TEXAS STATE UNIVERSITY – SAN MARCOS

RADIATION SAFETY
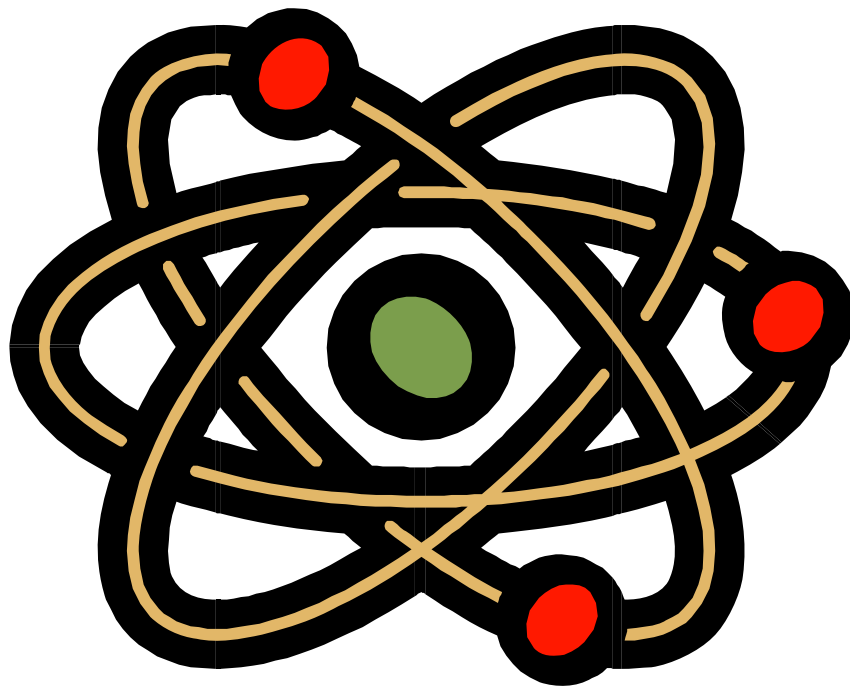
RAD MAT HANDLER TRAINING

Table of Contents

List of Figures

List of Tables

Appendices

I. INTRODUCTION

Radiation Safety is a concern for all persons whether or not they are directly or indirectly involved in the use of radioisotopes or radiation producing devices. The Texas State University at San Marcos is licensed by the state of Texas to use radioactive materials in research, development, and instruction. In addition, radiation producing devices are registered with the state. The goal of this course is to provide a basic understanding of radiological fundamentals to the individual so that when their course of study or research involves exposure to these hazards they can comprehend the risks and take appropriate precautions. There are two broad categories of radiation types which are: Non-ionizing and ionizing radiation both of these types will be introduced here.

A. *Non-ionizing radiation*

Electromagnetic radiation that does not have enough energy to ionize an atom is called non-ionizing radiation. Examples of non-ionizing radiation are radar waves, microwaves, infrared, ultraviolet, and visible light. Laser output is generally considered this type of radiation.

B. *Ionizing Radiation*

Ionizing radiation is energy (particles or rays) emitted from radioactive atoms, and some devices, that can cause ionization of other atoms. Examples of devices that emit ionizing radiation are X-ray machines, accelerators, and fluoroscopes. It is important to note that exposure to ionizing radiation without exposure to radioactive material, will NOT result in contamination of the individual. Radiation is a type of energy and contamination is radioactive material that is uncontained and in an unwanted place. Ionization is a particular characteristic of the radiation produced when radioactive elements decay. These radiations are of such high energy that when they interact with materials, they can remove electrons from the atoms in the material. This effect is the reason why ionizing radiation is hazardous to health, and provides the means by which radiation can be detected.

1. Radioactive Material

   There are two broad areas in which an individual could be exposed to ionizing radiation. The first radioactive material, is any material containing radioactive atoms is called either radioactive material or a radioactive source. These sources can be readily identified because of the radiation energy being emitted. At Texas State radioactive sources are used in research and instrument calibration, and radioactive waste generated through research operations. Radiation sources are either dispersible radioactive materials used in research (that is, they can be spread from the container) or are sealed (not able to be dispersed) and are used for
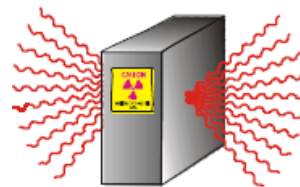
instrument calibration. Wave or ray penetrating radiation emitted from radioactive materials is called gamma radiation. Particle type radiation from these materials is called alpha or beta radiation. This types of radiation will be discussed in later sections of this training. Radioactive sources can also be found in medical diagnostics and radiography.

2. Radiation Generating Devices

    Radiation generating devices are machines that typically do not contain radioactive materials or sources but create fields of wave-type radiation when operated. When the machine is de-energized, there is no radiation field. Wave or Ray penetrating radiation emitted from radiation generating devices is called x-radiation, or x-rays. Types of radiation generating devices at Texas State include; Diagnostic X-ray machine used at the Student Health Center and Analytic X-ray machines used for research. Radiation produced by these machines penetrates materials, but does not make them radioactive. Personnel assigned to operate these devices must be trained in their safe operation before allowing them to use the machine as part of their research.

II.   OBJECTIVES

1. IDENTIFY sources of natural background radiation including their origin. (RWT.OBJ.001)
2. IDENTIFY sources of artificially produced background radiation including their origin. (RWT.OBJ.002)
3. DESCRIBE the radioactive decay processes. (RWT.OBJ.003)
4. DEFINE Radioactive Half-Life. (RWT.OBJ.004)
5. DEFINE the following terms:
    -   Ionization
    -   Excitation

    (RWT.OBJ.005)
6. DESCRIBE how the different types of radiation interact with atoms. (RWT.OBJ.006)
7. IDENTIFY and DEFINE terms associated with activity, exposure and dose. (RWT.OBJ.007)
8. Given the appropriate information PERFORM calculations.
    -   Half Life
    -   Gamma Exposure rate
    -   Inverse Square Law
    -   Beta Dose rates

    (RWT.OBJ.008)
9. IDENTIFY the biological effects associated with radiation exposure. (RWT.OBJ.009)
10. LIST the characteristics of radiosensitive tissue. (RWT.OBJ.010)
11. DESCRIBE the characteristics that determine if a radiation type is considered an external hazard and DISCUSS methods that can be used to reduce personal exposure. (RWT.OBJ.011)
12. DESCRIBE the characteristics that determine if a radiation type is considered an internal hazard and IDENTIFY routes of exposure. (RWT.OBJ.012)
13. DEFINE radioactive contamination, IDENTIFY three types of radioactive contamination and LIST their characteristics. (RWT.OBJ.013)
14. IDENTIFY the types of radioactive material and their characteristics most likely to be encountered at Texas State University – San Marcos. (RWT.OBJ.014)
15. DISCUSS the advantages and disadvantages of a Geiger-Mueller type detector. (RWT.OBJ.015)
16. DISCUSS radioactive waste handling and disposal practices. (RWT.OBJ.016)

III. SOURCES OF RADIATION

Exposure to radiation is generally discussed in two broad categories, radiation doses to the general public (background) and radiation dose received while performing work at your place of employment (occupational).

IDENTIFY sources of natural background radiation including their origin.

A. *Background Radiation*

Background radiation, to which everyone is exposed, comes from both natural and manmade sources.

1. Natural Sources

   a. Cosmic

   Radiation comes from outer space and our own sun. The earth's atmosphere and magnetic field affects the levels of cosmic radiation which reaches the surface, so your dose from cosmic radiation is determined by where you live.

   For example, the dose rate at sea level is about 24 mrem/ year, while the dose rate in Denver, Colorado is 50 mrem/year. The average dose from cosmic radiation in the U.S. is 28 mrem/year.

   b. Terrestrial

   Terrestrial sources exist because a number of materials have remained radioactive since the formation of the earth. These natural radioactive materials are found in the ground, rocks and building materials. Some of the contributors to terrestrial sources are the natural radioactive elements radium, uranium and thorium. In fact, there are some areas in Brazil and India where the natural background radiation levels reach 3,000 mrem/year. The average dose from terrestrial sources in the United States is 28 mrem/year. Radon gas; comes from the radioactive decay of uranium and thorium naturally present in the soil. The radon gas can migrate through the soil and into the air. The decay products of radon attach to dust particles and may be inhaled. The decay products of radon will then deliver a dose to the tissue of the lungs. The dose from radon is dependent upon the amount of uranium/thorium in the soil. The average effective dose equivalent from radon in the United States is 200 mrem/year. The combined dose for Terrestrial sources total 228 mrem/year.

c. Food

Our bodies contain various, naturally occurring radioactive elements due to consumption. Potassium (40K) is one of the major contributors to your internal dose. The average dose from internal sources in the United States is about 40 mrem/year.

IDENTIFY sources of artificially produced background radiation including their origin.

2. Man-made sources

a. Medical Exposures

This includes diagnostic (such as chest or dental x-ray) and therapeutic uses of radiation (such as radiation therapy for tumors). Because medical and dental doses are so individualized, your dose may vary from a few millirem to several thousand mrem. The average dose from medical and dental sources in the United States is about 51 mrem/year.

b. Consumer Products

Some consumer products contain small amounts of radioactive material. Examples include certain ceramic dishes (usually with an orange glaze), some luminous dial watches, and some smoke detectors. These consumer products account for a very minor contribution to the background dose. The average dose from consumer products in the United States is about 10 mrem/year.

c. Other

This category includes radiation doses from fallout caused by bomb testing, accidents such as Chernobyl, and operation of nuclear facilities. The average dose from other sources in the United States is about 3 mrem/year.

Manmade sources contribute an average of about 50 mrem per year to the whole body from medical procedures such as chest X-rays. The deep dose equivalent from a chest X-ray is 5 - 10 mrem, a dental X-ray is 50 - 300 mrem, and mammography is 0.5 - 2 rem.

Overall, the average radiation dose to a member of the general population in the United States, from natural background and man-made sources is about 360 mrem/year, or about 25,000 mrem over the average lifetime.

Legend
■ Terrestrial
■ Medical
■ Food
■ Cosmic
■ Consumer Products
■ Other

Pie chart values: 3, 1%; 10, 3%; 28, 8%; 40, 11%; 51, 14%; 228, 63%
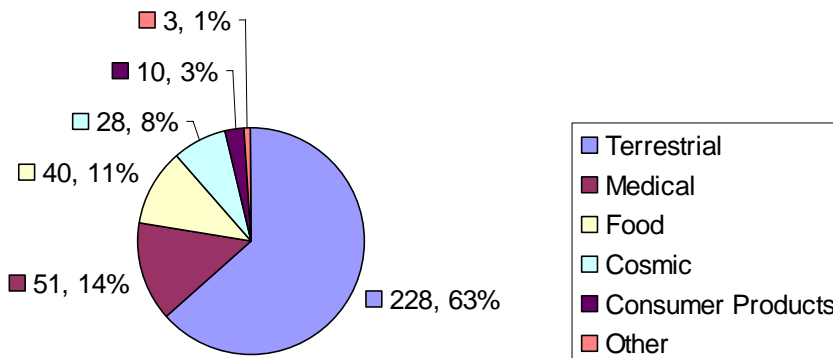
Background Radiation Sources

B. *Occupational Radiation Exposure*

The other broad category of radiation sources is occupational. Occupational dose is that which is received while working at your job. This includes any dose from previous employers or the military. Occupational dose does not include doses received from background radiation, medical treatment or therapy.

Chapter III Review Questions

1. What are the two broad categories of background radiation?

2. Identify three sources of natural background radiation sources.

3. Which of the three sources of background radiation contributes the highest average dose to individuals in the United States?

4. Medical exposures include what two uses of radiation?

5. Define Occupational Exposure.

CHECK YOUR ANSWERS

IV. RADIATION FUNDAMENTALS

For the purposes of this manual, we can use a simplistic model of an atom. The atom can be thought of as a system containing a positively charged nucleus and negatively charged electrons which are in orbit around the nucleus.
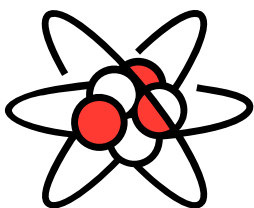
A. The Atom

The nucleus is the central core of the atom and is composed of two types of particles, protons which are positively charged and neutrons which have a neutral charge. Each of these particles has a mass of approximately one atomic mass unit (amu). (1 amu $\approx$ 1.66 x 10-24 g)

Electrons surround the nucleus in orbitals of various energies. (In simple terms, the farther an electron is from the nucleus, the less energy is required to free it from the atom.) Electrons are very light compared to protons and neutrons. Each electron has a mass of approximately 5.5 x 10-4 amu.

A nuclide is an atom described by its atomic number (Z) and its mass number (A). The Z number is equal to the charge (number of protons) in the nucleus, which is a characteristic of the element. The A number is equal to the total number of protons and neutrons in the nucleus. Nuclides with the same number of protons but with different numbers of neutrons are called isotopes. For example, deuterium ($_1^2H$) and tritium ($_1^3H$) are isotopes of hydrogen with mass numbers two and three, respectively. There are on the order of 200 stable nuclides and over 1100 unstable (radioactive) nuclides. Radioactive nuclides can generally be described as those which have an excess or deficiency of neutrons in the nucleus.

> DESCRIBE the radioactive decay processes.

B. Radioactive Decay

Radioactive nuclides (also called radionuclides) can regain stability by nuclear transformation (radioactive decay) emitting radiation in the process. The radiation emitted can be particulate or electromagnetic or both. The various types of radiation and examples of decay are shown below.

1. Alpha (α)

   Alpha particles have a mass and charge equal to those of helium nuclei (2 protons + 2 neutrons). Alpha particles are emitted from the nucleus during the decay of some very heavy nuclides (Z > 83).

$$_{88}^{226}Ra \xrightarrow[1599\ yrs]{} {}_{86}^{222}Rn + {}_2^4\alpha + \gamma$$

2. Beta (β-, β+)
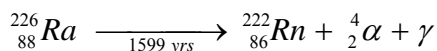
Beta particles are emitted from the nucleus and have a mass equal to that of electrons. Betas can have either a negative charge or a positive charge. Negatively charged betas are equivalent to electrons and are emitted during the decay of neutron rich nuclides. During β- decay an anti-neutrino is also emitted (see discussion section III.C.2).

$$\ce{^{14}_{6}C} \xrightarrow[5715\ yrs]{} \ce{^{14}_{7}N} + {}^{0}_{-1}\beta + \overline{\nu}$$
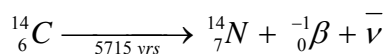
Positively charged betas (positrons) are emitted during the decay of proton rich nuclides. During β+ decay a neutrino is also emitted (see discussion section III.C.2).

$$\ce{^{22}_{11}Na} \xrightarrow[2.604\ yrs]{} \ce{^{22}_{10}Ne} + {}^{1}_{0}\beta + \nu$$

3. Gamma (γ)

Gammas (also called gamma rays) are electromagnetic radiation (photons). Gammas are emitted during energy level transitions in the nucleus. They may also be emitted during other modes of decay.

$$\ce{^{99m}_{43}Tc} \xrightarrow[6.01h]{} \ce{^{99}_{43}Tc} + \gamma$$
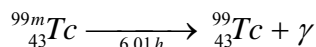
4. Electron Capture

In certain neutron deficient nuclides, the nucleus will capture an orbital electron resulting in conversion of a proton into a neutron. This type of decay also involves gamma emission as well as x-ray emission as other electrons fall into the orbital vacated by the captured electrons.
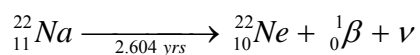
$$\ce{^{125}_{53}I} + {}^{-1}_{0}e \Rightarrow \ce{^{125}_{52}Te} + \gamma$$
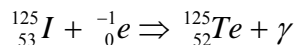
5. Fission

Fission is the splitting of an atomic nucleus into two smaller nuclei and usually two or three neutrons. This process also releases a large amount of energy in the form of gammas and kinetic energy of the fission fragments and neutrons.

$$\ce{^{235}_{92}U} + {}^{1}_{0}n \Rightarrow \ce{^{93}_{37}Rb} + \ce{^{141}_{55}Cs} + 2\ {}^{1}_{0}n + \gamma$$
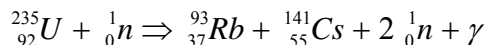
6. Neutrons

For a few radionuclides, a neutron can be emitted during the decay process.

$$\ce{^{17}_{7}N} \xrightarrow[4.714\ sec]{} \ce{^{17}_{8}O}* + {}^{-1}_{0}\beta \rightarrow \ce{^{16}_{8}O} + {}^{1}_{0}n$$
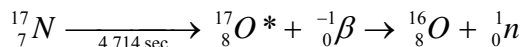
7. X-rays

X-rays are photons emitted during energy level transitions of orbital electrons.

Bremsstrahlung x-rays (braking radiation) are emitted as energetic electrons (betas) are decelerated when passing close to a nucleus. Bremsstrahlung must be considered when using large activities of high energy beta emitters such as P-32 and S-90.

C. *Characteristics of Radioactive Decay*

In addition to the type of radiation emitted, the decay of a radionuclide can be described by the following characteristics.

<div style="border:1px solid black; padding:8px;">
DEFINE Radioactive Half-Life.
</div>

1. Half-Life
   The half-life of a radionuclide is the time required for one half of a collection of atoms of that nuclide to decay. Decay is a random process which follows an exponential curve. The number of radioactive nuclei remaining after time (t) is given by:

$$N_t = N_0\, e^{-(0.693t/T)}$$

Where:
N_0 = original number of atoms
N_t = number remaining at time t
t = decay time
T = half-life

2. Energy
   The basic unit used to describe the energy of a radiated particle or photon is the electron volt (eV). An electron volt is equal to the amount of energy gained by an electron passing through a potential difference of one volt. The energy of the radiation emitted is a characteristic of the radionuclide. For example, the energy of the alpha emitted by Cm-238 will always be 6.52 MeV, and the gamma emitted by Ba-135m will always be 268 keV. Many radionuclides have more than one decay route. That is, there may be different possible energies that the radiation may have, but they are discreet possibilities. However, when a beta particle is emitted, the energy is divided between the beta and a neutrino. (A neutrino is a particle with no charge and infinitesimally small mass.)

   Consequently, a beta particle may be emitted with an energy varying in a continuous spectrum from zero to a maximum energy (Emax) which is characteristic of the radionuclide. The average energy is generally around forty percent of the maximum. (See Figure 1)

Chapter IV Review Questions

1. The nucleus of the atom is comprised of what two types of subatomic particles?

2. List four types of radioactive decay processes.

3. Define the term radioactive half-Life.

4. Which radioactive decay process results in a particle being emitted with an energy that varies from zero to an Emax? Why?

5. What is a neutrino?

CHECK YOUR ANSWERS

V. INTERACTION OF RADIATION WITH MATTER

A. *Energy Absorption*

The transfer of energy from the emitted particle or photon to an absorbing medium has several mechanisms. These mechanisms result in ionization and excitation of atoms or molecules in the absorber. The transferred energy is eventually dissipated as heat.

> DEFINE the following terms:
> - Ionization
> - Excitation

1. Ionization

   Ionization is the removal of an orbital electron from an atom or molecule, creating a positively charged ion. In order to cause an ionization to occur, the radiation must transfer enough energy to the electron to overcome the binding force on the electron. The ejection of an electron from a molecule can cause dissociation of the molecule. (See Figure 2)

2. Excitation

   Excitation is the addition of sufficient energy to an orbital electron thereby transferring the atom or molecule from the ground state to an excited state. (See Figure 3)

> DESCRIBE how the different types of radiation interact with atoms.

B. *Alpha Particles*

Interactions between the electric field of an alpha and orbital electrons in the absorber is the cause ionization and excitation events. Because of their double charge and low velocity (due to their large mass), alpha particles lose their energy over a relatively short range. One alpha will cause tens of thousands of ionizations per centimeter in air. The range in air of the most energetic alpha particles commonly encountered is about 10 centimeters (4 inches). In denser materials, the range is much less. Alpha particles are easily stopped by a sheet of paper or the protective (dead) layers of skin. See Table 4 for characteristics summary.

C. *Beta Particles*

Normally, a beta particle loses its energy in a large number of ionization and excitation events. Due to the smaller mass, higher velocity and single charge of the beta particle, the range of a beta is considerably greater than that of an alpha of comparable energy. The maximum ranges of beta particles in various absorbing media are shown in Figure 4. Since its mass is equal to that of an

electron, a large deflection can occur with each interaction, resulting in many path changes in an absorbing medium.

If a beta particle passes close to a nucleus, it decreases in velocity due to interaction with the positive charge of the nucleus, emitting x-rays (bremsstrahlung). The energy of the bremsstrahlung x-rays has a continuous spectrum up to a maximum equal to the maximum kinetic energy of the betas. The production of bremsstrahlung increases with the atomic number of the absorber and the energy of the beta. Therefore, low Z materials are used as beta shields. A positron will lose its kinetic energy through ionizations and excitations in a similar fashion to a negative beta particle. However, the positron will then combine with an electron. The two particles are annihilated, producing two 511 keV photons called annihilation radiation. See Table 2 for characteristics summary.

D. *Photons*

Gammas and x-rays differ only in their origin. Both are electromagnetic radiation, and differ only from radio waves and visible light in having much shorter wavelengths. They have zero rest mass and travel with the speed of light. They are basically distortions in the electromagnetic field of space, and interact electrically with atoms even though they have no net electrical charge. While alphas and betas have a finite maximum range and can therefore be completely stopped with a sufficient thickness of absorber, photons interact in a probabilistic manner. This means that an individual photon has no definite maximum range. However, the total fraction of photons passing through an absorber decreases exponentially with the thickness of the absorber. See Table 3 for characteristics summary. There are three mechanisms by which gammas and x-rays lose energy.

1. Photoelectric Effect
    The photoelectric effect is one in which the photon imparts all its energy to an orbital electron. The photon simply vanishes, and the absorbing atom becomes ionized as an electron (photoelectron) is ejected. This effect has the highest probability with low energy photons (< 50 keV) and high Z absorbers. (See Figure 5)

2. Compton Scattering
    Compton scattering provides a means for partial absorption of photon energy by interaction with a "free" (loosely bound) electron. The electron is ejected, and the photon continues on to lose more energy in other interactions. In this mechanism of interaction, the photons in a beam are scattered, so that radiation may appear around corners and in front of shields. (See Figure 6)

3. Pair Production

    Pair Production occurs only when the photon energy exceeds 1.02 MeV. In pair production the photon simply disappears in the electric field of a nucleus, and in its place two electrons, a negatron and a positron, are produced from the energy of the photon. The positron will eventually encounter a free electron in the absorbing medium. The two particles annihilate each other and their mass is converted into energy. Two photons are produced each of 0.511 MeV. The ultimate fate of these two photons is energy loss by Compton Scattering or the photoelectric effect. (See Figure 7)

E.   Secondary Ionizations

The electrons from ionizations and pair production will themselves go on to cause more ionization and excitation events in the same way as described for betas.

Chapter V Review Questions

1. Differentiate between excitation and ionization.

2. When an alpha particle interacts with an atom, what causes the ionization and excitation events to occur?

3. Describe the interaction that results in bremsstrahlung X-rays.

4. How do gammas and x-rays differ?

5. Describe Compton Scattering.

CHECK YOUR ANSWERS

> IDENTIFY and DEFINE terms associated with activity, exposure and dose.

VI. ACTIVITY, EXPOSURE, AND DOSE DEFINITIONS

Activity is the rate of decay (disintegrations/time) of a given amount of radioactive material.

Dose is a measure of energy deposited by radiation in a material, or of the relative biological damage produced by that amount of energy given the nature of the radiation.

Exposure is a measure of the ionizations produced in air by x-ray or gamma radiation. The term exposure (with its "normal" definition) is sometimes used to mean dose. (e.g. "He received a radiation exposure to his hand.")

A. *Units*

1. Activity

   1 Curie (Ci) = 3.7 x 10^{10} disintegrations per sec (dps). The Becquerel (Bq) is also in use as the International System of Units (SI) measure of disintegration rate.

   > 1 Bq = 1 dps, 3.7 x 1010 Bq = 1 Ci, and 1 mCi = 37 MBq.

2. Exposure

   The unit of radiation exposure in air is the roentgen (R). It is defined as that quantity of gamma or x-radiation causing ionization in air equal to 2.58 x 10-4 coulombs per kilogram. Exposure applies only to absorption of gammas and x-rays in air.

3. Dose

   The rad is a unit of absorbed dose. One rad is equal to an absorbed dose of 100 ergs/gram. (1 erg = 6.24 x 10^{11} eV)

   The SI unit of absorbed dose is the Gray (Gy). 1 Gy = 1 joule/kilogram = 100 rad. An exposure of 1 R results in an absorbed dose of 0.87 rad.

4. Quality Factor

   A quality factor (Q) is used to compare the biological damage producing potential of various types of radiation, given equal absorbed doses. The effectiveness of radiation in producing damage is related to the energy loss of the radiation per unit path length. The term used to express this is linear energy transfer (LET). Generally, the greater the LET in tissue, the more

effective the radiation is in producing damage. The quality factors for radiations frequently encountered are:

Radiation	Q
Gamma & X-ray	1
Beta particles & electrons	1
Alpha particles & fission fragments	20
Neutrons	10

5. Rem

    The rem is a unit of dose equivalent. The dose equivalent in rem is equal to the absorbed dose in rad multiplied by the quality factor. Dose equivalent determinations for internally deposited radioactive materials also take into account other factors such as the non-uniform distribution of some radionuclides (e.g. I-125 in the thyroid). The SI unit for dose equivalent is the Sievert (Sv). 1 Sv = 100 rem.

Given the appropriate information PERFORM calculations.

- Half Life

- Gamma Exposure rate

- Inverse Square Law

- Beta Dose rates

B. *Calculation of Activities*

1. Half-Life

    The half-life of a radionuclide is the time required for one-half of a collection of atoms of that nuclide to decay. This is the same as saying it is the time required for the activity of a sample to be reduced to one-half the original activity. The equation on page 10 can be rewritten as:

    $$A_t = A_0 \, e^{-(0.693t/T)}$$

    Where:
    A_0 = original activity
    A_t = activity at time t
    t = decay time
    T = half-life

EXAMPLE P-32 has a half-life of 14.3 days. On January 10, the activity of a P-32 sample was 100 mCi. What will the activity be on February 6? February 6 is 27 days after January 10 so

$$A_t = 100\ e^{-(.693(27)/14.3)}$$
$$A_t = 100\ e^{-1.308}$$
$$A_t = 100 \times 0.27$$
$$A_t = 27\ mCi$$

A quick estimate could also have been made by noting that 27 days is about two half-lives. So the new activity would be about one-half of one-half (i.e. one-fourth) of the original activity.

C. *Calculation of Exposure Rates*

1. Gamma

   a. Gamma exposure constants (Γ) for many radionuclides are given in Table 1. Γ is the exposure rate in R/hr at 1 cm from a 1 mCi point source.

   b. An empirical rule which may also be used is:

   $$6\ CEn = R/hr\ @\ 1\ foot$$

   Where:
   C = source strength in curies.
   E = energy of the emitted photons in MeV.
   n = fraction of decays resulting in photons with an energy of E

   It should be noted that this formula and the gamma constants are for exposure rates from gammas and x-rays only. Any dose calculations would also have to include the contribution from any particulate radiation that may be emitted.

2. Inverse Square Law

   Exposure rate varies inversely with the square of the distance from a point source of radiation. This is often referred to as the inverse square law (or 1/r2 rule).

   $$ER2 = ER1 \times (d1/d2)^2$$

   Where:
   ER2 = exposure rate at distance 2
   ER1 = exposure rate at distance 1
   d1 = distance 1
   d2 = distance 2

EXAMPLE, from Table 1, the Γ for Co-60 is 13.2.

Therefore, the exposure rate at 1 cm from a 1 mCi source would be 13.2 R/hr.

At 30 cm from the same source, the exposure rate would be:

$(13.2\ R/hr)(1/30)^2 = 0.0147\ R/hr = 14.7\ mR/hr.$

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3. Beta Dose Rates

For a beta emitter point source, the dose rate can be calculated using the empirical equation

$$300 \times Ci = \text{rad/hr @ 1 foot}$$

Where:
Ci = source strength in curies.

This calculation neglects any shielding provided by the air, which can be significant. For example, the maximum range in air for a beta from S-35 is less than one foot, so the dose rate at one foot is zero for any size S-35 source.

4. Skin Dose

For energies above 0.6 MeV, the dose rate to the skin from a uniform deposition of 1 μCi/cm2 of a beta emitter on the skin is about 9 Rem/hr.

Chapter VI Review Questions

1. What is activity? What are the two common units of activity?

2. Define Roentgen.

3. What is Quality factor and what is the Quality factor for Beta particles?

4. Calculate the quantity of I-125 remaining after 75 days. Given A0 = 2 mCi, T1/2 = 59.4 days.

5. What is the beta dose rate at 1 foot from a 250 mCi P32 source.

6. What is the dose rate at 54" from a point source if the dose rate at 1 foot is 2.5 R/hr?

CHECK YOUR ANSWERS

> IDENTIFY the biological effects associated with radiation exposure.

VII. BIOLOGICAL EFFECTS OF IONIZING RADIATION

A. *Radiation Hazards*

The hazards associated with the absorption of radiation in mammalian systems and tissue are related to both the type of radiation and the nature of the absorbing tissue or organ system.

1. Alpha

   Alpha particles will be stopped by the dead layers of skin, so they are not an external hazard. However, many alpha emitters or their daughters also emit gammas which are penetrating and therefore may present an external hazard. Internally, alphas can be very damaging due to their high linear energy transfer (LET). That is, they deposit all of their energy in a very small area. Based on their chemical properties, alpha emitters can be concentrated in specific tissues or organs.

2. Beta

   Externally, beta particles can deliver a dose to the skin or the tissues of the eye. Many beta emitters also emit gammas. A large activity of a high energy beta emitter can create a significant exposure from bremsstrahlung x-rays produced in shielding material. Internally, betas can be more damaging, especially when concentrated in specific tissues or organs.

3. Photons

   Externally, the hazard from low energy (< 30 keV) gammas and x-rays is primarily to the skin or the tissues of the eye. Higher energies are more penetrating and therefore a whole body hazard. Internally, gamma emitters can effect not only the tissues or organs in which they are deposited, but also surrounding tissues.

B. *Mechanisms of Damage*

As discussed earlier, radiation causes atoms and molecules to become ionized or excited. These ionizations and excitations can result in:
- Production of free radicals.
- Breakage of chemical bonds.
- Production of new chemical bonds and cross-linkage between macromolecules.
- Damage to molecules which regulate vital cell processes (e.g. DNA, RNA, proteins).

> LIST the characteristics of radiosensitive tissue.

C. *Tissue Sensitivity*

The most radiologically sensitive part of the cell is the nucleus. The major effect of radiation on the cell nucleus is the inhibition of DNA replication. This means that the cell is unable to prepare for division. Before a cell divides it produces a complete duplicate set of chromosomes which carry all the information needed to reproduce the organism. With damaged DNA, duplicate chromosomes cannot be manufactured. If this process is delayed long enough, the cell dies and the death of the cell can be compared to death in childbirth. At lower doses DNA production is delayed only a short time. As the dose is increased, the delay period gets longer until death occurs.

"The radiosensitivity of a tissue is directly proportional to its reproductive capacity and inversely proportional to its degree of differentiation." In other words, cells most active in reproducing themselves and cells not fully mature will be most harmed by radiation. This is considered to be a rule-of-thumb, with some cells and tissues showing exceptions. It is generally accepted that cells tend to be radiosensitive if they are:

- Cells that have a high division rate.
- Cells that have a high metabolic rate.
- Cells that are of a non-specialized type.
- Cells that are well nourished.

D. *Effects of Acute High Radiation Doses*

A whole body radiation dose of greater than 25 to 50 rem received in a short time results in the clinical "acute radiation syndrome." This syndrome, which is dose related, can result in disruption of the functions of the bone marrow system (>25 rem), the gastro-intestinal system (>500 rem), and the central nervous system (>2000 rem). An acute dose over 300 rem can be lethal.

E. *Effects of Low Radiation Doses*

There is no disease uniquely associated with low radiation doses. Immediate effects are not seen below doses of 25 Rem. Latent effects may appear years after a dose is received. The effect of greatest concern is the development of some form of cancer. The National Academy of Sciences Committee on Biological Effects of Ionizing Radiation (BEIR) issued a report in 1990 entitled "Health Effects of Exposure to Low Levels of Ionizing Radiation," also known as BEIR V. The following is an excerpt from the Executive Summary of the report:

On the basis of the available evidence, the population-weighted average lifetime risk of death from cancer following an acute dose equivalent to all body organs of 0.1 Sv (0.1 Gy of low-LET radiation) is estimated to be 0.8%, although the lifetime risk varies considerably with age at the time of exposure. For low LET radiation, accumulation of the same dose over weeks or months, however, is expected to reduce the lifetime risk appreciably, possibly by a factor of 2 or more. The Committee's estimated risks for males and females are similar. The risk from exposure during childhood is estimated to be about twice as large as the risk for adults, but such estimates of lifetime risk are still highly uncertain due to the limited follow-up of this age group.

The Committee examined in some detail the sources of uncertainty in its risk estimates and concluded that uncertainties due to chance sampling variation in the available epidemiological data are large and more important than potential biases such as those due to differences between various exposed ethnic groups.
Due to sampling variation alone, the 90% confidence limits for the Committee's preferred risk models, of increased cancer mortality due to an acute whole body dose of 0.1 Sv to 100,000 males of all ages range from about 500 to 1200 (mean 760); for 100,000 females of all ages, from about 600 to 1200 (mean 810).
This increase in lifetime risk is about 4% of the current baseline risk of death due to cancer in the United States. The Committee also estimated lifetime risks with a number of other plausible linear models which were consistent with the mortality data. The estimated lifetime risks projected by these models were within the range of uncertainty given above. The committee recognizes that its risk estimates become more uncertain when applied to very low doses. Departures from a linear model at low doses, however, could either increase or decrease the risk per unit dose.

Texas State's whole body dose limit for planned exposures is 5 rem/year (0.05 Sv/yr). If a Texas State worker were to receive the maximum allowable planned dose each year for twenty years, the total dose received would be 100 rem (1.0 Sv). According to the BEIR V report, the worker's chance of death from cancer would increase by approximately 0.4%. This is fairly small compared to the normal chance of death from cancer in the U. S. of about 20%.

Chapter VII Review Questions

1. State two reasons that alpha emitters can be very damaging if they are internally deposited.

2. Why are gamma photons considered a whole body hazard.

3. Identify two possible results of ionization of living human cells.

4. What is the most radiologically sensitive part of the human cell?

5. List two factors that tend to make a human cell more radiosensitive.

6. What acute radiation dose can be lethal?

CHECK YOUR ANSWERS

Example:

At 10 cm, a 5 mCi I-125 source has an exposure rate of 75 mR/hr.

Moving to 30cm would reduce the exposure rate to $(75 \text{ mR/hr})(10/30)^2 = 8.3$ mR/hr

Note:

The $1/r^2$ formula (also known as the inverse square law) does not take into account shielding provided by air. This can be significant for particulate radiation. Even the most energetic alpha particles commonly encountered have a range in air of about 4 inches. A beta from the decay of S-35 has a maximum range in air of about 12 inches.

4. Shielding:

Shielding offers a form of protection that requires prior planning and anticipation of safety requirements for given work. Protection offered by shielding depends on the following:

o Initial radiation dose rate without shield.

o Material used for shielding.

o Thickness of the shield.

o Type and energy of radiation.

As gammas and x-rays pass through an absorber their decrease in number (by the processes discussed in Chapter IV) is governed by the energy of the radiation, the density of the absorber medium, and the thickness of the absorber. This can be expressed approximately as

a. TVL & HVL

The thicknesses of an absorber needed to reduce the radiation intensity by a factor of two and by a factor of ten are called the half-value layer (HVL) and the tenth-value layer (TVL), respectively. Approximate lead TVL's, and HVL's for some radionuclides are listed in Table 5.

b. Shielding Concerns

When designing shielding there are several points to be kept in mind.

• Persons outside the shadow cast by the shield are not necessarily protected.

• A wall or partition may not be a safe shield for people on the other side. Radiation can be "scattered" around corners.

• Bremsstrahlung

The absorption of high energy beta radiation (e.g. P-32 and Sr-90) in high Z materials such as lead and tungsten may result in the production of electromagnetic radiation (bremsstrahlung) which is more penetrating than the beta radiation that produced it. Low Z materials such as plastics and glass minimize the production of bremsstrahlung.

> DESCRIBE the characteristics that determine if a radiation type is considered an internal hazard and IDENTIFY routes of exposure.

B. *Internal Radiation Hazards*

The types of ionizing radiation that are generally considered an internal hazard are alpha and beta particles. These types of ionizing radiation have an electrical charge, and in the case of an alpha significant mass, their ability to penetrate to the sensitive organs and cells of the body are rather limited. For this reason these types of emitters must be taken into the body to cause significant damage. There are four methods by which radioisotopes can enter the body. Once internal the concept of time, distance and shielding can no longer be applied. The methods by which radioisotopes can become internal are:

1. Ingestion

    Via the digestive tract, for this reason, eating, chewing, and drinking in an area that radioactive materials are handled is strictly prohibited.

2. Inhalation

    Via the respiratory system, a more difficult method of entry to control, different means of controlling radioactive material ingress are:
    o   Prohibiting smoking in contamination areas. This prevents both inadvertent ingestion as well as inhalation of radioactive materials in the smoke.
    o   Engineering controls to remove contaminants from the air.
    o   Respiratory protection to prevent entry

3. Absorption

    Generally occurs when radioactivity comes and stays in contact with the skin of the body. Two methods to control this means of entry are control of contamination levels and through the use of protective clothing to prevent inadvertent contact between the skin and radioactive substances. Some tritium and carbon-12 compounds can be absorbed readily into the skin even through protective gloves.

4. Injection

    Similar to absorption, but includes entry into the body via a cut, abrasion, or through a puncture of some sort.

> DEFINE radioactive contamination, IDENTIFY three types of radioactive contamination and LIST their characteristics.

C. Radioactive Contamination

Radioactive contamination is radioactive material where you do not want it. Recall that radioactive material is material that contains unstable "radioactive" atoms. Even when this radioactive material is properly contained, it still emits radiation and may be an external dose hazard, but it will not be a contamination hazard. When radioactive material is inadvertently released from its container (e.g., a spill), it is then referred to as radioactive contamination. Radiation is energy, contamination is a material. Exposure to radiation does NOT result in contamination. Radioactive Contamination can be grouped into 3 types:

- Fixed.
- Removable/transferable.
- Airborne.

1. Fixed Contamination
   Fixed contamination is contamination that cannot be readily removed from surfaces. It cannot be removed by casual contact, wiping, brushing, or washing. It may be released when the surface is disturbed (buffing, grinding, using volatile liquids for cleaning, construction, etc.). Over time it may "weep," leach, or otherwise become loose or transferable.

2. Removable/transferable contamination
   Removable/transferable contamination, also known as "loose" contamination, is contamination that can be readily removed or transferred from surfaces. It may be removed or transferred by casual contact, wiping, brushing, or washing. Air movement across this type of contamination could cause the contamination to become airborne. This type of contamination must be strictly controlled to prevent its spread to uncontrolled areas and to prevent inadvertent intake by ingestion and/or absorption.

3. Airborne contamination
   Airborne contamination is contamination suspended in air. This creates a particular hazard because of the possibility of intake by inhalation. Inhalation is the most common mode of uptake of radioactive material in the working environment. In addition to the hazard to the worker, radioactive materials may be carried into ventilation systems, the material may be deposited on surfaces over a large area, and there is the potential for releases outside of the facility. Elemental iodine-125 is extremely volatile and can readily become an airborne contaminant if handled improperly.

D. *Handling Precautions*

Here are some of the radiological characteristics of and special precautions associated with some radionuclides commonly used on campus. Refer to Appendix C for other radioisotopes commonly used in research. In addition to the specific precautions for each nuclide, the following general precautions should always be followed when applicable to your work.

- Whenever practical, designate specific areas for radioactive material handling and use. Clearly label the area and all containers. Minimize and confine contamination by using absorbent paper and spill trays. Handle potentially volatile materials in certified fume hoods.
- Do not smoke, eat, or drink in rooms where radioactive materials are used.
- Do not store food or drink in refrigerators, freezers, or cold rooms used for radioactive material storage.
- Use an appropriate instrument to detect radioactive contamination. Regularly monitor the work area.
- Always monitor yourself, the work area, and equipment for contamination when your experiment or operation is completed. Decontaminate when necessary.
- Use appropriate shielding when handling millicurie or greater amounts of gamma emitters or high energy beta emitters.
- Wear the dosimeters issued to you while using radioactive materials.
- Wash your hands before leaving the lab, using a telephone, or handling food.

> IDENTIFY the types of radioactive material and their characteristics most likely to be encountered at Texas State University – San Marcos.

1. P-32 INFORMATION
   Radioactive half-life: 14.3 days
   Decay mechanism: Beta emission
   Energy: Emax = 1.709 MeV
   Contamination monitoring: Thin window Geiger-Mueller detector
   Shielding: 1 cm lucite
   Dosimetry: micro-curie quantities – none, milli-curie quantities - Film badge, TLD ring, urinalysis

P-32 Decay Table

days	0	1	2	3	4	5	6
0	1000	953	908	865	824	785	748
7	712	679	646	616	587	559	533
14	507	483	460	439	418	398	379
21	361	344	328	312	298	284	270
28	257	245	234	223	212	202	192
35	183	175	166	159	151	144	137
42	131	124	119	113	108	102	98
49	93	89	84	80	77	73	70
56	66	63	60	57	55	52	50

a. The dose rate on contact on the side of a 1 mCi delivery vial can be on the order of 1000 mrem/hr. If possible, avoid direct hand contact with vials and sources. When working with 100 μCi or more of P-32, work should be done behind a 1 cm lucite shield.

b. One microcurie of P-32 in direct contact with 1 cm^2 of bare skin gives a dose rate to the skin of about 9 rem/hr. Always protect your skin and eyes when handling unsealed materials. Wear gloves, lab coats, safety glasses, and shoes.

c. A thin window G-M survey meter should always be available. A survey should be made immediately after use and any "hot spots" should be decontaminated.

d. Film badges and TLD rings should be worn for all P-32 work when handling 1 millicurie or more.

e. Handle and store your radioactive waste carefully. The bottles for liquid waste should be placed in a secondary container (e.g. a bucket or tray) to contain spills or leaks. When more than a millicurie is involved, place 1 cm lucite in front of the container for shielding.

2. <u>H-3 (Tritium) Information</u>

   Radioactive half-life: 12.4 years

   Decay mechanism: Beta emission

   Energy: Emax = 18.6 keV

   Contamination monitoring: Liquid scintillation counter for wipe surveys

   Dosimetry: Urinalysis

   a. Because the beta emitted has a very low energy, tritium can not be detected with the usual survey meters found in the lab. Therefore, special care is needed to keep the work area from becoming contaminated. Tritium can be detected by doing a wipe survey and counting the wipes in a liquid scintillation counter.

   b. Many tritiated compounds readily penetrate gloves and skin. Wearing two pairs of gloves and changing the outer pair every fifteen or twenty minutes will reduce the chances of cross contamination and absorption through the skin.

3. <u>C-14 INFORMATION</u>

   Radioactive half-life: 5730 years

   Decay mechanism: Beta emission

   Energy: Emax = 0.156 MeV

   Contamination monitoring: Thin window Geiger-Mueller detector, liquid scintillation counter for wipe surveys

   Dosimetry: Urinalysis

   a. Some C-14 labeled compounds can penetrate gloves and skin. Wearing two pairs of gloves and changing the outer pair every fifteen or twenty minutes will reduce the chances of absorption through the skin.

   b. C-14 may be difficult to distinguish from S-35. If both nuclides are being used in the same laboratory, establish controls to ensure they are kept separate. If "unknown" contamination is found, treat it as C-14.

Chapter VIII Review Questions

1. List four methods that can be used to reduce external radiation exposure.

2. List four methods by which radioactive material may become an internal hazard.

3. List three categories of radioactive contamination.

4. List three radionuclides you are likely to encounter at Texas State University.

CHECK YOUR ANSWERS

IX. RADIATION SURVEY METERS

There are several types of portable radiation survey instruments in use on campus. Various types have different qualities and can therefore have very different detection capabilities. As a user of radioactive materials or radiation producing machines, you are expected to be able to use the survey meters in your laboratory. During your initial training, you will learn how to operate the instruments in your lab. You should know their capabilities and limitations and be able to interpret the meter readings.

> DISCUSS the advantages and disadvantages of a Geiger-Mueller type detector.

A. *Geiger-Mueller Detector*

The Geiger-Mueller (G-M) counter is the most common radiation detection instrument on campus. In this type of meter, an ionization in the detector results in a large output pulse that causes meter and audio responses. Because of the inherent characteristics of the detector, all initial ionizing events produce the same size output pulse. Therefore, the meter does not differentiate among types or energies of radiation. Most G-M detectors have a thin mica film "window" at one end. This window is very fragile. Always use the thin end window for detecting pure beta emitters and low energy photons (e.g. P-32, S-35, C-14, Fe-55, I-125, and x-rays less than 40 keV). The aluminum side wall should be used only for the detection of penetrating x-rays and gamma radiation. However, covering the window with plastic wrap or paraffin film will stop most or all of their betas from entering the detector.

Very low energy beta emitters such as H-3 and Ni-63 are not detectable since their betas do not have enough energy to penetrate the window. They are best detected by using liquid scintillation counting techniques. 14C and 35S emit betas energetic enough to pass through the thin window.

The efficiency of a meter for a specific source of radiation is given by the ratio of the meter count rate to the actual disintegration rate of the source. This means actual rate = meter reading/efficiency. Some examples of approximate G-M efficiencies through the end window at 1 inch from a point source are given below:

Radioisotope	Efficiency
H-3	Not detectable
C-14, S-35	0.2% - 0.8% *
P-32	3% - 8%
I-125	0.01% - 0.03%
* Not detectable if the detector window is covered with paraffin film, plastic wrap, or other material.	

EXAMPLE

Your G-M counter reads 5000 cpm at one inch from a small spot of P-32 contamination on the bench. What is the total activity of the contamination (assuming a 5% efficiency)?

actual disintegration rate = (5000 cpm)/(0.05 cpm/dpm)
= 100,000 dpm = 1667 dps
= 1667 Bq = 45 nCi

Because of the randomness of radioactive decay, the meter reading at low count rates often fluctuates widely. For this reason, the audio speaker is sometimes a better indicator of small amounts of radioactivity than the meter reading. At higher count rates, the speaker response is often faster than the meter reading. It is better, therefore, to have the speaker on when using a G-M counter.

Very high radiation fields may temporarily overload the detector circuit resulting in a partial or complete loss of meter or audio response. If this happens, remove the meter and yourself from the area and push the reset button or turn the meter off then back on. The meter should resume normal operation. Always turn on a survey meter before entering an area that might have high radiation fields.

B. *Scintillation Detector*

Scintillation detectors which incorporate a sodium iodide crystal are used for the detection of low energy gamma emitters such as I-125. Some survey meters allow the use of either a G-M detector or a scintillation detector. The efficiency of a low energy scintillation probe for the detection of I-125 is about 5% at one inch --- over a hundred times better than a G-M probe.

C. *Ion Chamber*

Ionization chambers are suitable for measuring radiation exposure rate or cumulative radiation exposure at high radiation intensities. They are not especially useful at low radiation intensities or for detecting small quantities of radioactive material.

Chapter IX – Review Questions

1. What is the most common type of radiation detector used on campus?

2. What type of detector is best to monitor for low energy Beta emitters?

3. What type of detector is best suited for measuring radiation exposure at high radiation intensities?

CHECK YOUR ANSWERS

DISCUSS radioactive waste handling and disposal practices.

X.   RADIOACTIVE WASTE DISPOSAL

A. *Mixed Hazardous/Radioactive Waste*

Radioactive waste containing any hazardous chemicals requires special handling. Risk Management & Safety **must be consulted** before any such waste is generated. RMSO recommends that a biodegradable scintillation cocktail such as *Fisher Scientific Scintiverse BD Cocktail* be used when for liquid scintillation counting. This cocktail has been tested and it contains no hazardous chemicals which greatly reduces the cost of disposal.

B. *Waste Minimization*

Since all radioactive waste must be stored on campus until it decays or until it can be shipped to an authorized LLRW disposal facility, it is important that the amount of waste generated be kept to a minimum. Some ways to minimize radioactive waste are listed below.

- Design experiments to use as little radioactive material as possible.
- Use proper handling techniques. (See Chapter VIII.D.) This will reduce the chance of contamination.
- When practical, use techniques which do not involve radioactive materials. There are many new techniques and products available which can be used in place of radioactive materials.
- Monitor for contamination and dispose of as little as possible. If there is a spot of contamination on a piece of absorbent paper, cut out that spot and dispose of it rather than the whole piece. Don't automatically place your gloves in the radioactive waste. Monitor them. If there is no detectable contamination, throw them in the regular trash.
- Liquid radioactive waste includes the radioactive material and the first rinse of its experimental container. After the first rinse, the container can be washed in the sink.

C. *Segregation by Half-Life*

All radioactive waste must be segregated according to radionuclide half-life. The three categories for segregation are:
- Half-life less than 15 days (P-32)
- Half-life between 15 and 90 days (S-35, Cr-51, I-125)
- Half-life greater than 90 days (H-3, C-14, Ca-45)

Waste containers should be marked with the category of waste they are intended for. It is very important that waste is placed in the proper container. If waste contains two different radionuclides, place it in the container appropriate for the longer half-life.

D. *Lead Pigs/Shielding*

Lead shipping containers and other lead shielding should not be disposed of as ordinary trash or placed in solid radioactive waste containers. Lead which is boxed and identified will be picked up by Risk Management & Safety when requested.

E. *Liquids*

Liquids are collected in plastic containers with screw caps of 4 liter or smaller volume. The liquid waste containers must be stored in a Secondary Containment capable of holding the waste containers contents in the event of catastrophic failure of the container. Liquids must also be segregated as aqueous or organic.

F. *Dry Solids*

Store in plastic bags (provided by RMSO) inside of a large receptacle (i.e. plastic or metal trash can with a lid). Use a cardboard box or other means lined with plastic to contain glass or sharp material.

G. *Gels*

If a gel is very solid at room temperature, it may be disposed of as solid waste.
If it is soft or semi-solid at room temperature, use a solubilizer to liquefy it and dispose of it as liquid waste.

Chapter X – Review Questions

1. What type of scintillation cocktail is recommended to be used and why?

2. What are the criteria for separating radioactive waste by half-life?

3. List two techniques that can be used to minimize the amount of radioactive waste generated.

4. What two criteria are used to segregate liquid waste.

CHECK YOUR ANSWERS

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- Radiological Contamination Control Training for Laboratory Research, DOE-HDBK-1106-97
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Chapter III - Sources of Radiation Answers

1. Natural and Man-made

2. Cosmic, Terrestrial, and Food

3. Terrestrial

4. Diagnostic and therapeutic

5. Radiation exposure from sources associated with your employment.

Chapter IV - Radiation Fundamentals Answers

1. Protons and neutrons

2. Alpha, Beta (+/-), Gamma, Electron Capture, Fission, Neutrons, X-Ray

3. The time interval required for one half of a collection of atoms of a radionuclide to decay.

4. Beta decay. During Beta decay, two particles are emitted, the Beta and a neutrino, the energy is divided between these two particles. Consequently a beta particle may be emitted with a varying energy up to a maximum energy for that decay.

5. A neutrino is a particle with no charge and infinitesimally small mass.

Chapter V - Interaction of Radiation with Matter Answers

1. Excitation is the addition of sufficient energy to an orbital electron to transfer the atom from the ground state to an excited state. Ionization is the removal of an orbital electron from an atom thereby creating a positively charged ion.

2. Interactions between the electric field of the alpha and the orbital electrons in the absorber.

3. As a beta particle passes close to a nucleus, it decreases in velocity due to interaction with the positive charge of the nucleus, emitting x-rays (bremsstrahlung). The production of bremsstrahlung increases with the atomic number of the absorber and the energy of the beta.

4. In their origin.

5. Compton scattering provides a means for partial absorption of photon energy by interaction with a "free" (loosely bound) electron. The electron is ejected, and the photon continues on to lose more energy in other interactions.

Chapter VI- Activity, Exposure, and Dose Definitions

1. Activity is the rate of decay (disintegrations/time) of a given amount of radioactive material. Becquerel = 1 dps and Curie = 3.7 x 10^{10} dps

2. That quantity of gamma or x-radiation causing ionization in air equal to 2.58 x 10-4 coulombs per kilogram.

3. Quality factor (Q) is used to compare the biological damage producing potential of various types of radiation, given equal absorbed doses. Beta Q = 1

4. $A = A_0 \ e^{-\lambda t / T}$
   $A = 2 \ e^{-.693(75)/59.4}$
   $A = 2 * 0.41686 = 0.83 mCi$

5. 300 x 0.25 = 75 rad/hr @ 1 ft

6. 2.5 R/hr * (12/54)2 = 0.123 R/hr = 123 mR/hr

Return to Chapter 6 Questions

Chapter VII – Biological Effects of Ionizing Radiation

1. Alphas have a high linear energy transfer and tend to concentrate in specific tissues or organs.

2. Higher energy gammas are more penetrating.

3. Production of free radicals: breakage of chemical bonds: Production of new chemical bonds and cross linkage between macromolecules; damage to molecules which regulate vital cell processes.

4. The cell nucleus.

5. Cells with a high division rate; high metabolic rate; are non-specialized; are well nourished.

6. 300 Rem

Chapter VIII – Radioactive Material Handling and Laboratory Safety Answers

1. Reduce quantity, minimize time, maximize distance, use shielding.

2. Ingestion, inhalation, absorption, and injection

3. Fixed, removable/transferable, and airborne

4. P-32, C-14, H-3

Chapter IX – Radiation Survey Meters

1. Geiger-Mueller detectors

2. Scintillation detector

3. Ionization chambers

Return to Chapter 9 Questions

Chapter X – Radioactive Waste Disposal

1. Biodegradable scintillation cocktail (e.g. Fisher Scientific Scintiverse BD Cocktail)

2. Short Lived < 15 days; Intermediate 15 to 90 days; long lived > 90 days

3. Any two of the following:
   Design experiments to use as little radioactive material as possible.
   Use proper handling techniques.
   When practical, use techniques which do not involve radioactive materials.
   Monitor for contamination and dispose of as little as possible.
   Liquid radioactive waste includes the radioactive material and the first rinse of its experimental container. After the first rinse, the container can be washed in the sink.

4. Half-life separation and whether aqueous or organic

Figure 1 - Typical Beta Energy Curve
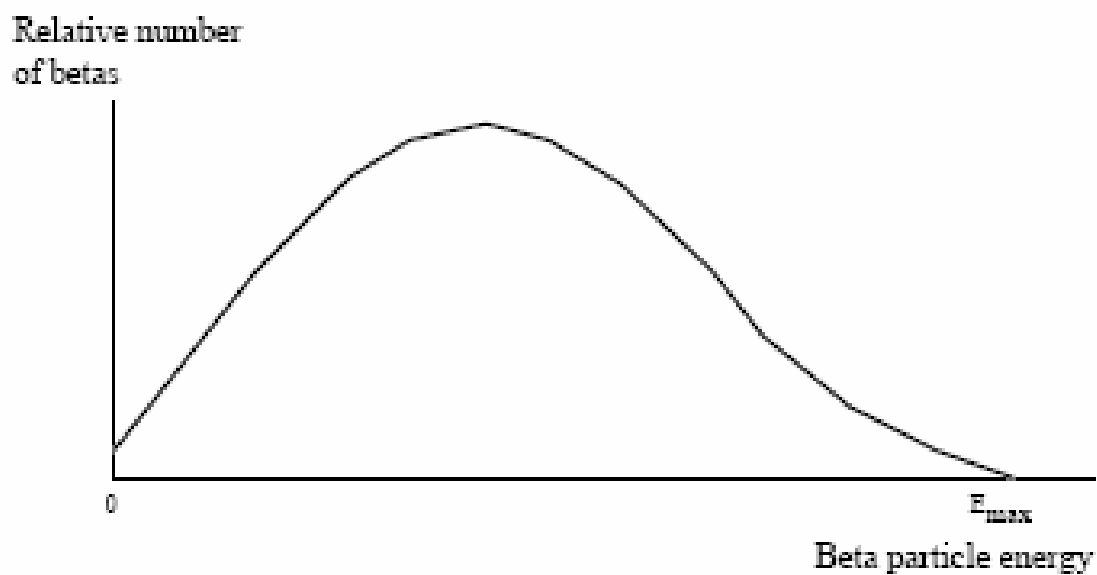
Return

Figure 2 - Ionization
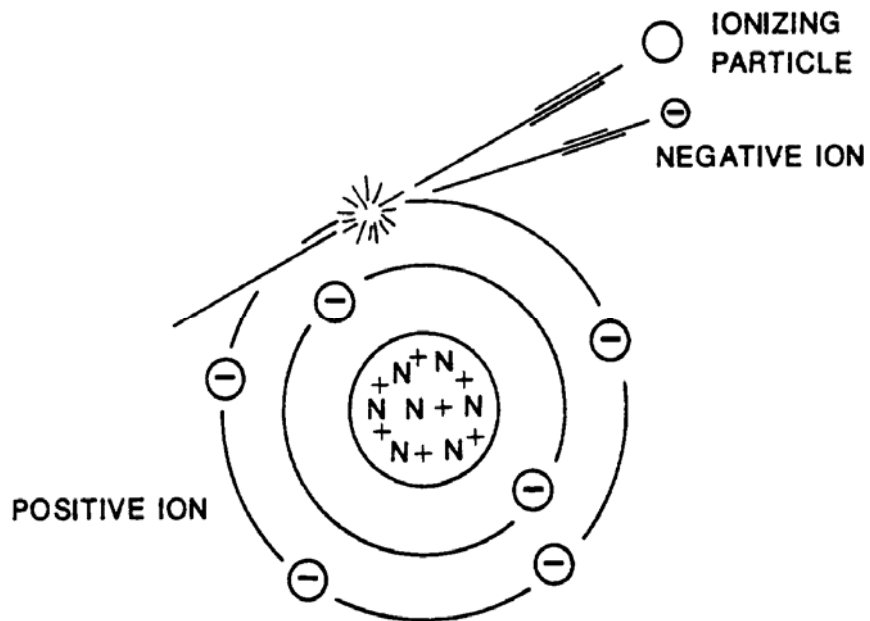
Figure 3 - Excitation

Figure 4 - Maximum Range of Beta in Various Materials vs. Energy

Figure 5 - Photoelectric Effect

Figure 6 – Compton Scattering
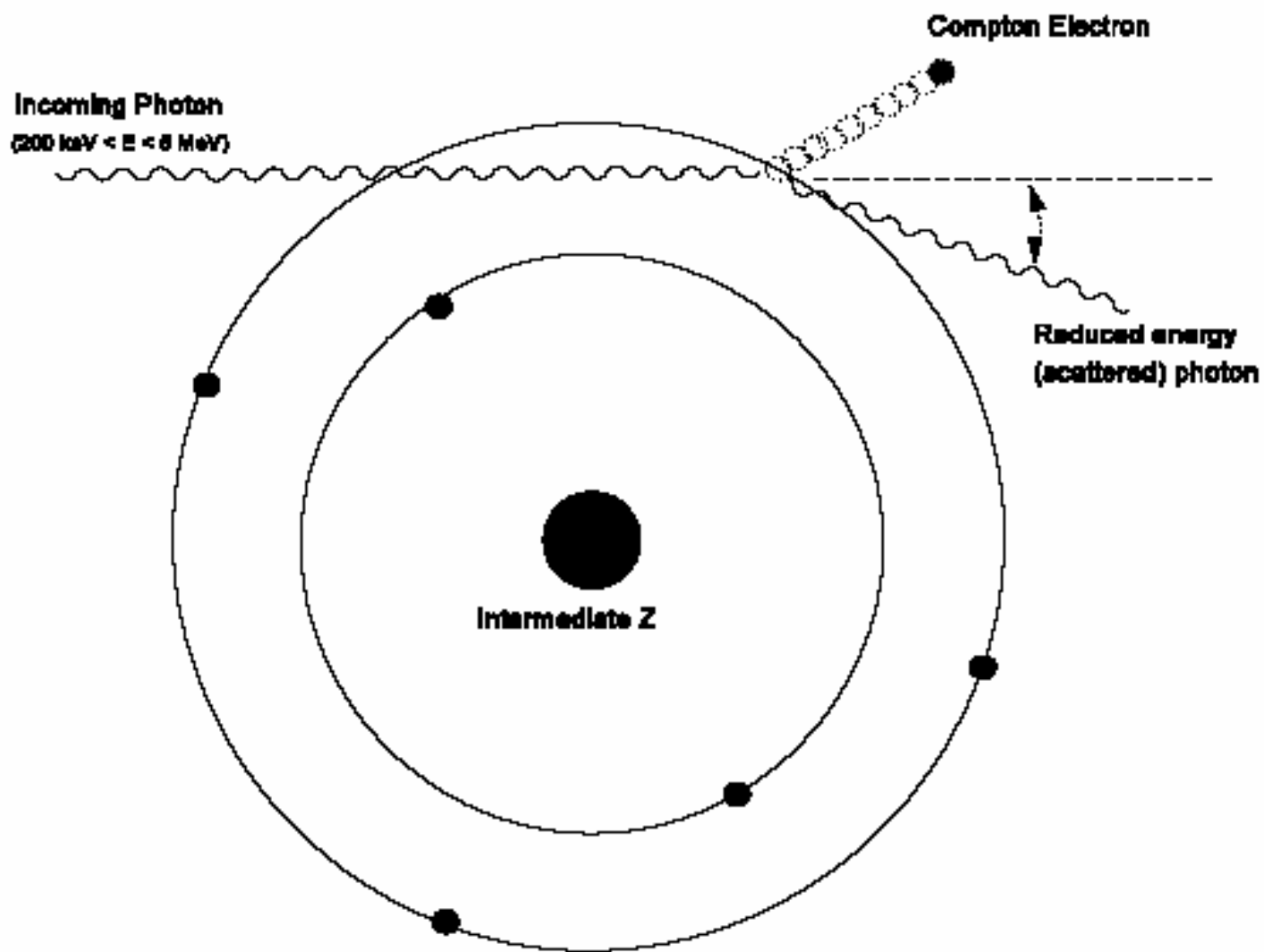
Return

Figure 7 - Pair Production

High Z

Gamma photon
(E > 1.022 MeV)

Electron

0.511 MeV photon

Positron
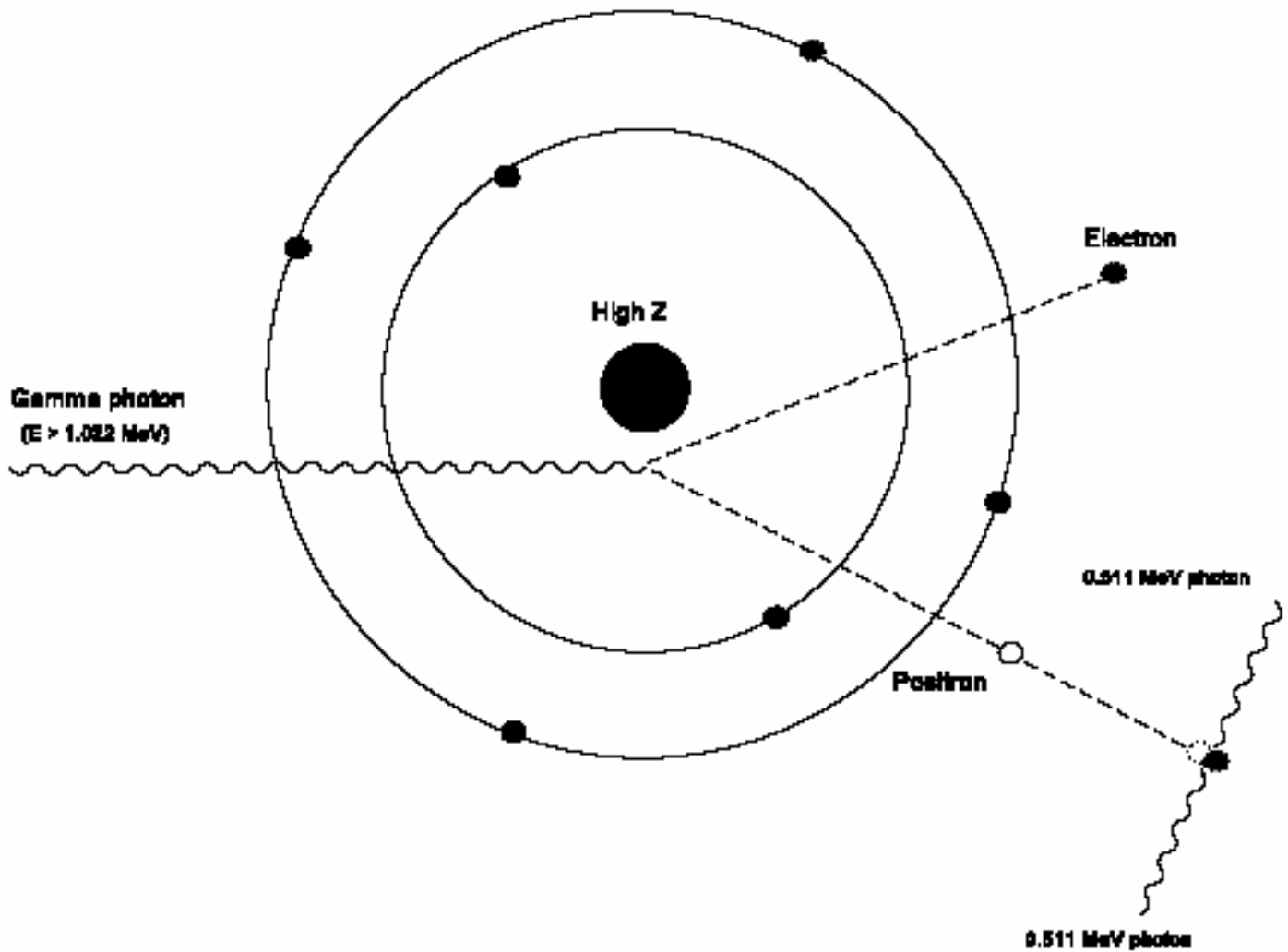
0.511 MeV photon

Table 1 - Gamma Exposure Constants (Γ)

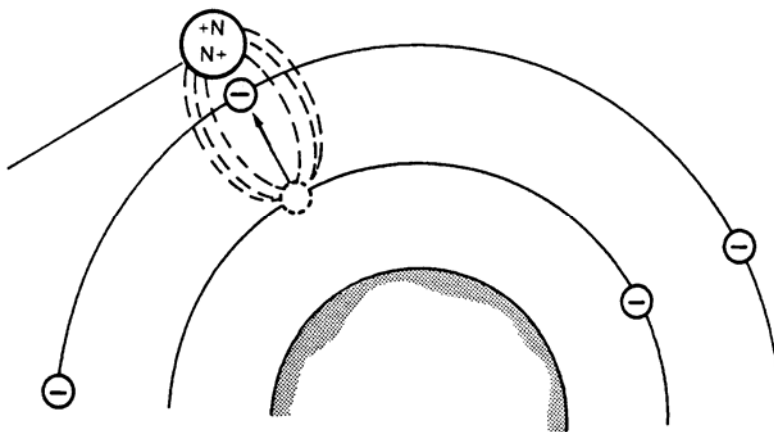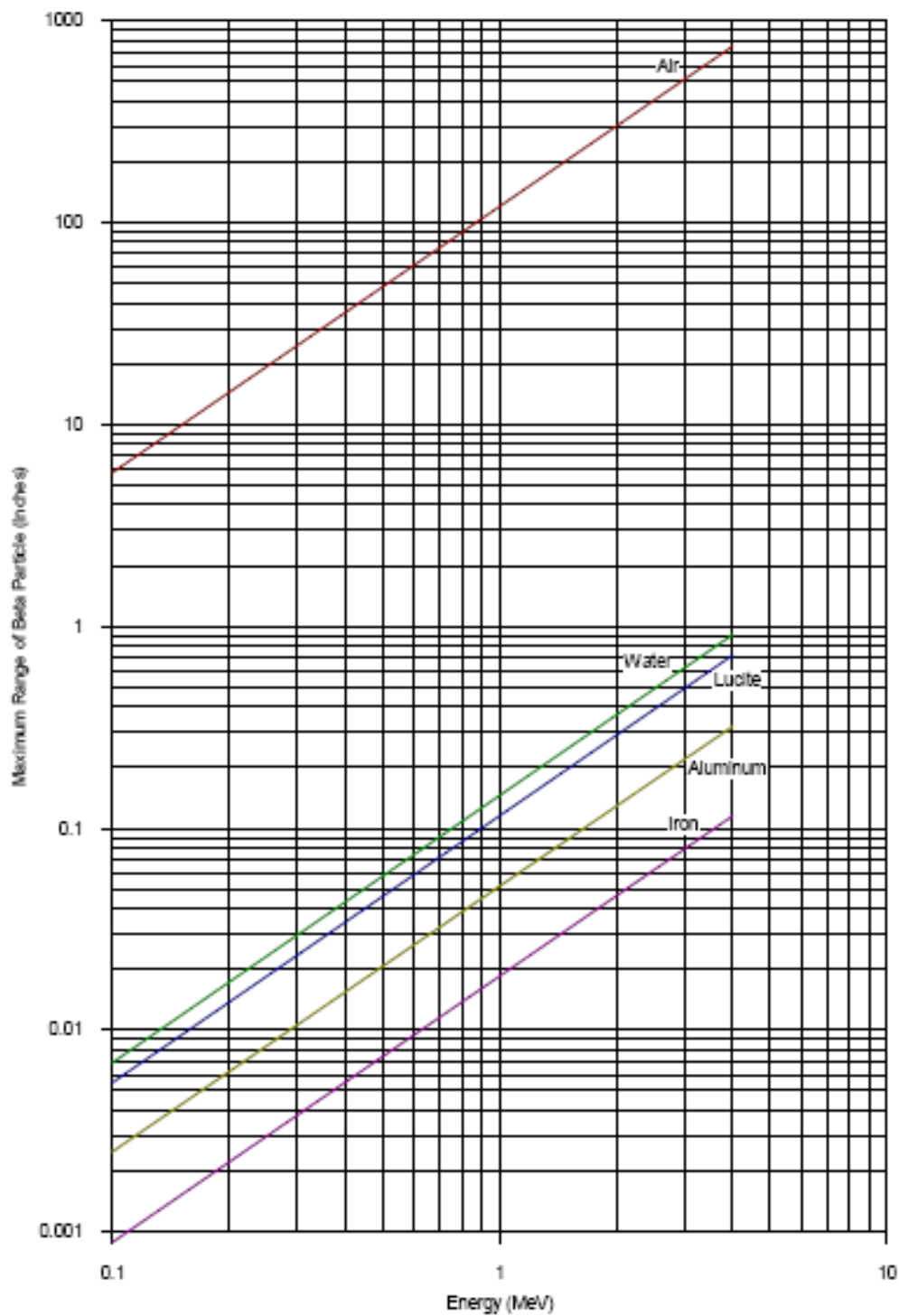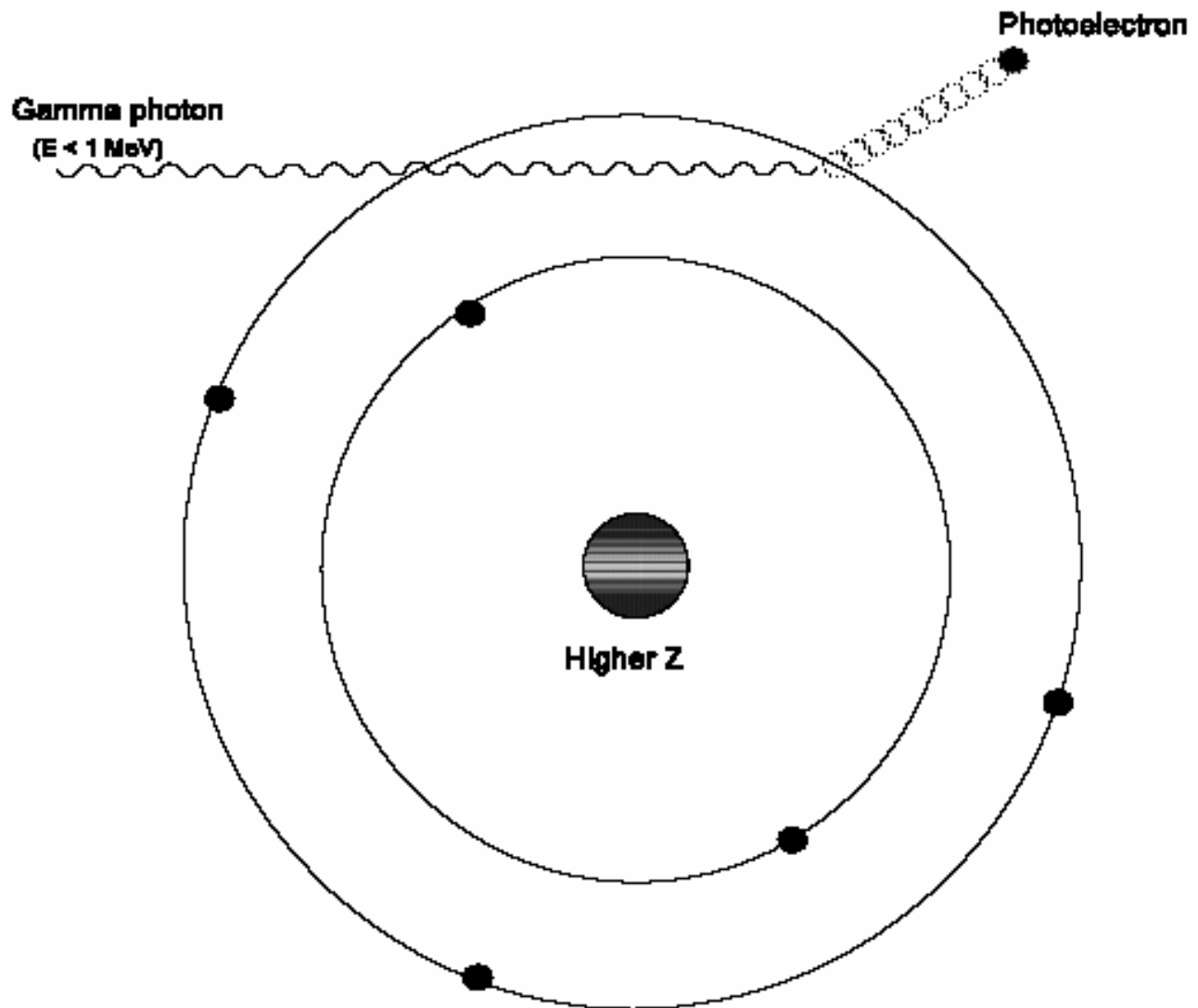| Nuclide	Γ	Nuclide	Γ	Nuclide	Γ
Actinium-227	2.2	Gold-198	2.3	Potassium-43	5.6
Antimony-122	2.4	Gold-199	0.9	Radium-226	8.25
Antimony-124	9.8	Hafnium-175	2.1	Radium-228	5.1
Antimony-125	2.7	Hafnium-181	3.1	Rhenium-186	0.2
Arsenic-72	10.1	Indium-114m	0.2	Rubidium-86	0.5
Arsenic-74	4.4	Iodine-124	7.2	Ruthenium-106	1.7
Arsenic-76	2.4	Iodine-125	1.5	Scandium-46	10.9
Barium-131	3.0	Iodine-126	2.5	Scandium-47	0.56
Barium-133	2.4	Iodine-130	12.2	Selenium-75	2.0
Barium-140	12.4	Iodine-131	2.2	Silver-110m	14.3
Beryllium-7	0.3	Iodine-132	11.8	Silver-111	0.2
Bromine-82	14.6	Iodine-124	4.8	Sodium-22	12.0
Cadmium-115m	0.2	Iodine-194	1.5	Sodium-24	18.4
Calcium-47	5.7	Iron-59	6.4	Strontium-85	3.0
Carbon-11	5.9	Krypton-85	0.04	Tantalum-182	6.8
Cerium-141	0.35	Lanthanum-140	11.3	Tellurium-121	3.3
Cerium-144	0.4	Lutecium-177	0.09	Tellurium-132	2.2
Cesium-134	8.7	Magnesium-28	15.7	Thulium-170	0.025
Cesium-137	3.3	Manganese-52	18.6	Tin-113	1.7
Chlorine-38	8.8	Manganese-54	4.7	Tungsten-185	0.5
Chromium-51	0.16	Manganese-56	8.3	Tungsten-187	3.0
Cobalt-56	17.6	Mercury-197	0.4	Uranium-234	0.1
Cobalt-57	0.9	Mercury-203	1.3	Vanadium-48	15.6
Cobalt-58	5.5	Molybdenum-99	1.8	Xenon-133	0.1
Cobalt-60	13.2	Neodymiun-147	0.8	Ytterbium-88	0.4
Cobalt-64	1.2	Nickel-65	3.1	Yttrium-88	14.1
Europium-152	5.8	Niobium-95	4.2	Yttrium-91	0.01
Europium-154	6.2	Osmium-191	0.6	Zinc-65	2.7
Europium-155	0.3	Palladium-109	0.03	Zirconium-95	4.1
Gallium-67	1.1	Platinum-197	0.5		
Gallium-72	11.6	Potassium-42	1.4		

Γ = exposure rate in R/hr @ 1 cm from a 1 mCi point source

Γ/10= exposure rate in mR/hr @ 1 meter from a 1 mCi point source

Table 2 - Beta Decay Characteristics Summary

Physical Characteristics	Small mass -1 charge or +1 charge
Range	Short distance (one inch to 20 feet)
Shielding	Plastic Glass Safety glasses
Biological Hazard	Internal hazard (due to short range) Externally, may be hazardous to skin and eyes
Campus Locations	Various research laboratories use C-14, P-32 and/or H-3

Table 3 - Gamma/X-ray Characteristics Summary

Physical Characteristics	No mass No Charge Electromagnetic wave or photon Similar (difference is origin and energy level)
Range	Range in air is very far It will easily go several hundred feet Very high penetrating power
Shielding	Lead Concrete Water
Biological Hazard	Whole body exposure The hazard may be external and/or internal This depends on whether the source is inside or outside of the body.
Campus Locations	Various labs use sealed sources.

Table 4 - Alpha Decay Characteristics Summary

Physical Characteristics	Large mass (Helium nucleus) - +2 charge
Range	Extremely short distance (several centimeters)
Shielding	Paper Outer layer of skin
Biological Hazard	Internal hazard (due to extremely short range) Externally, may be hazardous to skin and eyes
Campus Locations	None

Table 5 - Lead HVL & TVL for Select Radionuclides

Nuclide	γ Energy (MeV)	HVL (mm)	TVL (mm)
I-125	0.035	0.05	0.16
Am-241	0.060	0.14	0.45
Co-57	0.122	2.0	6.7
Cs-137	0.662	6.5	21
Na-22	1.28	9.6	32
Co-60	1.17 & 1.33	12	40

Table 6 - Common Metric System Prefixes

Factor	Prefix	Symbol		Factor	Prefix	Symbol
10^{18}	exa	E		10^{-1}	deci	d
10^{15}	peta	P		10^{-2}	centi	c
10^{12}	tera	T		10^{-3}	milli	m
10^{9}	giga	G		10^{-6}	micro	μ
10^{6}	mega	M		10^{-9}	nano	n
10^{3}	kilo	k		10^{-12}	pico	p
10^{2}	hecto	h		10^{-15}	femto	f
10^{1}	deka	da		10^{-18}	atto	a

ALPHA PARTICLES

➢ An alpha energy of at least 7.5 MeV is required to penetrate the protective layer of the skin (0.07mm).

BETA PARTICLES

➢ A beta energy of at least 70 keV is required to penetrate the protective layer of the skin (0.07mm).

➢ The average energy of a beta-spectrum is approximately one-third the maximum energy.

➢ The range of beta particles in air is about 12 ft per MeV. (e.g. The maximum range of P-32 betas is 1.71 MeV x 12 ft/MeV $\approx$ 20 ft).

➢ The skin dose rate from a uniform thin deposition of 1 μCi/cm2 is about 9 Rem/hr for energies above 0.6 MeV.

➢ For a beta emitter point source, the dose rate in rem/hr at one foot is approximately 300 x Ci where Ci is the source strength in curies. This calculation neglects any shielding provided by the air, which can be significant. For example, the maximum range in air for a beta from S-35 is less than one foot, so the dose rate at one foot is zero for any size S-35 source.

GAMMAS AND X-RAYS

➢ For a point source gamma emitter with energies between 0.07 and 2 MeV, the exposure rate in R/hr at 1 foot is approximately 6CEn, where C is the activity in curies; E is the energy in MeV; and n is the number of gammas per disintegration.

➢ Gammas and x-rays up to 2 MeV will be attenuated by at least a factor of 10 by 2 inches of lead.

Exposure and Exposure Rate

The roentgen (R) is the traditional unit of measurement for exposure, the charge produced in air by γ or x-rays. The Traditional unit of exposure is coulombs per kilogram (C/kg) of air.

$$1 \text{ C/kg} = 3876 \text{ R}$$
$$1 \text{ R} = 2.58 \times 10^{-4} \text{ C/kg}$$

No special name has been given to this SI unit (C/kg) and since there is no convenient conversion to other SI units, it is seldom used. In traditional units, exposure rate from a sealed source has typically been expressed in roentgens/hour at a distance of 1 meter from the source.

Absorbed Dose

This is the amount of energy imparted to matter, and the rad has been the traditional unit of measurement. The SI unit for absorbed dose is the gray (Gy).

$$1 \text{ Gray (Gy)} = 100 \text{ rad}$$
$$1 \text{ rad} = 0.01 \text{ Gy}$$

One roentgen of X-radiation in the energy range of 0.1-3 MeV produces 0.96 rad in tissue.

Dose Equivalent

The dose equivalent is the absorbed dose multiplied by modifying factors such as a quality factor (accounts for the biological effect of different types of radiation) and the dose distribution factor. The rem is the traditional unit of measurement that has been used, and the SI unit is the sievert (Sv).

$$1 \text{ Sv} = 100 \text{ rem}$$
$$1 \text{ rem} = 0.01 \text{ Sv}$$

CONVERSION TABLE FOR RADIOACTIVITY

Curie Units	Becquerel Units
µCi	kBq
mCi	MBq
Ci	GBq
0.1	3.7
0.25	9.25
0.5	18.5
0.75	27.75
1	37
2	74
3	111
5	185
7	259
10	370
20	740
25	925
µCi	MBq
mCi	GBq
Ci	TBq
50	1.85
60	2.22
100	3.7
200	7.4
250	9.25
500	18.5
800	29.6
1000	37

To convert from one unit to another, read across from one column to the other ensuring the units are in the same line of the column headings. For example:

From the first table:	From the second table:
0.1 mCi = 3.7 MBq	50 mCi = 1.85 GBq
0.1 Ci = 3.7 GBq	3.7 MBq = 100 µCi

SI Units

1 becquerel (Bq) = 1 disintegration/second

1 becquerel = 2.7027 x 10^{-11} curie or ≈ 27 picocuries (pCi)

To convert becquerels to curies, divide the becquerel figure by 37 x 10^9 (alternatively multiply the becquerel figure by 2.7027 x 10^{-11})

1 curie (Ci) = 3.7 x 10^{10} disintegrations/second or 37 gigabecquerels (GBq)

To convert curies to becquerels, multiply the curie figure by 37 x 10^9

Curie units that are frequently used:
1 Curie (Ci) = 1000 mCi
1 millicurie (mCi) = 1000 μCi
1 microcurie (μCi) = 1000 nCi
1 nanocurie (nCi) = 1000 pCi (picocuries)

Becquerel units that are frequently used:
1 kilobecquerel (kBq) = 1000 Becquerels (Bq)
1 megabecquerel (MBq) = 1000 kBq
1 gigabecquerel (GBq) = 1000 MBq
1 terabecquerel (TBq) = 1000 GBq

1 Ci = 37 GBq
1 mCi = 37 MBq
1 　Ci = 37 kBq
1 nCi = 37 Bq

S-35 INFORMATION
Radioactive half-life: 87.4 days
Decay mechanism: Beta emission
Energy: Emax = 0.167 MeV
Contamination monitoring: Thin window Geiger-Mueller detector, liquid scintillation counter
for wipe surveys
Dosimetry: Urinalysis

S-35 Decay Table

days	0	1	2	3	4	5	6
0	1000	992	984	976	969	961	954
7	946	939	931	924	916	909	902
14	895	888	881	874	867	860	853
21	847	840	833	827	820	814	807
28	801	795	788	782	776	770	764
35	758	752	746	740	734	728	722
42	717	711	705	700	694	689	683
49	678	673	667	662	657	652	646
56	641	636	631	626	621	616	612

1. Radiolysis of S-35 labelled amino acids may lead to the release of S-35 labelled volatile impurities. Delivery vials should therefore be opened in a fume hood.
2. The addition of stabilizers (buffers) will reduce, but not eliminate, the evolution of S-35 volatiles from tissue culture media. Incubators should be checked for contamination after using S-35 methionine or other volatile compounds.
3. S-35 may be difficult to distinguish from C-14. If both nuclides are being used in the same laboratory, establish controls to ensure they are kept separate. If "unknown" contamination is found, treat it as C-14.

I-125 INFORMATION

Radioactive half-life: 59.6 days
Decay mechanism: Electron capture (gamma and x-ray emission)
Energy: 27-35 keV
Contamination monitoring: Thin crystal NaI detector, liquid scintillation counter for wipe surveys
Shielding: Thin lead
Dosimetry: Film badge, TLD ring, thyroid scan

I-125 Decay Table

days	0	1	2	3	4	5	6
0	1000	988	977	966	955	944	933
7	922	911	901	890	880	870	860
14	850	840	830	821	811	802	792
21	783	774	765	756	748	739	731
28	722	714	705	697	689	681	673
35	666	658	650	643	635	628	621
42	614	606	599	593	586	579	572
49	566	559	553	546	540	534	527
56	521	515	509	504	498	492	486

1. The dose rate at 1 cm from a 1 mCi point source is about 1.5 rem/hr The dose rate is inversely related to the square of the distance from the source. Thus while a small amount of I-125 held for a short time can result in a significant dose to the hands, a relatively short separation distance reduces the dose rate to an acceptable level.
2. The volatility of iodine requires special handling techniques to minimize radiation doses. Solutions containing iodide ions (such as NaI) should not be made acidic or be frozen. Both lead to formation of volatile elemental iodine. Once bound to a protein, the volatility of the radioiodine is tremendously reduced.
3. Always work in a fume hood with a minimum face velocity of at least 125 linear feet per minute when working with NaI. The sash should be below the breathing zone.
4. Use shoulder length veterinary gloves with short vinyl gloves on top to minimize skin absorption.
5. Avoid opening the septum on delivery vials. It is preferable to remove radioiodine using a hypodermic needle and syringe.
6. A radiation survey instrument should be available in the immediate area. A low energy scintillation detector is preferable to a G-M detector. You should do a wipe survey in your work areas after each use.
7. Film badges must be worn for all radioiodine work, and finger rings are required when handling 1 mCi or more of I-125.
8. Use lead to shield quantities of 1 mCi or more. 1 mm of lead will essentially block all of the radiation emitted from I-125.
9. A thyroid assay should be performed after using 1mCi or more of NaI, or in cases of suspected accidental contamination.
10. Until waste is picked up, it should be kept in the waste containers and stored in a fume hood.

ABSORBED DOSE: The energy imparted by ionizing radiation per unit mass of irradiated material.

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

ACTIVITY: The rate of decay (disintegrations/time) of a given amount of radioactive material.

ALARA: An acronym for As Low As Reasonably Achievable. The principal that radiation doses should be kept as low as reasonably achievable taking into account economic and social factors.

ALPHA PARTICLE (α): A strongly ionizing particle emitted from the nucleus during radioactive decay which is equivalent to a helium nucleus (2 protons and 2 neutrons).

ANNIHILATION RADIATION: The two 511 keV photons produced when a positron combines with an electron resulting in the annihilation of the two particles.

ATOMIC MASS UNIT (amu): One-twelfth the mass of a neutral atom of C-12. (1 amu ⹀ 1.66 x 10-24 g)

ATOMIC NUMBER (Z): The number of protons in the nucleus of an atom.

ATTENUATION: Process by which a beam of radiation is reduced in intensity when passing through material, a combination of absorption and scattering processes.

BACKGROUND RADIATION: Ionizing radiation arising from sources other than the one directly under consideration. Background radiation due to cosmic rays and the natural radioactivity of materials in the earth and building materials is always present.

BECQUEREL (Bq): The SI unit of activity equal to one disintegration per second. (1 Bq = 2.7 x 10-11 Ci).

BETA PARTICLE (β): A charged particle emitted from the nucleus of an atom, having a mass equal to that of the electron, and a single positive or negative charge.

BIOLOGICAL HALF-LIFE: The time required for the body to eliminate by biological processes one-half of the amount of a substance which has entered it.

BREMSSTRAHLUNG: X-rays produced by the deceleration of charged particles passing through matter.

CARRIER FREE: An adjective applied to one or more radionulcides of an element in minute quantity, essentially undiluted with stable isotope carrier.

COMPTON SCATTERING: The elastic scattering of a photon by an essentially free electron.

CONTAMINATION: The deposition of radioactive material in any place where it is not desired, particularly in any place where its presence may be harmful.

COUNT: The external indication of a device designed to enumerate ionizing events.

CURIE (Ci): The unit of activity equal to 3.7 x 1010 disintegrations per second.

DOSE: A general term denoting the quantity of radiation or energy absorbed in a specified mass.

DOSE EQUIVALENT: The product of the absorbed dose in tissue, quality factor, and all other necessary modifying factors at the location of interest.

EFFECTIVE HALF-LIFE: Time required for a radioactive nuclide in the body to be diminished fifty percent as a result of the combined action of radioactive decay and biological elimination.

$$\text{Effective half-life} = \frac{\text{Biological half-life x Radioactive half-life}}{\text{Biological half-life + Radioactive half-life}}$$

EFFICIENCY: The ratio of the count rate given by a radiation detection instrument and the actual disintegration rate of the material being counted.

ELECTRON CAPTURE: A mode of radioactive decay involving the capture of an orbital electron by its nucleus resulting in conversion of a proton to a neutron.

ELECTRON VOLT (eV): A unit of energy equal to the amount of energy gained by an electron passing through a potential difference of 1 volt.

ERG: A unit of energy. 1 erg = 6.24×10^{11} eV.

ERYTHEMA: An abnormal reddening of the skin due to distention of the capillaries with blood.

EXPOSURE: A measure of the ionizations produced in air by x-ray or gamma radiation. Sometimes used to mean dose.

FILM BADGE: A packet of photographic film in a holder used for the approximate measurement of radiation dose.

GAMMA (γ): Electromagnetic radiation (photon) of nuclear origin.

GEIGER-MUELLER (G-M) COUNTER: A radiation detection and measurement instrument.

GRAY (Gy): The SI unit of absorbed dose equal to 1 Joule/kilogram.

HALF VALUE LAYER: The thickness of any specified material necessary to reduce the intensity of an x-ray or gamma ray beam to one-half its original value.

ION: Atomic particle, atom, or chemical radical bearing an electrical charge, either negative or positive.

IONIZATION: The process by which a neutral atom or molecule acquires either a positive or a negative charge.

IONIZATION CHAMBER: A radiation detection and measurement instrument.

IONIZING RADIATION: Any electromagnetic or particulate radiation capable of producing ions, directly or indirectly, by interaction with matter.

ISOTOPES: Nuclides having the same number of protons in the nuclei, and hence having the same atomic number, but differing in the number of neutrons, and therefore in mass number. Almost identical chemical properties exist among isotopes of a particular
element.

LABELED COMPOUND: A compound consisting, in part, of radioactive nuclides for the purpose of following the compound or its fragments through physical, chemical, or biological processes.

LINEAR ENERGY TRANSFER (LET): Average amount of energy lost per unit track length by the individual particles or photons in radiation passing through an absorbing medium.

MASS NUMBER (A): The number of protons and neutrons in the nucleus of an atom.

NUCLIDE: An of atom characterized by its mass number, atomic number, and energy state of its nucleus.

POSITRON: A particle having a mass equal to that of an electron and a charge equal to that of an electron, but positive.

QUALITY FACTOR (Q): The LET-dependant modifying factor that is used to derive dose equivalent from absorbed dose.

RAD: The unit of absorbed dose equal to 100 erg/gram (or 0.01 Joule/kilogram).

RADIATION: Energy propagated through space or a material medium.

RADIOACTIVE DECAY: Disintegration of the nucleus of an unstable nuclide by the spontaneous emission of charged particles, neutrons, and/or photons.

RADIOACTIVE HALF-LIFE: The time required for a radioactive substance to lose fifty percent of its activity by decay.

RADIOACTIVITY: The property of certain nuclides of spontaneously disintegrating and emitting radiation.

RADIONUCLIDE: An unstable (radioactive) nuclide.

RADIOTOXICITY: The potential of a radioactive material to cause damage to living tissue by radiation after introduction into the body.

REM: The unit of dose equivalent equal to the absorbed dose in rad multiplied by any necessary modifying factors.

ROENTGEN (R): The unit of radiation exposure in air equal to 2.58 x 10-4 coulombs/kilogram.

SCINTILLATION COUNTER: A radiation detection and measurement instrument in which light flashes produced in a scintillator by ionizing radiation are converted into electrical pulses by a photomultiplier tube.

SHALLOW-DOSE EQUIVALENT: The dose equivalent at a tissue depth of 0.007 cm from external exposure of the skin or an extremity.

SIEVERT (Sv): The SI unit of dose equivalent equal to 1 Joule/kilogram.

SPECIFIC ACTIVITY: Total activity of a given radionuclide per unit mass or volume.

SYSTEME INTERNATIONAL (SI): A system of units adopted by the 11th General Conference on Weights and Measurements in 1960 and used in most countries of the world.

THERMOLUMINESCENT DOSIMETER (TLD): A dosimeter made of a crystalline material which is capable of both storing energy from absorption of ionizing radiation and releasing this energy in the form of visible light when heated. The amount of light released can be used as a measure of absorbed dose.

WEIGHTING FACTOR: The proportion of the risk of stochastic effects for an organ or tissue when the whole body is irradiated uniformly.

X-RAY: Electromagnetic radiation (photon) of non-nuclear origin having a wavelength shorter than that of visible light.