**FUNDAMENTALS OF INDUSTRIAL HYGIENE, 6TH ED.**

**HOMEWORK #6**

**INDIVIDUAL MEASUREMENT OF RADIOACTIVITY**

**Objective:** Students will become familiar with the fundamentals of nuclear radioactivity and the measurement of radioactivity, including half-lives, nuclear activity (radioactivity), and radiation biology.

**Background:** There is an ongoing quest to find substructures of matter. At one time, it was thought that atoms would be the ultimate substructure, but just when the first direct evidence of atoms was obtained, it became clear that they have a substructure and a tiny nucleus. The nucleus itself has spectacular characteristics. For example, certain nuclei are unstable, and their decay emits radiations with energies millions of times greater than atomic energies. Some of the mysteries of nature, such as why the core of the earth remains molten and how the sun produces its energy, are explained by nuclear phenomena. The exploration of radioactivity and the nucleus revealed fundamental and previously unknown particles, forces, and conservation laws.

In 1896, physicist Antoine Becquerel accidentally found that a uranium-rich mineral called pitchblende emits invisible, penetrating rays that can darken a photographic plate enclosed in an opaque envelope. The rays therefore carry energy; but amazingly, the pitchblende emits them continuously without any energy input. This is an apparent violation of the law of conservation of energy, one that we now understand is due to the conversion of a small amount of mass into energy, as related in Einstein’s famous equation *E* = *mc*2. It was soon evident that Becquerel’s rays originate in the nuclei of the atoms and have other unique characteristics. The emission of these rays is called *nuclear radioactivity* or simply *radioactivity*. The rays themselves are called *nuclear radiation*. A nucleus that spontaneously destroys part of its mass to emit radiation is said to *decay*. A substance or object that emits nuclear radiation is said to be *radioactive*.

Radiation does not vary with chemical state—that is, uranium is radioactive whether it is in the form of an element or compound. In addition, radiation does not vary with temperature, pressure, or ionization state of the uranium atom. Nuclear radiation has energies of the order of 106*eV* per event, which is much greater than the typical atomic energies (a few *eV*), such as that observed in chemical reactions.

In 1898, Marie Curie and her husband Pierre Curie discovered two new radioactive elements, which she named polonium (after her native land) and radium (because it radiates). These two new elements filled holes in the periodic table and, further, displayed much higher levels of radioactivity per gram of material than uranium. Over a period of four years, the Curies processed more than a ton of uranium ore to isolate a gram of radium salt. Radium salt became highly sought after, because it was about two million times as radioactive as uranium and glowed visibly from the radiation. Marie’s radioactive fingerprints on some pages of her notebooks can still expose film.

Research begun by Ernest Rutherford soon after the discovery of nuclear radiation indicated that different types of rays are emitted. Eventually, three types were distinguished and named alpha (**α**), beta (**β**), and gamma (**γ**), because, like x-rays, their identities were initially unknown. Rutherford passed the rays through a magnetic field, and in doing so discovered that gamma rays were unaffected, while the alphas and betas were deflected in opposite directions, indicating the alphas are positive, the betas negative, and the gammas uncharged. Rutherford used both magnetic and electric fields to show that alphas have a positive charge twice the magnitude of an electron, or +2, and a charge-to-mass ratio several thousand times smaller than the electron’s. Later on, Rutherford collected alphas from a radioactive source and passed an electric discharge through them, obtaining the spectrum of recently discovered helium gas, proof that alpha radiation is the emission of a helium nucleus.

Other researchers had already proved that betas were negative and have the same mass and same charge-to-mass ratio as the recently discovered electron. By 1902, it was recognized that beta radiation is the emission of an electron. Although betas are electrons, they do not exist in the nucleus before it decays and are not ejected atomic electrons—the electron is created in the nucleus at the instant of decay.

Since gammas remain unaffected by electric and magnetic fields, it was natural to think they might be photons. Evidence for this grew, but it was not until 1914 that this was proved. In fact, gamma radiation comes from the de-excitation of a nucleus, just as an x-ray comes from the de-excitation of an atom. The names "gamma ray" and "x-ray" identify the source of the radiation.

Note: Since alphas consist of matter (two protons) and betas consist of matter (one electron), they are referred to as particles. Gammas and x-rays, consisting of photons (energy) are referred to as rays.

Two of the most important characteristics of **α**, **β**, and **γ** rays were recognized very early. All three types of nuclear radiation *produce ionization in materials, but they penetrate different distances* in materials—that is, they have different ranges.

Like x-rays, nuclear radiation in the form of **α**s, **β**s, and **γ**s has enough energy per event to ionize atoms and molecules in any material. The energy emitted in various nuclear decays ranges from a few *keV* to more than 10 *MeV*, while only a few *eV* are needed to produce ionization. The effects of x-rays and nuclear radiation on biological tissues and other materials, such as solid state electronics, are directly related to the ionization they produce. In addition, methods for detecting x-rays and nuclear radiation are based on ionization, directly or indirectly. Apart from **α**, **β**, and **γ**, there are other forms of nuclear radiation as well, and these also produce ionization with similar effects. Ionizing radiation is defined as any form of radiation that produces ionization whether nuclear in origin or not, since the effects and detection of the radiation are related to ionization.

Radiation can be absorbed or shielded by materials, such as the lead aprons dentists drape on us when taking x-rays. Different types of radiation have different ranges when compared at the same energy and in the same material. Alphas have the shortest range, betas penetrate farther, and gammas have the greatest range. This is directly related to charge and speed of the particle or type of radiation. At a given energy, each **α**, **β**, or **γ** will produce the same number of ionizations in a material (each ionization requires a certain amount of energy on average). The more readily the particle produces ionization, the more quickly it will lose its energy.

The *effect of charge* is as follows: The **α** has a charge of +2 , the **β** has a charge of −1 , and the **γ** is uncharged. The electromagnetic force exerted by the **α** is thus twice as strong as that exerted by the **β** and it is more likely to produce ionization. Although chargeless, the **γ** does interact weakly because it is an electromagnetic wave, but it is less likely to produce ionization in any encounter.

The *speed of travel* is the other major factor affecting the range of **α**s, **β**s, and **γ**s. The faster they move, the less time they spend in the vicinity of an atom or a molecule, and the less likely they are to interact. Since **α** s and **β** s are particles with mass (helium nuclei and electrons, respectively), their energy is kinetic (**α**s travel about 5-10% the speed of light). The mass of the **β** particle is thousands of times less than that of the **α**s, so that **β**s must travel much faster than **α**s to have the same energy. **β**s move faster (at nearly the speed of light), thus, they have less time to interact than **α**s. Since gamma rays are photons, which must travel at the speed of light, they are even less likely to interact than a **β**. The range of **γ**s is thus greater than the range of **β**s.

Alpha radiation from radioactive sources has a range much less than a millimeter of biological tissues, usually not enough to even penetrate the dead layers of our skin. On the other hand, the same **α** radiation can penetrate a few centimeters of air, so mere distance from a source prevents α radiation from reaching us. This makes **α** radiation relatively safe for our body compared to **β** and **γ** radiation. Typical **β** radiation can penetrate a few millimeters of tissue or about a meter of air. Beta radiation is thus hazardous even when not ingested. The range of **β**s in lead is about a millimeter, and so it is easy to store **β** sources in lead radiation-proof containers. Gamma rays have a much greater range than either **α**s or **β**s. In fact, if a given thickness of material, like a lead brick, absorbs 90% of the **γ**s, then a second lead brick will only absorb 90% of what got through the first. Thus, **γ**s do not have a well-defined range; we can only cut down the amount that gets through. Typically, **γ**s can penetrate many meters of air, go right through our bodies, and are effectively shielded (that is, reduced in intensity to acceptable levels) by many centimeters of lead.

**Half-Life**

Examine Figure 1, which shows how the number of radioactive nuclei in a sample decreases with time.

The time in which half of the original number of nuclei decay is defined as the half-life (*t*1/2).

Half of the remaining nuclei decay in the next half-life, and half of what remains will decay in the next half-life.

Therefore, the number of radioactive nuclei decreases from *N* to *N*/2 in one half-life, *N*/4 in the next, *N*/8 in the next, and so on.

If *N* is a large number, then many half-lives must pass before all of the nuclei decay.

Think of nuclear decay as a statistical process.

If *N* is reasonably large, half of the original nuclei decay in a time of one half-life.

If an individual nucleus makes it through the first half-life, it still has a 50% chance of making it through then next.

No matter how many half-lives a given nucleus has survived, it still has a 50% chance of surviving through one more.

The probability of decay is the same no matter when you start counting.

There is a tremendous range in the half-lives of various nuclides, from as short as 10−23 *s* for the most unstable, to more than 1016 *y* for the least unstable, or about 46 orders of magnitude.

Nuclides with the shortest half-lives are those for which the nuclear forces are least attractive, an indication of the extent to which the nuclear force can depend on the particular combination of neutrons and protons.



**Figure 1:** Radioactive decay reduces the number of radioactive nuclei over time. In one half-life (*t*1/2), the number decreases to half of its original value. This is an exponential decay, as seen in the graph of the number of nuclei present as a function of time.

**Activity and Decay Constant**

Another important quantity applicable to radioactive sources is activity.

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

Note that while activity tells us how many decays happen per second, it says nothing about the energy or type of radiation emitted.

At any point in time, the activity of a source (*A*1) is directly proportional to how many atoms of the radioactive material are present at that time (*N*1) and inversely proportional to the half-life of the material (*t*1/2).

$$A\_{1}=\left[\frac{0.693}{t\_{1/2}}\right]  N\_{1}$$

where: *A*1 = activity of a source

 0.693 = natural log of 2

 *t*½ = half life of the material

 *N*1 = number of atoms of material present

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

An alternate representation of this equation is:

*A*1 = λ*N*1

where: λ = $\frac{0.693}{t\_{1/2}}$

**Example Problem: Calculating Radiation Activity**

1) What is the activity of 1 milligram of pure C11? (1 *mg* = 0.001 *g*)

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

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

$$N\_{1}=\left(\frac{0.001 g}{{11 g}/{mol}}\right)  \left(\frac{6.022  10^{23} atoms}{mol}\right)$$

$$N\_{1}=0.0000909 mol  \left(\frac{6.022  10^{23} atoms}{mol}\right)$$

$$N\_{1}=5.47  10^{19} atoms$$

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

$$A\_{1}=\left[\frac{0.693}{20.4 min}\right]  \left(5.47  10^{19} atoms\right)$$

$$A\_{1}=\left[\frac{0.693 \left(5.47  10^{19} atoms\right)}{20.4 min}\right]$$

$$A\_{1}=\left[\frac{3.79  10^{19} atoms}{20.4 min}\right]$$

$$A\_{1}=\frac{1.858  10^{18} atoms}{min}$$

$$A\_{1}=\frac{1.858  10^{18} atoms}{min}  \frac{min}{60 s}$$

$$A\_{1}=\frac{3.1  10^{16} atoms}{s}$$

or 3.1  1016 *Bq*

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

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

$A\_{2}=A\_{1}  e^{\left(\frac{-0.693  Δt}{t\_{1/2}}\right)}$ or $\left[A\_{2}=A\_{1}  e^{\left(-λ  Δt\right)}\right]$

2) In the first calculation, an activity of 3.1  1016 *Bq* was calculated for 1 *mg* of pure C11.

What would the activity of that C11 be after a decay time (*t*2 – *t*1) of 24 hours?

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

$$A\_{2}=A\_{1}  e^{\left(\frac{-0.693  Δt}{t\_{1/2}}\right)}$$

$$A\_{2}=\left(3.1  10^{16} Bq\right)  e^{\left(\frac{-0.693  24 h}{20.4 min}\right)}$$

$$A\_{2}=\left(3.1  10^{16} Bq\right)  e^{\left(\frac{-0.693  24 h  60 {min}/{h}}{20.4 min}\right)}$$

$$A\_{2}=\left(3.1  10^{16} Bq\right)  e^{\left(\frac{-997.9}{20.4}\right)}$$

$$A\_{2}=\left(3.1  10^{16} Bq\right)  e^{-48.9}$$

$$A\_{2}=\left(3.1  10^{16} Bq\right)  \left(5.79  10^{-22}\right)$$

$$A\_{2}=0.00002 Bq$$

**Biological Half-Life**

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

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

The radioactive half-life for a given radioisotope is physically determined and is unaffected by the physical or chemical conditions around it.

However, if that radioisotope is in a living organism, it may be excreted so that it no longer is a source of radiation exposure to the organism.

For a number of radioisotopes, the rate of excretion has been cast in the form of an effective biological half-life.

The rate of decrease of radiation exposure is then affected by both the physical and biological half-life, giving an effective half-life for the isotope in the body.

Though the biological half-life cannot be expected to be as precise as the physical half-life, it is useful to calculate an effective half-life, since it will provide at least an approximation of potential radiation exposure.

**Effective Half-Life**

In the case of a radioactive compound, both the decay (or physical) half-life of the radioisotope and the biological half-life cause the amount of the radioisotope in the body to decrease.

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

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

The effective half-life is calculated:

$$t\_{^{1}/\_{2}}\left(eff\right)=\frac{t\_{{1}/{2}}(phy)  t\_{{1}/{2}}(bio)}{t\_{{1}/{2}}\left(phy\right)+ t\_{{1}/{2}}(bio)}$$

**Example Problem: Calculation of Effective Half-Life**

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

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

$$t\_{^{1}/\_{2}}\left(eff\right)=\frac{t\_{{1}/{2}}(phy)  t\_{{1}/{2}}(bio)}{t\_{{1}/{2}}\left(phy\right)+ t\_{{1}/{2}}(bio)}$$

$$t\_{^{1}/\_{2}}\left(eff\right)=\frac{4500 d  12 d}{4500 d+ 12 d}$$

$$t\_{^{1}/\_{2}}\left(eff\right)=\frac{54000 d^{2}}{4512 d}$$

$$t\_{^{1}/\_{2}}\left(eff\right)=11.97 d$$

**Radiation Biology**

**Relative Biological Effectiveness**

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

$$RBE \left(100\% bacterial lethality\right)= \frac{dose required using 250 kVp x-rays}{dose required using 1 MeV electrons}$$

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

For a given level of activity, radiation with high linear energy transfers (LET) (i.e., radiation that transfers its energy to the recipient in a short distance/range) are more effective.

**Quality Factor**

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

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

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

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

photons (x-rays, gamma rays) 1

electrons 1

alpha particles 20

fission fragments and 10

heavy particles of unknown charge

neutrons of unknown energy 10

high energy protons 10

**Tissue Dose Weighting Factor**

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

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

gonads 0.25



breast 0.15

red bone marrow 0.12

lung 0.12

thyroid 0.03

bone surfaces 0.03

remainder 0.30

whole body Σ = 1

**Quantifying Radiation – External Radiation Sources**

**Absorbed Dose**

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

However, the most useful quantity is usually the dose equivalent (DE), which is given in units of Sieverts (*Sv*).

**Dose Equivalent**

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

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

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

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

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

 *Q* = radiation quality factor

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

*DE* = *Σ* (*Dose* **)

**Example Problem: Calculation of Dose Equivalent**

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

Using the quality factors from the table on the previous page, the dose equivalent would be:

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

*DE* = 0.04 + 0.10

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

**Effective Dose Equivalent**

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

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

*Effective Dose Equivalent* (*EDE*) = Σ (*DE* **)

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

 *W*t = 

**Protective Measures in Radiation Safety – Distance**

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

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

The three factors critical to reducing dose levels from external sources are: time, distance, and shielding.

As it relates to distance, increasing the distance between a person and a radiation source can dramatically decrease the radiation dose rate.

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

$$DR\_{2}= DR\_{1}  \frac{r\_{1}^{2}}{r\_{2}^{2}}$$

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

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

**Example Problem: Calculation of Distance Effect**

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

$$DR\_{2}=\left(1 Sv/h\right)  \frac{10 cm^{2}}{20 cm^{2}}$$

$$DR\_{2}=\left(1 Sv/h\right)  \frac{100}{400}$$

$$DR\_{2}=\left(1 Sv/h\right)  0.25$$

$$DR\_{2}=\left(0.25 Sv/h\right)$$

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

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

$$DR\_{2}=\left(0.01 Sv/h\right)  \frac{100 cm^{2}}{10 cm^{2}}$$

$$DR\_{2}=\left(0.01 Sv/h\right)  \frac{10000}{100}$$

$$DR\_{2}=\left(0.01 Sv/h\right)  100$$

$$DR\_{2}=\left(1 Sv/h\right)$$

**FUNDAMENTALS OF INDUSTRIAL HYGIENE, 6TH ED.**

**HOMEWORK #6**

**INDIVIDUAL MEASUREMENT OF RADIATION**

**Name:**

**EXERCISES:** Perform the calculations identified below. Show your work neatly and clearly in a manner similar to the examples provided above (i.e., write the formula, define each variable in the formula where requested, show steps of your calculations).

**Part I: Calculation of Radiation Activity**

The average 70 *kg* adult human body contains approximately 7.0  1027 atoms. Almost 99% of the mass of the human body is made up of six elements: oxygen (43 *kg* – 65%), carbon (16 *kg* – 18%), hydrogen (7 *kg* – 10%), nitrogen (1.8 *kg* – 3%), calcium (1.0 *kg* – 1.4%), and phosphorous (0.78 *kg* – 1.1%). Of the remainder, about 0.85% is composed of another five elements: potassium (0.14 *kg* – 0.25%), sulfur (0.14 *kg* – 0.25%), sodium (0.10 *kg* – 0.15%), chlorine (0.10 kg – 0.15%), and magnesium (0.019 *kg* – 0.05%).

1a) Of the total 16 *kg* of carbon in the average human body, approximately 24 nanograms consist of C14.

Nano- (*n*) is the prefix used in the SI system of measurement to mean one-billionth (10-9). One gram contains one billion (1,000,000,000) nanograms. Therefore, 24 *ng* = 2.4  10-8 *g* (0.000000024 *g*).

What is the activity of the 24 *ng* of C14 in your body?

The weight of 1 mole (6.022  1023) of C14 atoms is . *(2 points)*

Therefore, the number of C14 atoms in 24 nanograms is:

*N*1 =

*N*1 =

*N*1 =

The physical half-life of C14 (see Appendix A – do not use table in text) is . *(8 points)*

*A*1 = where: *A*1  =

 0.693 =

 *t*1/2 =

 *N*1 =

*A*1 =

*A*1 =

*A*1 =

*A*1 =

*A*1 =

*A*1 = or *Bq*

1b) In the above calculation, an activity of was calculated for 24 *ng* of pure C14.

What would the activity of that C14 be after a decay time (*t*2 – *t*1) twenty-five years? *(6 points)*

*A*2 = where: *A*1  =

 *e* =

 *Δt* =

 t1/2 =

*A*2 =

*A*2 =

*A*2 =

*A*2 =

2a) Of the total 0.14 *kg* of potassium in the average human body, approximately 14 *mg* (0.014 *g*) consists of K40.

What is the activity of the 14 *mg* of K40 in your body?

The weight of 1 mole (6.022  1023) of K40 atoms is . *(1 point)*

Therefore, the number of K40 atoms in 14 milligrams is: *(1 point)*

*N*1 =

*N*1 =

*N*1 =

The physical half-life of K40 (see Appendix A – do not use table in text) is . *(3 points)*

*A*1 =

*A*1 =

*A*1 =

*A*1 =

*A*1 =

*A*1 = or *Bq*

2b) In the above calculation, an activity of was calculated for 14 *mg* of pure K40.

What would the activity of that K40 be after a decay time (*t*2 – *t*1) of eighty years? *(3 points)*

*A*2 = where: 80 years = days

*A*2 =

*A*2 =

*A*2 =

3) Conduct a brief research on “background radiation” using at least the following internet sources:

http://en.wikipedia.org/wiki/Background\_radiation

http://web.princeton.edu/sites/ehs/osradtraining/backgroundradiation/background.htm

http://w1.rso.utah.edu/train/Natbkg.html

http://www.nrc.gov/reading-rm/basic-ref/glossary/background-radiation.html

a) What is “background radiation”? What is the average exposure to background radiation in the U.S.? *(2 points)*

b) What are the two broad *sources* of background radiation? How much radiation is received by each source annually? Identify three specific radiation sources within each broad source. *(10 points)*

Source #1: Amount from Source #1:

Specific Sources: 

 

 

Source #2: Amount from Source #2:

Specific Sources: 

 

 

c) Explain the role of C14 and K40 in the ‘background radiation’ dose received by humans (± all mammals). *(5 points)*

**Part II: Calculation of Effective Half-Life**

**Background: Nuclear Medicine and Radioisotopes**

Nuclear medicine is a branch of medicine that uses radiation to provide information about the functioning of a person’s specific organs or to treat disease. In most cases, this information is used by physicians to make a quick, accurate diagnosis of a patient’s illness. The thyroid, bones, heart, liver, kidneys, and many other organs can be easily imaged, and disorders identified. Over 10,000 hospitals worldwide use radioisotopes in medicine, and about 90% of the procedures are for diagnosis. A radioisotope used for diagnosis must emit radiation (beta particles or gamma rays) of sufficient energy to escape the body, while having a half-life short enough for it to decay away soon after imaging is completed. Alternatively, longer half-life radioisotopes can be used provided they do not become incorporated into the patient’s tissues and are rapidly excreted from the body.

**Tritium** (H3) is a low energy beta emitter, making it non-dangerous externally (its beta particles are unable to penetrate the skin). However, it does pose a radiation hazard when inhaled, ingested, or absorbed through the skin. Tritium is used in tracer in life science research, in studies investigating the metabolism of organic compounds, and in ground water transport measurements. The chemical behavior of H3 is essentially the same as that of hydrogen (H2), meaning that it can combine with oxygen to form water (in this case, tritiated water – HTO). Just like regular water, tritiated water will migrate and become uniformly distributed throughout all parts of the human body.

Note: The U.S. EPA has recently documented that tritium from self-luminescent exit signs improperly disposed of in municipal landfills can mix with leachate and pass into waterways.

**Phosphorous** is found in many organic molecules and so P32 has many applications in medicine, biochemistry, and molecular biology where it can be used as a tracer for identifying metabolic pathways and radioactively labeling DNA. The beta radiation emitted is sufficiently penetrating to be detected outside the organism being studied. P32 is of particular use in the identification of malignant tumors because cancerous cells have a tendency to accumulate more phosphate than normal cells. P32 is also used for some kinds of bone scans; however, the phosphorous tends to become incorporated in the bones.

There are 37 known isotopes of **iodine**. Due to the preferential uptake of iodine by the thyroid, radioisotopes of iodine are extensively as tracers used in nuclear imaging (e.g., CT scans, PET scans) to evaluate the anatomic and physiologic function of the thyroid. I123 is a gamma ray emitter, while I131 emits beta particles capable of penetrating 0.6 to 2.0 *mm* into tissues surrounding the site of uptake. Since radioactive iodine is produced during nuclear fission (atomic bomb testing, nuclear plant accidents) potassium iodide tablets have been distributed to populations exposed to nuclear disasters such as at Chernobyl and Fukushima. Ingesting one of these tablets daily results in the thyroid gland becoming “flooded” with non-radioactive iodine, thus preventing the uptake and storage of radioactive iodine present in fallout.

**Strontium** belongs to the same periodic family as calcium (alkaline earth metals), and is metabolized into teeth and bones a similar fashion. Sr89 is used in the treatment of bone cancers and prostrate cancer, preferentially targeting active regions of the bone where calcium turnover is greatest. Additionally, Sr89 may be helpful in relieving pain associated with bone cancers. Sr90 is found in the fallout of fission nuclear weapon testing and in waste from nuclear reactors, but is also used as a radioactive tracer and treatment (eye diseases, bone cancer) in medical studies. Both Sr89 and Sr90 are beta emitters.

**Technetium** is the lowest atomic number element without any stable isotopes; every form of it is radioactive. Nearly all technetium is produced synthetically, and only minute amounts are found in nature. In 1937, technetium became the first predominantly artificial element to be produced, hence its name from the Greek word for “artificial”. The isotope Tc99m emits gamma rays and low-energy beta particles, and is widely used in nuclear medicine for a wide variety of diagnostic tests.

1) Complete the table, calculating the effective half-lives for P32, Sr89, Sr90, I123, I131, and Tc99m *(6 points)* and show your calculations for two of the isotopes *(2 points)*.

(See Appendix A for physical and biological half-lives – do not use table in text.)

***Physical, Biological, and Effective Half-Lives of Selected Isotopes (in days)***

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Isotope** | **Type of Radiation** | **Physical Half-Life***t*1/2(*phy*) | **Biological Half-Life***t*1/2(*bio*) | **Effective Half-Life***t*1/2(*eff*) |
| H3 | *beta* | *4500* | *10* | *9.98* |
| P32 | *beta* |  |  |  |
| Sr89 | *beta* |  |  |  |
| Sr90 | *beta* |  |  |  |
| I123 | *gamma* |  |  |  |
| I131 | *beta* |  |  |  |
| Tc99m | *gamma and beta* |  |  |  |

a) Isotope #1:

$$t\_{^{1}/\_{2}}\left(eff\right)=$$

$$t\_{^{1}/\_{2}}\left(eff\right)=$$

$$t\_{^{1}/\_{2}}\left(eff\right)=$$

b) Isotope #2:

$$t\_{^{1}/\_{2}}\left(eff\right)=$$

$$t\_{^{1}/\_{2}}\left(eff\right)=$$

$$t\_{^{1}/\_{2}}\left(eff\right)=$$

2) Based on the behavior and half-lives of the radioisotopes only (i.e., ignore the energy levels of emitted radiation), respond to the following questions. *(2 points each – 8 pts. total)*

a) Why is Technetium (T99m) a favorite for diagnostic scans, having been used for over 40 million procedures and accounting for 80% of all nuclear medicine procedures worldwide?

b) For strictly imaging purposes, which radioisotope of Iodine would you recommend? Why?

c) Identify a concern you would have about recommending a bone scan using P32.

d) Of the radioisotopes identified in the table, which is the most hazardous? Why?

**Part III: Calculation of Dose Equivalent and Effective Dose Equivalent**

1) Calculate the Dose Equivalent of 0.055 (5.5  10-2) *Gy* resulting from exposure to a 5.59 *mEV* alpha source emitter. *(4 points)*

*DE* = where: =

 =

*DE* =

*DE* =

2) Given that the lungs are the organ/tissue suffering the greatest exposure, calculate the Effective Dose Equivalent. *(4 points)*

*EDE* = where: =

 =

*EDE* =

*EDE* =

3) Calculate the Dose Equivalent of 0.023 (2.3  10-2) *Gy* resulting from exposure to a 7.78 *MeV* alpha source emitter and a simultaneous 0.069 (6.9  10-2) *Gy* resulting from exposure to a 0.19 *MeV* gamma source emitter. *(2 points)*

*DE* =

*DE* =

*DE* =

4) Given that the radiation source in the above example is a self-luminous wristwatch with radium-painted dials, and owner never takes the watch off and sleeps with his arm draped across his chest such that the watch dial lies directly over his right breast, calculate the Effective Dose Equivalent. *(2 points)*

*EDE* =

*EDE* =

*EDE* =

**Part IV: Calculation of Radiation Distance Factor**

1) If the dose rate at 2 *cm* from a small-sized Ra226 source is 0.34 *Sv/h* (34 *rem/h*), the dose rate at 17 *cm* is calculated: *(4 points)*

*DR*2 = where: =

 =

*DR*2 =

*DR*2 =

*DR*2 =

*DR*2 =

2) If the dose rate at 275 *cm* from the Ra226 source is known to be 0.000018 (1.8  10-5) *Sv/h*, the dose rate at 56 *cm* is calculated: *(2 points)*

*DR*2 =

*DR*2 =

*DR*2 =

*DR*2 =

3) **BONUS:** If the acceptable dose rate for a particular radioactive material has been established at 0.027 *Sv/h* and the dose rate at 16 *cm* has been determined to be 0.004 *Sv/hr*, how close can a worker come to the source? *(2 points)*

**Appendix A**

**Half-Lives of Various Radioisotopes**

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

Hydrogen H3 4500 days 12 days

Carbon C14 5730 years 40 days

Sodium Na22 850 days 11 days

Phosphorus P32 14.3 days 1155 days

Sulfur S35 87.4 days 90 days

Chlorine Cl36 3.0  105 years 29 days

Potassium K40 4.6  1011 days 16 days

Calcium Ca45 165 days 18000 days

Chromium Cr51 28 days 616 days

Iron Fe59 45 days 600 days

Cobalt Co60 1930 days 10 days

Zinc Zn65 244 days 933 days

Rubidium Rb86 18.8 days 45 days

Strontium Sr89 50.6 days 18000 days

Strontium Sr90 10548 days 18000 days

Technetium Tc99m 0.25 days 1 day

Iodine I123 0.54 days 138 days

Iodine I131 8 days 138 days

Cesium Cs137 11000 days 70 days

Barium Ba140 12.8 days 65 days

Gold Au198 2.7 days 280 days

Polonium Po210 138 days 60 days

Radium Ra226 580000 days 16000 days

Uranium U235 7.1  108 years 15 days

Plutonium Pu239 2.4  104 years 73000 days

Note: For more information, visit Science Gateway website: [www.sciencegateway.org/isotope/](http://www.sciencegateway.org/isotope/)

**Appendix B**

**Calculator Keystrokes**



**common logarithm, log base 10** Calculator Key: **LOG**

Example: the log of 100 is: Keystrokes: 100, LOG = {2}

**inverse log** Calculator Key: **10*x***

Example: the inverse log of 1 is: Keystrokes: 1, 2nd, 10*x* = {10}

**raised to the power** Calculator Key: ***yx***

Example: Avagadro’s number (622000000000000000000000) is: Keystrokes: 6.22, X, 10, *yx*, 23, = {6.2223}

**natural logarithm** Calculator Key: **LN**

Example: the natural log of 2 is: Keystrokes: 2, 2nd, LN = {0.693}

**inverse natural log** Calculator Key: ***ex***

Example: the inverse natural log of -48.9 is: Keystrokes: 48.9, +⮀-, 2nd, *ex* = {5.79  10-22}