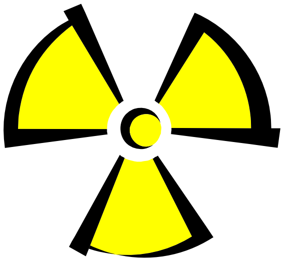
Introduction to Radiation



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1.0 NATURE OF RADIOACTIVITY

Radioactivity is a spontaneous process characteristic of atoms with unstable nuclei in which the nucleus releases energy either as a particle with kinetic energy or as electromagnetic energy. Upon release of this energy the nucleus may be stable or it may still be unstable and will acquire stability through an additional transformation(s). The original species prior to radioactive disintegration is often termed the ‘parent’ with the species after the transformation called the ‘daughter’ or ‘progeny’. A given transformation (one parent/daughter transition) is termed a ‘disintegration’ or a ‘decay’.

The rate of radioactive disintegration is often used to indicate the ‘radioactivity’ of a sample and is termed the activity. Two different definitions of activity are used - the older definition of activity defines the Curie (Ci) as the amount of radioactive material (RAM) having a disintegration rate of 3.7 E10 (37 billion) per second. It is common to express activities in Curies (Ci), milliCuries (1 thousand mCi = 1 Ci), microCuries (1 million µCi = 1 Ci), nanoCuries (1 billion nCi = 1 Ci), picoCuries (1 trillion pCi = 1 Ci), etc. It is important to note that activity denotes only the rate of disintegration; it provides no information regarding the kind of radiation emitted during the radioactive disintegration. The newer definition of activity defines its basic unit as the Becquerel (Bq); a Becquerel corresponds to a disintegration rate of one disintegration per second, dps. It is common to express activities in kilobequerels (kBq - one thousand dps), megaBequerels (MBq - one million dps), etc.

An important characteristic of any radionuclide (any specific nuclear combination of neutrons and protons comprise a nuclide; an unstable nuclide is termed a radionuclide) is its half-life. The half-life corresponds to the time necessary for one-half of the radioactive atoms of a sample to disintegrate. The fraction of atoms (or activity) remaining as a function of the number of selected elapsed half-lives is as follows:

Number of Half-Lives	Fraction of Activity Remaining
0	1.0 (100%)
1	0.5 (50%)
2	0.25 (25%)
3	0.125 (12.5%)
4	0.0625 (6.25%)
10	0.000977 (0.1 %)

In general, the fraction remaining is expressed by the relationship fraction remaining = $(1/2)^n$ where n = number of half-lives.

It is interesting that of the approximately 1300 different radionuclides the most frequently found half-life is about 1 hour. Approximately 24% have a half-life of 1 hour to 1 day and 20% have a half-life of 1 day to 1 year. The half-lives of the most commonly used radionuclides at CWRU are as follows:

Radionuclide	**Half-life**
Hydrogen-3	12.3 years
Carbon-14	5700 years
Phosphorus-32	14.3 days
Phosphorus-33	25.3 days
Sulfur-35	88 days
Chromium-51	28 days
Iodine-125	60 days
Iodine-131	8.1 days
Calcium-45	165 days

In biological systems, the physical half-lives tell only part of the story. The rate of biological removal or elimination can often be expressed as a biological half-life. If a radioactive element with a physical half-life (Tp) is incorporated in a compound that is eliminated with a biological half-life (Tb), the effective half-life (Teff) can be expressed as:

$$\mathbf{Teff = \frac{Tp \times Tb}{Tp + Tb}}$$

As an example, the biological half-life of radioiodine in a human thyroid is about 60 days. Since the physical half-life of I-125 is 60 days, the effective half-life is given by:

$$\text{Teff} = \frac{60 \times 60}{60 + 60} = 30 \text{ days}$$

It should be noted that Teff is less than either Tb or Tp provided they are finite.

Only a limited number of types of transformation have been observed in the disintegration of radionuclides. The names of the 4 most common types of radioactive disintegration are:

- Alpha disintegration
- Beta disintegration
- Electron capture
- Isomeric transition

Prior to discussing these types of radioactive disintegration it is helpful to introduce a unit of energy - the ‘Electron Volt’ (eV). This unit is used to denote particle and photon energies in atomic physics and it represents the energy change experienced by an electron while undergoing a potential energy change of one volt. It is common to express certain energies in kilo electron volts (keV = one thousand electron volts), mega electron volts (MeV = one million eV), etc. For comparative purposes, the kinetic energy of an air molecule at typical room temperature is about 0.025 eV and diagnostic x-rays average about 50 keV.

1.1 Alpha Emission

Alpha emission is generally limited to isotopes of the heavy elements. Isotopes are different nuclear varieties of an element - same atomic number (Z) but different mass numbers (A). In alpha emission, a particle consisting of 2 protons and 2 neutrons (a Helium nucleus), is ejected from the parent nucleus with high kinetic energy - typically, about 4 MeV. The alpha particle, although its initial energy is great, is stopped by a few centimeters of air or by a few microns of tissue. After the emission of the alpha particle, the daughter atom may be in an excited level of that particular species. The resulting transition to the ground state is generally accompanied by the emission of a gamma ray, a photon of electromagnetic energy that is emitted from the nucleus of the excited atom.

1.2 Beta Emission

1.2.1 Simple Beta Decay

Beta emission is the name of a transition that results in the emission of a positron or an electron from the nucleus. The emitted particle may be positively charged, (a positron) or negatively charged (an electron). The disintegration process also results in the emission of an accompanying particle - a neutrino for positron emission, an antineutrino for electron emission. The sum of the kinetic energies of the two particles, electron and antineutrino or positron and neutrino, is characteristic for each beta-emitting radionuclide. As examples, this sum is 1.71 MeV for P-32 and 0.156 MeV for C-14. The sum represents the maximum kinetic energy ever associated with the emitted beta particle. As an example, the betas emitted by P-32 are polyenergetic with individual kinetic energies from 0 to 1.71 MeV. In every disintegration, a sum of 1.71 MeV of kinetic energy is shared by the beta and the anti-neutrino. The mean or average beta-particle energy is approximately 1/3 of the characteristic maximum or ‘end-point’ energy. Although the neutrino or anti-neutrino carries the other 2/3rds of the total kinetic energy, on average, it has no practical interaction with matter and, consequently, produces no biological effects.

There are about 25 cases of simple beta disintegration (the daughter nucleus) is at ‘ground state’ subsequent to the disintegration. Important examples of such radionuclides are H-3 (Tritium), C-14 (Carbon-14), P-32 (Phosphorous-32), S-35

(Sulfur-35), and Ca-45 (Calcium-45). In these cases, the only emissions are the beta-particle and the neutrino.

1.2.1.a. Example #1 Tritium (H-3) Simple Beta Decay

Tritium (H-3) decays by beta decay to the ground state of its daughter, Helium-3. The maximum beta particle energy is 0.018 MeV while the average beta particle energy is about 1/3 x 0.018 = 0.006 Mev.

However, the more common situation is for the daughter to be in an 'Excited Isomeric State' of the nuclide with the subsequent emission (usually promptly) of a photon of electromagnetic radiation from the nucleus that is called a 'gamma-ray'. The energy of the gamma-ray is equal to the difference of the 2 energy levels associated with the transition. These 2 types of decay are termed Isomeric Transition and Electron Capture.

1.2.2 Isomeric Transition

Because the excited levels and the ground state level of a radionuclide differ only in nuclear energy content the various levels are called nuclear 'isomers' and the transitions between them are called isomeric transitions. These transitions normally occur promptly after formation of the excited level 'promptly' usually implies de-excitation times of the order of nanoseconds) and generally result in x-rays of energy equal to the difference of the energies of the two isomeric levels involved in the transition.

1.2.2.a. Example #2 Cesium-137 (Cs-137) Isomeric Transition

Cs-137 decays by beta decay to Ba-137 by 2 different pathways. In the first pathway that occurs 6.5% of the time, the resulting betas have an endpoint energy of 1.176 MeV and the daughter is at its ground state. For the other pathway, occurring 93.5% of the time, the endpoint energy is 0.0514 MeV; this suggests an average beta particle kinetic energy of about 1/3 x 0.514 = 0.171 MeV. This pathway leaves the daughter of the decay at an excited level, approximately 0.662 MeV above the ground state. A prompt de-excitation change takes the nucleus to the ground state and results in the emission of a gamma ray of 0.662 MeV from the nucleus. This transition is termed an 'Isomeric Transition'.

1.2.3. Electron Capture

An unstable nucleus of certain species can convert a proton to a neutron by a process termed Electron Capture. An orbital electron is ‘captured’ while passing through the nucleus of these unstable nuclides. The captured electron combines with a nuclear proton to yield a neutron; a reaction product, a neutrino, is emitted from the nucleus. A rearrangement of the orbital electrons then results to fill the vacancy due to the captured electron. This rearrangement of orbital electrons is generally accompanied by the emission of characteristic x-rays. In addition, if the disintegration leaves the daughter at an excited level then gamma rays are likely to be emitted in the subsequent transition(s) to the ground state of the daughter nucleus.

1.2.3.a. Example 3 Chromium-51 (Cr-51) Electron Capture

Cr-51 decays via Electron Capture to the ground state of the daughter, Vanadium-51, 91% of the time. These transformations result in neutrinos and vanadium characteristic x-rays. However, the Electron Capture transformation leaves the daughter in an excited state (0.32 MeV above the ground state) about 9% of the time. The subsequent isomeric transitions to the ground state yield 0.32 MeV gamma rays.

Occasionally, there are instances in which the excited state of a daughter nucleus is relatively long-lived, the transition to the ground level being delayed not by nanoseconds but by minutes or hours. The protracted excited level is termed a metastable level and is denoted by adding the letter ‘m’ to the mass number. Technesium-99m (Tc-99m) with a half-life of the metastable state of 6 hours, is an example.

2.0 INTERACTION OF RADIATION WITH MATTER

2.1. X-ray and Gamma Radiation

X-rays and gamma rays are electromagnetic radiation. The terms x-ray and gamma ray refer to the origin of the radiation; x-rays are generated by electrons whereas gamma rays are emitted by nuclei involved in radioactive disintegration. Hence, x-rays and gamma rays of the same energy are identical in every respect except origin. They are known to interact with matter by more than 10 different processes. However, there are only three important interactions:

- Photoelectric Absorption
- Compton Scattering
- Pair Production

In some interactions the radiation behaves like particles called photons. They travel with the speed of light and are characterized by their energy. The following summarizes the important photon interactions with matter.

2.1.1. Photoelectric Absorption

In this process the incident photon is absorbed by a bound electron and ceases to exist. The electron is ejected from its previously bound state and carries away most of the absorbed energy as Kinetic Energy. A rearrangement of orbital electrons to fill the vacancy caused by the ejected electron results in the emission of characteristic x-rays and the products of a competing process, Auger Electrons.

The probability of Photoelectric Absorption is very dependent upon the energy of the radiation and upon the atomic number of the absorption material. In general, Photoelectric Absorption is the dominant absorption process at low radiation energies and it occurs, for a given energy, much more in materials of high atomic number than in materials with low atomic number. Thus, Lead with an atomic number of 82 is an excellent material for absorbing radiation by the photoelectric process.

2.1.2. Compton Scattering

In this interaction the incident photon undergoes a billiard-ball type collision with an electron of the interacting material. The photon is deflected or scattered by the collision and continues with reduced energy. Compton interactions occur to about the same degree in unit masses of different materials (a gram of wood is about as effective as a gram of Lead) if the attenuation process is Compton Scattering. The probability of Compton Scattering in any material steadily decreases as the energy of the radiation increases.

2.1.3. Pair Production

In this attenuation process, the incident photon materializes into a pair of particles (an electron and a positron) in the vicinity of a nucleus. The minimum or threshold energy for this interaction is 1.02 MeV. This corresponds to the rest mass energy-equivalence of the 2 created particles. The probability of Pair Production increases after the threshold and it occurs more in matter with high atomic number constituents than matter of low atomic number.

In general, photoelectric absorption is the dominant interaction at low energies while Pair Production is the dominant interaction at very high energies. Compton Scatter is the important mechanism for intermediate energies.

2.2. Half-Value-Layer

It is frequently convenient to express the attenuation properties of a material in terms of its Half-Value-Layer, HVL. The HVL is defined as the thickness of the material required to reduce the transmitted radiation to one-half of the incident value.

The transmitted fraction (f) through '**n**' Half-Value-Layers (HVL) is given by the expression:

$$\mathbf{f = (1/2)^n}$$

Thus 1/2 (50%) of the incident radiation is transmitted through one HVL, 1/4 (25%) through 2 HVL's. 1/8 (12.5%) through 3 HVL's, and so on.

2.3. Particle Interactions

Every swiftly moving, charged particle, such as an alpha particle or beta particle (electron), ionizes some of the atoms that lie along its path as it traverses matter. It is this ionization that is responsible for the radiobiological effects of radiation and also which makes possible the detection of radiation with various types of instruments. In passing through air, a typical particle will produce on the order of thirty thousand ionizations along its path before being brought to rest. The density of ionization along the path of a charged particle is approximately proportional to the square of the charge on the particle. Hence, for alpha particles it is four times as great as for protons or electrons having the same velocity.

Also, the ionization per unit path length is approximately inversely proportional to the square of the velocity of the particle. Thus, slow moving particles ionize much more densely than swift particles. Typical values of the specific ionization along the path of an alpha particle is about 5,000 ion pairs per millimeter of air or per micron of water or tissue while typical values for electrons are in the order of 5-10 ion pairs per millimeter of air or per micron of tissue.

As a charged particle passes among the atoms of an absorbing material it may:

- Dislodge electrons from atoms to form positive and negative ions (ionization)
- Excite electrons to higher energy levels in atoms
- Set up vibrations of molecules in the path
- Break molecular bonds
- Produce electromagnetic radiation subsequent to a sudden change in its course (Bremsstrahlung).

Of the 34 eV dissipated on the average per ion produced in air only about 16% goes into the production of ions, the remaining 84% going into the other dissipating processes.

The energy that a particle loses to its surroundings for each unit of path length is called the Linear Energy Transfer (LET) and is usually expressed in keV/ micron. The distance that charged particle travels from its point of origin to its end point (Rest Point) is its range. As an example, the range of a 1 MeV electron is 4.2 mm in water (tissue).

The paths of heavy particles are essentially straight with few drastic deflections. However, for electrons the paths are very tortuous and the average path length is about twice as great as the range.

The Bremsstrahlung process deserves attention. For electrons of a given energy (E) expressed in (MeV), the fraction of energy (f) that appears as Bremsstrahlung (x-rays) is given by the expression:

$$\mathbf{f=ZE/1400}$$

where Z = the absorber atomic number. Thus, it is preferred to shield a pure beta emitter of high energy such as P-32 with a low atomic number such as plexiglass, in order to minimize the production of penetrating x-ray.

3.0 MEASUREMENT OF RADIATION LEVELS

It is important to know the ‘Radiation Level’ to which workers are exposed. There are 3 different concepts of determining personnel radiation levels:

- Radiation Exposure
- Absorbed Dose
- Dose Equivalent

3.1. Radiation Exposure

The concept of ‘exposure’ is based on the ability of x-ray and gamma-radiation to ionize matter. Specifically, the amount of electrical charge liberated in air is used to measure radiation level. The unit of radiation exposure is the Roentgen. Electronic devices called Ionization Chambers are designed to monitor x-ray and gamma-radiation exposure levels.

3.2. Absorbed Dose

Absorbed Dose is a computed quantity that denotes the energy imparted to matter by ionizing radiation per unit mass of irradiated material at a place of interest. The unit of Absorbed Dose is the 'Rad' and it is defined as the energy absorption of 100 ergs per gram of material.

3.3. Dose Equivalent

Dose equivalent is a computed quantity that denotes the potential biological effect of the ionizing radiation. It is defined as the 'product' of the absorbed dose and certain modifying factors. The unit of the 'product' (the unit of dose equivalent) is the 'Rem'. Although several modifying factors have been proposed only the 'Quality Factor' (QF) has been extensively used. The Quality Factor is a subjective measure of the 'relative hazard or biological effect' of a given type of radiation. Examples of the quality factors for common types of radiation are as follows:

Radiation Type	Q
X-ray, Beta, Gamma	1
Thermal neutron	2
Fast neutron	10
Alpha	20

An estimate of biological effect (the dose equivalent in Rems) is computed by simply multiplying the absorbed dose in 'Rads' by the appropriate QF. Example: If an individual received a fast neutron absorbed dose of 2 Rads, then the calculated dose equivalent is 20 Rem.

The relationships among the three units are complicated. However, the following simplification is helpful: a dose equivalent of approximately of 1 Rem or an absorbed dose of approximately 1 Rad is imparted to human tissues at a location where a survey instrument indicates an exposure of 1 Roentgen due to x- or gamma-radiation. To provide some perspective regarding these units the 'Background Radiation' level is due primarily to:

- Radiation reaching the earth from outer space
- The radioactive content of all terrestrial materials (including human tissues) in the Cleveland area is approximately 0.3 Rem (300 mRems) per year.

4.0 BIOLOGICAL EFFECTS OF LOW LEVEL RADIATION

Radioactive material (RAM) emits ionizing radiation, the interaction of which with human tissues can result in biological damage. The biological damage to tissues is primarily due to secondary charged particles that result when the tissues are exposed to the ionizing radiation. The energetic secondary particles yield highly reactive free radicals that interact with molecules in the tissues breaking chemical bonds and causing other chemical changes. Some of the resulting damage is repairable, and some is not. Biological effects of low level radiation (low level radiation means acute whole body doses of 10 Rems or less or substantially larger doses if received over an extended length of time) can be classified into 3 categories:

4.1. Somatic Effects

These are effects occurring in the exposed person. The somatic effect thought to be associated with low-level radiation doses is cancer induction. The following is known regarding radiation-induced cancers:

- The manifestation is delayed after exposure to radiation - a few years for leukemia development and perhaps as many as 20 years for solid tumor formation.
- The resultant forms of cancer are indistinguishable from the cancers spontaneously occurring in people.
- The probability of fatal radiation induced cancer, based on the linear no-threshold model, is very conservatively estimated to be 120 x 10^{-6} per Rem (about one chance in 8,000 per Rem) of whole body radiation. This means that, according to the linear no-threshold model, if you are exposed to a whole body dose equivalent of 1 Rem, your fatal cancer risk is 0.0125%. Since your fatal cancer risk based on national life expectancy statistics is 25%, your fatal cancer risk due to the 1 Rem of radiation dose would be increased to 25.0125% rather than 25.0000%. The linear no-threshold model has no supporting data. In fact there is much to show it grossly over-predicts the effects of radiation exposure.

Again based on the linear no-threshold model the fatal risk of 1 Rem of whole body dose is calculated to be equivalent to the fatal risks of the following actions:

- Traveling 7000 miles by car
- Smoking approximately 200 cigarettes
- Working three years in atypical factory

Thus, while the only known ‘Somatic Effect’ of low-level radiation exposure is cancer induction, the chance of occurrence is small.

4.2. Developmental Effects

These are effects occurring due to exposure of the unborn. The risks of in-utero exposure of the developing child are summarized as follows:

- Radiation exposure during the first 2 weeks of pregnancy is thought to result in an 'All or Nothing' response. If a response occurs, the embryo is spontaneously reabsorbed and the pregnancy is terminated. Otherwise, the pregnancy continues in normal fashion with no deleterious effects. It is estimated that a radiation dose of 10 Rem during the first 2 weeks of pregnancy results in a 0.1% increase in embryonic re-absorption rate that occurs naturally.
- The most critical period occurs between approximately the second and eighth week. The organ systems of the fetus are developing and radiation disturbances can result in congenital abnormalities - skeletal abnormalities tend to occur due to early exposure while neurologic abnormalities occur later in the two-eight week organogenesis period. It is estimated that a dose of 10 Rem to the fetus will increase the frequency of congenital abnormalities by 1% above the normally occurring level.
- The induction of childhood cancer occurs following irradiation at any time in the gestation period. It is estimated that the dose of 1 Rem to the unborn will result in two to fifteen cases of radiation-induced cancer per 100,000 live births.

4.3. Genetic Effects

Current knowledge of radiation-induced genetic effects suggest that at genetic equilibrium there would be a risk of serious genetic disorders in offspring of about 120 x 10^{-6} per Rem of paternal radiation with the understanding that the risk may be nearly twice that large for paternal and smaller for maternal exposure. To date all radiation genetic risk estimates have been derived from mouse data. The susceptibly of humans has been assumed to be equal to that of mice in development of the risk factors, although evidence from the Japanese A-bomb survivors has indicated that humans are probably less susceptible.

No evidence of radiation-induced genetic effects in human beings exists. The incidents of serious genetic disease among live-born children in the United States are estimated to be about 3.1%. Using the risk parameter derived from mouse data each of the children of male radiation workers exposed to 0.1 Rem/ year for 11 years prior to conception (29 years is the average age of fathers at time of birth in the U.S.) 18 years is the minimum age for occupational exposure has a risk of about

$$11 \times 0.1 \times 2 \times 120 \times 10^{-6} = 2.6 \times 10^{-4} \text{ (one chance in 3,800)}$$

of a serious birth defect (applies to a population at genetic equilibrium consisting of radiation workers; only about one-tenth of this rate would apply to the first generation).

This represents an added risk that is about 1% of the spontaneous serious genetic disorder rate. It is well known that chromosomal abnormalities in offspring increase in frequency with both maternal and paternal age with Down's Syndrome associated with maternal age the most familiar. It has been shown that the risk of an average U.S. radiation worker (0.6 Rem/ year; 20 times our institutional average) to have children with serious genetic disease is roughly equal to that of delaying conception of his younger children by one year.

5.0 RADIATION MONITORING DEVICES

5.1. Personnel Monitors

The use of personnel monitoring devices, or dosimeters, permit evaluation and documentation of the radiation levels incurred by individuals working with RAM. Personnel monitoring of external radiation usually employs one of the following types of dosimeters.

5.1.1. Photographic Film Monitors

A strip of photographic film emulsion sandwiched between sets of filters (filters made of Plastic, Aluminum, Tin, Lead, etc.) can be used to evaluate both the radiation level and the nature of the radiation (penetrating gamma-radiation vs. non-penetrating beta radiation, high energy gamma-radiation vs. low energy gamma-radiation, etc.). Such film dosimeters are adequate for recording personnel doses as low as 10 mRem and as high as several hundred Rem. Film monitors can be used to record whole body doses, skin doses, hand doses, eye doses, etc., depending on where the monitor is worn. Film monitors are relatively inexpensive but the dosimetry results can be adversely affected by several extraneous factors (exposure to heat and moisture, minute light leaks, etc.).

5.1.2. Thermoluminescent Dosimeters

The Thermoluminescent Dosimeter (TLD) utilize several ‘chips’ of special material (typically lithium fluoride) that have the unique property of emitting a quantity of light (luminescence) when heated (thermo) that is proportional to the dosimeter's prior radiation dose. The monitors generally contain 2 chips and two filters for monitoring skin dose (penetrating plus non-penetrating radiation) and whole body dose (penetrating radiation). In addition, ring monitors containing a single chip are used to measure doses to the fingers of selected personnel. TLD body and ring monitors have minimum sensitivities of 10 and 30 mRem respectively.

5.1.3. Luxel Dosimeter

The Luxel dosimeter that is used at CWRU measures radiation exposure using an Optically Stimulated Luminescence (OSL) technology. The detector is a thin strip of aluminum oxide that is stimulated with selected frequencies of laser light causing it to luminesce in proportion to the amount of radiation exposure. The aluminum oxide strip is sandwiched within a three-element filter pack that is heat-sealed. The dose measurement range is 1 mRem-1000 Rem for photons (x –rays and gamma rays), and 10 mRem to 1000 Rem for beta particles. Beta exposures are reported as a shallow dose equivalent and exposures to photons will have a deep, shallow, and lens of the eye value reported.

The following rules apply to the proper use of personnel monitors:

- They should only be used by the person intended and not be shared with another individual.
- They should never be worn when an individual is exposed as a patient to medical or dental x-rays.
- They should be stored in a radiation free area when not being worn.
- They should not be taken home, since this increases their chance of being lost or laundered.
- They should be promptly returned to the Radiation Safety Office (RSOF) for evaluation after completion of the use period.

5.2. Portable Survey Instruments

Portable survey instruments are used for a variety of tasks:

- The routine area surveys of the laboratory
- The clean-up phase of experiments in which radioactivity was used

- To monitor radioactive waste material prior to transfer to Radiation Safety for disposal.

Portable survey instruments used at our institution are of three types:

- Geiger-Mueller (GM) Survey Instrument
- Ionization Chamber Survey Instrument
- Scintillation Survey Instrument

5.2.1. Geiger or G-M Survey Instrument

G-M instruments are widely used for radiation survey work because they are reliable and inexpensive. The instruments are compact, lightweight units with rugged electronics. These units utilize a gas detector that is capable of detecting beta, gamma, and x-ray radiation. Usually the detector is enclosed in a metal shield that precludes beta-particle detection except through a thin portion of the shield that is called the ‘window’. When the window is open, the probe can detect beta, gamma, and x-ray radiation. With the window closed, the device can detect only x and gamma radiation. The exposure rate scale of a G-M device will yield a fairly accurate indication of the true exposure rate only when exposed to x-ray or gamma radiation. When the device is used to detect beta-particle radiation the exposure rate (in mRem/ hr) should not be used. Only counts per minute (cpm) scale is appropriate for particle detection. Thin-window G-M's monitor low energy beta emitters with low efficiency (3% for C-14 and S-35) and they do not respond at all to the betas from Tritium (H-3).

5.2.2. Ionization Chamber Survey Instruments

Survey instruments utilizing an air ionization chamber are designed to measure exposure in mRems. They exhibit much less ‘energy-dependence’ of response than G-M devices and can be used at much higher rate levels.

5.2.3. Scintillation Survey Instruments

Portable survey units are available that utilize a solid sodium iodide crystal coupled to a sensitive photomultiplier tube as the detector. The solid scintillator provides excellent sensitivity making them ideal for monitoring large contaminated areas. Unfortunately, survey instruments of this type are very energy dependent and should be calibrated with radionuclides that they are subsequently used to monitor. These devices are more expensive and more fragile than their G-M counterparts.

6.0 CONTROL OF RADIATION EXPOSURE

Controlling radiation exposure for all of the radionuclides used at our institution can be achieved by:

- Recognizing sources of potential external exposure
- Avoiding intake

6.1. Protection from External Radiation

6.1.1. X-RAY and Gamma Emitters

One should limit the involvement time and maximize the distance from the radioactivity within reason to control external exposure. In special cases shielding is used to achieve acceptable exposure levels. The three concepts of time, distance, and shielding are considered the cardinal principles for controlling external radiation.

Distance from the source is a valuable ally. The exposure level varies inversely with square of the distance from the source (this inverse square relationship applies for distances largely compared to the physical dimensions of the radiation source). Thus, doubling the distance will result in a 4-fold reduction of dose rate, tripling the distance will result in a 9-fold reduction, etc.

A measure of the exposure rate in air due to a small unit source of activity at a standard distance is given by the radionuclide's ‘exposure rate constant’. This constant is also referred to as the gamma-factor. Chromium-51, Iodine-125, and Iodine-131 are commonly used gamma-emitting radionuclides.

Normally small quantities of gamma-emitting radionuclides are stored in individual vials placed in Lead-lined storage area, either in a heavily shielded container known as a ‘pig’ or behind Lead bricks. The thickness of the shielding and its location far from personnel can help maintain acceptable exposure situations even for high activities of radionuclides.

6.1.2. Beta Emitters

Most of the pure beta-emitting radionuclides used at CWRU emit only low energy particles that are not very penetrating. The beta particle emitted by Hydrogen-3, Carbon-14, Sulfur-35, and Calcium-45 will not penetrate the walls of most vessels and, accordingly, pose little or no threat except for internal contamination. However, one extensively used radionuclide, Phosphorus-32 (P-32), emits beta particles of sufficient energy to penetrate both the container walls and the dead-layer of skin. The maximum range is 7mm of unit density material (the range in other materials can be estimated by simply dividing the range in unit density material by the material's specific gravity; thus, the range of the beta-particles of P-32 in aluminum is 7 mm / 2.7 = 2.6 mm).

High skin and eye radiation doses can be incurred while handling P-32. For example, the dose rate to fingers in contact with the sides of a small glass vial of P-32 is about 400 mRem/ hour/ mCi. The beta dose incurred while handling P-32 or other high energy beta-emitters can be maintained at a low level by keeping fingers as far from the radioactivity as possible (use tongs when feasible) and utilizing Plexiglas shielding to absorb the betas. A ring badge is required for all personnel who handle more than 0.5 mCi of any high-energy beta emitter, such as P-32.

6.2. Protection from Internal Radiation

Fortunately, most of the RAM used at CWRU poses little or no external radiation threat. Hence, efforts to minimize internal contamination are important. To provide some perspective regarding tolerable internal contamination levels, the Ohio Department of Health (ODH) specifies maximum ‘annual limits on intake’ (ALI). The concept of the ALI is that it represents the quantity of a given radionuclide that, if ingested or inhaled by an individual, will result in the same cancer risk as that attributed to 5 Rem of whole body dose. The ALI's for some commonly employed radionuclides as per OAC 3701:1-38-12 of the Ohio Department of Health:

Annual Limit on Intake

Radionuclide	Oral Ingestion (μCi)	Inhalation (μCi)
Tritium (H-3)	80,000	80,000
Carbon-14	2,000	2,000
Phosphorus-32	600	900
Calcium-45	2,000	800
Chromium-51	6,000	10,000
Iodine-125	40	60
Iodine-131	30	50

However, annual intake of less than 0.01% of the ALI's shown above is possible even in the case of personnel who handle large quantities of radionuclides. Practices that help to minimize internal contamination include:

- Laboratory coats or other protective clothing should be worn at all times when handling unsealed RAM.
- Disposable gloves and safety goggles should be worn while handling unsealed RAM.
- Potentially contaminated gloves should not be worn when handling non-contaminated materials.
- Hands, shoes, and clothing should be monitored for contamination after each procedure and before leaving the area.
- No eating, drinking, smoking or application of cosmetics should occur in areas where RAM is used or stored.
- Food or beverages should not be stored with RAM.
- Telephones, light switches, faucet handles, and doorknobs, etc. should not be handled with contaminated gloves.
- Absorbent pads should be used for containing and easily disposing of small amounts of contamination.
- Procedures involving RAM should be confined to as small an area of the laboratory as is reasonable, thus limiting the potentially contaminated space.
- Please consult the Radiation Safety Manual, which is located on the EHS website, for classifying the spill and the procedure for spill clean up.
- Wipe tests should be conducted periodically according to laboratory's protocol and any University or ODH requirements.

Most of the radionuclides used at CWRU are considered only slightly toxic with regard to internal contamination. However, I-125 and I-131 are considered highly toxic because of their specificity for the thyroid gland. Internal contamination via ingestion, inhalation, or skin absorption can result in a high thyroid dose. Computed thyroid doses are 3.2 and 5.2 Rem/ uCi in the thyroid for I-125 and I-131 respectively.

7.0 RULES AND REGULATIONS AFFECTING THE USE OF RADIOACTIVE MATERIAL

The possession and use of the majority of the RAM at CASE is authorized by licenses issued by the Ohio Department of Health (ODH). Some of the more important regulations are as follows:

Occupational Dose Limits as per OAC 3701:1-38-12 of the ODH

Dose Category	Limit per Calendar Year (Rem)
Total effective dose equivalent (whole body)	5.0
Sum of deep-dose equivalent and the committed dose equivalent to an individual organ or tissue other than the lens of the eye	50
A shallow dose equivalent to the skin or any extremity	50
Lens of the eye	15
Dose to the embryo/fetus of a Declared Pregnant Woman during duration of pregnancy	0.5

In addition, the CWRU endorses and practices a program of maintaining radiation worker doses ‘as low as reasonably achievable’ (ALARA). The program has the goal of maintaining personnel doses and environmental releases to less than 10% of the limits authorized by federal law. The CWRU ALARA limits are as follows:

* Whole Body	100 mRem/ qtr
* Extremity	500 mRem/ qtr
* Fetal	50 mRem for duration of pregnancy

7.1. Classification of Areas

7.1.1. Restricted Areas

A restricted area is one where the access to which is controlled by the licensee to protect individuals from undue risks from exposure to radiation and RAM. Restricted areas are posted with warning signs and have limited access. The signs may be any of the following:

- ‘Caution Authorized Personnel Only’ - Used to inform individuals entering the area of a potential hazard.
- ‘Caution Radioactive Materials’ - Signifies that significant amounts of radioactive material are used or stored in the area.

- ‘Caution Radiation Area’ - Denotes areas accessible to personnel in which the dose rate may exceed 5 mRem per hour.
- ‘Caution Airborne Radioactivity Area’ - Used to warn individuals that airborne activity concentration exceeds of the state limit for airborne activity in a restricted area or may exceed 25% of the state limit when the activity is averaged over the hours that any individual is in the area.

Each of the signs bears the three-bladed trefoil used as the universal symbol for radiation. The symbol is usually magenta or purple on a yellow background.

7.1.2. Unrestricted Areas

An area is unrestricted (access to the area is not limited or controlled for radiation protection purposes) if the radiation dose in the area is less than 2 mRem per hour or 100 mRem per year.

7.2. Personnel Monitoring

Personnel monitoring is required if an individual receives or is likely to receive radiation doses exceeding 10% of the ODH limits previously specified.

7.3. Environmental Contamination Levels

The concentration of radioactivity in air and water are restricted by State law to values according to radionuclide as per OAC 3701:1-38-12 of the ODH.

7.4. Radioactive Waste Disposal

The disposal of radioactive waste is strictly regulated. Most of the institutional radioactive waste is disposed through the Radiation Safety Office (RSOF). Disposal of small amounts of radioactive wastes via approved drains and ventilation systems are permitted in the laboratories provided records of the levels are maintained. It is imperative that radioactive waste be segregated from the regular waste of the University.

7.5. Posting of Notices to Workers

The ODH ‘Notice to Employees’ must be posted wherever individuals work in restricted areas. In addition, certain documents (CWRU’s licenses with the

ODH, the applicable state regulations, notices of violation and the institution's response, etc.) must be available to employees.

8.0 CONDITIONS IMPOSED BY THE CWRU RADIATION SAFETY PROGRAM

The Radiation Safety Manual is a detailed discussion of all areas of the CWRU Radiation Safety Program and can be downloaded from our website at: https://www.case.edu/ehs/RadSafety/ .

9.0 GLOSSARY OF TERMS

-A-

Accelerator Produced Material: Any material made radioactive by a particle accelerator.

Activation: The process of inducing radioactivity by irradiation.

Activity: The name for the measure of the quantity of a radionuclide in terms of the number of nuclear transformations occurring per unit time. The new SI unit of activity is the Becquerel (Bq). The older special unit of activity is the Curie (Ci).

Alpha Particle: A heavy charged particle emitted from a radionuclide undergoing alpha disintegration. The alpha particle is a nuclide equivalent to the nucleus of a helium atom.

Atom: Smallest particle of an element that is capable of entering into a chemical reaction.

Atomic Mass: The mass of a neutral atom of a nuclide, usually expressed in terms of ‘atomic mass units.’ The ‘atomic mass units’ is one-twelfth the mass of one neutral atom of carbon-12; equivalent to 1.6604 E-24 grams.

Atomic Number (Z): The number of protons in the nucleus of a neutral atom of a nuclide. The ‘effective atomic number’ is calculated from the composition and atomic numbers of a compound or mixture. An element of this atomic number would interact with photons in the same way as the compound or mixture.

Atomic Weight: The weighted mean of the masses of the neutral atoms of an element expressed in atomic mass units.

Attenuation: The process by which a beam of radiation is reduced in intensity when passing through some material. It is the combination of absorption and scattering processes and leads to a decrease in flux density of the beam when projected through matter.

Audit: Any periodic review of the documentation and activities carried out under this license in order to verify compliance with the requirements of the license. The audits shall be conducted using written procedures or checklists, and the results shall be documented.

Authorized User (AU): A faculty member who, with joint approval by the RSC and the RSO, is duly and immediately responsible for the proper and safe use, storage and ultimate disposal of a source or sources of ionizing radiation.

-B-

Becquerel (Bq): The SI name for the unit of radioactivity. 1 Bq = 1 dps = 2.7E-11 Ci.

By-product Material: Any RAM, except special nuclear material, made radioactive by exposure to the radiation produced while using special nuclear material.

Beta Particle: Charged particle emitted from the nucleus of an atom, with a mass and charge equal in magnitude to that of an electron.

Bremsstrahlung: Secondary photon (x-ray) radiation produced by acceleration of beta particles interacting with Coulombic positive field of a nucleus.

-C-

Calibration:
- To determine the ‘correction factor’ to be applied to an instrument reading.
- To determine the magnitude of the radiation beam intensity produced by any RGE.
- To determine the true activity and/or radiation field intensity of a RAM source.

Chamber, Ionization: An instrument designed to measure a quantity of ionizing radiation in terms of the charge of electricity associated with ions produced within a defined volume.

Common Use Area: An area, often a room, identified as a work area for one or more radiation sources and used by more than one persons holding USE PERMITS for one or more of the sources. One of these individuals is responsible for the safe operation of the work area.

Contamination, Radioactive: Deposition of RAM in any place where it is not desired, particularly where its presence may be harmful. The harm may be in spoiling an experiment or a procedure, or in actually being a source of danger to personnel.

Controlled Area: A defined area in which the occupational exposure of personnel (to radiation) is under the supervision of the Authorized User.

Count (Radiation Measurements): The external indication of a device designed to enumerate ionizing events. It may refer to a single detected event or to the total number registered in a given period of time. The term often is erroneously used to designate a disintegration, ionizing event, or voltage pulse.

Counter, Geiger-Mueller: Highly sensitive, gas filled radiation-measuring device. It operates at voltages sufficiently high to produce avalanche ionization.

Counter, Scintillation: The combination of phosphor, photomultiplier tube, and associated circuits for counting light emissions produced in the phosphors.

Curie: The special unit of activity. One Curie equals 3.7×10^{10} nuclear transformations per second or 3.7×10^{10} Bq, (Abbreviated Ci). Several fractions of the Ci are in common use:

- MicroCurie (uCi): One-millionth of a Ci (3.7×10^{4} disintegrations/ sec).
- MilliCurie (mCi): One-thousandth of a Ci (3.7×10^{7} disintegrations/ sec).
- PicoCurie (pCi): One-millionth of a uCi (3.7×10^{-2} disintegrations/ sec or 2.22 disintegrations/ min).

-D-

Dose: A general form denoting the quantity of radiation or energy absorbed. For special purposes it must be appropriately qualified. If unqualified, it refers to absorbed dose.

Absorbed Dose: The energy imparted to matter by ionizing radiation per unit mass of irradiated material at the place of interest. The unit of absorbed dose is the ‘Rad’. 1 Rad equals 100 ergs/ gram. (See Rad.) The SI unit of absorbed dose is the ‘Gray’.

Cumulative Dose (Radiation): The total dose resulting from repeated exposures to radiation.

Dose Equivalent (DE): A quantity that expresses, on a common scale for all types of radiation, a measure of the biological effect on a given tissue. The DOSE EQUIVALENT is the product of the ABSORBED DOSE and a QUALITY FACTOR. (See QUALITY FACTOR.) The SI unit for Dose Equivalent is the Sievert (Sv). The common unit of Dose Equivalent is the ‘Rem’.

Dose Rate: Absorbed dose delivered per unit time.

Dosimeter: Instrument to detect and measure accumulated radiation exposure. In common usage, a small Luxel dosimeter is used for personnel monitoring.

-E-

Efficiency (Counters): A measure of the probability that a count will be recorded when radiation is incident on a detector. Usage varies considerably, so it is well to ascertain which factors (window transmission, sensitive volume, energy dependence, etc.) are included in a given case.

Exempt Quantity: A quantity of a radionuclide that may be possessed by persons without regulatory concern. The only ‘exemptions’ under our broad scope license apply to special conditions for reportability and disposal. Simply, no RAM is exempt from licensing control.

Exposure: A measure of the radiation intensity in air. This measure is in terms of the electric charge deposited in a unit mass of air’ due to the ionization produced by X-RAYor gamma radiation intensity in the air. The special unit of exposure is the ‘Roentgen’.

-F-

Film Badge: A pack of photographic film, which measures radiation exposure for personnel monitoring. The badge may contain two or three films of differing sensitivity and filters to shield parts of the film from certain types of radiation for determination of energy ranges and direction and intensity of radiation. These have been replaced by Luxel dosimeters.

Finger Tab/Ring: A radiation dosimeter in the form of a ring to be worn around the finger.

-G-

Gamma Ray: Short wavelength electromagnetic radiation of nuclear origin (range of energy from 10 keV to 9 MeV) emitted from the nucleus.

Gray (Gy): is the SI name for the unit of Absorbed Dose. It is measured in Joules per kilogram. 1 Gy = 1 J/ kg = 100 Rad.

-H-

Half-life, Radioactive: Time required for a radioactive substance to lose 50 percent of its activity by disintegration. Each radionuclide has a unique half-life.

High Radiation Area: A high radiation area is a restricted area to which access is controlled to limit exposure to radiation levels and or contamination by radioactive materials. Radiation levels may exceed 100 mRem/ hr at 30 cm from a source. See RADIATION AREA. NOTE. When radiation levels in this range are present, a ‘Caution - High Radiation Area’ sign must be displayed. When radioactive materials are present, a ‘Caution - Radioactive Materials’ sign must be displayed.

-I-

Inspection: An official examination of all or part of an AU's area of responsibility for items controlled by this program.

Ionizing Radiation: Gamma rays and x-rays, alpha and beta particles, high-speed electrons, neutrons, protons, and other atomic or nuclear particles or rays that cause ionization when they interact with matter.

-M-

Monitor:

- To measure radiation or surface contamination levels for immediate information without documentation as in ‘to monitor gloves while doing a procedure.’
- To accumulate a record of exposure as in ‘a personal radiation monitor’.

Monitoring: Periodic or continuous determination of the amount of ionizing radiation or radioactive contamination present in an occupied region.

- Area Monitoring: Routine monitoring of the radiation level or contamination of a particular area, building, room, or equipment. Some laboratories or operations distinguish between routine monitoring and survey activities.
- Personnel Monitoring: Monitoring any part of an individual, his breath, or excretions, or any part of his clothing.

-N-

Non-Ionizing Radiation: Means any ELECTROMAGNETIC RADIATION except X-RAYS and GAMMA RAYS that does not produce ionization (laser light and microwaves).

-P-

Particle Accelerator: Any device capable of accelerating charged particles to energies in excess of 1 MeV.

Photon: A quantity of electromagnetic energy (E) whose value in joules is the product of its frequency (v) in hertz and Planck constant (h). The equation is: E= hv.

Positron: Particle equal in mass to the electron and having equal but positive charge.

-Q-

Quality Factor (QF): The linear-energy-transfer-dependent factor by which absorbed doses are multiplied to obtain (for radiation protection purposes) a quantity that expresses- on a common scale for all ionizing radiation - the effectiveness of the absorbed dose. These dimensionless quantities (QF) used to calculate DOSE EQUIVALENT from the ABSORBED DOSE are given here.

RADIATION TYPE	QF
X-ray, Gamma or Beta	1
Medium energy protons	20
And alpha particles	20
High energy protons and neutrons	10

-R-

Rad: The unit of absorbed dose equal to 100 ergs per gram or 0.01 Gy in any medium. (See Absorbed Dose.)

Radiation:

- The emission and propagation of energy through space or through a material medium in the form of waves; for instance, the emission and propagation of electromagnetic waves, or of sound and elastic waves.
- The energy propagated through space or through a material medium as waves; for example, energy in the form of electromagnetic waves or of elastic waves. Such radiation commonly is classified, according to frequency, as hertzian, infrared, visible (light), ultra-violet, x-ray, and gamma ray. (See Photon.)
- By extension, corpuscular (particulate) emissions, such as alpha and beta radiation, or rays of mixed or unknown type, as cosmic radiation.

Radiation Area: A radiation area is a RESTRICTED AREA into which access is controlled to limit exposure to radiation levels and or contamination by radioactive materials. Radiation levels may exceed 5 mRem/hr at 30 cm from a source. See HIGH RADIATION AREA. NOTE: When radiation levels in this range are present, a ‘Caution-Radiation Area’ sign must be displayed.

When radioactive materials are present, a ‘Caution-Radioactive Materials’ sign must be displayed.

Radiation Generating Equipment (RGE): Any device that produces radiation only while in operation.

Radiation Safety Committee (RSC): A Case Western Reserve University (CWRU) committee formed and maintained to assist the President and Administration in generating, implementing, and monitoring a Radiation Control and Safety Program necessary to assure compliance with state and Federal regulations.

Radiation Safety Office (RSOF): The Radiation Safety Officer (RSO) and support staff. Telephone Number (216) 368-2906.

Radiation Safety Officer (RSO): The CWRU individual who is given the authority by the Radiation Safety Committee (RSC) to implement and oversee the Radiation Control and Safety Program.

Radiation Source: Any source of RAM or any RGE controlled by this program.

Radiation Worker: An individual who has successfully fulfilled the administrative and training requirements identified by the Radiation Safety Office (RSOF) for the use of radiation sources for research and academic purposes at Case Western Reserve University (CWRU).

Radioactive Material (RAM): Any material that emits radiation spontaneously.

Radiological Emergency: A state of affairs in which radiation levels or radionuclides present or are about to present an immediate danger to personnel or facilities.

Release: The unintentional escape of RAM into air that produces concentrations in excess of the permissible air concentrations established for that area.

Rem: A special unit of dose equivalent. The dose equivalent in Rem is numerically equal to the absorbed dose in Rad multiplied by the quality factor. The SI unit is the Sievert (Sv). (1 Sv =100 Rem)

Restricted Area: Any area to which access is controlled for the purpose of limiting personnel exposure to ionizing radiation.

Roentgen (R): The special unit of exposure. One roentgen equals 2.58 e-04 coulomb per kilogram of air. (See Exposure.)

-S-

Sealed Source: A radioactive source sealed in an impervious container that has sufficient mechanical strength to prevent contact with and dispersion of the RAM under the conditions of use and wear for which it was designed.

Shield: A body of material used to prevent or reduce the passage of particles or radiation. A shield may be designated according to what it is intended to absorb (as a gamma-ray shield or neutron shield), or according to the kind of protection it is intended to give (as a background, biological, or thermal shield).

SI: The symbol for the international system of units.

Sievert (Sv): The SI special name for the unit of DOSE EQUIVALENT.
1 Sv = 1 J/kg = 100 Rem.

Source Material:

- Any form or combination of uranium or thorium or
- Ores with 0.05% or more of uranium or thorium.

Special Nuclear Material: Any of, or any material enriched with, the following but excluding SOURCE MATERIAL. Plutonium, U-233, and materials enriched with U-233 or U-235. (Materials that are readily fissionable with ‘thermal’ neutrons.)

Special Unit: A unit name in use but not in the list of standard units defined by SI.

Spill: The unintentional escape of RAM onto a surface, which produces contamination levels in excess of the permissible surface contamination levels established for that area.

Survey:

- A documented evaluation of the radiation safety status of a laboratory.
- A documented evaluation of radiation levels in an area.
- A documented evaluation of the amount of tested removable contamination on wipe tested surfaces

Survey, Radiation: Evaluation of the radiation hazards incident to the production, use, or existence or radioactive materials or other sources of radiation under specific conditions. Such evaluation customarily includes a physical survey of the disposition of materials and equipment, measurements or estimates of the levels of radiation that may be involved, and sufficient knowledge of processes using or affecting these materials to predict hazards resulting from expected or possible changes in materials or equipment.

-T-

Tritium (H-3): The hydrogen isotope with one proton and two neutrons in the nucleus.

-W-

Wipe Test: A procedure designed to evaluate the amount of removable radionuclide contamination present on a surface. A small, clean absorbent pad is wiped over a 100cm2 area. The wipe (the contaminated pad) is assayed for radionuclide content. The assay result is in dpm.

-X-

X-Rays: Penetrating electromagnetic radiation whose wavelengths are shorter than those of visible light. Bombarding a metallic target with fast electrons in a high vacuum usually produces them. In nuclear reactions, it is customary to refer to photons originating in the nucleus as gamma rays, and those originating in the extra-nuclear part of the atom as x-rays.