As stated earlier, the details of the system are explained during radiation worker training.

## **Spill Procedures**

No matter how careful a radiation worker handles radioactive material there may come a time when an accidental spill occurs. A spill has occurred if radioactive material is spread anywhere outside a taped-off work area. It can be identified immediately if the radiation worker sees the spill occur or it can be discovered during an after-use survey. In either case the RSO should be called immediately for assistance.

Laboratory personnel should take the following actions while RSO personnel respond. Each laboratory is required to have a spill recovery kit available for immediate use (The location and use of the spill kit is covered in Lab-specific training). The acronym "SWIM" can be used to assist in remembering the actions to be taken for a spill.

**Stop** the continuing spread of contamination. Upright a tipped container, stop a pump, or place absorbent on or around spilled liquid to prevent spread.

**Warn** others in the immediate area of the spill and be sure to call Radiation Safety for help. If the spill is discovered during a routine or after-use survey, have everyone in the laboratory check their shoes for contamination and start surveying at the entrance to the laboratory to determine if contamination has been spread outside.

**Isolate** the area by shutting the door to the laboratory, placing barrier tape across entrance areas, and/or placing physical barriers in pathways. When barriers are set, verify that no contamination has spread outside the boundaries that are established.

**Minimize** personnel exposure by removing any contaminated clothing and by washing contamination off the skin. This is especially important with beta emitters like high energy  $^{32}\text{P}$  that could lead to significant skin exposure if the contamination remains in contact for an extended period of time.

## **The Non-Compliance "Point" System**

The RCSP uses a "point" system to assess the compliance of an Authorized User and the radiation workers under their supervision. When RSO of personnel visit a RAM-use laboratory space, they check to ensure that proper safety and regulatory procedures are being followed. These inspections may be during a formal audit, a routine survey, a waste pickup, or a randomly scheduled walk-through. A radiation worker must always work safely and follow the regulatory rules. The details of the "point" system are in the AU Manual and will be covered in Advanced radiation worker training.

Some of the more common ways a radiation worker can cause non-compliances for the Authorized User are discussed next.

- Leave radioactive material unsecured while the room is unlocked and no one is present to guard against unauthorized access. This includes radioactive waste and includes leaving even for a few seconds. At all times radioactive material must be locked up or in someone's line of sight.
- Disposing of radioactive material into a non-radioactive material waste container. This usually occurs because an improper survey was performed on a glove or absorbent material that was removed from a radioactive material work area.
- Leaving an empty food or drink container anywhere in the laboratory, even in the trash. This is evidence of eating or drinking in the laboratory. It is not as serious as actually eating, drinking, smoking, chewing gum or using tobacco products, having food or drink in the RAM-use laboratory, or applying cosmetics, but if an empty container is found, non-compliance points are issued. A common excuse that will not have the points removed is that the food was consumed outside the laboratory and the container was carried in and disposed of in the trash.
- Leaving an applicator of lipstick or lip balm lying on a workbench would be considered as evidence of applying cosmetics.
- Ordering radioactive material directly from a vendor without first obtaining approval from the RSO of using a Form 14 or changing the Form 14 order after the Authorized User and the RSO of approved it. If more radioactive material is needed, complete another Form 14 or submit a revised Form 14.
- Ordering more than the amount approved on the Authorization Possession Limit.
- Failing to label radioactive material with the required information: Authorized User's name, radionuclide, activity, calibration date, and the trefoil symbol. A common error is not adding the AU's name to the information provided by the vendor on the original container. Remember to label all liquids and other solutions made from the original stock before placing into storage. Also, once

RAM waste is added, a waste container must have all required labeling information.

## **Good Laboratory Practices**

Good laboratory practices can greatly reduce the possibility of radioactive material being spread to cause contamination. Good laboratory practices are covered in detail in the Authorized User's Manual; however, a summary is given here.

- Always wear a lab coat and gloves when handling unsealed radioactive material.
- Use the minimum amount of space necessary for radioactive work.
- Keep non-essential materials and equipment outside of radioactive work areas, including survey meters.
- Perform a practice run without radioactive material before conducting an experiment for the first time.
- Use shielding when appropriate.
- Use absorbent paper to cover workbenches and other areas where radioactive material is used. Ensure the radioactive material work area is clearly marked with radiation warning tape.
- Transport liquid radioactive material in a double container.
- Do not store food and drink in a radioactive material use laboratory.
- Do not eat, drink, chew gum, use tobacco products or apply cosmetics in a radioactive material use laboratory.
- Wash hands before leaving a radioactive material use laboratory and monitor clothing for radioactive contamination.
- Ensure the RSO surveys all equipment used in a radioactive material work area before it is released from the laboratory for maintenance, repair, disposal, or transfer.

## Glossary

Absorbed dose means the energy imparted by ionizing radiation per unit mass of irradiated material. The units of absorbed dose are the rad and the gray (Gy). 1 Gy = 100 rad.

Activity is the rate of disintegration (transformation) or decay of radioactive material. The units of activity are the curie (Ci) and the becquerel (Bq). 1 Bq =  $2.7 \times 10^{-11}$  Ci.

ALARA (acronym for "as low as is reasonably achievable") means making every reasonable effort to maintain exposures to radiation as far below the dose limits as is practical consistent with the purpose for which the licensed activity is undertaken, taking into account the state of technology, the economics of improvements in relation to state of technology, the economics of improvements in relation to benefits to the public health and safety, and other societal and socioeconomic considerations, and in relation to utilization of nuclear energy and licensed materials in the public interest.

ALI (acronym for "Annual Limit on Intake") means the derived limit for the amount of radioactive material taken into the body of an adult worker by inhalation or ingestion in a year. ALI is the smaller value of intake of a given radionuclide in a year by the reference man that would result in a committed effective dose equivalent of 5 rem (0.05 Sv) or a committed dose equivalent of 50 rem (0.5 Sv) to any individual organ or tissue.

Background radiation means radiation from cosmic sources; naturally occurring radioactive material, including radon (except as a decay product of source or special nuclear material) and global fallout as it exists in the environment from the testing of nuclear explosive devices or from past nuclear accidents such as Chernobyl that contribute to background radiation and are not under control of the licensee. "Background radiation" does not include radiation from source, byproduct, or special nuclear materials regulated by the Nuclear Regulatory Commission.

Becquerel is an SI unit of measurement of radioactivity equal to one transformation per second. 1 Bq =  $2.7 \times 10^{-11}$  Ci.

Bioassay (radiobioassay) means the determination of kinds, quantities or concentrations, and, in some cases, the locations of radioactive material in the human body, whether by direct measurement (in vivo counting) or by analysis and evaluation of materials excreted or removed from the human body.

Byproduct material means any radioactive material (except special nuclear material) yielded in, or made radioactive by, exposure to the radiation incident to the process of producing or utilizing special nuclear material.

Calibration is the check or correction of the accuracy of a measuring instrument to assure proper operational characteristics.

Committed dose equivalent ( $H_{T,50}$ ) means the dose equivalent to organs or tissues of reference (T) that will be received from an intake of radioactive material by an individual during the 50-year period following the intake.

Committed effective dose equivalent ( $H_{E,50}$ ) is the sum of the products of the weighting factors applicable to each of the body organs or tissues that are irradiated and the committed dose equivalent to these organs or tissues ( $H_{E,50} = \sum W_T H_{T,50}$ )

Contamination is the deposition of unwanted radioactive material on the surfaces of structures, areas, objects, or personnel.

Controlled areas are areas, outside of restricted areas but inside the site boundary, access to which can be limited by the licensee for any reason.

### CPM Counts Per Minute

Declared pregnant woman means a woman who has voluntarily informed the licensee, in writing, of her pregnancy and the estimated date of conception. The declaration remains in effect until the declared pregnant woman withdraws the declaration in writing or is no longer pregnant

Decontamination is the reduction or removal of radioactive material from a structure, area, object, or person. Decontamination may be accomplished by treating the area to remove or reduce contamination or by allowing the radioactive material to decay.

Deep-dose equivalent ( $H_d$ ), which applies to external whole-body exposure, is the dose equivalent at a tissue depth of 1 cm ( $1000 \text{ mg/cm}^2$ ).

Dose equivalent ( $H_T$ ) means the product of the absorbed dose in tissue, quality factor, and all other necessary modifying factors at the location of interest. The units of dose equivalent are the rem and sievert (Sv).  $1 \text{ Sv} = 100 \text{ rem}$ .

### DPM Disintegrations Per Minute

Effective dose equivalent ( $H_E$ ) is the sum of the products of the dose equivalent to the organ or tissue ( $H_T$ ) and the weighting factors ( $W_T$ ) applicable to each of the body organs or tissues that are irradiated ( $H_E = \sum W_T H_T$ ).

Exposure means being exposed to ionizing radiation or to radioactive material.

External dose means that portion of the dose equivalent received from radiation sources outside the body.

Extremity means hand, elbow, arm below the elbow, foot, knee, or leg below the knee.

Film badge is a pack of photographic film used for approximate measurement of radiation exposure for personnel monitoring purposes.



Gray (Gy) is the SI unit of absorbed dose. One gray is equal to an absorbed dose of 1 Joule/kilogram (100 rads). 1 Gy = 100 rads.

High radiation areas are areas, accessible to individuals, in which radiation levels could result in an individual receiving a dose equivalent in excess of 0.1 rem (1 mSv) in 1 hour at 30 centimeters from the radiation source or from any surface that the radiation penetrates.

Internal dose means that portion of the dose equivalent received from radioactive material taken into the body.

Minor means an individual less than 18 years of age.

Nonstochastic effect means health effects, the severity of which varies with the dose and for which a threshold is believed to exist. Radiation-induced cataract formation is an example of a nonstochastic effect (also called a deterministic effect).

Occupational dose means the dose received by an individual in a restricted area or in the course of employment in which the individual's assigned duties involve exposure to radiation and to radioactive material from licensed and unlicensed sources of radiation, whether in the possession of the licensee or other person. Occupational dose does not include dose received from background radiation, as a patient from medical practices, from voluntary participation in medical research programs, or as a member of the general public.

#### PPE Personal Protective Equipment

Public dose means the dose received by a member of the public from exposure to radiation and to radioactive material released by a licensee, or to any other source of radiation under control of the licensee. Public dose does not include occupational dose or doses received from background radiation, from any medical administration the individual has received, from exposure to individuals administered radioactive material and released in accordance with federal regulations, or from voluntary participation in medical research programs.

Quality factor (Q) means the modifying factor (listed in tables 1004(b).1 and 1004(b).2 of 10 CFR 20.1004) that is used to derive dose equivalent from absorbed dose.

Rad is the special unit of absorbed dose. One rad is equal to an absorbed dose of 100 ergs/gram or 0.01 Joule/kilogram (0.01 gray). 1 rad = 0.01 Gy.

Radiation areas are areas, accessible to individuals, in which radiation levels could result in an individual receiving a dose equivalent in excess of 0.005 rem (0.05 mSv) in 1 hour at 30 centimeters from the radiation source or from any surface that the radiation penetrates.

Radioactive Waste is radioactive material that has been brought under the control of the Radiation Safety Office and entered into the Radioactive Waste Management System. Even though RAM is referred to as waste in the

laboratory once it is no longer useful, RAM is not considered waste under the RCSP until it has been analyzed and classified by the Radiation Safety Office and entered into the Waste Management System.

### RCSP Radiation Control and Safety Program

Rem is the special unit of any of the quantities expressed as dose equivalent. The dose equivalent in rems is equal to the absorbed dose in rads multiplied by the quality factor (1 rem = 0.01 sievert).

Restricted areas are areas, access to which is limited by the licensee for the purpose of protecting individuals against undue risks from exposure to radiation and radioactive materials. Restricted areas do not include areas used as residential quarters, but separate rooms in a residential building may be set apart as a restricted area.

### RSOf Radiation Safety Office

Sealed source is radioactive material that is permanently bonded or fixed in a capsule or matrix designed to prevent release and dispersal of the radioactive material under the most severe conditions which are likely to be encountered in normal use and handling.

Shallow-dose equivalent ( $H_s$ ), which applies to the external exposure of the skin or an extremity, is taken as the dose equivalent at a tissue depth of 0.007 centimeter ( $7 \text{ mg/cm}^2$ ) averaged over an area of 1 square centimeter.

Sievert is the SI unit of any of the quantities expressed as dose equivalent. The dose equivalent in sieverts is equal to the absorbed dose in grays multiplied by the quality factor (1 Sv = 100 rems).

Site boundary means that line beyond which the land or property is not owned, leased, or otherwise controlled by the licensee.

Stochastic effects means health effects that occur randomly and for which the probability of the effect occurring, rather than its severity, is assumed to be a linear function of dose without threshold. Genetic mutations and the induction of cancer are examples of stochastic effects.

Survey means an evaluation of the radiological conditions and potential hazards incident to the production, use, transfer, release, disposal, or presence of radioactive material or other sources of radiation. When appropriate, such an evaluation includes a physical survey of the location of radioactive material and measurements or calculations of levels of radiation, or concentrations or quantities of radioactive material present.

Survey meter is any portable radiation detection instrument especially adapted for inspecting an area to establish the existence and amount of radioactive material present.

### TLD Thermoluminescent Dosimeter

Total Effective Dose Equivalent (TEDE) means the sum of the deep-dose equivalent (for external exposures) and the committed effective dose equivalent (for internal exposures).

Unrestricted area means an area, access to which is neither limited nor controlled by the licensee.

Unsealed source is radioactive material that is not permanently bonded or fixed in a capsule or matrix designed to prevent release and dispersal of the radioactive material.

Weighting factor ( $W_T$ ), for an organ or tissue (T) is the proportion of the risk of stochastic effects resulting from irradiation of that organ or tissue to the total risk of stochastic effects when the whole body is irradiated uniformly. The values of  $W_T$  for various organs or tissue are in 10 CFR 20.1003.

Whole body means, for purposes of external exposure, head, trunk, (including male gonads), arms above the elbow, or legs above the knee.

### **Additional Reading**

Cember, H., *Introduction to Health Physics*, 3d ed, McGraw-Hill, New York, 1996.

Code of Federal Regulations, Title 10, Parts 19 & 20, Revised 1 January 1999, U.S. Government Printing Office: 1999.

Turner, J.E., *Atoms, Radiation, and Radiation Protection*, Pergamon Press, New York, 1986

United States Nuclear Regulatory Commission, Regulatory Guide 8.13, *Instruction Concerning Prenatal Radiation Exposure*, (Proposed Rev. 3), DRAFT REGULATORY GUIDE DG-8014, October 1994.

United States Nuclear Regulatory Commission, Regulatory Guide 8.29, *Instruction Concerning Risks From Occupational Radiation Exposure*, Rev. 1, February 1996.

University of Cincinnati, *Radiation Control and Safety Program Manual (RCSP Manual)*, 1 April 1998.

University of Cincinnati, *Radiation Protection Procedures Manual (Authorized User Manual)*, 1 January 1996.