



# DEPARTMENT OF ENVIRONMENTAL SAFETY, SUSTAINABILITY & RISK

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## **Radiation Protection Training Manual & Study Guide**

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December 1986  
Revised 1994

Radiation Safety Office  
Radiation Protection Training Course  
**Course Outline**

Time	Lecture Topic	Reference Material
20 Min	<b>Introduction</b>	Radiation Safety Manual and ESSR RSO Procedures
1 Hour	<b>Fundamental Radiation Concepts</b> <ul style="list-style-type: none"><li>• The Radioactive Atom</li><li>• Radioactive Decay Modes</li><li>• Radioactive Decay Equation</li><li>• Radioactive Units</li><li>• Interactions of Radiation with Matter</li></ul>	Study Guide Chapter I Problem Set 1
	Demonstration: <ul style="list-style-type: none"><li>• Inverse Square Law, Penetrability of Radiation</li></ul>	
1 Hour	<b>Radiation Instrumentation</b> <ul style="list-style-type: none"><li>• Portable Survey Instruments</li><li>• Use of Radiation Survey Instruments</li><li>• Calibrations and Efficiency</li><li>• Liquid Scintillation Counting</li><li>• Statistics of Counting</li></ul>	Study Guide Chapter 2 Problem Set2
	Demonstration: <ul style="list-style-type: none"><li>• GM, Ion Chamber, Alpha Proportional Survey Instruments</li></ul>	
1 Hour	<b>Source and Effects of Radiation</b> <ul style="list-style-type: none"><li>• Biological Effects of Radiation</li><li>• Radiation Exposure Limits</li><li>• Radiation from Background, Medical and Consumer Products</li></ul>	Study Guide Chapter 3 Problem Set 3
	Demonstration:	

	<ul style="list-style-type: none"> <li>• Radioactive Material in Consumer Products</li> </ul>	
3 Hours	<b>Radiation Protection and Laboratory Techniques</b> <ul style="list-style-type: none"> <li>• External Radiation Protection</li> <li>• Internal Radiation Protection</li> <li>• Protective Clothing</li> <li>• Workplace</li> <li>• Manipulations of Radioactive Materials</li> <li>• Emergency Procedures</li> <li>• Radioactive Waste Disposal</li> <li>• Contamination Surveys</li> <li>• Radioactive Contamination Limits</li> <li>• Decontamination Procedures</li> </ul> <p><i>Video Tape:</i></p> <ul style="list-style-type: none"> <li>• Laboratory Techniques and Emergency Procedures</li> </ul>	Study Guide Chapter 4 Problem Set 4
2 Hours	<b>Radiation Protection Program</b> <ul style="list-style-type: none"> <li>• Rules and Regulations</li> <li>• Applicable UMD Directives</li> <li>• Course Review</li> <li>• Course Evaluation</li> <li>• Examination</li> </ul> <p><i>Video Tape:</i></p> <ul style="list-style-type: none"> <li>• Radiation Safety</li> </ul>	Study Guide Chapter 5

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## **Introduction**

This Training Manual and Study Guide serves as the main text for the UMD Radiation Safety Office Training Course entitled "Basic Radiation Safety". Each of the five chapters correspond to the lecture topics presented during an eight hour course. This course is offered periodically in conformance with State regulations requiring that individuals working with radioactive materials and radiation producing equipment be adequately trained. The practical problem sets at the end of each chapter and their detailed solutions also make the Guide useful for self-study in the event that participation in the formal course is not possible. The concepts and ideas presented in the text require a fundamental understanding of biology, physics and mathematics. While the material is presented in its most basic form, undoubtedly some ambiguities will remain. A bibliography is provided for the interested student to further his or her knowledge in this area. The Radiation Safety Office is available to answer any question or aid any user in the radiation science field. We welcome all inquiry and would appreciate comments and suggestions on how to improve this Study Guide, Training Course or our Radiation Safety Program.

## **Radiation Safety Office**

The Radiation Protection Training Course has been established to satisfy the training requirements for University of Maryland personnel who use or are subjected to radioactive materials. The course will be presented periodically. Personnel who are unable to attend the formal lecture presentation may pursue a course of study on their own by using the Radiation Protection Training Manual and Study Guide for study and completing the Problem Sets which are included. Upon completion of the study course or lecture, an examination will be given to authenticate completion of the program requirements. Receipt of the completed examination by the Radiation Safety Officer will be the only acceptable course completion documentation. A Certificate of Achievement will be presented to those who have successfully completed the course and a permanent record of training completion will be on file in the Radiation Safety Office.

## **Radiation Protection Training Course Lesson Plan Outline**

**Instructional Subject:** Fundamental Radiation Concepts

- The Radioactive Atom
- Radioactive Decay Modes
- Radioactive Decay Equation
- Radioactive Units
- Interactions of Radiation with Matter

**Instructor:** To be determined

**Instructional Goal:** To provide the participant with a basic knowledge of radiation concepts.

**Instructional Objectives:** The participant should be able to accomplish the following:

- Recognize the differences of radioactive materials
- Know where to go for information on decay modes
- Be able to use decay equation to determine activity of isotopes
- Be able to identify and use radioactive units
- Know how interactions occur

**Training Support Material:** Handouts  
Study Guide

**Video Tapes:** None

**Slides:** As determined by the instructor

**Equipment Required:** As determined by the instructor

**Reference Material:** Radiation Protection Training Manual and Study Guide - Chapter 1, Problem Set 1

## **Radiation Protection Training Course Lesson Plan Outline**

Instructional Subject:	Radiation Instrumentation <ul style="list-style-type: none"> <li>• Portable Survey Instruments</li> <li>• Use of Radiation Survey Instruments</li> <li>• Calibrations and Efficiency</li> <li>• Liquid Scintillation Counting</li> <li>• Statistics of Counting</li> </ul>
Instructor:	To be determined
Instructional Goal:	To provide the participant with a basic knowledge of instruments available and how they are used
Instructional Objectives:	Upon completion of this instructional period, the accomplish the following: <ul style="list-style-type: none"> <li>• Identify the different types of instruments and detectors</li> <li>• Be able to perform surveys with the appropriate instrument</li> <li>• Understand how instruments are</li> <li>• Have a basic understanding of statistics</li> </ul>
Training Support Material:	Handouts Study Guide
Video Tapes:	None
Slides:	As determined by the instructor
Equipment Required:	As determined by the instructor
Reference Material:	Radiation Protection Training Manual and Study Guide - Chapter 2, Problem Set 2

## **Radiation Protection Training Course Lesson Plan Outline**

Instructional Subject:	Sources and Effects of Radiation
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	<ul style="list-style-type: none"> <li>• Biological Effects of Radiation</li> <li>• Radiation Exposure Limit</li> <li>• Radiation from Background Medical and Consumer Products</li> </ul>
Instructor:	To be determined
Instructional Goal:	To provide the participant with information concerning the effects and limits of radiation exposure
Instructional Objectives:	<p>Upon completion of this instructional period, the participant should be familiar with the effects and limits allowed for radiation exposure in the use of radioisotopes and/or equipment and:</p> <ul style="list-style-type: none"> <li>• Be familiar with methods of protection</li> </ul>
Training Support Material:	Handouts Study Guide
Video Tapes:	None
Slides:	As determined by the instructor
Equipment Required:	As determined by the instructor
Reference Material:	Radiation Protection Training Manual and Study Guide - Chapter 3, Problem Set 3

### **Radiation Protection Training Course Lesson Plan Outline**

Instructional Subject:	<p>Radiation Protection and Laboratory Techniques</p> <ul style="list-style-type: none"> <li>• Internal and External Radiation Protection</li> </ul>
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	<ul style="list-style-type: none"> <li>• Work place and Protective Clothing</li> <li>• Manipulations of Radioactive Materials</li> <li>• Radioactive Waste Disposal</li> <li>• Surveys, Limits, and Decon Procedures</li> </ul>
Instructor:	To be determined
Instructional Goal:	To provide the participant with a basic knowledge of the work environment, methods of protection, equipment, and procedures for decontamination
Instructional Objectives:	<p>Upon completion of this instructional period, the participant should be able to accomplish the following:</p> <ul style="list-style-type: none"> <li>• Recognize internal and external radiation protection methods</li> <li>• Identify proper protective equipment to be used</li> <li>• Know how to segregate radioactive waste material</li> <li>• Be able to perform proper surveys, know limits, and use decontamination procedures</li> </ul>
Training Support Material:	Handouts Study Guide
Video Tapes:	As determined by instructor
Slides:	As determined by the instructor
Equipment Required:	As determined by the instructor
Reference Material:	Radiation Protection Training Manual and Study Guide - Chapter 4 Problem Set 4

## **Radiation Protection Training Course Lesson Plan Outline**

Instructional Subject:	<p>Radiation Protection Program</p> <ul style="list-style-type: none"> <li>• Rules and Regulations</li> <li>• Course Review</li> <li>• Course Evaluation</li> </ul>
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	<ul style="list-style-type: none"> <li>• Examination</li> </ul>
Instructor:	To be determined
Instructional Goal:	To provide information to the participant on requirements of a radiation protection program; Review all material covered and provide RSO with an evaluation of the course
Instructional Objectives:	<p>Upon completion of this instructional period, the participant should be able to accomplish the following:</p> <ul style="list-style-type: none"> <li>• Be knowledgeable of the rules and regulations and the requirements to have a radiation training program</li> <li>• Be able to demonstrate acceptable knowledge of the information presented to easily pass the test for the course</li> </ul>
Training Support Material:	Handouts Study Guide
Video Tapes:	As determined by instructor
Slides:	As determined by the instructor
Equipment Required:	As determined by the instructor
Reference Material:	Radiation Protection Training Manual and Study Guide - Chapter 5

## **Chapter I**

### **Fundamental Radiation Concepts**

#### **1. The Radioactive Atom**

All matter is composed of elements and all elements are composed of atoms. The atom contains a nucleus consisting of protons and neutrons with electrons revolving in circular and elliptical orbits about the nucleus. Electrons carry a negative charge, protons carry positive charge, and

the neutrons have no electrical charge. An atom normally has one electron in orbit for each proton in the nucleus, leaving the atom electrically neutral.

The atomic structure of an element is denoted as

where:

A

is the **Mass Number**, defined as the sum of the number of protons and neutrons in the nucleus. Thus, A minus Z gives the number of neutrons. An element may have different numbers of neutrons and still be chemically the same.

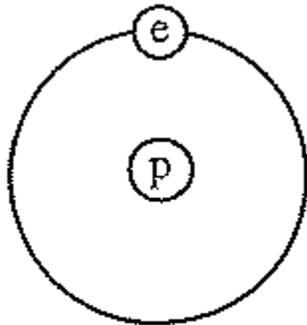
X

is the chemical symbol of the element:

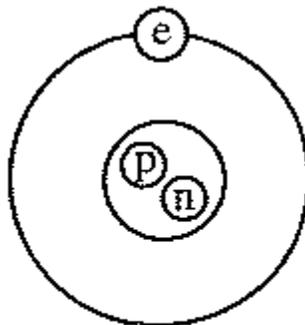
Z

is the **Atomic Number**, defined as the number of protons in the nucleus. This determines the chemical identity of the element:

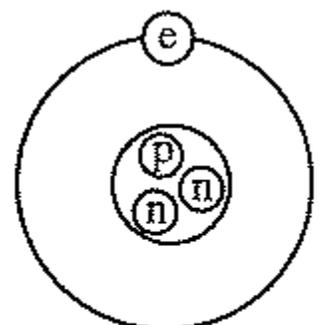
Each individual arrangement of protons and neutrons is referred to as a **Nuclide**. Nuclides which have the same number of protons are called **Isotopes**. Shown below are examples of isotopes of Hydrogen:



${}^1\text{H}$  Hydrogen  
1



${}^2\text{H}$  Deuterium  
1



${}^3\text{H}$  Tritium  
1

Many nuclides, but not all, are unstable or "radioactive". In the above examples, only tritium is radioactive. Radioactivity is defined as the spontaneous disintegration of unstable nuclei with the resulting emission of radiation that results in the formation of new nuclei. Stability of the nucleus is related to its ratio of neutrons to protons. For low atomic numbered elements, approximately equal numbers of neutrons and protons in the nucleus are necessary for stability. For elements of higher atomic number, the ratio rises to approximately 1.6 to 1. As a nuclide departs from this stable ratio, changes in the nucleus occur which tend to bring the product to a more stable arrangement. This approach to stability is accomplished by one or more of 5 "radioactive decay modes".

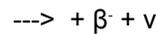
## 2. Radioactive Decay Modes

### A. Beta Decay

When the neutron to proton ratio is too high, a neutron "transforms" into a proton and electron with the electron being ejected from the nucleus. The ejected electron is called a "beta particle". Beta particles are not emitted with a single energy but are emitted with a spectrum of energies up to some maximum value. This is due to a division of the total energy of each disintegration between the beta particle and a neutrino. The Neutrino is a massless, chargeless particle that carries off varying amounts of the released energy. The neutrino has a negligibly small mass and no charge. It therefore travels great distances, losing little energy in nearby materials and causes no biological damage.

The energy of the ejected beta particle is characteristic of each nuclide and is one criterion used for identification purposes. In general, the average energy per particle is about 1/3 of the maximum energy.

The generalized atomic equation for beta decay is as follows:



X: Original (parent) atom  
Y: New (daughter) atom  
 $\beta^-$ : Beta particle (electron)  
 $\nu$ : Neutrino

Examples of Beta decay:



MeV: 1 million electron volts  
 $\beta^-$  max: Maximum beta particle energy

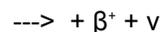


### B. Positron Decay

When the neutron to proton ratio is too low, the nucleus emits a beta particle with a positive charge (positron) resulting from the transformation of a proton into a neutron.

The positron behaves exactly as an electron except that when the positron comes in contact with a free electron, the two particles combine and are annihilated. This gives rise to two gamma rays whose energies correspond to the rest mass equivalence of the particles (0.511 MeV/gamma). See page 13 for a description of annihilation radiation.

The generalized atomic equation for positron decay is as follows:



$\beta^+$ : Positron (positive electron)

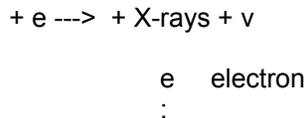
Example of Positron decay:



## C. Electron Capture

In this decay mode, one of the orbital electrons is captured by the nucleus and combines with a proton to form a neutron. Electron capture competes with positron decay when there is a low neutron to proton ratio. If the atom is unable to meet the energy requirements of positron decay, then decay occurs by electron capture. Whenever an atom decays by electron capture, X-rays (page 10) are emitted that are characteristic of the newly formed nuclide. No particles are emitted during electron capture decay.

The generalized atomic equation for electron capture is:



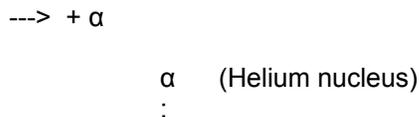
Example of electron capture decay:



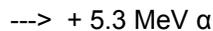
## D. Alpha Decay

Alpha decay occurs for those nuclides that have an atomic number greater than 82. Such heavy nuclides have no stable configuration of neutrons and protons and as a result emit an alpha particle consisting of 2 protons and 2 neutrons. Generally, a series of alpha (as well as beta) decays are required until a lighter, more stable element is reached. Unlike beta particles, alpha particles are emitted with a discrete energy.

The generalized atomic equation for alpha decay is:



Example of alpha decay:



## E. Nuclear Transition - Gamma Ray Emission

Gamma rays (page 8) are emitted when the emission of a particle leaves the product nucleus in a partially excited or "metastable" state. The gamma rays carry away the excess energy of the partially excited nucleus after a decay event. Such gamma rays are of discrete energy, are characteristic of the particular nuclide involved and can be used for identification purposes.

Nuclear transition can occur after beta decay, positron decay, electron capture and alpha decay.

Example of radionuclides that undergo nuclear transition are shown below:

$$\text{---> } + 0.318 \text{ MeV } \beta^- + 1.17 \text{ MeV } \gamma; 1.33 \text{ MeV } \gamma$$

$$\text{---> } + 0.546 \text{ MeV } \beta^+ + 1.27 \text{ MeV } \gamma$$

$$\text{---> } + 0.035 \text{ MeV } \gamma (6.67\%) + \text{X-rays}$$

$$\text{---> } + 4.78 \text{ MeV } \alpha (93.4\%) + 4.59 \alpha (5.7\%) + 0.186 \text{ MeV } \gamma + \text{X-rays}$$

The [Chart of the Nuclides \(Appendix I\)](#) list all known nuclides and is a useful reference for radioactive decay and energy data.

### 3. The Radioactive Decay Equation

A radioactive nuclide disintegrates or decays spontaneously at a rate depending on the number of original atoms present and upon its decay constant, lambda ( $\lambda$ ). This constant  $\lambda$  is defined as the instantaneous fraction of atoms decaying per unit time. Each radioactive nuclide has its own characteristic decay constant.

The instantaneous time rate of change of the number of atoms, N, for a radionuclide is given by:

$$= -\lambda N$$

If we started with  $N_0$  radioactive atoms at some time  $t=0$ , the number of atoms at some other time  $N_t$ , can be obtained by integrating:

$$= -\lambda dt$$

The  $e^{-\lambda t}$  term indicates that the radioactive atoms decay exponentially. This equation is called the decay equation.

$$N_t = N_0 e^{-\lambda t}$$

If we were to substitute into the decay equation the time, T, it takes for the reduction of a quantity of radioactive atoms to half of the original, we get:

$$N_T = N_0$$

$$N_0 = N_0 e^{-\lambda T_{1/2}}$$

$$= e^{-\lambda T_{1/2}}$$

$$\ln \frac{1}{2} = -\lambda T_{1/2} \text{ Therefore } (\ln \frac{1}{2} = \ln 1 - \ln 2; \ln 1 = 0)$$

$$\text{Therefore } -\ln 2 = -\lambda T_{1/2}$$

$$T_{1/2} = \ln 2 / \lambda (\ln 2 = 0.693)$$

$$\text{Therefore } \lambda =$$

Thus, the decay constant,  $\lambda$ , can be calculated for any radioactive nuclide from its half-life.

## 4. Radioactivity Units

The instantaneous number of atoms,  $N$ , remaining at a particular instant in time is given by:

$$A = \lambda N$$

$A$  is the activity, defined as the instantaneous number of atoms decaying per unit time. The activity determines the quantity of radioactive material in a sample. The special unit for activity is called the Curie (Ci).

$$\begin{aligned} 1 \text{ Curie} &= 3.7 \times 10^{10} \text{ disintegrations per second (DPS)} \\ &= 3.7 \times 10^{10} \text{ Becquerel} \end{aligned}$$

OR

$$1 \text{ Curie} = 2.22 \times 10^{12} \text{ disintegrations per minute (DPM)}$$

The International System (SI) of units has defined the Becquerel (Bq) as the unit of activity, equal to 1 disintegration per second. The Becquerel is already in use in some parts of the world and will eventually replace the Curie.

Because the Curie is a very large quantity, fractions of the Curie are often used:

$$\begin{aligned} 1 \text{ millicurie (mCi)} &= 2.22 \times 10^9 \text{ DPM} &= 10^{-3} \text{ Curies} \\ 1 \text{ microcurie} &= 2.22 \times 10^6 \text{ DPM} &= 10^{-6} \text{ Curies} \\ (\mu\text{Ci}) & & \\ 1 \text{ nanocurie (nCi)} &= 2.22 \times 10^3 \text{ DPM} &= 10^{-9} \text{ Curies} \\ 1 \text{ picocurie (pCi)} &= 2.22 \text{ DPM} &= 10^{-12} \text{ Curies} \end{aligned}$$

Since radioactive material is measured in units of activity, the decay equation now takes the form:

$$A = A_0 e^{-\lambda t}$$

Where

- $A$ : Activity after some time  $t$
- $A_0$ : Original activity of the sample
- $\lambda$ : The radioactivity decay constant equal to
- $T_{1/2}$ : Half-life of isotope
- $t$ : Decay time

Note. The decay time and half-life must be expressed in the same units of time.

## 5. Interactions of Radiations with Matter

Radiation interacting with matter can be either scattered or absorbed. The mechanisms of the absorption of radiation is of interest because:

- Absorption in the body tissue may result in biological injury.
- Absorption is the principle upon which detection of radiation is based.
- The degree of absorption is the primary factor in determining proper shielding requirements.

The transfer of energy from emitted radiations to matter occurs in two major ways: Ionization and Excitation.

**Ionization:**

The process resulting in the removal of an electron from an atom, leaving the atom with a net positive charge.

**Excitation:**

Addition of energy to an atomic system, transferring it from the ground state to an excited state.

Radiation can be classified into two groups:

- Particulate radiation (charged particles) such as alpha and beta particles: or
- Electromagnetic radiation such as X or gamma rays.

## A. Interaction of Charged Particles

All atoms are normally electrically neutral. When a charged particle strikes an orbital electron, it ejects it from the atom resulting in the formation of an ion pair. Since the removal of the electron from the atom decreases the total number of negative charges by one, it leaves the atom with a net positive charge. The ion pair consists of:

1. The positively charged atom.
2. The negatively charged electron.

Such particles capable of creating ion pairs in this manner are called ionizing radiation. The term used to compare and relate the ionizing powers of different types of charged particles is called the "specific ionization" Specific ionization is defined as the number of ion pairs per unit path length formed by ionizing radiation in a medium:

Specific Ionization =

The specific ionization is dependent on the velocity of the charged particle (and therefore its energy), and the density of the absorbing material (the number of atoms available for ionization).

### 1. Alpha Particles

An alpha particle is a helium nucleus stripped of its orbital electrons. It is emitted from a radioactive atom with a velocity of about 1/20 that of the speed of light and with energies ranging from 4 to 9 MeV. Alpha particles cause ionizations in matter when they are deflected by the positive charge of a nucleus and pull the orbital electrons (attracted by the alpha's positive charge) along with them. Alpha particles also cause excitation along their path by pulling inner orbital electrons to

outer orbits. No ion pair is formed, but energy is lost from the alpha particle and added to the atom. The added energy is then given off by the atom as fluorescent radiation or low energy X-Rays when the electrons drop back down to the inner orbital vacancies.

Because of its relatively large mass (2 neutrons and 2 protons), high electrical charge (+2) and low velocity, the specific ionization of an alpha particle is very high. That is, it creates many ion pairs in a very short path length. Because of this, it loses all of its energy in a very short distance. The range in air is only several centimeters even for the most energetic alpha particles.

Since the alpha particle has a very limited range in matter, it presents no external radiation hazard to man. Many alpha particles cannot penetrate the protective layer of skin. However, once inside the body, surrounded by living tissue, damage will be to the local area in which the alpha emitter is deposited. Thus, alpha emitters are an internal hazard and intake to the body must be prevented. (See Chapter IV, "Radiation Protection Techniques").

## **2. Beta Particles**

Beta particles are emitted from the nucleus of a radioactive atom with a wide range of energies up to some maximum value. When a beta is emitted that is below the maximum value, the neutrino carries away the rest of the energy.

Beta particles, like alpha particles, lose their energy by ionization and excitation, but because of their small mass (1/7300 of an alpha) and lower charge (1/2 of that of an alpha) the interactions take place at less frequent intervals. Therefore, the beta particles do not produce as many ion pairs per centimeter of path as alpha particles, and thus, have a greater range in matter. The beta particle's range in matter depends on the energy and the composition of the material. (See Appendix III, "Penetration Ability of Beta Radiation").

Beta particles can interact with a nucleus of an element and give rise to X-rays by a method called Bremsstrahlung. Bremsstrahlung (German for "Breaking Radiation") occurs when high speed beta particles approach the nucleus of an atom. The electrical interaction between the negative beta particle and the positively charged nucleus causes the beta particle to be deflected from its original path or stopped all together. Their stoppage or deflection results in a change in velocity of the beta particle with the emission of X- rays of various energies. The likelihood of Bremsstrahlung production increases with increasing atomic number of the absorber. For this reason, beta shields are made from low atomic numbered material, like aluminum or plastics.

Beta particles require an energy of greater than 70 keV to penetrate the protective layer of the skin, and thus, are somewhat of an external hazard. The beta can also constitute an internal hazard. A beta particle has a greater range in tissue compared to an alpha particle due to its low specific ionization. The beta particle gives up less energy per unit volume of tissue and, therefore, is not as effective in causing damage as an alpha particle.

## **B. Interaction of X-Rays and Gamma-Rays**

From a practical radiation protection point of view, X-rays and gamma rays are identical, differing only in their place of origin. Gamma rays are emitted from excited **nuclei** with a discrete energy. X-rays are emitted when the **extra-nuclear atomic structure** undergoes a transition; i.e., an outer shell electron replaces a missing lower shell electron and an X-ray is produced. The energy of the X-ray is approximately equal to the difference in the electron energy levels.

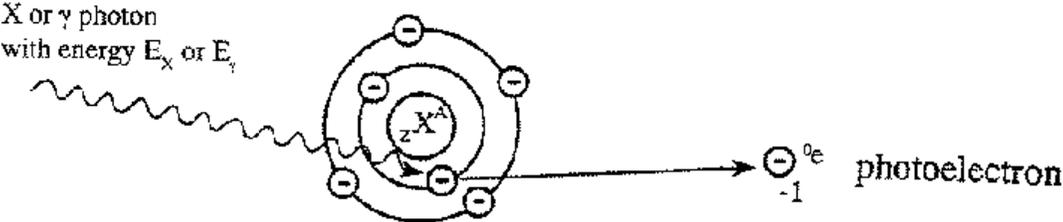
Since X and  $\gamma$  rays are chargeless, they do not interact by electrostatic forces as in the case of charged particles, which cause ionization of matter directly along their path of travel. However, X and gamma rays do have sufficient energy to release high energy secondary charged particles (electrons) from matter through one of three basic interactions:

- The Photoelectric Effect
- The Compton Effect
- Pair Production

The high speed electrons resulting from these interactions then cause ionization of the medium.

### 1. The Photoelectric Effect

The Photoelectric Effect is the interaction of X or  $\gamma$ -ray photons\*\* as well as other photons (such as light), whereby all of the energy of the photon is transferred to an inner shell electron (usually the K shell), ejecting it from the atom and leaving the atom with an inner shell vacancy. This shell vacancy creates an excitation energy which corresponds to the Binding Energy (BE) of the ejected photoelectron.



$$KE_{\text{photoelectron}} = E_x \text{ or } E_\gamma - \text{BE of inner shell electron ejected}$$

The Kinetic Energy (KE) of the photoelectron is equal to the energy of the X or  $\gamma$ -ray photo minus the BE of the electron ejected.

If the X or  $\gamma$ -ray photon does not have sufficient energy to knock the inner shell electron loose, the reaction will not occur.

The resultant atom is now in an excited state and will decay to the ground state by emission of X-rays and fluorescent radiation with the total energy equal to the BE of the photoelectron. The energies of the secondary radiations are usually much lower than the primary X or  $\gamma$ -ray energies.

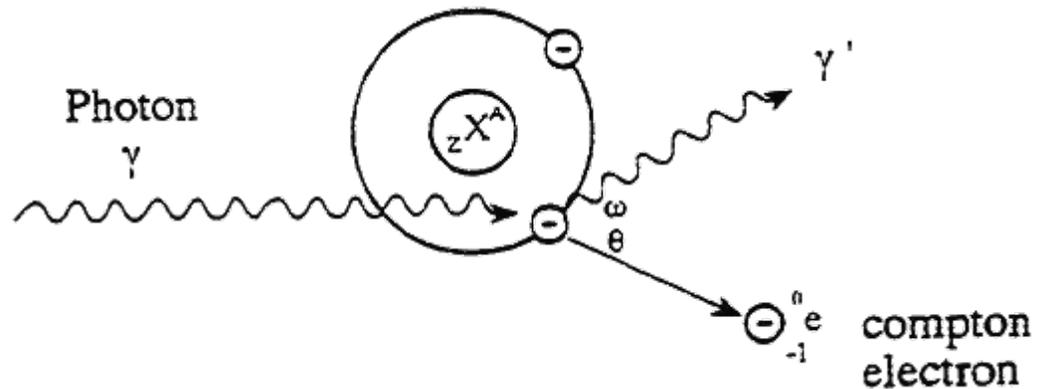
#### Application of the Photoelectric Effect

Gamma rays emitted from excited nuclei, and X-rays emitted from excited atoms, have discrete energy characteristics of the specific nuclides and elements, respectively. Thus, the energy of these  $\gamma$  or X photons can be used as "finger prints" to identify unknown nuclides and elements.

\*. A photon, as described by the Quantum Theory, is a "particle" or "quantum" that contains a discrete quantity of electromagnetic energy which travels at the speed of light, or  $3 \times 10^8$  meters per second.

## 2. The Compton Effect

Photons with energies much greater than the BE of the electrons in an atom may interact through essentially elastic scattering interactions in which the total KE of the system is conserved. In this interaction, the electron appears to the photon as a free electron.



The primary  $\gamma$  loses part of its energy to the Compton electron which gets scattered at an angle from the original direction of the incident  $\gamma$ , while the Compton scattered  $\gamma$  ( $\gamma'$ ) is scattered as an angle. In this process, the scattered photon and Compton electron share the energy of the incident  $\gamma$ .

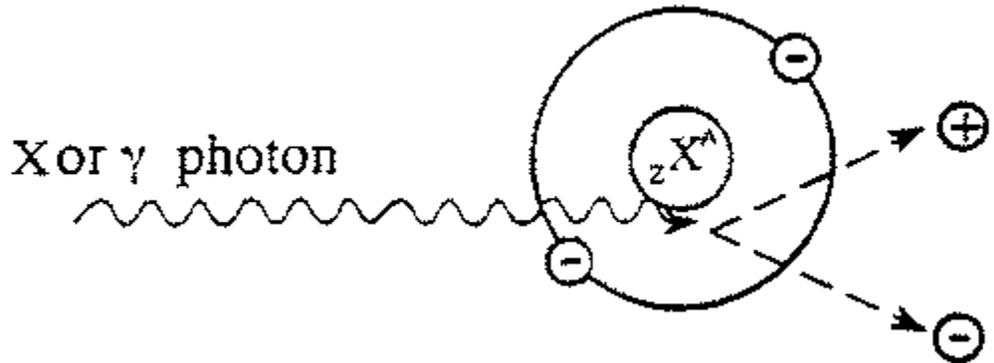
The KE carried off by the Compton electron may be deposited locally (i.e., absorbed immediately by the surroundings). However, the energy carried off by the Compton scattered photon is not deposited locally. Therefore, this scattered photon can significantly contribute to the dose outside a shielding apparatus.

### Application of the Compton Effect

Due to its characteristic peaks, the Compton Effect aids in the identification of unknown nuclides. However, in a detecting system, the Compton scattered electron can mask lower energy photons interacting by the photoelectric effect making interpretation of results difficult.

## 3. Pair Production

High energy gamma photons transfer their energy primarily by pair production. A high energy X or  $\gamma$ -ray passing close to a nucleus suddenly disappears and an electron and a positron appear in its place. This interaction must take place in the neighborhood of a nucleus to conserve momentum.



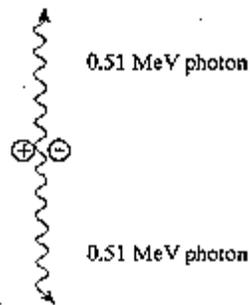
Since both particles are created from energy supplied by the incident photon, the process is energetically possible only if  $E_\gamma$  or  $E_x$  is greater than 1.02 MeV.

When the positron slows down (i.e., loses its KE), it will annihilate itself by combining with an electron. This produces two photons with an energy of 0.51 MeV each. This "annihilation radiation" represents the energy equivalent of the rest mass of two electrons which is converted to pure energy according to the principles of Einstein's theories, in particular,  $E = mc^2$ ; where

$E$  = Energy of two 0.51 MeV photons

$m$  = Rest mass of two electrons ( amu)

$c$  = Velocity of light ( $3 \times 10^8$  )



### Applications of Pair Production

Again, due to characteristic peaks observed for various known nuclides, Pair Production is an aid in the identification of unknowns.

## 2. Radiation Dose Units

Radiations are measured in four basic units - the gray, the rad, the rem and the Sievert:

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

**The rad** (radiation absorbed dose) is a measure of energy deposition in any medium by all types of radiation. The rad is equal to 100 ergs/gram.

**The rem** (radiation equivalent man) is a unit of dose equivalent used for radiation safety purposes. The rem is defined as the dose (in rads) multiplied by appropriate Quality Factor (QF). The Quality Factor is a term used to derive dose equivalent from absorbed dose and takes into account the different abilities of radiation types to cause damage in a biological system. Below is a table listing Quality Factors for various types of radiations:

**The Sievert** is the SI unit of any of the quantities expressed as dose equivalent. The dose equivalent in rems is equal to the absorbed dose in grays multiplied by the quality factor.

**Quality Factor**

Absorbed dose equal to a unit Quality dose

Radiation	Quality Factor	Dose Equivalent *
X, $\gamma$ or $\beta$	1	1
Neutrons of Unknown Energies	10	0.1
Alpha Particles	20	0.05
High-Energy Protons	10	0.1

Thus, the rem allows us to add doses of different radiation types to obtain total effective dose.

\*Absorbed dose in rad equal to 1 rem or the absorbed dose in gray equal to 1 Sievert.

Example: What is an individual's dose equivalent from 10 mrad of gamma rays, 5 mrad of  $\beta$ -particles and 10 mrad of neutrons? (m = milli = 1/1000)

Dose Equivalent	= mrad x QF	= mrems
Gamma dose equivalent	= 10 x 1	= 10
Beta dose equivalent	= 5 x 1	= 5
Neutron dose equivalent	= 10 x 10	= 100
Total		115

The SI unit for dose equivalent is the Sievert (Sv) and is equal to 1 Joule/kg. 1 Sievert = 100 rem.

## Problem Set 1

*Multiple-choice questions may have more than one correct response. Refer to Appendix IV for reference data.*

1. The structural difference between various nuclides of an element are due to different numbers of:
  - a. electrons
  - b. protons
  - c. neutrinos
  - d. neutrons
2. Beta decay results in:
  - a. decrease in atomic number and mass number of nucleus
  - b. decrease in atomic number
  - c. increase in atomic number
  - d. increase in atomic number and mass number
  - e. increase in atomic number and decrease in mass number
3. One millicurie equals:
  - a.  $3.7 \times 10^7$  dps
  - b.  $3.7 \times 10^{10}$  dps
  - c.  $2.22 \times 10^9$  dpm
  - d.  $2.22 \times 10^6$  dpm
  - e. none of the above
4. The decay constant,  $\lambda$ , is equal to:
  - a.  $A/N$

- b.  $0.693/T_{1/2}$
  - c.  $0.693/t$
  - d.  $e^{-NT}$
5. Gamma rays interact directly with matter by:
- a. ionization and excitation
  - b. Compton scattering
  - c. pair production
  - d. photoelectric effect
6. A charged particle interacts with matter by:
- a. Compton scattering
  - b. photoelectric effect
  - c. excitation and ionization
  - d. pair production
7. The activity of a radioactive sample is measured by:
- a. Roentgens.
  - b. Curies.
  - c. Rems.
  - d. Rads.
8. The rem is equal to:
- a. Rads x Quality Factor
  - b. Rads x X-Rads
  - c. Rads ÷ Quality Factor
  - d. Rads - Quality Factor
9. An exposure to 1 mrad of gamma, 10 mrad of  $\beta^-$  particles, and 5 mrad of fast neutron radiations would give an individual a dose equivalent of:
- a. 16 mrem
  - b. 16  $\mu$ Ci
  - c. 61 mrem
  - d. 61 mrads
10. List the names and give specific examples for the types of radioactive decay processes in which particles are emitted:

Name of Process	Example
-----------------	---------

- |    |       |       |
|----|-------|-------|
| a. | _____ | _____ |
| b. | _____ | _____ |
| c. | _____ | _____ |

11. Now, do the same for two types of decay which do not emit particles:

- |    |       |       |
|----|-------|-------|
| a. | _____ | _____ |
| b. | _____ | _____ |

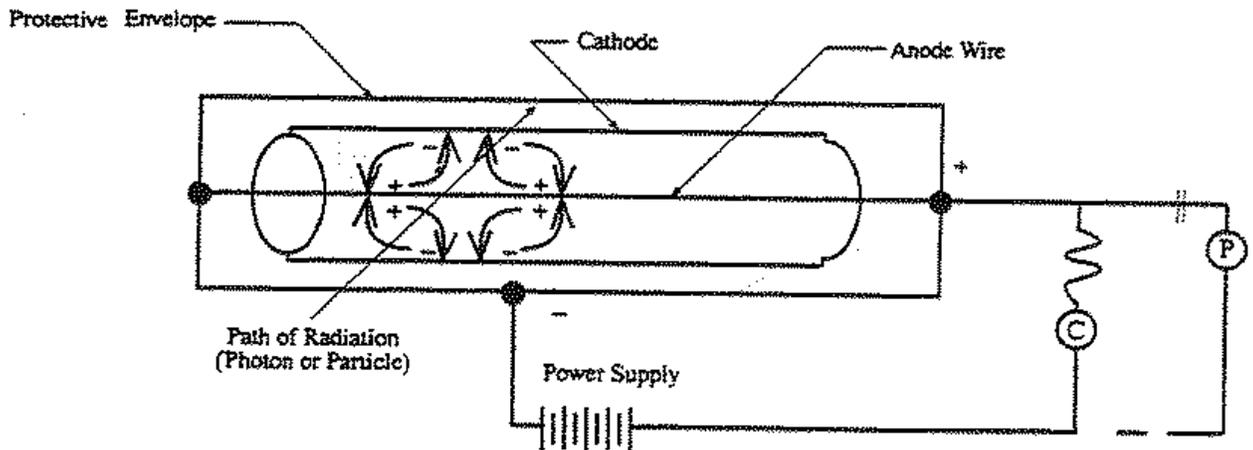
12. A particular radioisotope sample with a half-life of 30 minutes is determined to have an activity of 10,000 dpm at noon.
- a) What is the value of its decay constant,  $\lambda$ ? Show units \_\_\_\_\_
- b) How many radioactive atoms must have been present in the sample at noon? \_\_\_\_\_
- c) How many dpm will it exhibit at 1:30 PM? \_\_\_\_\_
13. At 9 a.m. Tuesday, you assay an unknown radioactive sample and get 15,000 dpm. The next day at 9 a.m. you assay the sample again and find it has decayed to 3,885 dpm. What is the half-life of the isotope? What is the isotope?
14. Assume that you have converted an ancient piece of wood to benzene for Carbon-14 dating. You obtained 3 grams of benzene. The disintegration rate of this sample you found to be 18 dpm. Your modern carbon sample has a disintegration rate of 9 dpm per gram of benzene. Calculate the age of the wood sample.
15. A user requires 2 mCi of Cu-64 for his experiments. If the delivery time is three days, what activity must the Vendor ship in order for the user to receive the correct activity?

## Chapter II

### Radiation Instrumentation

#### 1. Portable Survey Instruments

The major principle for sensing and measuring radiations in survey instruments is based on the ionizations radiation produces when interacting in a gas filled detector. As described in the previous chapter, radiations passing through matter create ion pairs. In a detector, these ion pairs are collected to form an electrical signal through the use of an electric field. The signal, either a current or a pulse, is then used to register the presence or amount of radiation. There are a number of different types of radiation detectors, each operating on this basic principle, but designed for specific purposes. The two major types of portable radiation survey instruments, the Ion Chamber and Geiger Counter, are discussed below.



Ionization produced in the gas converts neutral molecules to positive ions and electrons within the sensitive volume. This volume is contained between charged electrodes, one positive, the other negative. The charged species are collected at the electrodes of opposite sign.

Either a photon (X or gamma ray), producing primary electrons along its path, or a particle (alpha or beta) producing secondary electrons, will create ions that will travel to the electrodes and be collected. A sufficient potential must be applied across the electrodes to prevent ion recombination and make collection possible. As the ions are collected, a current will flow. This will be measured on a sensitive measuring circuit "C" shown in the diagram above. Alternatively, the current may be measured as a pulse by a pulse counter "P" from the collection of each primary particle.

## A. Ionization Chambers

Ionization chamber type instruments are designed to measure exposure rates of ionizing radiation in units of  $\text{mr/hr}$  or  $\text{r/hr}$ . The detector is usually cylindrical, filled with air and fixed to the instrument. When radiation interacts with the air in the detector, ion pairs are created and collected generating a small current. The amount of ionization charge deposited in air and the measurement of this ionization current will indicate the exposure rate.

## B. Geiger-Muller Counter

The most common type of portable radiation survey instrument is the Geiger Counter, also known as a Geiger-Muller (GM) Counter. The GM counter's detector consists of a tube filled with a mixture of "Q-gas", containing 98% helium and 1.3% butane; and usually can be removed from the instrument to survey an area. Instead of measuring the average current produced over many interactions, as in Ion Chambers, the output is recorded for each individual interaction in the detector. Thus, a single ionizing event causes the GM tube to produce a "pulse" or "count". Because all pulses from the tube are the same sizes, regardless of the number of original ion pairs that initiated the process, the GM counter cannot distinguish between radiation types or energies. This is why most GM counters are calibrated in "counts per minute" (CPM). However, GM counters can be used to measure exposure rates in  $\text{mr/hr}$  or  $\text{r/hr}$  as long as the energy of the X or gamma radiation is known and the instrument is calibrated for this particular fixed energy. At best, for a given X or gamma ray energy, the count rate will respond linearly with the intensity

of the radiation field. However, in most applications, the radioactive source will have X or gamma rays of various energies which can result in erroneous and unreliable readings. Therefore, GM counters are primarily used to detect the presence of radioactive material.

## 2. Use of Radiation Survey Instruments

Radiation instruments are designed with specific purposes in mind. Choose the instrument depending on your particular needs. Generally, Geiger Counters are more sensitive than Ion Chambers and can monitor low levels of contamination in the laboratory. If you wish to measure radiation levels in the laboratory, the Ion Chamber is the proper instrument to use. Each instrument comes with an operating manual that describes its function and limitations such as warm up time, battery life, operating temperature range, minimum sensitivities, etc. Outlined as follows are simple instructions on the proper use of portable radiation survey instruments.

- a. **Read the instrument's operating manual.** Gain familiarity with the controls and operating characteristics.
- b. **Check the batteries.** Most instruments have a battery check indicator. Replace weak batteries. Turn off the instrument when not in use. When storing the instrument for extended periods, remove the batteries to prevent damage from battery acid leakage.
- c. **Check the operability of the detector.** Pass the detector over a radioactive check source (sometimes attached to the side or end of the instrument) to verify that the detector responds to radiation.
- d. **Determine the instrument's response time.** By passing the detector at varying speeds over a check source, you can determine how long it takes for the detector to respond to the radiation. It is possible to miss contamination or radiation fields if the detector is moved too rapidly over the area being surveyed.>
- e. **Determine the operating background.** Note the instrument's response in an area free of contamination or radiation levels. This is normally due to natural sources of radiation called "background" (See Chapter III, Part 3). Subtract this value from the "gross" reading to obtain the "net" results due to the sample itself:  $S_{\text{net}} = S_{\text{gross}} - S_{\text{background}}$ .

When using portable instruments, caution should be used when extending the detector cord as this may generate electrical noise and register as "counts". Also, thin window GM tubes used to detect alpha or low energy beta particles are fragile and can easily break if dropped or punctured. In a mixed beta-gamma field, the reading due to beta radiation only will be the reading with a beta shield off the detector minus the reading with the beta shield on the detector.

## 2. Calibrations and Efficiency

In order for the results of a survey instrument to be meaningful, the instrument must be calibrated. Calibrations should be performed at least every six month or when battery or test functions indicate a problem. Ion chambers are usually calibrated against Cs-137, Co-60, or an X-ray radiation field. The true exposure rate is determined by multiplying correction factors (if any) by the reading on the instrument. GM counters are usually calibrated against a specified reference standard at a fixed distance from the detector (usually 1 centimeter) and a variable pulse generator.

Efficiencies for instruments expressing results in terms of counts rates can be calculated from the following formula:

Efficiency =

Divide the observed sample count rate by the detector efficiency to obtain the actual disintegration rate.

Example. A Carbon-14 standard has a disintegration rate of 85,000 dpm. Your GM counter measures a count rate of 4,500 cpm. If the background is 250 cpm, what is the efficiency of the counter?

$$\text{Efficiency} = \frac{4,500 - 250}{85,000} \times 100 = 5\%$$

### 3. Counting Statistics

Since radioactive decay is a random process, the number of disintegrations in a given time will fluctuate around an average value. The best estimation of this function is given by the standard deviation. For a single measurement,  $N$ , the standard deviation represents 68% probability that the actual value lies within the range  $N \pm \sigma$ . The standard deviation for a large number of measured events (i.e. counts) is given by the square root of  $N$ :

However, it is usually the counting rate which is of interest and the standard deviation becomes:

$$\sigma = \frac{\sqrt{N}}{t} \quad t: \text{Counting time}$$

Example: What is the standard deviation of the count rate for a sample that yielded 1,000 counts in two minutes and for a sample that yielded 10,000 counts in twenty minutes?

$$\text{Count Rate} = \frac{1,000}{2} \pm \frac{\sqrt{1,000}}{2} = 500 \pm 15.8 \text{ cpm}$$

$$\text{Count Rate} = \frac{10,000}{20} \pm \frac{\sqrt{10,000}}{20} = 500 \pm 5 \text{ cpm}$$

One can see that in counting, greater statistical accuracy can be achieved by increasing the total counts which is usually accomplished by increasing the counting time of the sample. Generally, between 1,000 and 10,000 counts are needed for a sample to have statistical validity.

#### A. Percentage Error

Often it is desired to express the counting results in terms of percentage error, which is related to the standard deviation for a large sample.

The percentage error of a counting measurement is determined entirely by the total number of counts accumulated:

$$\epsilon = \frac{\sigma}{r} \times 100$$

r: Count rate  
N: Total number of counts  
:

To reduce the percentage error in your measurement, you must collect as many counts as possible. When expecting low counting rates, increase the counting time to lower the error to an acceptable level.

Example: What is the percentage error of the count rate for a sample that yielded 20 counts in one minute and for a sample that yielded 200 counts in 10 minutes?

$$\epsilon = 20 \text{ counts/ min} \pm 100 \div 20^{1/2} = 20 \text{ cpm} \pm 22\%$$

$$\epsilon = 200 \text{ counts/ 10 min} \pm 100 \div 200^{1/2} = 20 \text{ cpm} \pm 7\%$$

## B. Minimum Detectable Activity

The minimum detectable activity (MDA) is that amount of activity which in the same counting time gives a count which is different from the background by three times the standard deviation of the background counting rate:

$$\text{MDA} = \text{Bkg cpm} + 3 \times \text{Bkg}^{1/2} \div t$$

Example: What is the MDA for a counter with a background of 750 counts in 10 minutes?

$$\text{MDA} = 75 \text{ cpm} + 3 \times 750^{1/2} \div 10 \text{ min} = 83 \text{ gross cpm}$$

Thus, any gross count more than 83 cpm can be considered to be due to radioactivity.

However, the MDA for a counting system must be expressed in terms of a net count so that the results can be converted to dpm or  $\mu\text{Ci}$ . Thus, the MDA becomes:

$$\text{MDA} = 3 \times \text{Bkg}^{1/2} \div t$$

To calculate the MDA (in dpm) for a known nuclide, divide by the efficiency of the nuclide. Report the MDA for any nuclide for which a net count of zero is calculated or whenever the standard deviation of the sample counting rate brings the net count at or below the MDA. Note that the MDA can be reduced by increasing the counting time and lowering the background. The lower the MDA, the more accurately the activity of samples with low counting rates can be determined.

Example: What is the MDA (in dpm) for a counter with a background of 750 counts in 10 minutes and an efficiency of 50% for the nuclide of interest?

$$\text{MDA} = 3 \times 750^{1/2} \div 10 \text{ min} = 8 \text{ net cpm}$$

$$= = 16 \text{ dpm OR } 7.2 \times 10^{-6} \mu\text{Ci}$$

## C. Liquid Scintillation Counting

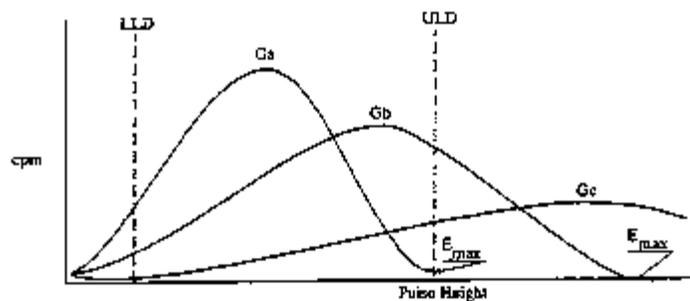
Liquid Scintillation Counting is the most common technique for the measurement of radioactivity of low energy beta emitters. Such emitters (H-3, C-14, S-35, Ca-45, etc.) are difficult to detect using portable survey instruments since the beta may not be able to penetrate the thin window of the gas filled detector. In liquid scintillation counting, the sample is dissolved in a counting solution. The energy of the beta is absorbed by solvent molecules causing them to become excited. This excitation energy is transferred to a solute (known as a scintillator) resulting in a flash of light or "scintillation" when the scintillator molecules return to the ground state. The number of scintillations emitted is proportional to the energy of the beta particle. A photomultiplier tube (PMT) is used to

detect and amplify the light photons from the sample. The emitted light causes the emission of photoelectrons from the PMT which are multiplied by the PMT into a measurable electrical pulse. The height (amplitude) of the pulse is proportional to the number of photons which interact in the PMT. Therefore, the pulse height at the output of the PMT is proportional to the energy of the beta particle in the sample. These pulses can be analyzed to provide the energy of the beta particle and the rate of beta emission in the sample. It is also possible to count very low energy gamma emitters by liquid scintillation since most of the gammas are absorbed in the counting solution.

Not all pulses from the PMT are due to radiation from the sample. Pulses are generated by the electronics, the PMT and from environmental radiation. These "noise" pulses are identical to pulses due to scintillations from the sample. To distinguish the pulses, two PMT's are arranged in a "coincidence" mode. Because noise pulses are random events, it is unlikely that two PMT's will receive a pulse simultaneously. But most beta particles have sufficient energy to produce more than one photon in the solution. Therefore, it is probable that both PMT's will simultaneously receive photons due to a single beta decay event. A coincidence circuit is established to check if a pulse from one PMT is accompanied by a corresponding pulse from the other. The requirement that both PMT's receive a pulse within a certain time (coincidence resolving time) excludes the vast majority of noise pulses from the sample count.

Beta particles will produce PMT pulses up to a maximum amplitude. An upper level discriminator (ULD) can be introduced to the system which can exclude pulses which have a greater amplitude than the maximum amplitude for the nuclide of interest. A lower level discriminator (LLD) can be arranged to exclude all pulses smaller in amplitude than a given value. A gain control is used to determine the PMT pulse height to which a given discriminator setting corresponds. Changes in gain alter the amplitude of the pulses before analysis by the LLD and ULD. The limits of pulse height accepted by a pair of discriminators and gain setting is referred to as a "window" (see Figure 1). Correct settings of gain controls and discriminators will discriminate between pulses of given nuclide from those of another. To separate pulses from beta events in samples containing nuclides of differing energies, a number of separate channels of pulse height analysis are necessary. The instrument's operating manual should be referred to for specific procedures on how to optimize the counter for each particular nuclide to be analyzed.

Figure 1



Pulse height spectrum of a beta emitter showing the effect of gain. Note that the pulse spectrum is centered between the window set by LLD and ULD to give the maximum counting rate (Gain Setting  $G_a$ ).

Pulse height spectrum of a beta emitter showing the effect of gain. Note that the pulse spectrum is centered between the window set by LLD and ULD to give the maximum counting rate (Gain Setting  $G_a$ ).

## I. Optimum Counting Conditions

By adjusting the gain and discriminator settings, different counting windows can be established. Some windows may yield a high sample count as well as a high background count. The optimum settings (based on statistics) for the window settings is given by the Figure of Merit:

Figure of Merit =

Where: S: Net sample counts  
B: Background counts

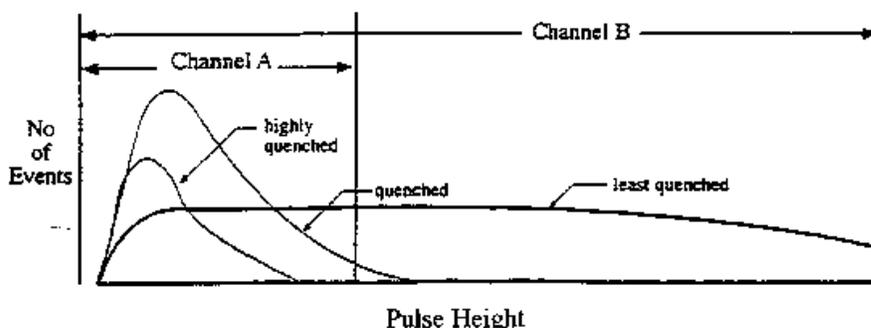
The larger the Figure of Merit, the more significant the sample measurement is.

## II. Counting Efficiency and Quenching

Counting efficiency depends on the windows used and the ability of the beta particle to interact with the scintillator to produce light-emitting events. A decrease in the ability produce or transfer light to the PMT's is called quenching and occurs mainly from the optical properties of the sample (i.e. color and/or turbidity) or the chemical composition of the sample. Samples containing equal amounts of activity of the same nuclide can produce different counts rates due to quenching.

PMT's, the scintillations appear as beta particles of lower emission energies. The effect of quenching is a shift in the pulse height spectrum (see Figure 2). Thus, some low energy events which would normally exceed the coincidence threshold in unquenched samples will produce insufficient photons for detection in quenched samples.

Figure 2



Because quenching occurs to some degree in all samples, a loss in counting efficiency will result. The three basic techniques used to determine sample

counting efficiency in a liquid scintillation counter are Internal Standard, Sample Channels Ratio, and External Standard.

### a. Internal Standard

The internal standard method for determining counting efficiency requires that the sample be counted in the usual manner, then a calibrated amount of a radioactive standard added to the sample and the sample plus standard mixture recounted. The increase in counts (due to the added standard) is used to determine the counting efficiency according to the following formula:

Efficiency =

Where:

C1 Net cpm of the sample without internal standard  
:  
C2 Net cpm of the sample with internal standard  
:

In order to be most accurate, the material added as the standard should be of the same material as the sample, as to not introduce quenching, and added in small volume (0.1 ml or less) so not to alter the characteristics of the original sample. The amount of activity added must be accurately determined and should be equal to or greater than the sample activity.

### b. Sample Channels Ratio

The channels ratio method of determining counter efficiency is based on the fact that the pulse height spectrum is always displaced when quenching occurs. A counter using two different channels of pulse height analysis can determine the shift. A set of quenched standards, each vial containing exactly the same amount of activity (dpm) but different amounts of a quenching agent, is used to establish a correlation between the ratios of the counts in the two channels and the corresponding efficiencies.

To use the channels ratio method to determine the efficiency of a single nuclide, one of the windows (Ch. A) is set narrower than the normal window of analysis (Ch. B) for that nuclide as shown in Figure 2. As the quenched standards set is counted, more and more counts will be shifted out of window B into window A. The counting efficiency in channel B and the net samples channels ratio (SCR) for each standard is calculated. A graph of the efficiency vs SCR is obtained and a curve drawn:

#### Sample Channels Ratio Calculations

**Counting Mode:** Single Nuclide (C-14)

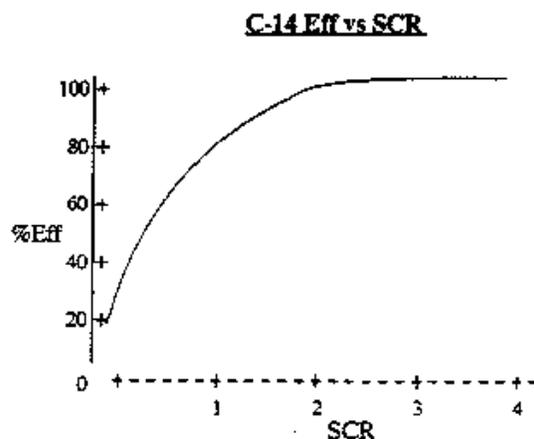
**Counting Time:** 1 Minute

**Background Count Rate:** Channel A = 90 cpm; Channel B = 27 cpm.

**Quenched Standards Set:** 10 samples, each containing 97,600 dpm of C-14.

Sample #1: Least Quenched;  
 Sample #10: Most Quenched

#	Ch. A cpm	Ch. B cpm	ChB/ A SCR	%Ef f
1	19787	8745	4.42	89.6
2	22541	8617	3.923	88.3
3	28738	8267	2.877	84.7
4	34977	7897	2.258	80.9
5	47505	7117	1.498	72.9
6	55311	6365	1.151	65.2
7	63448	5313	0.837	54.4
8	65492	3985	0.608	40.8
9	58511	2444	0.417	25.1
10	45768	1124	0.245	11.5



*The SCR technique is of limited use in dual label counting and in low activity samples.*

### c. External Standard

The most widely used method for determining counting efficiency uses a high energy source positioned external to the sample vial in the counting chamber. The interaction of the gamma radiation with the vial produces electrons in the scintillation solution due to the Compton effect. The Compton electrons behave as beta particles, causing scintillations. The more quenched the sample, the fewer scintillations detected. These counts are then monitored by a separate (internal, usually factory pre-set) pulse height analyzer and directly related to an efficiency correlation graph, prepared from a set of quenched standards (see data table and graph). Some counters use two channels of analysis to come up with an External Standard Ratio (ESR), which minimizes the effects of volume changes and changes in counting geometry.

#### External Standard Ratio Calculations

**Counting Mode:** Single Label, Ch. A set for H-3; Ch. B set for C-14  
**Counting Time:** 1 Minute  
**Background Count Rate:** Channel A = 90 cpm; Channel B = 27 cpm.

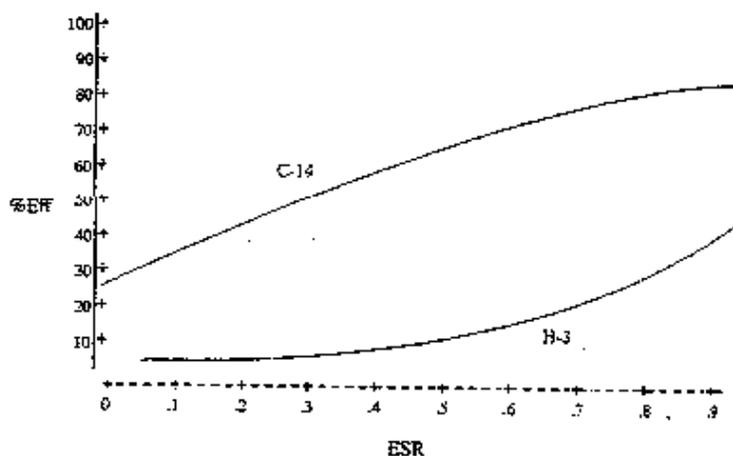
**Quenched Standards Set:** 10 samples, each containing 262,166 dpm of H-3;  
 10 samples, each containing 97,600 dpm of C-14.

Sample #1: Least Quenched;

## Sample #10: Most Quenched

C-14 Quenched Standard Set					H-3 Quenched Standard Set				
#	Ch. A cpm	Ch. B cpm	ESR	%Eff	#	Ch. A cpm	Ch. B cpm	ESR	%Eff
1	19787	87456	1.007	89.6	1	146489	59773	1.015	55.8
2	22541	86171	0.9745	88.3	2	124867	37083	0.9586	47.6
3	28738	82670	0.8976	84.7	3	107576	23921	0.8924	41.1
4	34977	78970	0.7861	80.9	4	89517	14000	0.7816	34.1
5	47505	71174	0.6622	72.9	5	64457	5728	0.6722	24.6
6	55311	63652	0.5567	65.2	6	42870	1989	0.5184	16.4
7	63448	53135	0.3921	54.4	7	28025	759	0.3449	10.7
8	65492	39859	0.1964	40.8	8	17313	255	0.1582	6.6
9	58492	24441	0.0322	25.1	9	9348	96	0.0154	3.6
10	45768	11243	0.0011	11.5	10	4770	41	0	1.8

*Eff vs ESR for H-3 & C-14 for Single Label Samples*



The External Standard method can be used to determine efficiency in any sample regardless of its radioactive content and is suitable for single and dual label counting as well as for samples of low activity.

### III. Sample Preparation

In preparing samples for liquid scintillation counting, the physical and chemical characteristics of the sample determine the type of counting solution required. Many references are available on the types of solvents and scintillators for a particular application. The main objective is to produce a clear, colorless and homogenous sample so that counting efficiencies can be determined by one of the three methods described above. However, it may not always be possible to achieve a homogeneous sample, for example when the radioactive material is isolated on filter paper, membrane filters, or gels. The determination of counting efficiency for such heterogeneous samples is a problem because it is difficult to

duplicate the exact counting environment of the experimental samples. The proper method to determine the activity of a heterogeneous sample is to either elute the radioactivity or to solubilize the sample prior to counting. The internal standard method of efficiency determination is best suited for heterogeneous samples.

Another factor to consider when preparing samples for liquid scintillation counting is the introduction of high background count rates as a result of photoluminescence, chemiluminescence, and static electricity. In photoluminescence (also called phosphorescence), photons are generated by interactions of the ultra-violet component of light with the sample vial and contents. Therefore, samples should avoid exposure to direct sunlight and fluorescent light, and counting solutions should be stored in amber containers. Incandescent light will not cause photoluminescence. The level and duration of photoluminescence is a function of the light intensity and exposure time. When a sample has been photoactivated, it must be dark adapted until it decays to background levels.

In chemiluminescence, photons are generated during sample preparation as a result of chemical interactions of the sample components. The amount and duration is temperature dependent and the effect decays faster at higher temperatures. However, cooling the sample will slow down the effect to a point where the coincidence circuitry of the counter can discriminate between chemiluminescence and radioactive decay. Thus, storing samples in a refrigerator overnight should remove most of the background counts due to chemiluminescence and photoluminescence.

The usual method for detection of luminescence is to recount the sample after an appropriate interval. A decrease in the second count rate indicates a strong possibility of luminescence.

During dry seasons or when using an ambient counter, static electricity may be the cause of high background count rates. When a static charge deposited on a vial discharges, light photons are produced in proportion to the charge. If the vial is being counted at the time of discharge, an incorrect, high sample count rate will result. This problem can be reduced by humidifying the counter and by wiping the vials with a moist cloth.

## **IV. Cerenkov Counting**

Cerenkov radiation is produced when a charged particle travels through a transparent medium, such as water, at a velocity greater than the speed of light in the same medium. In Cerenkov counting, energetic beta particles in an aqueous solution produce a faint, blue-white light which is amplified by the liquid scintillation counter's PMT to produce pulses in the usual manner. A beta emitter must have an energy greater than 263 keV to be detected in water by Cerenkov counting. Phosphorus-32 is the most common nuclide measured by the Cerenkov counting technique.

Sample preparation for Cerenkov is simple and economical since additional scintillators are not needed and the solvent can be almost any colorless liquid. Samples analyzed by Cerenkov counting are not affected by chemical quenching, but are highly vulnerable to color quenching. Also, counting efficiencies for Cerenkov radiation are relatively low because the Cerenkov light is highly directional. As a result, light photons generated may be detected by only one PMT and thus rejected as a count by the coincidence network. Counting efficiencies can be increased by the addition of a wavelength shifter to the solution and/or by deactivating the coincidence circuitry.

## V. General Counting Procedures

Always count a reference sample and a background with any set of samples. Verify that the instrument settings are correct for the type of samples to be counted. Identify your samples and keep track of the settings so that they may be reproduced for a subsequent set of samples. Remove your samples from the counter as soon as possible after they have been counted.

## D. Gamma Counting

A common method of detecting gamma and X radiations involves the use of a scintillator coupled to a photomultiplier tube (PMT). The most popular scintillation material for this purpose is the sodium iodide (NaI) crystal. Gamma ray interactions within the crystal via the photoelectric effect, Compton Effect, and pair production result in light or scintillations which are amplified and converted into an electrical pulse by the photomultiplier tube.

Sodium iodide crystals can be made in various sizes, some small enough to use in portable survey instruments. Larger crystals (3 inches in diameter by 3 inches deep) are common for most radioisotope counting room applications such as isotope identification by characteristic photo peaks. Still others have a hole or "well" in the center, allowing the sample to be surrounded by the crystal, resulting in a very high detection efficiency. This type of detector is found in most laboratory "gamma counters" where a large number of samples can be counted automatically.

Unlike liquid scintillation counting, the sample does not need special preparation. The sample can be counted in any physical form. However, care must be taken to have the sample properly contained so as not to contaminate the counting equipment. Gamma emitting isotopes such as I-125, Cr-51, and those decaying by electron capture are best assayed using a NaI detector.

## Problem Set 2

*Multiple choice questions may have more than one correct response.*

1. When using portable instruments you should:
  - a. read the operator's manual
  - b. check the batteries and detector operability
  - c. extend the probe cord to its fullest length when monitoring

- d. determine the detector's efficiency
- 2. Ion chamber (IC) type instruments are best suited for:
  - a. radiation field intensity measurements
  - b. radioactive contamination monitoring
  - c. determination of radiation energy
  - d. identification of radioisotopes
- 3. GM type instruments are best suited for:
  - a. radiation field intensity measurements
  - b. radioactive contamination monitoring
  - c. determination of radiation energy
  - d. identification of radioisotopes
- 4. What instrument(s) would be most appropriate for detecting the following?

	GM	Ion Cbr	Nal Ctr	LSC
a. Non-Removable Surface Contamination	( )	( )	( )	( )
b. X-Rays from a Dental Machine	( )	( )	( )	( )
c. H-3 Labelled Water	( )	( )	( )	( )
d. A P-32 Labeled	( )	( )	( )	( )
e. A Cr-51 Labeled Protein	( )	( )	( )	( )
f. A Mn-54 Labeled Bacteria	( )	( )	( )	( )
g. A 10 mr/hr radiation of Beta and Gamma Rays	( )	( )	( )	( )

- 5. A 0.05  $\mu\text{Ci}$  standard yields 89,200 counts in two minutes. The counter background is 200 cpm. What is the efficiency of the detector?
  - a. 80%
  - b. 60%
  - c. 40%
- 6. If a sample was counted for 10 minutes and yielded 20,000 counts, the standard deviation of the count rate would be:
  - a.  $\pm 100$  cpm
  - b.  $\pm 3.16$  cpm
  - c.  $\pm 141$  cpm
  - d.  $\pm 14.1$  cpm
- 7. Gamma (Nal) and liquid scintillation detection is based upon what physical property?
  - a. radiolysis of an organic solvent
  - b. absorption of electromagnetic energy
  - c. emission of visible light
  - d. ionization of a gas
- 8. Quenching in a liquid scintillation counting system results in:
  - a. a loss in efficiency
  - b. less light reaching the photomultiplier tube
  - c. shifting of the beta spectrum to lower energy values
  - d. an increase in pulse height
- 9. You have determined that the counting system efficiency for your tracer experiment with I-125 is 25%. You decide that you need a counting rate of 1,000 cpm in your final sample. If 10% of the trace ends up in the final sample, determine the total dpm of I-125 you must use to get the desired 1,000 cpm.

10. You are designing a tracer experiment using P-32. You are going to isolate a metabolic product of the labeled compound which you feed your test animals. The best available information indicates that 10% of the feed material leads to the metabolic product. You elect to use a liquid scintillation counter. You also estimate that you need a minimum count rate of 300 cpm in the counted sample. A 0.01  $\mu\text{Ci}$  standard of P-32 has a gross count rate of 15,575 cpm. In 10 minutes, the background yields 250 total counts.
- The net standard count rate is:
    - 15,325 cpm
    - 15,550 cpm
    - 15,575 cpm
    - 15,600 cpm
    - 15,825 cpm
  - The counter efficiency, assuming 0.01  $\mu\text{Ci}$  at the time of counting is:
    - 1.43%
    - 70%
    - 77%
    - 0.70%
    - 0.77%
  - The disintegration rate in a sample necessary to give 300 cpm is:
    - 429 dpm
    - 390 dpm
    - 400 dpm
    - 513 dpm
    - 210 dpm
  - The  $\mu\text{Ci}$  content of the labeled material to be fed to yield the desired dpm in the sample is:
    - 0.019  $\mu\text{Ci}$
    - 0.100  $\mu\text{Ci}$
    - 0.001  $\mu\text{Ci}$
    - 0.010  $\mu\text{Ci}$
    - 0.0019  $\mu\text{Ci}$
  - The minimum detectable activity of the liquid scintillation counter for P-32 is:
    - 6.8 dpm
    - 21.4 dpm
    - 42.5 dpm
    - 57.1 dpm

### Chapter III

## Sources and Effects of Radiation

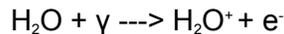
# 1. Biological Effects of Radiation

Living organisms are a collection of complex systems of many symbiotic parts arranged and packaged in a manner to allow maintenance of their internal environment and self-reproduction. The basic units are composed of cells. Cells of similar origin and structure are further grouped to form tissues. The four main groups of tissues are: muscle, nerve, connective and epithelial. Associated cells and tissues form organs which, taken collectively, function to create and control the necessary internal conditions suitable for life.

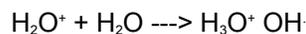
A great diversity exists among the different kinds of cells found in the body. Many have a brief lifespan, undergoing division (a process called mitosis) in a period of hours, while others (such as nerve cells) do not divide at all after birth. Mitosis represents the production of the chromosome, on which the genes containing all the genetic information necessary for cell function resides. Any alteration of the genetic information carried by the genes, or of the processes associated with mitosis can result in either a permanent change in the nature of the cell (mutation), or in the cell's death. When a cellular component is damaged by any agent (chemicals, radiation, excessive heat, etc.), a multitude of measurable effects can result. The changes may initially be restricted to a single or a few types of cells. In time, whole organs or organ systems may be affected due to the absence of a required function that upsets the equilibrium or control of the whole interrelated system. Gross physiological or morphological changes may result from an initial damage to a sufficient number of many kinds of cells. The type of cell damage will depend upon what the specific agent is that the cell is exposed to, and the amount of damage will be related to how much of the agent reaches that particular kind of cell. Biological effects from radiation are produced as a result of the transfer of energy from the radiation to the cells through ionization and excitation as described in the next section.

## A. Radiosensitivity of Cells

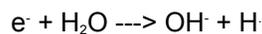
Radiation passing through living cells causes ionization or excitation of atoms and molecules contained in the cell. This is the same process that occurs in any material, as described in Chapter I, Part 5. Since most of the human body is water, water molecules are a likely target for being hit by photons or charged particles. The reaction which occurs when this happens is an ionization to form a positive ion and an electron:



and the  $\text{H}_2\text{O}^+$  is rapidly hydrated to form:



Here the  $\text{OH}^-$  is a "free radical", a species that contains an unpaired orbital electron, and is highly reactive chemically. The free electron will also react with a water molecule (after it slows down from bumping into other molecules) to yield another free radical, this time hydrogen:



The overall reaction is thus:

with the products separated by a considerable distance so that immediate back reactions to form water are not favored. Such radicals can combine with each other and with

dissolved oxygen to give a variety of potent oxidizing agents such as hydrogen peroxide, superoxide, molecular oxygen and the perhydroxy radical.

Both the initial radicals and these products can migrate to biologically important molecules (like DNA - the structural material of genes) and cause bond breakage and/or oxidation of attached groups. In this way, energy of the radiation is transferred to biologically significant molecules, changing their structure. This mode of energy-transfer is known as the **Indirect Effect** and can account for an appreciable fraction of damage. Note that the presence of oxygen can magnify this pathway due to additional radical formation.

In addition to the indirect effect, radiation may itself cause ionization in DNA or other biological molecules. The energy of ionization is far greater than the bond energy in organic molecules, thus causing bond breakage. The amount of this **Direct Effect** occurring depends on the number of a particular type of molecule in the cells, and its size. The larger a molecule is, the better target it makes. Since DNA is the largest molecule in the cell as well as the site of all the genetic information, its response has a central role in the mediation of radiation effects. Depending on how it is damaged, different results will occur. If the damage results in a strand break in its backbone (breaking the molecule in half), subsequent mitoses may fail resulting in cellular death. If the break is in one of its side groups (bases), it will then transmit different genetic data during subsequent division resulting in some kind of a mutation. Both direct and indirect effects contribute to the overall number of such damaging events to the DNA and will vary for individual cell types.

The radiosensitivity of a particular cell depends on a number of factors. An early observation of this difference is reflected in the "Law of Bergonie and Tribondeau" which states "the radiosensitivity of a tissue is directly proportional to the reproductive activity and inversely proportional to the degree of differentiation". Tissues consisting of rapidly dividing stem cells (like blood or sperm cell precursors) are quite sensitive to radiation whereas cells that do not divide or only rarely divide (like nerve or muscle cells) are considerably more resistant. From microscopic examination, cells appear to get stuck in the division process and never successfully complete it after radiation exposure, which is consistent with the "Law" above. Other factors involved include metabolic rate, state of nourishment, oxygen level and presence of particular enzymes within the cell. The latter are most likely involved with the repair of some of the radiation damage.

The following table gives a summary of how various cell, tissues, organs and organ systems are affected by radiation. The doses reported are for X or gamma rays only and represent a single, acute exposure.

## Relative Radiosensitivity of Cells, Tissues and Organs

Type	Biological Response
------	---------------------

<p><b>Blood-forming Organs</b> lymph nodes, thymus, spleen, bone marrow</p>	<p><b><i>Extremely Radiosensitive</i></b> Exposures as low as 50 rad can affect the white cell population within 15 minutes. Red cell counts fall 2 to 3 weeks later. Results in a feeling of general weakness, anemia, and a lower resistance to infection.</p>
<p><b>Reproductive Organs</b> female, male</p>	<p><b><i>Moderately Radiosensitive</i></b> Exposures below 100 rad can reduce fertility. Temporary sterility can occur lasting 12 to 15 months following 200-300 rad. On the average, a larger exposure is needed to produce sterility in the male than in the female. Damage to the germ cells can lead to somatic and/or hereditary changes.</p>
<p><b>Digestive Organs</b> small intestine, lower intestine, pharynx, esophagus</p>	<p><b><i>Radiosensitive</i></b> Degenerative changes occur as soon as 30 minutes after exposure of 500-1000 rad. Initial effects are: impaired secretion of necessary fluids: cell breakdown results in failure of food and water absorption leading to infection and dehydration from diarrhea.</p>
<p><b>Vascular System</b> arteries (lg &amp; sm) capillaries, veins</p>	<p><b><i>Moderately Radiotesistant</i></b> Sensitivity varies for the vascular system. Damage is great only in the 600-1500 rad range. This damage by radiation contributes to some of the heart, changes in other tissues.</p>
<p><b>Skin</b></p>	<p><b><i>Radioresistant</i></b> Exposures between 500-1000 rad can produce skin changes. However, as little as 100 rad can cause cell death in the germinal layer.</p>
<p><b>Bone and Teeth</b></p>	<p>Some parts of bone can be damaged by 700-1500 rad. Regeneration can begin 2 to 6 weeks after exposure.</p>
<p><b>Respiratory System</b></p>	<p><b><i>Relatively Radioresistant</i></b> Inflammation of the lungs can occur at 1000-2000 rad. Possible hemorrhaging due to changes produced in blood vessels.</p>
<p><b>Urinary System</b></p>	<p>Secondary effects can show up years after exposure in the 500-2000 rad range due to changes in blood vessels.</p>
<p><b>Muscle and Connective Tissues</b></p>	<p><b><i>Very Radioresistant</i></b> Massive exposures (over 2000 rad) are needed to cause slight changes in these tissues.</p>
<p><b>Nervous Tissue</b></p>	<p><b><i>Extremely Radioresistant</i></b> Massive exposures are required (over 3000 rad) to bring</p>

about morphological changes in these tissues.

The most radiation-sensitive state of any individual is during embryonic development. If irradiated at a time when a particular tissue or organ is being differentiated, exposures as small as 25-50 rad can lead to gross malformations. In humans, this corresponds to 2-6 weeks of gestation. This sensitivity is due to the presence of only a few cells at this stage which ultimately will give rise to a particular tissue or organ. If these are destroyed, other cells cannot replace them.

## B. Acute Lethal Response

Lethal effects are observed in mammals within a period of 30 days from acute exposures in the few-hundred rad range. Acute exposure refers to a short time period of delivery of the radiation, generally within minutes. Expression of this response is known as the  $LD_{50}^{30}$  or the dose which yields 50% lethality in an irradiated group of a particular species measured at 30 days. At doses appreciably below the  $LD_{50}^{30}$ , very little lethality occurs; whereas at doses appreciably above, 100% lethality occurs.

### Acute Lethal Responses

Species	RADS
guinea pig	175-409
dog	350
goat	350
man	350-450
mouse	550
rat	590-970
monkey	600
rabbit	800
fowl	1000
goldfish	2300

The ranges shown above represent an uncertainty only in the case of man, where precise experimental data does not exist. Other ranges represent a difference depending on the particular strain of the species used. The cause of death at the  $LD_{50/30}$  is due to response of the blood forming organs (described previously). Death occurs when the radiation exposure has reduced the number of these cells surviving to a level below that necessary for life. Interestingly, at the tissue level, a given dose yields about the same observable damage in any species. Some species, however, are better able to cope with the damage and so survive.

When organisms are exposed at or above the acute LD<sub>50/30</sub> value, characteristic physiological responses are seen. These responses are known as "radiation sickness" and "acute radiation syndrome". The following tables illustrate the symptoms and their timing from various whole-body dosages.

### **Expected Effects of Acute Whole-Body Radiation Doses**

Acute Dose (rads)	Probable Effect
0 – 50	No obvious effect, except possibly minor blood changes.
80 – 120	Vomiting and nausea for about 1 day in 5 to 10 percent of exposed personnel. Fatigue but no serious disability.
130 – 170	Vomiting and nausea for about 1 day, followed by other symptoms of radiation sickness in about 25 percent of personnel. No deaths anticipated.
180 – 220	Vomiting and nausea for about 1 day followed by other symptoms of radiation sickness in about 50 percent of personnel. No deaths anticipated.
270 – 330	Vomiting and nausea in nearly all personnel on first day, followed by other symptoms of radiation sickness. About 20 percent deaths within 2 to 6 weeks after exposure; survivors' convalescent for about 3 months.
400 – 500	Vomiting and nausea in all personnel on first day, followed by other symptoms of radiation sickness. About 50 percent deaths within 1 month; survivors' convalescent for about 6 months.
550 – 750	Vomiting and nausea in all personnel within 4 hours from exposure, followed by other symptoms of radiation sickness. Up to 100 percent deaths; few survivors convalescent for about 6 months.
1000	Vomiting and nausea in all personnel within 1 to 2 hours. Probably no survivors from radiation sickness.
5000	Incapacitation almost immediately. All personnel will be fatalities within 1 week.

*The Effects of Nuclear Weapons U.S. Government Printing Office, May 1957*

### **Acute Radiation Syndromes**

Response	Dose (rads)	Syndrome
Hematopoietic Death	700 to 1000	Death in 10-21 days caused by blood changes resulting in infection or hemorrhaging.

Gastro-intestinal Death	1000 to 10000	Death in 4-7 days. Nausea, vomiting and diarrhea; food and water intake depressed. Death by severe morphological changes in gastrointestinal tract.
Central Nervous System Death	10000 to 100000	Death within 2 days. Minutes after exposure disorientation, incoordination and semi-consciousness develops. Coma and death occurs from central nervous system damage.
Molecular Death	over 100000	Immediate death. Death caused by inactivation of substances required for basic metabolic processes.

### C. Chronic Exposure Response

If a given radiation exposure is delivered over a longer time period, the effect observed is less. Experiments utilizing the "split-dose" technique have shown that radiation damage is repaired by the organism as long as any single exposure is less than the LD<sub>50/30</sub>. For example, if animals are given one-half of the LD<sub>50/30</sub> (called a "conditioning dose") followed some time later by another equal dose (called the "test dose") with sufficient separation of the two doses (say, a few weeks), the animals will survive. If no time elapses between them, death occurs within 30 days. Spreading the dose over weeks or months at a low rate reduces the effect appreciably. For the induction of mutations in mice, the mutation yield for chronic exposure is about half that for acute exposure. Many other responses appear to follow this reduction in effectiveness under chronic exposure conditions.

### D. Late Effects of Radiation

Radiation, given either acutely or chronically, increases the incidence of a number of conditions observable from 5-20 years after the exposure was delivered. None of these responses are unique to radiation exposure, they occur with some normal incidence in the general population, but are increased in frequency in irradiated populations. The following have been shown to be associated with radiation:

#### Types of Late Effect

**Carcinogenesis** The reason for increases in certain forms of cancer by radiation (or other carcinogenic agents) is still speculative. Leukemia, skin, lung and bone cancers are radiogenic.

**Tissue Effects** Of most concern are cataracts and sterility. Cataracts develop slowly, but can stop or even regress. Sterility can be either permanent or temporary.

**Hereditary Effects** Since the time between generations is long, and controlled experimentation can only be performed in animals which may or may not represent the human response, the ultimate effect on us remains in question.

**Lifespan Shortening** Chronic exposure results in about a 7% lifespan shortening for every dose equivalent to the LD<sub>50</sub> received. A survivor of an acute LD<sub>50</sub> dose has a life expectancy reduced to 50% of an unirradiated control.

The above late effects can only be predicted for large populations. For an individual in an irradiated group, death cannot be identified as to its exact cause, either natural or from one of the many environmental agents capable of producing the same effect. No amount of experimentation is expected to yield any way to identify the precise agent which may be the cause of any of these effects when several are present. That is because each agent will contribute to the risk in proportion to its amount and effectiveness, as well as factors related to the genetic resistance or sensitivity of the individual exposed.

## E. Comparison of Health Effects

Studies have compared the projected loss of life expectancy resulting from exposure to radiation with other health risks. Estimates are calculated by looking at large numbers of individuals, recording the age at which death occurs from apparent causes, and estimating the number of days of life lost as a result of these early deaths. The total number of days of life lost is then averaged over the total group observed.

Estimated Loss of Life Expectancy from Health Risks

Health Risk	Estimate of Days of Life Expectancy Lost
Smoking 20 cigarettes/day	2370 (6.5 yr.)
Overweight by 20%	985 (2.7 yr.)
Auto accidents	200
5 rem/yr. for 30 years (calculated)	150
Alcohol consumption (US avg.)	130
Home accidents	95
Safest jobs (such as teaching)	30
1 rem/yr. for 30 years (calculated)	30
Natural background radiation (calculated)	8
Medical x-rays (calculated from US avg.)	6
Natural disasters	3.5
1 rem occupational dose (calculated)	1

Adapted from USNRC [Regulatory Guide 8.29](#)

These estimates illustrate that health risks from occupational radiation exposure are of the same order of magnitude as risks that we have historically encountered in normal day-to-day activities. Exposure to radiation should be considered in this perspective when considering its risk. As long as radiation exposure is kept at a value where its contribution to risk is a small part of the total sum of all risks, then it should not be of major concern.

## 2. Radiation Exposure Limits

## A. Historical Review

Soon after the discovery of X-rays and radium, the dangers of radiation exposure became well known. Standard setting organizations like the International Council on Radiation Protection (ICRP) and the National Council on Radiation Protection and Measurements (NCRP) were formed to recommend limits on the exposure of radiation. Prior to 1928, the radiation exposure limit was based on the amount of radiation needed to produce reddening of the skin (erythema). When the Roentgen (R) was defined in 1928, this "erythema exposure" was calculated to range from 0.04 R to 2 R per day. In 1935, the NCRP's first recommendation for exposure limitation was 0.1 R/day (31 R/year). This was an arbitrary limit, based on no observable effects on three technicians' exposure to radium gamma rays. In 1949, the NCRP reduced the limit to 0.05 R/day (0.3 R/week; 15 R/year) because radiations then being used were more penetrating. A major revision adopted by both the NCRP and ICRP took place in 1957 and was in effect until January 1, 1994. This limit allowed an individual to receive up to 3 Rem in 13 consecutive weeks, provided that the accumulated dose does not exceed  $5(N-18)$  Rem, where N is the individual's age. The latest revision eliminates what has been called a "bank" of available dose before exceeding the  $5(N-18)$  dose.

## B. Basis for the Current Radiation Exposure Limits

Occupationally exposed individuals are allowed higher radiation exposures than the general population for the following reasons:

1. The radiation worker accepts some small risk balanced against some benefit (through employment).
2. There is a conscious selection of occupationally exposed individuals: minors are excluded, medical histories can be obtained and maintained. Fertile women may be excluded. Preferential treatment is possible to those beyond the reproductive age.
3. There is a limit on the percentage of radiation workers in the total population.

## C. External Exposure

Current State and Federal guidelines describe the radiation exposure limits to an occupational radiation worker as follows:

1. Annual Limit:
  - a. An annual limit, which is the more limiting of:
    - i. The total effective dose equivalent being equal to 5 rems (0.05 Sv); or
    - ii. The sum of the deep-dose equivalent and the committed dose equivalent to any individual organ or tissue other than the lens of the eye being equal to 50 rems (0.5 Sv).
  - b. The annual limits to the lens of the eye, to the skin, and to the extremities, which are:
    - i. An eye dose equivalent of 15 rems (0.15 Sv), and
    - ii. A shallow-dose equivalent of 50 rems (0.50 Sv) to the skin or to any extremity.

2. Doses received in excess of the annual limits, including doses received during accidents, emergencies, and planned special exposures, must be subtracted from the limits for planned special exposures that the individual may receive during the current year and during the individual's lifetime.
3. The assigned deep-dose equivalent and shallow-dose equivalent must be for the part of the body receiving the highest exposure. The deep-dose equivalent, eye dose equivalent and shallow-dose equivalent may be assessed from surveys or other radiation measurements for the purpose of demonstrating compliance with the occupational dose limits, if the individual monitoring device was not in the region of highest potential exposure, or the results of individual monitoring are unavailable.

## D. Other Exposure Limits

Major Organs and Thyroid Gland:	15 rem/yr.
Fetus:	0.5 rem

The dose limit to the whole body for non-radiation workers, in addition to natural and medical sources is 0.1 rem/year.

The dose limit to the whole body for the U.S. population from all sources of radiation other than natural and medical sources is 0.1 rem/year per person.

## 3. Radiation from Background, Consumer Products, and Medical Exposure

The population as a whole is exposed to radiation whether it be from naturally occurring radioactivity present in the earth, from interstellar space, from medical sources, or from radioactivity contained in consumer products.

### A. Naturally Occurring Radiation

Naturally occurring radiation arises from three sources: cosmic rays entering the earth's atmosphere, naturally occurring radioactive materials in the earth's crust; and naturally occurring radioactive materials within the body.

#### 1. Cosmic Radiation

Primary cosmic rays are of galactic origin and consists of high energy protons,  ${}^4\text{He}$  ions, electrons, and photons (X and gamma rays). When these particles enter the atmosphere, they interact with the nuclei of the atoms in the air, giving rise to neutrons, electrons, protons, gamma rays, and other particles which are responsible for most of the observed cosmic ray dose. Because of the earth's magnetic field, the cosmic ray intensity varies with latitude, the lowest value at the geomagnetic equator. The intensity also varies with elevation, the highest levels being in the upper atmosphere. Cosmic rays from solar flares consists of X-Rays, protons, and alpha particles. Because these solar cosmic rays are relatively low in energy, they usually do not contribute significantly to increases in the radiation dose a ground level.

## 2. Terrestrial Radiation

Naturally occurring radionuclides in the environment are classed as either cosmogenic or primordial. Cosmogenic nuclides are those nuclides produced in the atmosphere when primary and secondary cosmic rays undergo nuclear reactions with nuclei of atoms in the air. The main contributors to external exposure from cosmogenic nuclides are Be-7, Na-22, and Na-24.

Primordial nuclides are those that are long lived and have existed in the earth's crust throughout history. The main contributors to external exposure from primordial nuclides are K-40, U-238, and Th-232, and their decay products. The concentrations of primordial nuclides in soil are dependent on the process by which the soil was formed. The table below shows the typical activity of these nuclides in various types of rock:

Typical Activity Concentration (pCi/gm)				
Type of Rock	K-40	U-23	Th-232	Absorbed dose rate in air (rad/hr.)
<u>Igneous</u>				
Acidic (e.g. granite)	27	1.6	2.2	12
Intermediate (e.g. diorite)	19	0.62	0.88	6.2
Mafic (e.g. basalt)	6.5	0.31	0.3	2.3
Ultrabasic (e.g. durite)	4	0.01	0.66	2.3
<u>Sedimentary</u>				
Limestone	2.4	0.75	0.19	2
Carbonate	---	0.72	0.21	1.7
Sandstone	10	0.5	0.3	3.2
Shale	19	1.2	1.2	7.9

Source: UNSCEAR 1977 Report

In various parts of the world, there are areas with high natural radiation levels. At the beach of the Black Sands in Guarppari, State of Espirito Santos, Brazil, it is possible to receive a radiation exposure of 5 mrad/hr due to the monazite (Thorium bearing minerals) sands. At Pocos de Caldas, State of Gerais, Brazil, the average range of radiation exposure is from 0.1 - 3 mrad/hr.

Naturally occurring radionuclides can give rise to external doses when contained in raw materials used to construct roads and buildings. Uranium and thorium are commonly found in cement, concrete blocks, and masonry products. For example, the possible annual dose near a granite wall at the "Redcap Stand" in

Grand Central Station, New York is 200 mrem (assuming an occupancy of 8 hrs/day).

### 3. Internal Radiation

Naturally occurring radionuclides enter the body through inhalation and ingestion. Of the cosmogenic nuclides only H-3, C-14, and Na-22 contribute to internal exposure. The major contribution to internal exposure from primordial nuclides are K-40 and the decay products of the uranium and thorium series.

#### a. Tritium

Tritium is produced in the atmosphere by secondary cosmic ray neutrons interacting with N-14 nuclides. The global inventory of tritium is calculated to be 34 Mega Curies\*. Most (99%) of the H-3 inventory is converted to tritiated water and takes part in the normal water cycle. Approximately 65% of the inventory is in the oceans as a result of transport by rain. About 30% of the inventory is in land surfaces with the remaining in the atmosphere.

#### b. Carbon-14

Carbon-14 is also produced by cosmic ray neutrons. The global inventory of C-14 is about 300 Mega Curies, with 94% distributed in the ocean, 4% in the land surface and biosphere and the remaining in the atmosphere. The natural specific activity of C-14 is 6.1 pCi/gm of carbon.

#### c. Potassium-40

Potassium is an essential element of the body and enters via the food chain. The amount of potassium in the body varies with age and sex. The average whole body activity concentration of K-40 is 1600 pCi/kg. Potassium-40 emits beta and gamma radiations and is, therefore, a source of both internal and external radiation exposure.

#### d. Uranium and Thorium Series

The radionuclides that contribute to internal exposure from the uranium series are: U-238, Ra-226, Rn-222, and its decay products Pb-210, Bi-210, and Po-210. The major nuclides that contribute to internal exposure from the thorium series are: Th-232, Ra-228, Ra-220, and its decay products Pb-212, Bi-212, and Po-212. The major contribution to the natural internal dose is from the decay products of Rn-222. The major source of these alpha emitting nuclides is through emanation of Rn-222 from the ground. The decay products form in clusters with water, oxygen, and other gases and attach themselves to aerosol particles. They can be inhaled, ingested, and through direct deposition on plant leaves and root absorption enter the food chain. Cigarettes are estimated to contain 0.6 pCi of Pb-210 and 0.4 pCi of Po-210. Brazil nuts and Pacific salmon have been found to contain larger concentrations (>5 pCi/kg) of radium-226. There are areas in the world in which water concentrations of

uranium and radium are high due to isolated deposits. Reindeer and caribou contain elevated levels of Pb-210 and Po-210 mainly because they feed on lichens in the winter which accumulate these isotopes. The Pb-210 in fish and mollusks range between 20-500 pCi/kg.

The main source of radon indoors is from building materials such as by-product gypsum, used for internal walls and ceilings, and concrete. Increasing the ventilation of the room will significantly reduce the radon levels. The highest levels found in poorly ventilated areas, such as basements, where radon diffuses out of the concrete walls and through cracks in the floor. Sealing the walls and floors with epoxy paint can reduce the emanation rate by a factor of four. Three layers of oil paint can reduce the emanation rate by an order of magnitude.

#### 4. Summary

The following table summarizes the estimated annual tissue absorbed dose from natural sources:

Source of Irradiation	Gonads (mrad)	Lungs (mrad)
<b>External Irradiation</b>		
Cosmic Rays:		
Ionizing component	28	28
Neutron component	0.35	0.35
Terrestrial Radiation: (Y)	32	32
<b>Internal Irradiation</b>		
Cosmogonic Radionuclides:		
H-3 ( $\beta$ )	0.001	0.001
Be-7 ( $\gamma$ )	---	0.002
C-14 ( $\beta$ )	0.5	0.6
Na-22 ( $\beta + \gamma$ )	0.02	0.02
Primordial Radionuclides:		
K-40 ( $\beta + \gamma$ )	15	17
Rb-78 ( $\beta$ )	0.8	0.4
U-238,U-234 ( $\alpha$ )	0.04	0.04
Th-230 ( $\alpha$ )	0.004	0.04
Ra-226, Po-214 ( $\alpha$ )	0.03	0.03
Pb-210, Po-210 ( $\alpha + \beta$ )	0.6	0.3
Rn-222, Po-214 ( $\alpha$ ) inhalation	0.2	30
Th-232 ( $\alpha$ )	0.004	0.04
Ra-228, Tl-208 ( $\alpha$ )	0.6	0.06
Rn-220, Tl-208 ( $\alpha$ ) inhalation	0.008	4
<b>Total (rounded):</b>	<b>78</b>	<b>110</b>

Source: UNSCEAR 1977 Report

#### B. Technologically Enhanced Exposures to Natural Radiation

Technologically enhanced exposure to natural radiation is defined as exposure to natural radiation to which man would not be exposed if some kind of technology had not been

developed. For example, travel by air, using natural gas for cooking or heating, and living near a coal fired power plant increase an individual's exposure to naturally occurring radiations.

Air travel increases the exposure due to cosmic rays and solar flares when flying at high altitudes. The following table shows calculated doses for various routes:

Comparison of Calculated Cosmic-Ray Doses to a Person Flying in Subsonic and Supersonic Aircraft Average Solar Conditions

Route	Subsonic Flight at 11 km		Supersonic Flight at 19 km	
	Flight Duration (hr.)	Dose per Round Trip (mrad)	Flight Duration (hr.)	Dose per Round Trip (mrad)
Los Angeles – Paris	11.1	4	3.8	3.7
Chicago – Paris	8.3	3.6	2.8	2.6
New York – Paris	7.4	3.1	2.6	2.4
New York – London	7	2.9	2.4	2.2
Los Angeles – New York	5.2	1.9	1.9	1.3
Sydney – Acapulco	17.4	4.4	6.2	2.1

Source: UNSCEAR 1977 Report

The table below shows the doses received by astronauts on various space missions. The largest part of the dose was received when the spacecraft passed through the earth's radiation belts. The belts contain protons, electrons, and alpha particles trapped by the earth's magnetic fields.

Absorbed Dose in Chests of Astronauts on Space Missions

Mission or Mission Series	Launch Date (yr-mo-dy)	Duration of Mission (hr.)	Type of Orbit	Dose (mrad)
Apollo VII	68-08-11	260	Earth Orbital	157
Apollo VIII	68-12-21	147	Circumlunar	150
Apollo IX	69-02-03	241	Earth Orbital	196
Apollo X	69-05-18	192	Circumlunar	480
Vostok 18-6			Earth Orbital	2-80
Vokshad 1,2			Earth Orbital	30-70
Soyuz 3-9			Earth Orbital	62-234

Source: UNSCEAR 1977 Report

Individuals living around coal-fired power plants are exposed to enhanced levels of Ra-226, Ra-228, U-238, Th-228, Th-232, and K-40 from gaseous and particulate combustion products of coal. The major contribution to the dose is from the alpha radiation of Pb-210, Th-228, and Th-232.

Phosphate products contain high concentrations of the nuclides in the U-238 decay series. About 1/2 of the phosphate rock that is mined is converted into fertilizer, the rest goes into commodities such as phosphoric acid, gypsum, and land fills. Thus, the use of phosphate fertilizers result in radiation exposures from the following:

1. Absorption of radionuclides by food crops.
2. External radiation from fertilizer storehouses and production plants.

3. Airborne radon decay products over land reclaimed after phosphate mining.
4. Radiation from gypsum used in building products.

## C. Consumer Products

Radiation exposure from consumer products are considered "Enhanced" since the radioactive material is deliberately incorporated into the product to serve a specific purpose.

### 1. Radioluminous Products

Products such as time pieces, aircraft instruments, signs, indicators, etc. contain various amounts of Ra-226, Pm-147, or H-3 to provide illumination. Light is generated when the radiations from these nuclides interact with a scintillator, usually zinc sulfide. The scintillator can be in the form of a paint (watch hands) or a coating inside of glass tubes (exit markers) to make the product "glow in the dark". With the exception of Ra-226, the low energy radiations are unable to penetrate watch crystals, glass tubes, etc. Because of the more energetic radiations from Ra-226, it is now rarely used.

### 2. Electronic and Electrical Equipment

Radioactive materials are used in lamps and electronic tubes to provide pre-ionization in gases for the purposes of passing an electrical current. This allows the equipment to respond faster and more reliably. Smoke detectors use alpha radiation from Am-241 to provide an ionization current. Smoke or combustion products entering the detection chamber cause a change in resistance (the alpha particles being stopped or absorbed by the smoke) triggering an alarm. Anti-static devices use Po-210 to ionize the air around a charged object, thereby allowing the charge to be neutralized.

### 3. Miscellaneous

Porcelains use in dentistry contain uranium in combination with cerium in order to simulate the natural fluorescence of teeth. Certain glazes used in ceramics contain uranium oxides and sodium uranite as pigments. Glazes ranging from black, brown, green, and the spectrum from yellow to red are used primarily to decorate pottery and tableware. Mantles in gas lanterns and yard lights consist mainly of thorium oxides. Major radiation exposure occurs during the first few hours that a new mantle is used, primarily from the inhalation of the thorium. Color televisions generate X-rays (via Bremsstrahlung) as a result of high speed electrons striking the phosphor screen of the picture tube. Most televisions today have high voltage controls and sufficient thickness of glass to absorb most of these low energy X-rays. The following tables describes various consumer products containing radioactive materials and some annual population dose rates:

<b>Selected Products Containing Radioactive Material</b>		
Product	Nuclides	Amount
<b>Radioactive Material Contained in Paint or Plastic:</b>		
Time Pieces	H-3	1 – 25 mCi
	Pm-147	65 – 200 µCi

	Ra-226	0.1 – 3 $\mu$ Ci
Compasses	H-3	5 – 50 mCi
	Pm-147	10 $\mu$ Ci
Thermostat Dials and Pointers	H-3	25 mCi
Automobile Shift Quadrants Speedometers	H-3	25 mCi
	Pm-147	0.1 mCi
<b>Radioactive Material Contained in Sealed Tubes:</b>		
Time Pieces, Marine Navigational Instruments	H-3	0.2 Ci
Exit Signs, Step markers, Public Telephone Dials, Light Switch Markers	H-3	0.2 – 3 Ci
<b>Electronic and Electrical Devices:</b>		
Fluorescent Lamp Starters	Ra-226	1 $\mu$ Ci
Vacuum Tubes, Electric Lamps, Germicidal Lamps	Natural Thorium	50 mg
Glow Lamps	H-3	0.01 mCi
High Voltage Protection Devices	Pm-147	3 $\mu$ Ci
Low Voltage Fuses	Pm-147	3 $\mu$ Ci
<b>Miscellaneous:</b>		
Smoke and Fire Detectors	Am-241	1 – 100 $\mu$ Ci
	Ra-226	1.1 – 15 $\mu$ Ci
	Kr-85	1.2 – 7 mCi
Incandescent Gas Mantles	Natural Thorium	0.5 gm
Ceramic Tableware Glaze	Natural Thorium Or Thorium	20% by weight of the glaze

Adapted from NCRP Report No. 56

## D. Medical Exposures

The population receives an exposure of radiation as part of planned medical procedures. This type of exposure is dependent on individual's health needs and is not considered as part of the individual's occupational exposure. Typical radiation exposures for various radiographic techniques are as follows:

Average Annual Population Dose Equivalents from Selected Consumer Products and Miscellaneous Sources

Product	mrem
TV Receivers	0.5
Airport X-Ray	0.001
Luminous Watches	0.05
Tobacco Products	2000
Coal Combustion	1
Natural Gas Combustion	5
Uranium in Dentures	10000

Source. Bureau of Radiological Health

## E. Summary

The table below summarizes the annual dose rates received from natural background, medical and other sources of radiation. The values indicated are averages and may vary slightly with other reported values:

<b>Annual Dose Rates to Population in USA. BEIR III (1980)</b>	
<b>Natural Background</b>	<b>mrem/yr.</b>
Cosmic	28
Terrestrial	26
Internal – C-14, Ra-226, Pm-222, K-40	28
	<hr/>
	82
<b>Medical</b>	
Diagnosis	77
Dental	1.4
Radiopharmaceutical	13.6
	<hr/>
	92
<b>Other</b>	
Weapon Tests (Fallout)	5
Power Plant and Nuclear Industry	< 1
Building Materials (Brick, Masonry)	5
TV Receivers	0.5
Airline Travel	0.5
	<hr/>
	12
<b>Total</b>	<b>186</b>

## Problem Set 3

Multiple choice questions may have more than one correct response.

1. The primary indirect effect of ionizing radiation upon biological target is:
  - a. erythema response.
  - b. free radical formation.
  - c. leukegenic response.
  - d. target absorption of the radiation.
2. The  $LD_{50/30}$  for humans is approximately
  - a. 100 mrem.
  - b. 1 rem.
  - c. 25 rem.
  - d. 450 rem.
3. The primary cause of death following and  $LD_{50}^{30}$  in humans is directly associated with irreparable and irreversible damage to:
  - a. the nervous system.
  - b. the heart, liver, and kidneys.
  - c. the hematopoietic organs (blood tissue producing).
  - d. the skeletal bone.
4. Which of the following cells are correctly grouped from radiosensitive to radioresistant?
  - a. lymphocytes (white blood cells), endothelial cells(cells lining the GI tract), nerve cells
  - b. nerve cells, lymphocytes, endothelial cells
  - c. endothelial cells, lymphocytes, nerve cells
  - d. endothelial cells, nerve cells, lymphocytes
5. Late Effects (5 - 20 yrs) of a large exposure to ionizing radiation may result in:
  - a. death as predicted by the  $LD_{50}$  concept.
  - b. carcinogenesis.
  - c. a change in skin pigmentation.
  - d. significant blood changes.
6. Immediate effects (within 30 days) of a large exposure to ionizing radiation may result in:
  - a. bacterial infections.
  - b. deaths.
  - c. development of tumors.
  - d. erythema.
7. Radiation damage to the body depends on:
  - a. the type of energy of the radiation.
  - b. the absorbed dose.
  - c. the time the radiation was distributed.
  - d. the area of the body affected.
8. An acute dose of 1 rem to the whole body may result in:
  - a. significant blood changes.
  - b. nausea, vomiting.
  - c. sterility.
  - d. no observable effects.
9. The "Law of Bergonie and Tribondeau" explains the radiosensitivity of tissues as:
  - a. directly proportional to the growth rate and inversely proportional to the degree of specialization.
  - b. directly proportional to the degree of specialization and inversely proportional to the growth rate.
  - c. directly proportional to the growth rate and directly proportional to the degree of specialization.

10. Name five factors that determine a given tissue's radiosensitivity:

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11. What are the allowed Federal Exposure Limits for radiation workers?

	<b>Rems per Calendar Year</b>	
	Average	Maximum
Whole Body	_____	_____
Skin	_____	_____
Extremities	_____	_____

12. \_\_\_\_\_ is the formula used to compute the maximum allowable accumulated lifetime exposure to ionizing radiation to the whole body for radiation workers.

13. Under what conditions can the maximum whole body exposure limits be applied?

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14. The yearly Federal whole body exposure limits for individual non-radiation workers is \_\_\_\_\_ rem.

15. The yearly whole body exposure limit for the U.S. population is \_\_\_\_\_ rem per person.

16. Occupational radiation dose limit for a minor is \_\_\_\_\_ % of the exposure limit for an adult.

17. A person becomes a radiation worker (with no previous radiation exposure history). What would be the maximum allowable whole body dose this person could receive in this year?

18. What are three major sources of natural background radiation?

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19. Why may the levels of natural radiation exposure be greater inside of some buildings than in open spaces?

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20. What naturally occurring isotopes contribute to external radiation exposure? Internal radiation exposure?

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# Chapter IV

## Radiation Protection and Laboratory Techniques

### 1. External Radiation Protection

The three basic methods used to reduce the external radiation hazard are time, distance, and shielding. Good radiation protection practices requires optimization of these fundamental techniques.

#### A. Time

The amount of radiation an individual accumulates will depend on how long the individual stays in the radiation field:

$$\text{Dose} = \text{Dose Rate} \times \text{Time}$$

$$\text{mrem} = \text{mrem/hr.} \times \text{hr.}$$

Therefore, to limit a person's dose, one can restrict the time spent in the area. How long a person can stay in an area without exceeding a prescribed limit is called the "stay time" and is calculated from the simple relationship:

$$\text{Stay Time} =$$

Example. How long can a radiation worker stay in a 1.5 rem/hr. radiation field if we wish to limit a dose to 100 mrem?

$$\text{Stay Time} = = 0.0667 \text{ hr.} = 4 \text{ minutes}$$

#### B. Distance

The amount of radiation an individual receives will also depend on how close the person is to the source.

##### 1. The Inverse Square Law

Point sources of X and gamma radiation follow the inverse square law, which states that the intensity of the radiation decreases in proportion to the inverse of the distance squared:

$$I \text{ proportional } D^{-2}$$

To represent this in a more useful formula:

$$I_1 = K =$$

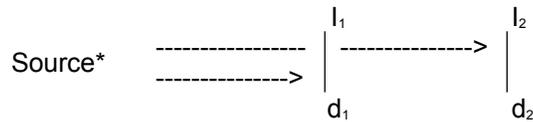
Therefore  $I_2 = K$

=

=

or

$$I_1 d_1^2 = I_2 d_2^2$$



And where:

$I_1$  = the radiation intensity at distance  $d_1$  from the radiation source.

$d_1$  = the shorter distance from the source where the radiation intensity is  $I_1$ .

$I_2$  = the radiation intensity at distance  $d_2$  from the radiation source.

$d_2$  = the longer distance from the source where the radiation intensity is  $I_2$ .

Therefore, by knowing the intensity at one distance, one can find the intensity at any given distance.

Example. The exposure rate one foot from a source is 500 mrem/hr. What would be the exposure rate three feet from the source?

$$I_1 = 500 \text{ mrem/hr.}$$

$$d_1 = 1 \text{ foot}$$

$$d_2 = 3 \text{ feet}$$

$$I_2 = \frac{I_1 d_1^2}{d_2^2} = \frac{500 \times 1^2}{3^2} = 55.6 \text{ mR/hr.}$$

## 2. Gamma Constants

Gamma radiation levels (in rem/hr.) for one Curie of many radionuclides at a distance of one meter have been measured. These "gamma constants" can be used to determine the expected exposure rate at a given distance (using inverse square) for a known quantity of a radionuclide or the number of Curies of a radionuclide from a measured exposure rate. Gamma constants ( $\Upsilon$ ) for selected radionuclides appear in [Appendix IV](#).

Example 1: What is the radiation exposure rate one foot from a 100 mCi point source of Cs-137? ( $\Upsilon = 0.33$ ).

$\Upsilon$  0.33 Rad/hr. at 1 meter/Curie (0.33 mrad/hr. at 1 meter/mCi)

$$I_1 d_1^2 = I_2 d_2^2$$

$$I_1 = ?$$

$$I_2 = 0.33 \text{ mrad/hr./mCi} \times 100 \text{ mCi} = 33 \text{ rad/hr.}$$

$$d_2 = 1 \text{ meter}$$

$$d_1 = 1 \text{ foot} = 0.3048 \text{ meter}$$

$$I_1 = = = 355 \text{ mrad/hr.}$$

Example 2: If the exposure rate from Cs-137 at one meter is 250 mrad/hr., how many Curies are present?

$$(Y = 0.33)$$

$$= 0.76 \text{ Curies}$$

### 3. Gamma Exposure Rate Formula

The exposure rate from a gamma point source can be approximated from the following expression:

$$R/\text{hr. at 1 foot} = 6CEn$$

Where C: Number of Curies of Gamma Emitter  
 E: Gamma Ray Energy in MeV  
 n: Number of Gammas per Disintegration

This expression holds only for gamma emitters with energies ranging from 0.07 MeV to 4 MeV. Example: What would the exposure rate be one foot from 100 mCi of I-131?

$$\text{I-131: } \lambda_1 = 0.363 \text{ MeV, } 81.2 \% \text{ Y/d}$$

$$\text{I-131: } \lambda_2 = 0.636 \text{ MeV, } 7.3 \% \text{ Y/d}$$

$$\text{rad/hr. at 1 foot} = 6(0.1\text{Ci})[(0.364 \times 0.812) + (0.636 \times 0.073)] = 0.21$$

or

$$210 \text{ mrad/hr. at one foot}$$

## C. Shielding

When reducing the time or increasing the distance may not be possible, one can choose shielding material to reduce the external radiation hazard. The proper material to use depends on the type of radiation and its energy.

### 1. Alpha and Beta Radiation

As discussed in Chapter I, alpha particles are easily shielded. A thin piece of paper or several cm of air is usually sufficient to stop them. Thus, alpha particles present no external radiation hazard. Beta particles are more penetrating than alpha particles. Beta shields are usually made of aluminum, brass, plastic, or

other materials of low atomic number to reduce the production of bremsstrahlung radiation. Appendix IV gives the range of beta radiation for selected radionuclides in air and plastic.

## 2. X and Gamma Radiation

Monoenergetic X or gamma rays collimated into a narrow beam are attenuated exponentially through a shield according to the following equation:

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

where

I:	Intensity Outside of a Shield of Thickness x
I <sub>0</sub> :	Unshielded Intensity
μ:	Linear Attenuation Coefficient
x:	Thickness of Shielding Material

The linear attenuation coefficient is the sum of the probabilities of interaction per unit path length by each of the three scattering and absorption processes photoelectric effect, Compton Effect, and pair production. Note that μ has dimensions of inverse length. The reciprocal of μ is defined as the mean free path which is the average distance the photon travels in an absorber before an interaction takes place.

Because linear attenuation coefficients are proportional to the absorber density, which usually does not have a unique value but depends somewhat on the physical state of the material, it is customary to use "mass attenuation coefficients" which removes density dependence:

Mass attenuation coefficient  $\mu_m = \mu / \rho = \text{density (gm/cm}^3\text{)}$

For a given photon energy,  $\mu_m$  does not change with the physical state of a given absorber. For example, it is the same for water whether present in liquid or vapor form. If the absorber thickness is in cm, then  $\mu_m$  will have units of:

which =

Values of the mass attenuation coefficient for lead are given in [Appendix IV](#).

Example. The intensity of an unshielded Cs-137 source is 1 rad/hr. If the source is put into a lead shield two inches thick, what would be the intensity on the outside of the shield? Density of lead = 11.35 gm/cm<sup>3</sup>

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

$$I_0 = 1 \text{ rad/hr.}$$

$$\mu = \mu_m \times \rho = (0.114 \text{ cm}^2\text{gm})(11.35 \text{ gm/cm}^3) = 1.29 \text{ cm}^{-1}$$

$$X = 2 \text{ inches} \times 2.54 \text{ cm/inch} = 5.08 \text{ cm}$$

$$I = (1\text{R/hr.}) \times e^{-(1.29 \text{ cm}^{-1})(5.08\text{cm})} = 0.0014 \text{ R/hr.} = 1.4 \text{ mR/hr.}$$

## 3. Half Value Layer

The half value layer (HVL) is the thickness of the shielding material required to reduce the intensity to one half of its original intensity and can be calculated from:

$$= 0.5 = e^{-\mu x}$$

$$X_{1/2} = \text{HVL}$$

Half value layers (for lead) are given for selected radioisotopes in [Appendix IV](#). Example. How much lead shielding must be used to reduce the exposure rate from an I-131 source from 32 mrad/hr. to 2 mrad/hr. HVL of lead for I-131 is 0.178 cm.

$$= 16 = 4 \text{ HVL } (2 \times 2 \times 2 \times 2 = 16)$$

$$4 \times 0.178 \text{ cm} = 0.71 \text{ cm}$$

## D. Personnel Monitoring

External radiation exposure is measured by personnel monitoring devices. Three major types of monitoring devices in use today are the pocked dosimeter, the film badge, and the thermoluminescent dosimeter (TLD). Personnel monitoring is required when it is likely that an individual will be exposed during any calendar year to a dose of 5.0 rems to the whole body (head and trunk, active blood forming organs, gonads); 15 rems to the lens of eye); 50 rems to the extremities (hands, forearms, feet, leg below the knee, ankles); 50 rems to the skin of the whole body; or in any work area where you can receive 100 mrems in any hour at 30 cm from the source or source container. Personnel monitoring provides a permanent, legal record of an individual's occupational exposure to radiation.

### 1. Pocket Dosimeters

Pocket dosimeters are small devices (about the size of a marking pen) one can carry in a shirt or lab coat pocket to record exposure to radiation. The dosimeter is set to zero prior to use by a separate battery or AC line operated charging device. When radiation passes through the sensitive volume of the dosimeter, the charge is dissipated in proportion to the amount of radiation received. "Self-reading" dosimeters have an optical system to allow the wearer to view the amount of radiation received by looking through the dosimeter like a telescope. "Indirect reading" dosimeters require a separate readout device (that also serves as the dosimeter charger). Several exposure ranges are available, the most common being from 0 to 200 mr.

The advantage of a pocket dosimeter is that it can provide an on-the-spot result of an individual's exposure to radiation. However, pocket dosimeters are susceptible to erroneous readings when exposed to excessive moisture, dust, or physical abuse. In each case, the dosimeter will read high. For this reason, two dosimeters are usually worn for periods of one day or less. The lower reading dosimeter is considered to be the more accurate. Another disadvantage is the dosimeter's limited exposure range. If the dosimeter is exposed to radiation beyond its range, then the total exposure received cannot be determined.

### 2. Film Badges

A typical film badge consists of a film packet and holder. The film packet usually contains two pieces of film, one sensitive to X or gamma radiation in the energy range 15 keV to 3 MeV, and the other sensitive to beta radiation in the energy range from 200 keV to 1 MeV. Radioisotopes with energies below those values referenced above cannot be detected. This is why users of low energy beta emitters such as H-3, C-14, and S-35 are not issued film badges. Exposure to radiation causes the film to turn black upon development, the degree of film blackening is then related to the amount of radiation exposure.

The badge holder contains filters that allow different radiation types (beta, X, gamma, neutron) and energies to be distinguished on the film. An "open" window (i.e., no filter) allows all radiations of sufficient energy to pass and expose the film. A plastic filter absorbs most low energy beta radiation. Other filters such as copper or lead absorb most high energy beta radiation and all but high energy gamma radiation. Fast neutrons interact with a cadmium filter to produce film blackening. Slow neutrons interact with the nitrogen atoms in the film's gelatin layer and the resulting proton tracks are counted.

Advantages of film badges are:

- a. They are relatively inexpensive compared to other dosimeter types.
- b. They provide a permanent record of an individual's dose (film are kept on file).
- c. Films are processed and results reported by a disinterested third party.

Disadvantages are:

- a. Films are susceptible to extremes of heat, pressure and moisture.
- b. Film processing and receipt of exposure results may take several weeks.

To eliminate this latter disadvantage, pocket dosimeters can be worn along with film badges. If the pocket dosimeter indicates a possible high exposure, the film badge can be evaluated on an emergency basis, usually within twenty-four hours after the receipt by the vendor.

### **3. Thermoluminescent Dosimeters (TLDs)**

TLDs are small chips (1/8" x 1/8" x 1/32") of lithium fluoride or calcium fluoride. The chips absorb energy from radiation which excites atoms to higher energy levels within the crystal lattice. Heating the chip releases the excitation energy as light, proportional to the amount of radiation received. Chips are placed in badge holders containing filters to distinguish between energy and type.

Advantages of TLDs are:

- a. They are small and can be used as extremity monitors.
- b. They can be read on-site or through a disinterested third party.
- c. They are reusable.

Disadvantages are:

- a. Once the chips are analyzed, the exposure information is lost and cannot be verified at a later date.
- b. Chips are relatively expensive.
- c. Chips are subject to physical damage such as cracking or breaking, etc.

#### 4. Proper use of Personnel Dosimeters

- a. Personnel dosimeters must be worn only by the person to whom it was issued. Any exposure information will then become a part of that person's exposure history record.
- b. Dosimeters should be worn on the part of the body where exposure to radiation is likely. Usually, they are worn between the neck and waist. Care must be taken to prevent items like pens, buttons, lab benches, hood aprons, etc. from shielding the badge holder.
- c. Store dosimeters along with the "control" dosimeter in a designated area, away from extremes in temperature and radiation. The purpose of the control is to record any non-occupational exposure while the badge is not being worn (i.e., during transit to and from the vendor).

### E. Posting and Labeling of Radioactive Materials

#### 1. Cautionary Signs

Cautionary signs are required to be posted under certain conditions as described below to warn other individuals in the area that radioactive material or radiation is present:

**Caution - Radioactive Materials:** In areas or on items where radioactive material is used or stored. Each label shall provide sufficient information to permit individuals handling or using containers or working in the general vicinity to take precautions to avoid or minimize exposure. Such information should include:

- a. The type of radioactive material
- b. The estimated activity
- c. Assay date
- d. The individual responsible for the material

**Caution - Radiation Area:** In areas where the level of radiation could cause a major portion of an individual's body to receive an exposure from external radiation that exceeds 5 mrem/hr. at 30 cm from source or container. "Radiation Area" postings should be at the point of entrance to the area.

**Caution - High Radiation Area or Danger - High Radiation Area:** In areas where the level of radiation could cause a major portion of an individual's body to receive an exposure from external radiation that exceeds 100 mrem/hr. at 30 cm from source or container. "High Radiation Area" postings should be at the point of entrance to the area.

**Grave Danger - Very High Radiation Area:** In areas where the level of radiation could result in an individual receiving an absorbed dose in excess of 500 rads/hr. at 1 meter from a radiation source or from any surface that the radiation penetrates.

In addition, individuals posting radiation warning signs should provide information on the sign to aid others in minimizing their exposure. Information may include:

1. The source of radiation
2. The exposure rate in mr/hr. or rem/hr. on contact at the highest spot
3. The name of the person posting the sign
4. The date the sign was posted

## 2. Department of Transportation (DOT) Warning Labels

Each package of radioactive material offered for transportation, unless exempted, must be labeled on two sides with one of the three labels shown below:



### DOT Warning Labels for Radioactive Materials Packages

The purpose of these labels is to alert individuals handling packages that special handling may be required. When the background color of the label is all white (Radioactive White-I), the external radiation level from the package is minimal and no special handling is necessary. If however, the background of the upper half of the label is yellow (Radioactive Yellow II or III), a radiation level may exist at the outside of the package, and precautions should be taken to minimize radiation exposures when handling the package. The radiation level in mrem/hr at one meter from the external surface of the package is known as the transport index, and is written in the space provided on the warning label. Furthermore, if the package bears a Radioactive Yellow III, the rail or highway vehicle in which it is carried must be placarded. The table below defines the label criteria for radioactive materials packages:

Label	Dose Rate Limits	
	Accessible Surface of Package	External Surface of Package
Radioactive – White I	0.5 mrem/hr.	0
Radioactive – Yellow II	50 rem/hr.	1 mrem/hr.
Radioactive – Yellow III (Requires Vehicle Placarding)	200 mrem/hr.	10 mrem/hr.

The cautionary signs and warning labels described in these sections must be removed or defaced when they are no longer needed.

## F. Internal Radiation Protection

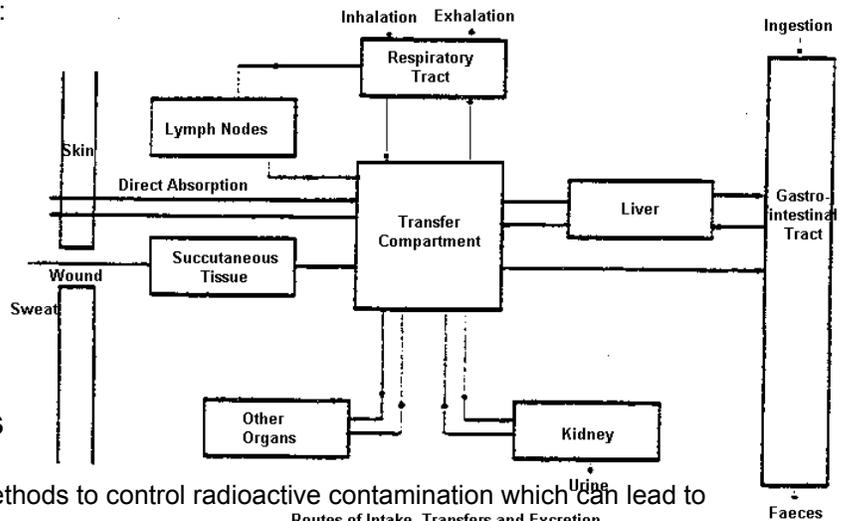
Internal radiation exposure results when the body is contaminated internally with a radioisotope. When radioactive materials enter the body, they are metabolized and distributed to the tissues according to the chemical properties of the elements and compounds in which they are contained. For example, consider a complex molecule which can be equally satisfied with a C-12 (stable) atom or a C-14 (radioactive) atom at its regular carbon position. If the C-14 decays to nitrogen, the molecular structure is affected. If the molecule were DNA, this might be equivalent to gene mutation. Once radioactive material is in the body, little can be done to speed its removal. Thus, internal radiation protection is concerned with preventing or minimizing the deposition of radioactive substances in the body.

### 1. Methods of Entry

Radioactive substances, like other toxic agents, may gain entry into the body by four processes:

- i. **Inhalation** - Breathing radioactive aerosols or dust.
- ii. **Ingestion** - Drinking contaminated water, or transferring radioactivity to the mouth.
- iii. **Absorption** - Entering through intact skin.
- iv. **Injection** - Entering through a puncture of the skin with an object bearing radioactive materials.

The following diagram is a summary of radionuclide entry, transfer, and exit within the body:



### 2. Guidelines

Three basic methods to control radioactive contamination which can lead to internal radiation exposures are:

1. Minimize the amount of radioactive material being handled. Use only as much activity that is needed.
2. Contain the radioactive material. Different physical states (gas, liquid, solid) require different containment techniques. Generally, two levels of containment should be provided. For example, a vial containing a stock solution of radioactive material should be properly capped and placed or

transported using a drip tray or other similar device lined with absorbent paper.

3. Follow established laboratory procedures. Proper protective clothing, designated work areas, surface contamination monitoring, etc., are required in all laboratories that use radioactive material (see Part IV 3. Radioisotope Laboratory Techniques).

## 2. Internal Exposure Limits

Annual Limits on Intake (ALIs) and Derived Air Concentrations (DACs) of Radionuclides for Occupational Exposure; Effluent Concentrations; Concentrations for Release to Sewerage are listed below for selected nuclides.

### Introduction

For the selected radionuclides, the chemical form which is to be used for selecting the appropriate ALI or DAC value is listed. The ALIs and DACs for inhalation are given for an aerosol with an activity median aerodynamic diameter (AMAD) of 1  $\mu\text{m}$  and for three classes (D,W,Y) of radioactive material, which refer to their retention (approximately days, weeks or years) in the pulmonary region of the lung. This classification applies to a range of clearance half-times of less than 10 days, for W from 10 to 100 days, and for Y greater than 100 days. The class (D,W, or Y) given in the column headed "Class" applies only to the inhalation ALIs and DACs given in Table 1 in columns 2 and 3.

### Table 1

Note that the columns in Table 1 captioned "Ingestion ALI", "Inhalation ALI", and "DAC," are applicable to occupational exposure to radioactive material.

The ALIs in this table are the annual intakes of a given radionuclide by "Reference Man" which would result in either (1) a committed effective dose equivalent of 5 rems (stochastic ALI) or (2) a committed dose equivalent of 50 rems to an organ or tissue (non-stochastic ALI). The stochastic ALIs are derived to result in a risk, due to irradiation of organs and tissues, comparable to the risk associated with deep dose equivalent to the whole body of 5 rems. The derivation includes multiplying the committed dose equivalent to an organ or tissue by a weighting factor,  $W_t$ . This weighting factor is the proportion of the risk of stochastic effects resulting from irradiation of the organ or tissue,  $t$ , to the total risk of stochastic effects when the whole body is irradiated uniformly. The values of  $W_t$  are listed under the definition of weighting factor indicated below. The non-stochastic ALIs were derived to avoid non-stochastic effects, such as prompt damage to tissue or reduction in organ function.

A value of  $W_t=0.06$  is applicable to each of the five organs or tissues in the "remainder" category receiving the highest dose equivalents, and the dose equivalents of all other remaining tissues may be disregarded. The following parts of the GI tract-stomach, small intestine, upper large intestine, and lower large intestine-are to be treated as four separate organs.

The derived air concentration (DAC) values are derived limits intended to control chronic occupational exposures. The relationship between the DAC and the ALI is given by:  $\text{DAC} = \text{ALI}(\text{in } \mu\text{Ci}) / (2000 \text{ hours per working year} \times 60 \text{ minutes/hour} \times$

$2E4 \text{ ml per minute}) = (ALI/2.4E9) \mu\text{Ci/ml}$ , where  $2E4 \text{ ml}$  is the volume of air breathed per minute at work by "Reference Man" under working conditions of "light work.". The DAC values relate to one of two modes of exposure: either external submersion or the internal committed dose equivalents resulting from inhalation of radioactive materials. Derived air concentrations based upon submersion are for immersion in a semi-infinite cloud of uniform concentration and apply to each radionuclide separately.

The ALI and DAC values relate to exposure to the single radionuclide named, but also include contributions from the ingrowth of any daughter radionuclide produced in the body by the decay of the parent. However, intakes that include both the parent and daughter radionuclides should be treated by the general method appropriate for mixtures. The value of ALI and DAC do not apply directly when the individual both ingests and inhales a radionuclide, when the individual is exposed to a mixture of radionuclides by either inhalation or ingestion or both, or when the individual is exposed to both internal and external radiation. When an individual is exposed to radioactive materials which fall under several of the translocation classifications (i.e., Class D, Class W, or Class Y) of the same radionuclide, the exposure may be evaluated as if it were a mixture of different radionuclides.

It should be noted that the classification of a compound as Class D, W, or Y is based on the chemical form of the compound and does not take into account the radiological half-life of different radioisotopes. For this reason, values are given for Class D, W, and Y compounds, even for very short-lived radionuclides.

### **Table 2 Air**

Table 2 provides concentration limits for airborne and liquid effluents released to the general environment.

### **Table 3**

Table 3 provides concentration limits for discharges to sanitary sewer systems.

The columns in Table 2 captioned "Effluents", "Air," and "Water," are applicable to the assessment and control of dose to the general public. The concentration values given in Columns 1 and 2 of Table 2 are equivalent to the radionuclide concentrations which, if inhaled or ingested continuously over the course of a year, would produce a total effective dose equivalent of 0.05 rem (50 millirem or 0.5 millisieverts).

Consideration of non-stochastic limits has not been included in deriving the air and water effluent concentration limits because non-stochastic effects are presumed not to occur at the dose levels established for individual members of the public. For radionuclides, where the non-stochastic limit is governing in deriving the occupational DAC, the stochastic ALI is used in deriving the corresponding airborne effluent limit in Table 2. For this reason, the DAC and airborne effluent limits are not always proportional.

The air concentration values listed in Table 2, Column 1, are derived by one of two methods. For those radionuclides for which the stochastic limit is governing,

the occupational stochastic inhalation ALI is divided by 2.4E9 ml relating the inhalation ALI to the DAC, as explained above, and then divided by a factor of 300. The factor of 300 includes the following components: a factor of 50 to relate the 5-rem annual occupational dose limit to the 0.1-rem limit for members of the public. A factor of 3 to adjust for the difference in exposure time and the inhalation rate for a worker and that for members of the public; and a factor of 2 to adjust the occupational values (derived for adults) so that they are applicable to other age groups.

For those radionuclides for which submersion (external dose) is limiting, the occupational DAC in Table 1, Column 3, was divided by 219. The factor of 219 is composed of a factor of 50, as described above, and a factor of 4.38 relating occupational exposure for 2,000 hours per year to full-time exposure (8,760 hours per year). Note that an additional factor of 2 for age considerations is not warranted in the submersion case.

**Table 2 Water**

The water concentrations are derived by taking the most restrictive occupational stochastic oral ingestion ALI and dividing by 7.3E7. The factor of 7.3E7 (ml) includes the following components: the factors of 50 and 2 described above and a factor of 7.3E5 (ml) which is the annual water intake of "Reference Man."

Radionuclide	Compound	Table 1 Occup. Values			Table 2 Effluent Conc.		Table 3 Releases to Sewers
		Column → 1 Oral Inj. ALI. μCi	2 Inh. AL. μCi	3 DA. μCi/ml	1 Air μCi/ml	2 Water Conc. μCi/ml	Monthly Average μCi/ml
1 H-3	Water	8E+4	8E+4	2E-5	1E-7	1E-3	1E-2
6 C-14	DAC includes skin abs. Monoxide	-	2E+6	7E-4	2E-6	-	-
	Dioxide	-	2E+5	9E-5	3E-7	-	-
20 Ca-45	Compounds	2E+3	2E+3	1E-6	3E-9	3E-5	3E-4
	W, all compounds	2E+3	8E+2	4E-7	1E-9	2E-5	2E-4
24 Cr-51	D, all compounds except those given for W and Y	4E+4	5E+4	2E-5	6E-8	5E-4	5E-3
	W, halides and nitrates	-	2E+4	1E-5	3E-8	-	-
27 Co-60	Y, oxides and hydroxides	-	2E+4	8E-6	3E-8	-	-
	W, all compounds except those given for Y	5E+2	2E+2	7E-8	2E-10	3E-6	3E-5
	Y, oxides,	2E+2	3E+2	1E-8	5E-11	-	-

	hydroxides, halides, and nitrates		1				
29 Cu-6	D, all compounds except those given for W and Y	1E+4	3E+4	1E-5	4E-8	2E-4	2E-3
	W, halides, nitrates and sulfides	-	2E+4	1E-5	3E-8	-	-
	Y, oxides and hydroxides	-	2E+4	9E-6	3E-8	-	-
55 Cs-137	D, all compounds	1E+2	2E+2	6E-8	2E-10	1E-6	1E-5
53 I-125	D, all compounds	4E+1	6E+1	3E-8	-	-	-
15 P-32	D, all compounds except phosphates given for W	6E+2	9E+2	4E-7	1E-9	9E-6	9E-5
	W, phosphates of Zn <sup>2+</sup> , S <sup>3+</sup> , Mg <sup>2+</sup> , Fe <sup>3+</sup> , Bi <sup>3+</sup> , and lanthanides	-	4E+2	2E-7	5E-10	-	-
15 P-33	D, see P-32	6E+3	8E+3	4E-6	1E-8	8E-5	8E-4
	W, see P-32	-	3E+3	1E-6	4E-9	-	-
16 S-35	Vapor	-	1E+4	6E-6	2E-8	-	-
	D, sulfides and sulfates except those given for W	1E+4	2E+4	7E-6	2E-8	-	-
	LLI Wall	8E+3	-	-	-	1E+4	1E-3
	W, elemental sulfur, sulfides of Sr, Ba, Ge, Sn, Pb, As, Sb, Bi, Cu, Ag, Au, Zn, Cd, Hg, W, and Mo	6E+3	-	-	-	-	-
	Sulfates of Ca, Sr, Ba, Ra, As, Sb, and Bi	-	2E+3	9E-7	3E-9	-	-

### Organ Dose Weighting Factors

Organ or Tissue	Weight
Gonads	0.25
Breast	0.15

Red Bone Marrow	0.12
Lung	0.12
Thyroid	0.03
Bone Surface	0.03
* Remainder	0.3
** Whole Body	1.0

- \* 0.30 results from 0.06 for each of 5 "remainder" organs, excluding the skin and the lens of the eye, that receive the highest doses.
- \*\* For the purposes of weighting the external whole body dose, (for adding it to the internal dose) a single weighting factor,  $W_t = 1.0$  is specified.

## B. Units of Radiation Dose.

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

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

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

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

### Quality Factors and Absorbed Dose Equivalencies

Type of Radiation	Quality Factor Dose	Absorbed Equivalent (Q)
X, Gamma, or Beta Radiation.....	1	1
Alpha Particles, Multiple-Charged Particles, Fission Fragments, and Heavy Particles of Unknown Charge.....	20	0.05
Neutrons of Unknown Energy.....	10	0.1
High-Energy Protons.....	10	0.1

Absorbed dose in rad is equal to 1 rem or the absorbed dose in gray is equal to 1 Sievert.

If it is more convenient to measure the neutron fluence rate than to determine the neutron dose equivalent rate in rems per hour or Sieverts per hour, 1 rem (0.01 Sv) of neutron radiation of unknown energies may be assumed to result from a total fluence of 25 million neutrons per square centimeter incident upon the body. If sufficient information exists to estimate the approximate energy distribution of the neutrons, the fluence rate per unit dose equivalent or the appropriate Q value from table above may be used to convert a measured tissue dose in rads to dose equivalent in rems.

Mean Quality Factors, Q, and Fluence Per Unit Dose Equivalent for  
Monoenergetic Neutrons

Neutron Energy (MeV)	Quality Factor (Q)	Unit Dose Equivalent (neutrons/cm <sup>2</sup> /rem) (Thermal)
2.5E-8	2	980E6
1E-7	2	980E6
1E-6	2	810E6
1E-5	2	810E6
1E-4	2	840E6
1E-3	2	980E6
1E-2	2.5	1010E6
1E-1	7.5	170E6
5E-1	11	39E6
1	11	27E6
2.5	9	29E6
5	8	23E6
7	7	24E6
10	6.5	24E6
14	7.5	17E6
20	8	16E6
40	7	14E6
60	5.5	16E6
1E2	4	20E6
2E2	3.5	19E6
3E2	3.5	16E6
4E2	3.5	14E6

### C. Units of Radioactivity.

Activity is expressed in the special unit of curies (Ci) or in the SI unit of Becquerel (Bq), or their multiples, or disintegrations (transformations) per unit of time.

One Becquerel	= 1		
	disintegrations/sec.		
One Curie	= 3.7E10	= 3.7E10	= 2.22e12
	disintegrations/sec.	Becquerel	disintegrations/min.

### D. Internal Exposure Monitoring

Internally deposited radioactive material can be monitored by measuring the radiation emitted from the body or by measuring the amount of radioactive material contained in the urine or feces. Such monitoring techniques are called "bioassays".

Bioassays are required whenever surveys or calculations indicate that an individual has been exposed to concentrations of radioactive material in excess of established limits or when required by State or Federal regulations.

## 2. Radioisotope Laboratory Techniques

All laboratories authorized to use radioactive materials require special precautions to minimize the external and internal hazard from radiation and radioactive contamination. This section deals with general regulations and techniques that should be followed in the radioisotope lab.

### A. Protective Clothing

1. Lab coats should be worn when manipulating radioactive materials to prevent contamination of street clothing.
2. Disposable plastic gloves should always be worn when using radioactive materials. Personnel with breaks in the skin should use waterproof tape to seal such breaks or not use radioactive material.
3. Care should be exercised not to transfer contamination from the hands or lab coat by reflex actions such as wiping one's brow or scratching an itch.

### B. The Workplace

1. Areas in which radioactive materials are used should be covered with plastic backed absorbent paper to contain spills and prevent contamination of the working surface.
2. Drip trays can be used to transfer beakers, test tubes, etc. from one location to another.
3. Change absorbent paper at regular intervals to prevent cross contamination.
4. Label all containers used for radioactive materials work. Keep the work areas neat and clean to prevent accidents as well as making it easier to decontaminate if accidental spills do occur.
5. Secure all radioactive materials from unauthorized removal. Close or lock the lab door when materials must be left unattended. Most refrigerator/freezers can be equipped with locks and make an ideal place for storage.
6. There must be no eating, drinking, smoking, or storage of food in areas in which radioactive materials are used.

### C. Manipulations of Radioactive Materials

1. No mouth pipetting of anything is allowed in a radio-isotope work area. Use a safety pipetting aid for dispensing with standard laboratory pipettes. Eppendorf or other precision pipettes can be used for smaller dispensing. Assume all pipettes and glassware in the work area are contaminated unless labeled otherwise. Contaminated glass pipettes can be placed in a pipette jar for washing. Contaminated Eppendorf tips and disposable pipettes should be placed in radioactive waste containers.
2. Containers used in vortexing, mixing, shaking, or centrifuging operations should be intact and sealed with parafilm or stoppers to prevent spillage.
3. Prepare samples carefully. Heating, drying, distilling, and other operations which could result in volatilization of the material should be performed in a fume hood or glove box.
4. Provide proper shielding to reduce exposure, but not so that you hinder the safe execution of the experiment.
5. Whenever possible, rehearse operation with non-radioactive materials to ensure that the technique will be reasonably free of incidents.

6. Accurate records of radioactive material inventory on hand should be maintained. Record withdrawals from the stock vial on inventory control forms received with the isotopes.

## D. Radioactive Material Spills

All spills of radioactive material must be cleaned promptly. The responsibility for cleaning up the spill rests on the individual working in the area involved and responsible for the spill. Under no circumstances should an untrained person attempt to examine or clean up a spill of radioactive material.

The following general procedures should be followed when dealing with spills of radioactive materials:

1. **Major Spills** - Those involving significant radiation hazards to personnel shall be decontaminated under the direct supervision of a qualified individual.
  - a. Notify all personnel not involved with the spill to vacate the area at once. Have an evacuee notify radiation authorities of the incident.
  - b. Affected persons should limit their movement to confine the spread of contamination.
  - c. Contain the spill from further spread.
  - d. Remove contaminated clothing at once: flush contaminated skin areas thoroughly.
  - e. Shut off ventilating equipment (if possible) that may transport contaminated air from the area to other parts of the building.
  - f. Vacate and post or cordon off the contaminated area.
  - g. Assemble in a nearby safe or clean area and begin monitoring and decontamination of affected persons. Do Not Leave the Area unless adequately decontaminated or with the permission of the responsible radiation authorities.
2. **Minor Spills** - Those involving little or no radiation hazard to personnel may be decontaminated by laboratory personnel under the direction of the laboratory supervisor.
  - a. Contain the spill: If the material is a liquid, place an absorbent material such as paper towels, tissues, cloth, etc. over the spill to prevent its spread. If the material spilled is a powdered solid, attempt to contain its spread by covering the area with a protective barrier such as a drip tray, empty beaker, section of kraft paper, etc. If appropriate, close doors and windows, turn off room ventilation fans.
  - b. Inform others of the spill. Adjust your response to the seriousness of the spill. Instruct those personnel present in the room at the time of the spill to remain in an evacuation area to prevent contamination spread. Evacuated personnel should not eat, drink, or smoke until they are monitored and found free of contamination.
  - c. Decontaminate the area: Plan ahead. Provide adequate protection and supplies for personnel involved in the cleanup. Begin at the periphery and work toward the center of the contamination. Cover cleaned area with plastic or paper to

prevent its recontamination. Place all contaminated items in the proper waste containers. The degree of decontamination arranged by the supervisor should be to the limit specified in Section G.

- d. Monitor the area: Using appropriate survey techniques, monitor the progress of the decontamination. Monitor all personnel and materials before releasing them to clean areas.

Other emergencies such as fire, lost or stolen radioactive material, accidental uptake of radioactive material, radiation injury, etc. require the same basic responses as described above - Containment, Notification, Corrective Action, Monitoring. The proper authorities should be notified at once of such incidents and will act with other authorities to control emergencies of this nature.

## **E. Radioactive Waste Disposal**

Waste retention areas should be managed with close attention to cleanliness. Housekeeping employees should be instructed not to move or empty radioactive waste containers during the course of their duties.

Waste should be segregated according to its radiologic half-life. Short lived waste can be stored until decayed and then be disposed of as regular waste, however, all radioactive labels, markings, tapes, etc., must be removed or defaced before disposal.

Non-radioactive waste must not be mixed with the radioactive waste as this adds to the cost of disposal. A simple wipe survey or instrument survey of the item can determine if it still contains any radioactivity. If only a portion of an item (i.e., lab bench soaker) is contaminated, just that portion should be disposed of into radioactive waste.

Care should be exercised when disposing of waste in different physical or chemical forms:

1. Liquid wastes containing acids should not be mixed with liquids containing bases. Aqueous liquids should not be mixed with organic liquids.
2. Pipettes and other sharp objects should be bundled together in order to prevent them from puncturing the inner liner of the dry waste container.
3. Biological waste should contain sufficient amounts of a preservative and absorbent to prevent decomposition.
4. Radioactive biohazard waste must be treated in the same manner as regular biohazard waste before being placed into radioactive waste containers.

## **F. Radioactive Contamination Survey Procedures**

Surveys for radiation and removable radioactive contamination must be performed after each use of radioactive materials. The purpose of this survey is to identify any contamination present and to prevent its spread. Appropriate radiation survey equipment should be available to users for the type of surveys required for the laboratory. Such survey equipment must be properly calibrated for energy and type of radionuclide in use at least every six months.

To perform a survey, choose sites in the lab where the radioactive material has been used. Areas or equipment such as benchtops, floors near the work area, waste containers, fraction collectors, water baths, storage areas, hoods, etc. are good places to start. Each site chosen should be labeled on a diagram or floor plan of the lab for later referral in interpreting results.

## 1. Survey for Removable Contamination

Contamination not fixed to a surface can be transferred to hands, clothing, notebooks, pens, etc. leading to internal exposure or contamination of clean areas. The most common survey procedure to detect the presence of loose contamination is called a wipe test. In this procedure, a piece of filter paper (usually about 1 inch square or circular) is used to wipe over a surface suspected of being contaminated. The area which the wipe should cover is approximately 100 square centimeters. Depending on the surface being wiped, or the type of material being surveyed for, it may be necessary to wet the wipe material with alcohol or other solvent for better adhesion of contaminated particles to the wipe material. A single wipe can be used to determine contamination over a large surface such as a floor or benchtop. If radioactivity is found a series of wipes covering smaller areas should be performed to localize the contamination. After wipes have been taken, place them in numbered scintillation vials or other carriers to organize and prevent cross contamination of the samples. Wipes should be treated as potentially contaminated until analyzed. Prepare the wipes for analysis as you would a regular sample. Analyze the wipe samples, using an appropriate instrument. For beta-emitting isotopes with energies above 100 keV, you can hold the wipe material one cm away from a GM tube and observe the count rate. Beta-emitting isotopes below 200 keV (H-3, C-14, S-35) should be analyzed using a liquid scintillation counting system. Wipe samples of gamma or x-ray emitters should be analyzed using a gamma counting system.

In most labs, a liquid scintillation counter (or gamma counter) is already optimized for the particular nuclides in use. Liquid scintillation and gamma counters should have a calibrated reference standard readily available. These standards should be counted each time samples are counted to verify efficiencies and machine settings. A control vial consisting of a "clean" wipe and counting solution must be counted with your samples to determine machine background. A set of quenched standards should be used to determine the counter's efficiency for various degrees of quench (see Chapter II - Liquid Scintillation Counting).

Report results on your diagram in terms of disintegrations per minute (dpm) per area surveyed according to the following formula:

Sample dpm =

Any wipe indicating a gross cpm greater than twice background cpm should be cleaned up. Record on the survey diagrams the maximum

contamination levels found as well as the final levels. Limits for removable contamination are shown in Section G.

## 2. Survey for Fixed Contamination

In laboratories where high energy beta (greater than 100 keV) radioisotopes are used, a survey for fixed contamination should be performed using a GM survey instrument. Where gamma emitting radioisotopes are used, a gamma survey instrument calibrated for the particular radioisotope should be used. Scan the area suspected of being contaminated with the instrument's probe. To prevent possible contamination of the probe, do not let it touch the surface being surveyed. Sites in which the results are twice the background rate could indicate radioactive contamination (Limits for fixed contamination are shown in Section J). Record the results of the survey on the laboratory diagram. Any fixed contamination should be tested for removable activity as described above.

## G. Radioactive Contamination Limits

The following removable contamination limits can be used as a guide when working with loose radioactive material. By observing good radioisotope laboratory practices, contamination levels should be kept to less than 10 % of the maximum limits.

Application	Limits			
	Removable Contamination Limits (dpm/100 cm <sup>2</sup> )			
	Alpha		Beta/Gamma	
	Control Point	Maximum	Control Point	Maximum
Basic Guide for Equipment or Surfaces in a Controlled Area	250	500	2500	5000
Clean Areas, Release of Materials	50	100	500	1000
Skin, Personal Clothing	Non-detectable		Non-detectable	

When contamination levels approach the Control Point values, appropriate control measures as described below should be taken. Contamination results greater than the maximum limits in any laboratory area should be reported to the laboratory supervisor and cleaned up right away. Corrective steps should be taken to prevent reoccurrences.

## H. Control Measures for Radioactive Contamination

The primary concern with radioactive contamination is to prevent its spread to other areas, and prevent its uptake into the body. Once contaminated, therefore it is important to stay in the area, alert others in the area of the problem, and request assistance.

## 1. Personnel Contamination

- a. Contamination of the skin or hair may be washed off with soap and water or commercially available decontamination solutions. Repeat washings with plenty of lather and water. Care must be taken not to break the skin when scrubbing. Stubborn fixed skin contamination on the hands may be "sweated" out by wearing a disposable glove sealed at the wrist.
- b. Contaminated clothing should be removed in a suitable area while being properly monitored. Clothing may be discarded as waste, stored for decay, or washed. The area must be surveyed after cleanup.
- c. If an uptake (inhalation, ingestion, etc.) is suspected contact authorities for appropriate bioassays.

## 2. Equipment or Area Contamination

- a. Equipment or work surfaces can be cleaned using soap or commercially available decontaminating solutions. Decontaminating procedures must prevent the spread of contamination and minimize the amount of waste generated.

Plan ahead:

1. Assemble all cleaning supplies and equipment before starting, remove or cover non-contaminated items.
  2. Place contaminated items in designated areas for clean-up, i.e., a fume hood if airborne activity can be generated during clean-up.
  3. Wear proper protective clothing.
  4. Control access to the designated work area and post appropriate cautionary signs.
  5. To minimize fixation of the contaminant, perform the decontamination as soon as practical.
  6. Start on the outside and work in to the most contaminated area.
  7. Monitor results of clean-up -- Perform surveys regularly.
- b. Fixed contamination can be sealed with paint, plastic, or covering to prevent egress.

## I. Radiation Survey Procedures

Radiation exposure rates should be measured using an ion chamber type survey instrument (i.e., Ludlum, Victoreen, etc.). GM counters can be used to measure exposure rates in mr/hr or r/hr as long as the energy of the X or gamma radiation is known and the instrument is calibrated for this particular energy. Before using any instrument, become familiar with its proper operation. Be certain that the instrument has been properly calibrated usually indicated by a calibration sticker on the instrument (see Chapter II).

## J. Radiation Limits

The following radiation limits should be used as a guide when planning areas for radioactive materials work, material storage, waste storage, etc.

Application	Limits	
	Radiation Limits	
	From Fixed Contamination	From Other Sources
Basic Guide for Equipment or Surface in a Controlled Area Facilities	1	2.5
Clean Areas	0.5	2
Skin, Personal Clothing	0.1	---
Release of Materials of Facilities	0.2	---

## K. Control Measures for Radiation Levels

The goal of each worker should be to maintain his or her exposure to radiation as low as reasonably achievable (ALARA). When working with radioactive material yielding high radiation levels, special precautions may be necessary to limit exposure to the worker and others in the area.

1. Perform a radiation survey of the material to determine what kind of radiation levels exist. If appropriate, a survey for removable contamination should be performed.
2. Determine if the material can be safely handled without creating a hazard to yourself or others in the area. A general rule of thumb is that the guide for radiation workers is 100 mrem per week (5 Rem/yr - 50 weeks/work year). Therefore, base how long you should work in an area without exceeding this or any other specified limit by calculating your stay time:

Stay Time =

3. Use appropriate handling tools and shielding to reduce overall radiation exposure.
4. When finished, perform an appropriate contamination or radiation survey.

## Problem Set 4

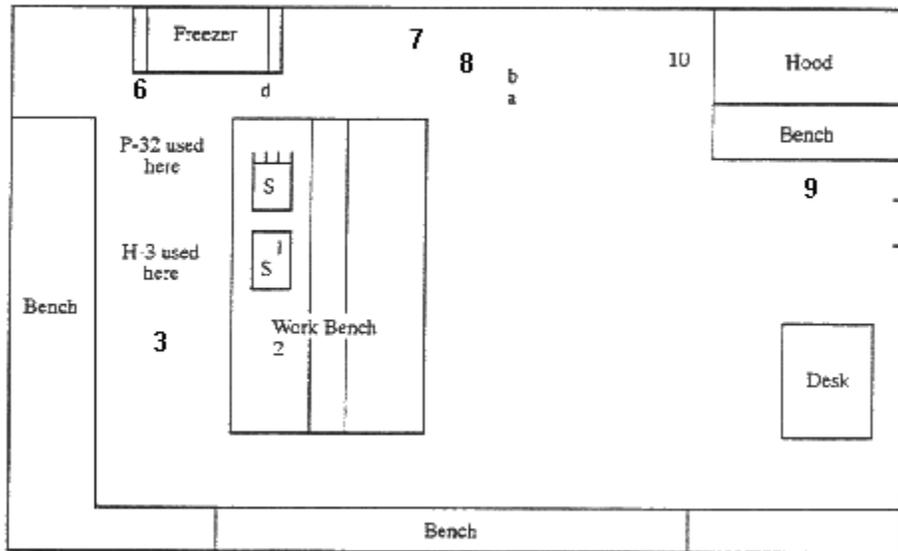
Multiple choice questions may have more than one correct response.  
Refer to Appendix IV for reference data.

- Film badge results are reported in units of:
  - rads
  - mrem/hr
  - rems
  - mCi
- Film badges cannot detect H-3, C-14, or S-35 because:
  - They are pure beta minus emitters
  - They have beta energies below the sensitivity of the film
  - They have beta energies above the sensitivity of the film
  - The specific ionization of the beta particles is too low
- The purpose of filters in a film badge holder is to:
  - Help in identifying the type of energy of radiation
  - Determine the amount of radiation exposure
  - Shield the film from radiation exposure
  - Determine the identity of radioisotopes the badge was exposed to
- Film badges and other personnel dosimeters should be worn:
  - Generally, between the neck and waist
  - On the area of the body where exposure to radiation is most likely
  - On only the person to whom it was issued
  - For extremity monitors, on the inside of protective gloves
- A radioactive package displaying a DOT "Radioactive Yellow II" warning label with a Transport Index of 0.2 means that:
  - The transport vehicle requires placarding
  - The radiation level at the surface of the package is 0.1 mrem/hr
  - The radiation level at 3 feet from the package is 0.1 mrem/hr
- If you have a source of radiation which emits high energy beta particles only, what is the most appropriate shielding material to use?
  - A container of lead.
  - A container of plastic.
  - A container of plastic inside a container of lead.
  - A container of lead inside a container of plastic.
- If you have a source of radiation which emits both high energy beta particles and gamma rays, what is the most appropriate shielding material to use?
  - A container of lead.
  - A container of plastic.
  - A container of plastic inside a container of lead.
  - A container of lead inside a container of plastic.
- What are the three basic methods for reducing exposure to radiation?
- Name four factors which are considered in evaluating the potential internal hazards from a radioisotope?
- If the intensity of a gamma source is 5 mrem/hr at a distance of one meter, what is the intensity one foot away from the source?
- The intensity of a source measured outside a 2 cm thick lead pig is 2 mrem/hr. If the pig is known to contain Cr-51, what would be the intensity of the source without the pig? (Density of lead = 11.35 gm/cm<sup>3</sup>)

12. A 20 Mci Cs-137 source (calibrated on 9/10/79) is to be used for the calibration of pocket dosimeters. The source is to be placed at the center of a board with the dosimeters distributed around a circle of a radius of 22 inches. What dose rate will the chambers receive? Where, how and at what distance should such a facility be posted?
13. What would be the approximate dose to an operator using this calibration facility, assuming the operator spent a total of 30 minutes near or adjacent to the dosimeters?
14. A radiation worker begins work six feet away from a source determined to be 5 mrem/hr at that point. The worker's daily dose limit is 50 mrem. If this person worked in the first area for five hours and then moved to an area three feet from the source, what would be the new exposure rate in this area and how long could the person remain there until the daily limit has been expended?
15. If commercially available lead blocks are 1 inch thick, how many blocks are needed to reduce the unshielding exposure rate from a vial of Co-60 to 1/8 its original value?
16. You have completed a survey for radiation levels and removable contamination for a radioisotope laboratory that uses H-3 and P-32. From the laboratory floor plan, raw data sheet, and quench curves supplied, answer the following questions:
  - a. For each of the areas surveyed, what is the level of removable contamination in dpm? (fill in the bottom section labelled "Removable Contamination Survey" on laboratory floor diagram).
  - b. Which of the contaminated areas are due to H-3? Which are due to P-32?
  - c. Which of the gross counts can be ignored due to statistical fluctuations? (Hint: =  $N^{1/2}$ )
  - d. Which of the areas exceed the allowable removable contamination limits?
  - e. What areas require posting with a "Caution-Radiation Area" sign. A "Caution-High Radiation Area" sign?
  - f. What is the most probable cause for contamination at site #6? What methods of decontamination would you recommend?
  - g. Which of the users is responsible for the contamination on the floor.
  - h. What recommendations would you give to the supervisor of this laboratory in order to improve radiation safety?

### **Routine Radiation and Contamination Survey**

**Example: Rm 1245 Teaching Lab**



**Recorded Data**

Radiation Survey

?? ?	(mR/hr.)	Remarks
a.	1	1 ft above floor Side of waste container
b.	5	On contact with side of waste container
c.	125	Unshielded containers in freezer
d.	0.1	On contact with freezer door closed

Instrument used: Victoreen Ion Chamber  
 Beta Shield off, neglecting air absorption.  
 Background = 0.1 mrem/hr.

Removable Contamination Survey

Net cpm ÷ Eff = dpm

1.	_____	_____	_____
2.	_____	_____	_____
3.	_____	_____	_____
4.	_____	_____	_____
5.	_____	_____	_____
6.	_____	_____	_____
7.	_____	_____	_____
8.	_____	_____	_____
9.	_____	_____	_____
10	_____	_____	_____
.	_____	_____	_____

**Raw Counting Data Sheet Example**

**Room 1245:** Teaching Lab

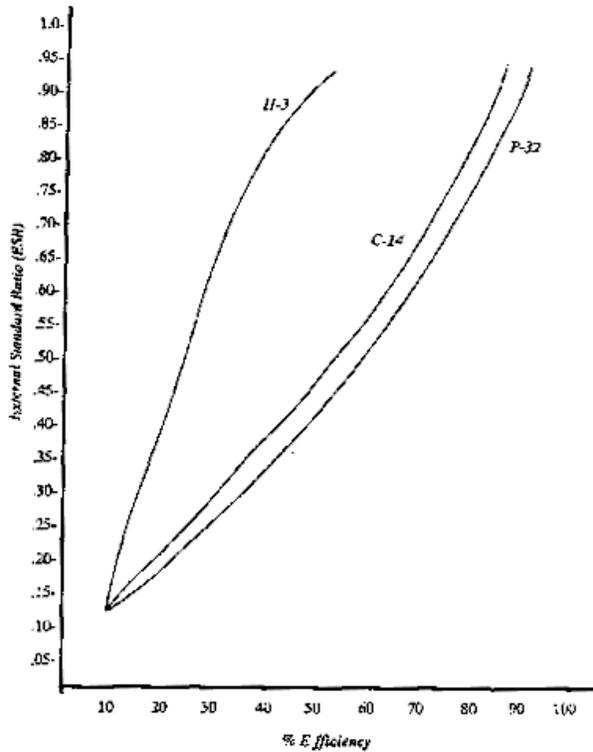
**Counter used:** Packard Tricarb Liquid Scintillation Counter

**Counting Time:** 1 Minute

**Sampling Technique:** Filter Paper Smear Covering an area of 100 cm<sup>2</sup>

Survey Site	Identification	Red Channel Counts	Green Channel Counts	External Std. Ratio
0	H-3 Standard	154,000	77,000	0.99
0	C-14 Standard	17,000	87,000	0.99
0	P-32 Standard	7,000	70,000	0.99
0	Background	50	25	0.98
1	Absorbent Paper	54	27	0.95
2	Laboratory Note	101	65	0.95
3	Floor	71	237	0.8
4	Pipettor Bulb	350	75	0.98
5	Isotope Storage Inside Freezer	120	60	0.45
6	Freezer Handle	450	4025	0.8
7	Liquid Waste Cover	150	925	0.9
8	Floor	110	525	0.85
9	Floor	70	225	0.8
10	Hood Apron	47	24	0.75

*Liquid Scintillation Counter Quench Curve*



This graph is to be used only with Problem Set 4. It represents the theoretical quench for a typical liquid scintillation counter. You must generate your own quench curves for the particular counter you are using to determine what efficiencies apply to your data.

# Chapter V

## Radiation Protection Program

### 1. General

Radioactive material under license by either State or Federal agencies must be used under an approved radiation protection program. This program is designed to protect the health and safety of workers and public from potentially harmful effects of radiation by maintaining both external and internal exposures As Low As Reasonably Achievable (ALARA).

The Radiation Safety Officer, and the Radiation Safety Committee (at UMD), has the responsibility to implement the radiation protection program. UMD's program includes:

- A. Authorization of individuals and work areas for use of radioactive materials or radiation producing equipment.
- B. Assuring the safe use of radioactive material and radiation producing equipment.
- C. Approval of all purchases of radioactive material.
- D. Receives all radioactive materials coming to UMD Campus.
- E. Maintaining an inventory of all radioactive material received.
- F. Assuring that all required surveys and records are maintained.
- G. Certifying the proper disposal of radioactive waste.
- H. Providing external and internal radiation exposure monitoring.
- I. Leak testing of sealed radioactive sources.
- J. Analysis and testing for radioactive materials.
- K. Assisting users in the design and implementation of laboratory experiments, safety equipment, etc.
- L. Surveys of radiation producing equipment.
- M. Calibration of radiation detection instruments.
- N. Responding to radiation emergencies.
- O. Providing training to personnel who use radioactive materials or radiation producing equipment.

Routine and unannounced inspections of laboratories and other use areas for compliance with applicable rules and regulations are performed by radiation safety personnel. Those working with radioactive materials and radiation producing equipment have the responsibility to report promptly to authorities any condition which may lead to or cause a violation of radiation safety regulations or cause unnecessary exposure to radiation or radioactive material. Thus, workers must be familiar with the conditions of their radioactive materials authorization, applicable State or Federal regulations.

### 2. UMD Radiation Protection Program

#### A. Regulatory Agency

Possession and use of radioactive materials at the University of Maryland, College Park is authorized under a license issued by the Maryland Department of the Environment, as specified in the Code of Maryland Regulations (COMAR) 26.12.01.01 – Regulations for the Control of Ionizing Radiation. These regulations are available at the link below:

[http://www.mde.maryland.gov/programs/air/radiologicalhealth/regulationsforcontrolofionizingradiation/pages/programs/airprograms/radiological\\_health/regulations/index.aspx](http://www.mde.maryland.gov/programs/air/radiologicalhealth/regulationsforcontrolofionizingradiation/pages/programs/airprograms/radiological_health/regulations/index.aspx)

## **B. Radiation Protection Services**

At the University of Maryland, the Radiation Safety Officer has the responsibility to develop and implement the radiation safety program in order to assure compliance with the provisions of the State Code and the University's radio-active materials license. This program is outlined in the "Radiation Safety Manual". This manual is available to all users and includes instructions for:

1. Obtaining authorization for use of radioactive material.
2. Ordering and receiving radioactive material.
3. Basic radiation protection techniques.
4. Survey techniques and contamination limits.
5. Personnel monitoring.
6. Radioactive waste disposal.

The Safety Manual also includes a description of the administrative organization of the safety program and other useful information applicable to the safe use of radioactive materials on Campus. Each user must become familiar with the requirements in the appropriate sections of the manual.

The Radiation Safety Office staff performs periodic inspections of laboratories using radioisotopes and radiation installations to assure compliance with the safety manual, license and State Code. Violations of established rules, regulations and procedures may result in the loss of privilege to use radioactive material as well as cause an undue hazard to both the user and the people in the surrounding work area. Therefore, radiation safety can only succeed when each user follows both the spirit and actual rules described by the Radiation Safety Manual and this Training Manual and Study Guide.

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## Chart of the Nuclides

The information contained herein is being made available by the National Nuclear Data Center of Brookhaven National Laboratory (BNL) in the interest of promoting the dissemination of technical knowledge. BNL assumes no responsibility for liability or damage which may result from the use of any of this information.

[Chart of the Nuclides](http://www.nndc.bnl.gov/chart/) (<http://www.nndc.bnl.gov/chart/>)

### Solutions to Problem Set 1

1 d    2 c    3 a, c    4 a, b    5 b, c, d    6 c    7 b    8 d    9 c  
 )        )        )        )        )        )        )        )

10) Alpha – U-238, Ra-226,      Beta – C-14, H-3, P-32  
 Positron – Na-22, Zn-65

11) Nuclear Transition (gamma) – Co-57, Mn-54  
 Electron Capture – I-125, Cr-51

12) a.  $\lambda = 0.0231 \text{ min}^{-1}$   
 b.  $A = \lambda N$ , therefore  $N = 432,900$  atoms  
 c.  $A = A_0 e^{-\lambda t}$  where  $t = 90$  minutes and  $A_0 = 10,000$  dpm  
 $= (10,000 \text{ dpm})e^{-(0.0231 \text{ min}^{-1})(90 \text{ min})} = (10,000)(0.125) = 1,250$  dpm

13)  $0.259 = e^{-\lambda t}$ ;  $0.259 = e^{-\lambda t}$   
 $\ln 0.259 = \ln e^{-\lambda t}$ ;  $(\ln e^{-\lambda t} = -\lambda t)$   
 $\ln 0.259 = -\lambda t$   
 $1.35 = (t) \cdot \lambda$        $T_{1/2} = (24 \text{ hrs.}) \cdot \lambda = 12.32$  hrs.

The isotope is potassium-42, determined by the half-life from Appendix IV.

14)  $0.6667 = e^{-\lambda t}$ ;  $0.6667 = e^{-\lambda t}$   
 $0.405 = (t) \cdot \lambda$        $t = 3,352$  years old

15)  $A_0 = 101.4$  mCi

### Solutions To Problem Set 2

1 a,b,    2 a    3 b  
 ) d        )        )

4 a) G b Ion c Liquid d Liquid e NaI f NaI g Ion  
 ) M ) Chambe ) Scintillatio ) Scintillatio ) ) ) Chambe  
 r r n n

5 c 6 d 7 c 8 a, b, c  
 ) ) ) )

9) = = 40,000 dpm

10 a.  $S_{\text{gross}} - S_{\text{bkg}} = S_{\text{net}}$  Therefore = 15,550  
 )

b.  $(0.1 \mu\text{Ci})(2.22 \times 10^6 \text{ dpm}/\mu\text{Ci}) = 2.22 \times 10^4 \text{ dpm}$   
 $\times 100 = E = 0.7 \times 100 = 70\%$

c.  $A = A_0 e^{-\lambda t}$  where  $t = 90$  minutes and  $A_0 = 10,000 \text{ dpm}$   
 $= (10,000 \text{ dpm})e^{-(0.0231 \text{ min}^{-1})(90 \text{ min})} = (10,000)(0.125) = 1,250 \text{ dpm}$

d)  $(429 \text{ dpm})(1) = 429 \text{ dpm}$   
 Therefore = 0.0019  $\mu\text{Ci}$

e) MDA = = 6.8 dpm (10 min count)

### Solutions To Problem Set 3

1 b 2 d 3 a, c 4 a 5 b 6 a, b, d 7 8 d 9 a  
 ) ) ) ) ) ) ) ) )

10) Rate of Cell Divison  
 State of Cell Division  
 Metabolic Rate  
 State of Nourishment  
 Oxygen Levels  
 Enzyme Levels Associated with the Repair Process

11) **Rems per Year**  
 Whole Body 5  
 Skin 50  
 Extremities 50

12) 50 Rem

13) As long as the total accumulated whole body dose does not exceed 50 Rem.

14) 0.5 Rem

15) 0.10 Rem

16) 10%

17) 5 Rem

18) Primary and secondary cosmic rays; naturally occurring radioactive materials in the earth's crust;  
 naturally occurring radioactive materials in the body.

- 19) Buildings made from materials containing Uranium, Thorium, Radium, and Potassium-40 can increase the natural background external exposure. If the ventilation rate is poor, radon gas and its decay products can build up and increase internal exposures.
- 20) External exposure from K-40, U-238, and Th-232 decay series; internal exposure from K-40, Radon, and Thorium.

## Solutions to Problem Set 4

1 c ) 2 b ) 3 a ) 4 a, b, c, d ) 5 b ) 6 a, b, d ) 7 c )

8) Reduce Stay Time; Increase Distance; Provide Shielding

- 9) 1. The type and energy of the radiation emitted.  
 2. The radiological half-life of the isotope.  
 3. The biological half-life of the isotope.  
 4. The isotope's distribution in the body.  
 5. The solubility of the compound containing the isotope.

Note: No. 2 and 3 are combined to give the "Effective half-life".

10)  $I_1 = 53.82 \text{ mR/hr}$ .

11)  $I = I_0 e^{-\mu x}$ , Where  $\mu = \mu_m \times \rho$

= mass attenuation coefficient for Cr-51 gamma (Appendix IV) for lead multiplied by the density of lead

$$= (0.369 \text{ cm}^2/\text{gm}) \times (11.35 \text{ gm}/\text{cm}^3) = 4.19 \text{ cm}^{-1}$$

$I_0 = 8718 \text{ mR/hr}$ . Therefore  $I_0 = 8718 \text{ mR/hr}$ .

12) For Cs-137:  $\gamma = 0.33 \text{ R/hr/meter/Ci}$  (Appendix IV)

For 20 mCi:  $0.33 \times 0.02 \text{ Ci} = 0.0066 \text{ R/hr/m}$

(Note: the source must be decay corrected for the true dose rate at present time).

$I_1 = 0.021 \text{ R/hr}$ .

**A Caution - Radiation Area sign must be posted at the point where the radiation field is 5 mR/hr.**

13)  $21 \text{ mR/hr} \times 0.5 \text{ hr} = 10.5 \text{ mR}$  approximately equals 11mRem

14)  $I_2 = 0.021 \text{ R/hr}$ .

Exposure =  $5 \text{ mR/hr} \times 5 \text{ hrs} = 25 \text{ mR}$

Stay time = = 1.25 hr.

(Note: 1 mR approximately equals 1 mRem)

15) Two lead blocks are required for a shield for the vial:

$$= = 0.125 = e^{-\mu x}$$

$$(\ln 0.125 = -2.0794):(\ln e^{-\mu x} = -\mu x)$$

$$x = = 3.1 \text{ cm}$$

$$3\text{HVL} = \text{reduction } (2 \times 2 \times 2 = 8)$$

$$\text{HVL for Co-60} = 1.035 \text{ cm} \times 3 = 3.1 \text{ cm}$$

$$\text{Since } 3.1 \text{ cm} \times = 1.22 \text{ inches}$$

**One block isn't enough shielding. Two blocks are required.**

Question 16 answers:

1)

No.	Gross cpm	Bkg	Net cpm	Eff *	= dpm
1	45	50	4	---	---
2	101	51	51	.5	102
3	237	25	212	.85	250
4	350	50	300	.55	546
5	120	50	70	.2	350
6	4025	25	4000	.85	4706
7	925	25	900	.9	1000
8	525	25	500	.88	569
9	225	25	200	.85	236
10	47	50	---	---	---

\* Determined off the quench curves for the particular ESR and isotope in question.

2. By observing the distribution of the standard counts in the red and green channels, you can determine which isotopes contributed to the contamination:

Sites 2, 4, 5, are contaminated with H-3.

Sites 3, 6, 7, 8, 9, are contaminated with P-32.

3) Sites 1 and 10 are within the statistical fluctuation of the background counts ( $50^{1/2} = 7.07$ ;  $(25)^{1/2} = 5$ ). Thus, any gross counts that fall between 43 and 57 in the red channel, or 20 and 30 in the green channel can be considered to be due to background. As a general rule of thumb, counts that are twice background counts can be considered to be from radioactivity.

4) Sites 6 and 7 exceed the removable contamination limits of 100 dpm/100 cm<sup>2</sup>.

5. The waste container should be posted with a "Caution-Radiation Area" sign since an individual could receive an exposure of 5 mr in one hour.

There are no areas in which an individual is likely to receive 100 mr in one hour. Even though the exposure rate is 125 mr/hr inside the freezer, one is not likely to stand there floor one hour. Therefore, a "Caution-High Radiation Area" sign is not required anywhere in the lab.

6) Opening the freezer with contaminated gloves is the most probable way the handle became contaminated. Since the handle is metal, soap and water should remove contamination. Other commercially prepared decontaminating solutions such as count-off or lift-away can be used if soap and water fail.

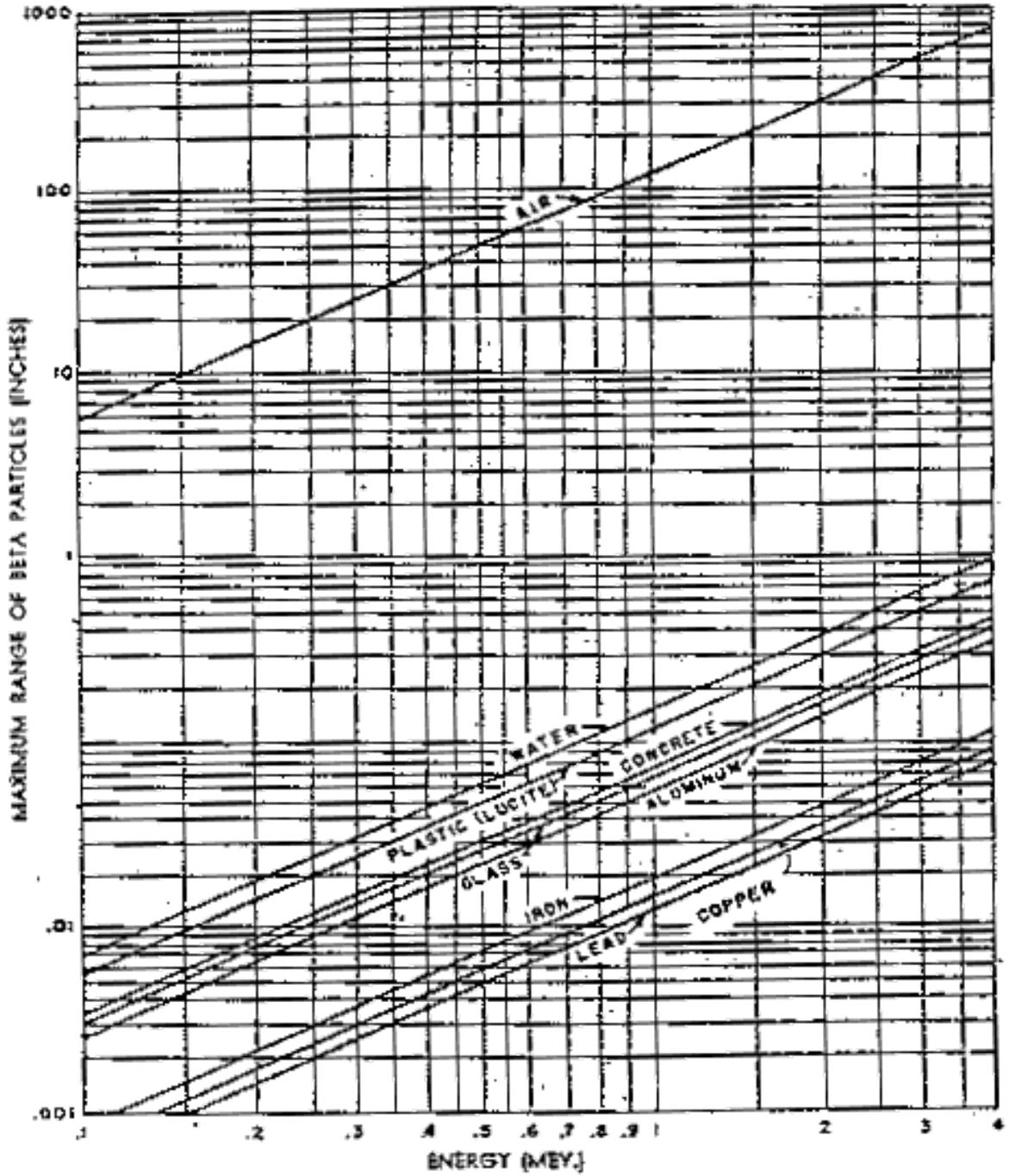
7. The person or persons using P-32 have contaminated the floor.

8) Recommendations:

- a. Keep articles like laboratory notebooks out of radioactive materials work areas; areas should be maintained as neat and as clean as possible to aid in controlling the spread of any contamination.
- b. Shield the radioactive waste container by placing it in another container made out of plastic or steel or move it to an area where there is little or no traffic.
- c. Shield the isotope storage area in the freezer by using plastic bins or shields since the high exposure rate is due to the P-32 beta radiation.
- d. A GM survey meter should be available whenever P-32 is being used so that areas of contamination can be instantly identified, limited, and decontaminated as appropriate. For areas of H-3 use, smears should be taken and evaluated as soon as possible after the manipulations have occurred. Equipment, surfaces, etc. should be treated as potentially contaminated until proven otherwise.
- e. More attention should be afforded to changing gloves given the probable instance by which the refrigerator handle and the cover of the liquid waste container were contaminated.
- f. Minimize and localize all items which may be used in procedures involving the use of radioactive materials. Contamination control effectiveness can be of crucial importance to the success of experimental data and results.
- g. Persons manipulating materials should be directly responsible for the monitoring and cleanup after they have worked, rather than having someone else find out how careless they may have been days after the occurrence. This is especially true in laboratory settings in which space is limited, people are numerous, and much time is spent in close quarters.
- h. The person working with P-32 received a pipette bulb from the person working with H-3 which was contaminated. This is not only poor safety practice, but could interfere with accuracy of the P-32 worker's experimental results.

# Appendix III

(Penetration Ability of Beta Radiation)



## Appendix IV

### Rules of Thumb and Useful Equations

#### Alpha Particles

Alpha particles of at least 7.5 MeV are required to penetrate the protective layer of the skin.

#### Beta Particles

Beta particles of at least 70 keV are required to penetrate the protective layer of the skin.

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

The range of beta particles in air is about 12 ft./MeV. Thus, the maximum range of P-32 is: 1.71 MeV x 12 ft./MeV = 20 Ft.

The dose rate in rads per hour in a solution by a beta emitter is  $2.12 EC/\rho$ , where E is the average beta energy per disintegration in MeV, C is the concentration in microcuries per cubic centimeter, and  $\rho$  is the density of the medium in grams per cubic centimeter. The dose rate at the surface of the solution is one-half the value given by the relation. Example: For P-32 average energy of approximately 0.7 MeV, the dose rate from 1  $\mu\text{Ci/cc}$  (in water) is 1.48 rads/hr.

The surface dose rate through the nominal protective layer of skin from a uniform thin deposition of 1  $\mu\text{Ci/cm}^2$  is about 9 rads/hour for energies above about 0.6 MeV.

For a point source of beta radiation (neglecting self and air absorption) of millicurie strength, the dose rate at 1 cm is approximately equal to  $200 \times \text{mCi} = \text{rads/hour}$  and varies only slowly with beta energy. Example. The dose rate for 1 mCi P-32 at 1 cm is:  $200 \times 1 \text{ mCi} = \text{approximately } 200 \text{ rads/hour}$  at one centimeter.

#### Gamma Rays

The dose rate to tissue in rads per hour in an infinite medium uniformly contaminated by a gamma emitter is  $2.12 EC/\rho$ , where C is the number of microcuries per cubic centimeter. 1675 (100) 11 .01 --- --- --- --- ---  
Whole Body 44.3 (400); Testes (90) Zinc-65 243.9 d 0.329 + (1.5) 30 .03 0.27 1.115(50.8) .925 0.066  
Whole Body 193.2 (60) I = Intensity h = hours d = days y = years G = rem/hour at one meter per Curie

## Appendix V Reference Data for Selected Radioisotopes

Contact RSO