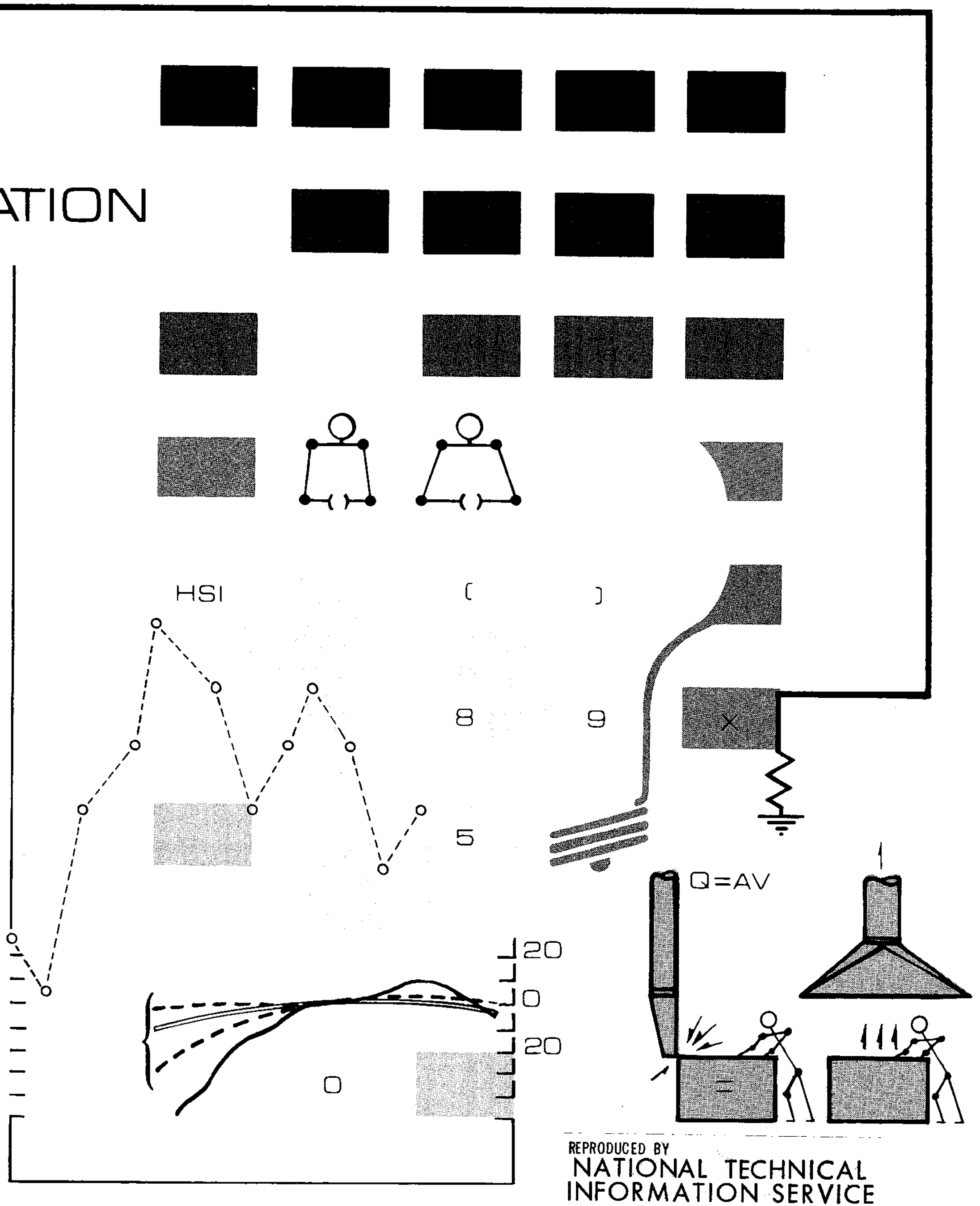
PB85-177616

552

INDUSTRIAL HYGIENE
ENGINEERING & CONTROL

RADIATION



Student
Manual

U.S. DEPARTMENT OF HEALTH, EDUCATION AND WELFARE
Public Health Service
Center for Disease Control
National Institute for Occupational Safety and Health

Division of Training and Manpower Development

INTRODUCTION TO INDUSTRIAL HYGIENE ENGINEERING AND CONTROL (552)

This is a modularized course designed for use as a one, two, or three week short course or as a one or two semester academic course at either the undergraduate or graduate level. It examines the fundamentals for design of controls to eliminate or satisfactorily deal with occupational health hazards. Lectures, augmented by problem solving sessions, are intended to assist the trainee in selecting, designing, and applying control methods in the work environment. Primary attention is given to industrial ventilation, noise and vibration control, heat stress, and industrial illumination as well as new engineering topics.

The training course manual has been specially prepared for the trainees attending the course and should not be included in reading lists of periodicals as generally available.

Section 6 — Student Manual

NONIONIZING AND IONIZING RADIATION

Division of Training and Manpower Development
National Institute for Occupational Safety and Health

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Center for Disease Control

Cincinnati, Ohio

November 1978

FACULTY AND STAFF
DIVISION OF TRAINING AND MANPOWER DEVELOPMENT

Dr. Alan D. Stevens	Director
James S. Ferguson	Deputy Director
Dr. N. Jack Berberich	Chief, Curriculum Development Branch
Edward D. Leininger	Chief, Direct Training Branch
Dr. Thomas C. Purcell	Chief, Educational Resource Development Branch

Stephen G. Bayer	Training Instructor
Dr. David E. Clapp	Safety Engineer/Instructor
John M. Blankenhorn	Industrial Hygienist
Larry W. DeArmond	Training Technician
Steven N. Dereniuk	Chemist
Horace E. Dimond	Safety Engineer
Ruth A. Duffy	Secretary
Pauline J. Elliott	Visual Information Specialist
Denise Gerth	Secretary
Joyce Huff	Secretary
Bernadine B. Kuchinski	Occupational Health Nurse Consultant/Educator
Judith A. Kuethe	Secretary
Laura Love	Secretary
Carl H. Moline	Industrial Hygienist
Sharon Moreland	Secretary
Dr. Paul D. Pedersen	Medical Officer
William H. Perry	Industrial Hygiene Chemist
Jane A. Raber	Grants Assistant
Dr. Pantelis G. Rentos	Training Grant Program Officer
Richard C. Robbins	Motion Picture Specialist
Joann R. Schloemer	Consulting Nurse
Raymond C. Sinclair	Television Production Specialist
Linda Smith	Secretary
Anne M. Stirnkorb	Visual Information Specialist
Marsha Striley	Secretary
David S. Thelen	Training Grants Coordinator
Linda Tull	Secretary
James B. Walters	Public Health Advisor
Kathleen Watkins	Staff Assistant
Robert B. Weidner	Senior Industrial Hygiene Consultant
William J. Weis	Manpower Specialist
Donna Welage	Staff Assistant
Roger L. Wheeler	Electronics Engineer
Glenda M. White	Audio Visual Production Officer
John M. Yacher	Chemical Engineer/Training Officer

FOREWORD

This text is designed for use by individuals at an advanced level of study in industrial hygiene. The emphasis is on the control of exposures to occupational health hazards. A series of lesson plans has been developed around the material presented in the text that can be utilized in a formal classroom setting for presentation as a course or a series of courses.

The text was developed under the sponsorship of the National Institute for Occupational Safety and Health, Division of Training and Manpower Development, Cincinnati, Ohio (Contract CDC—210—75—0076). Serving as Project Officer for the development of the text and lesson plans was Robert B. Weidner, J.D., Branch Chief, Division of Training and Manpower Development.

Authors of the text and lesson plans are:

Bruce B. Byers
Ronald J. Hritz
James C. McClintock

Also assisting as consultants to the development of the material were Ralph J. Vernon, Ph.D., and Richard B. Konzen, Ph.D., of the Department of Industrial Engineering, Texas A&M University. Art work for the text was prepared by Carole D. Byers. Preparation of the manuscript was the responsibility of Elaine S. Holmes.

TABLE OF CONTENTS

Section Chapter Title Page

1 **Introduction to Industrial Hygiene Engineering and Control**

2 **Industrial Ventilation**

3 **Thermal Stress**

4 **Sound**

5 **Industrial Illumination**

6 **Nonionizing and Ionizing Radiation**

7 Ergonomics

8 **Other Topics**

INTRODUCTION

The creation of this text came out of an attempt to design a course to teach the fundamentals of industrial hygiene engineering as related to the design of controls for exposure to health hazards in the workplace. During the design of the course, it was necessary to research the existing literature in the field of industrial hygiene. As this research was being conducted, it became evident that no single source provided sufficient coverage of the subject to be adequate for use as a text for the course. In fact, to the dismay of the authors, the subject of control received very little attention in many of the existing texts on industrial hygiene. For the most part, existing texts emphasize the recognition, measurement and evaluation of occupational health hazards. Though this is an important concern of the industrial hygienist, the sparse coverage of control topics indicated a need for an additional text.

The objective of this text is to fill this gap that was discovered; to provide a text that can act as a single reference source on the subject of industrial hygiene engineering and control. In the preparation of this text, the authors soon discovered a reason for the prior omission of such a single source. The control of occupational health hazard exposures requires a broad knowledge of a number of subject areas. To provide a text that includes the necessary theoretical foundation as well as the practical application of the theory is a significant undertaking. It is the hope of the authors that in some way the objective has been reached and that this text will prove to be a valuable and needed addition to the literature of industrial hygiene.

A second objective, or perhaps a hidden agenda, during the preparation of this text was to provide the reader with a systematic approach to problem solving in the field of industrial hygiene. Throughout the text, the systems approach to problem solving is emphasized. In fact, at one point consideration was given to titling the text "A Systems Approach to Industrial Hygiene Control." The systems approach has been utilized effectively in the area of occupational safety: witness the many texts on the topic of systems safety. However, the same emphasis has not been found in industrial hygiene. Systems analysis techniques are not limited in their application and thus should be equally applicable and useful to the field of industrial hygiene as they are to the field of occupational safety.

The text has been divided into eight (8) sections, each of which covers a subject area. This structure allows for reference to a single topic area without the need to consult other sections of the book, thus allowing for the use of the text as a basis for classroom instruction in a number of separate courses. For example, Section 2—Industrial Ventilation can serve as the basis for a one- or two-semester course.

The authors are indebted to the many who labored in the past to develop the field to the level at which it now exists. Much of that which is presented herein does not represent new knowledge but rather a reorganization of existing bodies of knowledge into a single document. Many of those responsible for the original work in the field are referenced within this text.

Bruce B. Byers
Ronald J. Hritz
James C. McClintock
1978

SECTION 6

NONIONIZING AND IONIZING RADIATION

CHAPTER 1

PRINCIPLES OF NONIONIZING RADIATION

Introduction

In prior chapters, the principles of visible radiation (light) have been discussed. As discussed, light has characteristics of both waves and particles, and a light wave is energy released from a de-excitation of an orbital electron. Further, energy released is in discrete units or quanta of energy referred to as photons. Each wave in the visible spectrum has a characteristic wavelength, frequency, and photon energy. These characteristics can be correlated by using the following formula:

$$C = f\lambda$$

where

C = the speed of light (3×10^{10} cm/sec)

f = the frequency of oscillations per second

λ = the wavelength (centimeters)

and by the equation

$$E = hf$$

where

E = the photon energy (Joules)

h = Plank's constant (6.624×10^{-34} Joules-seconds)

f = the frequency of oscillation per second (Hz)

The importance of the visible radiation is that the eye is sensitive to this specific range of the electromagnetic spectrum.

To expand on this, all ranges of the electromagnetic spectrum are fundamentally the same in that they are produced by moving electrical charges. Where light is produced by the movement of electrons, other ranges of electromagnetic radiation are formed by the movement of molecules, electrons, neutrons, etc. All of these radiations have the same basic properties as visible radiation, and all are referred to as "electromagnetic radiation."

Radiation--Overview

Radiation is the emission of particles or energy in wave form. The radiation varies in the wavelength and frequency. The electromagnetic spectrum is divided into regions, depending upon the wavelength and frequency of radiation being discussed. Figure 6.1.1 illustrates the electromagnetic spectrum and shows the various regions that will be discussed. Specifically, the discussion will emphasize radio frequencies, microwaves, infrared, ultraviolet, X-radiation, and gamma radiation. The upper region (shorter wavelength) is of particular concern to the physicist and scientist who describe radiation in terms of wavelength (angstrom, centimeters, microns, millimeters, and nanometers). The lower region (longer wavelengths) has been explored by the communications scientists and engineers, who prefer to describe electromagnetic radiation in terms of frequency (Hertz, megahertz, cycles, kilocycles, megacycles, and gigacycles).

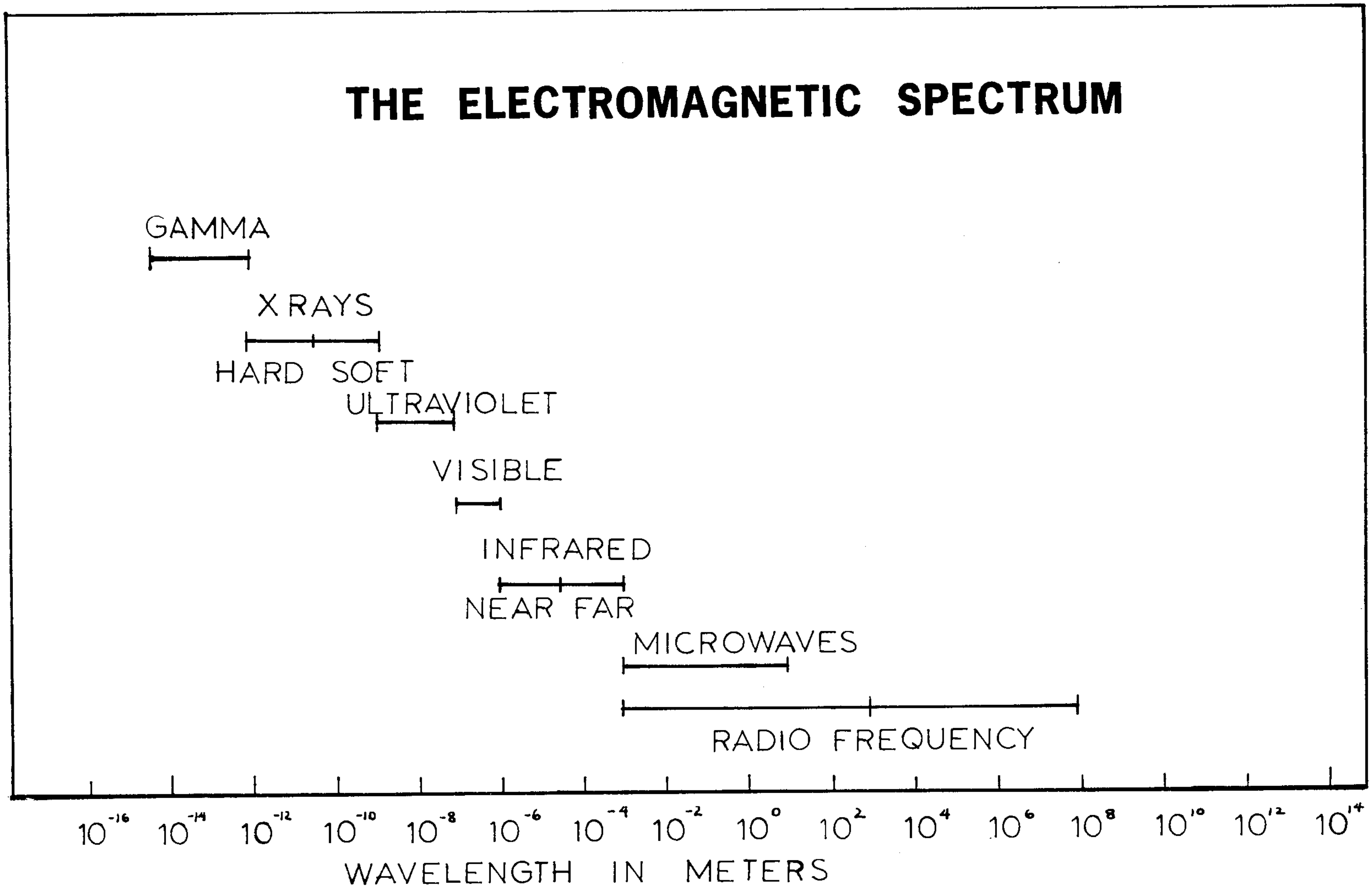
Units of Measure. Before discussing each of the regions of the electromagnetic spectrum, it is appropriate to review the units of measure that are used. The wavelength is the distance from peak to peak of a wave and is usually expressed in centimeters. The frequency refers to the number of oscillations per second, usually expressed in Hertz (Hz) or cycles per second as presented in Table 6.1.1.

Table 6.1.1

PHYSICAL UNITS

Unit	Symbol	Equivalent
	Wavelength	
centimeter	cm	1 cm
micrometer	μm	10^{-4} cm
nanometer	nm	10^{-7} cm
angstrom	Å	10^{-8} cm
	Frequency	
Hertz	Hz	1 cps
cycles per second	cps	1 cps
kilocycle	kc	1000 cps
megacycle	mc	10^{6} cps
gigacycle	Gc	10^{9} cps

Figure 6.1.1


THE ELECTROMAGNETIC SPECTRUM
GAMMA
X RAYS
HARD SOFT
ULTRAVIOLET
VISIBLE
INFRARED
NEAR FAR
MICROWAVES
RADIO FREQUENCY
10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} 10^{6} 10^{8} 10^{10} 10^{12} 10^{14}
WAVELENGTH IN METERS

Often times, unit prefixes (Table 6.1.2) are used to express the magnitude of the unit; e.g., 1 μm = 1 x 10^{-4} cm.

Table 6.1.2

TABLE OF UNIT PREFIXES

Multiples and Submultiples	Prefix	Symbols
1,000,000,000,000 = 10^{12}	tera-	T
1,000,000,000 = 10^{9}	giga-	G
1,000,000 = 10^{6}	mega-	M
1,000 = 10^{3}	kilo-	k
100 = 10^{2}	hecto-	h
10 = 10	deka-	D
0.1 = 10^{-1}	deci-	d
.01 = 10^{-2}	centi-	c
.001 = 10^{-3}	milli-	m
.000001 = 10^{-6}	micro-	μ
.000000001 = 10^{-9}	nano-	n
.000000000001 = 10^{-12}	pico-	p

The energy of electromagnetic radiation is expressed in terms of joules or electron volts. A joule is the work done when a constant force of one newton moves a body one meter. An electron volt is the energy acquired by an electron as it passes through a potential difference of one volt. To relate the two units, one electron volt (eV) is equal to 1.602 x 10^{-19} joules. If the energy is expressed over a given area, the energy density is being considered. Finally, power of electromagnetic radiation is referring to an energy over time, usually expressed in watts (W).

Radiation also exists that is not electromagnetic in nature but is made up of particles. This type of radiation is formed from radioactive decay or nuclear reactions. These particles do possess the high energy necessary to cause radiation. This particular radiation (alpha, beta, neutrons) will be discussed in later chapters.

Radiation can be divided into two types: ionizing and nonionizing. The difference between the two types of radiation is based upon the energy level of the radiation. Ionization is defined as the removal of electrons from an atom forming both a positive and negative ion. Nonionization, then, will refer to energy available in sufficient quantity to excite atoms or electrons but not sufficient to remove electrons from their orbitals. It is known that approximately 10 electrons volts (eV) is required to cause ionization of an oxygen or hydrogen molecule. Therefore, using 10 electron volts as a lower limit for ionizing energy level and the equations,

$$E = hf$$

and

$$C = f\lambda$$

the minimum wavelength can be determined which would have sufficient energy to cause ionization.

$$E = hf$$

$$C = f\lambda$$

$$E = \frac{Ch}{\lambda}$$

or

$$\lambda = \frac{hC}{E}$$

then

$$h = 6.602 \times 10^{-34} \text{ Joule-sec}$$

$$C = 3.0 \times 10^{10} \text{ cm/sec}$$

$$E = 10 \text{ eV} \times 1.602 \times 10^{-19} \text{ Joules/eV}$$

$$\lambda = \frac{(6.602 \times 10^{-34} \text{ J-sec})(3.0 \times 10^{10} \text{ cm/sec})}{10 \text{ eV} \cdot 1.602 \times 10^{-19} \text{ J/eV}}$$

$$= 1.24 \times 10^{-5} \text{ cm}$$

Therefore, electromagnetic radiation with a wavelength greater than 1.24 x 10^{-5} centimeters will not cause ionization and will be classified as nonionizing radiation. This will include the areas of the spectrum as follows: ultraviolet, visible, infrared, and radio frequencies.

Nonionizing Radiation--General

Nonionizing radiation is defined as radiation with sufficient energy to cause excitation of electrons, atoms, or molecules but insufficient energy to cause the formation of ions (ionization).

Electromagnetic radiation is caused by the movement of charges and is associated with a vibrating electrical field with accompanying magnetic field. The waves vary with proportional wavelength, frequency, and intensity. The radiation can act as discrete particles (quantum of energy), but they also have basic wave properties. It should be noted that there are no distinct dividing lines between regions on the electromagnetic spectrum. The regions that have been identified are arbitrarily established based upon general properties, but the distinction in region is not finite.

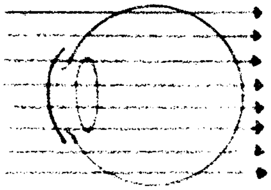
Nonionizing radiation comes from a variety of sources. The emission of electromagnetic radiation may be designed, as in a microwave oven unit or radio transmitter antenna. Or, the nonionizing radiation may be a by-product that is unwanted, such as the formation of infrared radiation in a welder's arc or in the processing of molten metal. The production of nonionizing electromagnetic radiation varies according to the frequency of the radiation. For example, radio frequencies are formed from the oscillation of electric current; infrared radiation is emitted from heated bodies and reflects the rotational movement of atoms; and visible radiation is the electron transition between energy levels. Specific sources of each type of nonionizing radiation will be discussed further in later chapters.

Even though nonionizing radiation does not cause the formation of ions, excessive levels of nonionizing radiation do present a potential health hazard in the working environment. The eye is the most sensitive organ to electromagnetic radiation injury; however, it is not equally sensitive to all wavelengths. Figure 6.1.2 illustrates the sensitivity of the eye to the various wavelengths. Even though it is not equally sensitive to all wavelengths of electromagnetic radiation, it can be a good indicator of exposure because of its sensitivity.

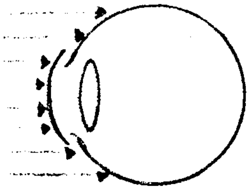
Nonionizing radiation will affect other parts of the body through different means. For example, if the body absorbs nonionizing radiation, it will potentially have a thermal effect and cause heating of the tissue. It is also possible for nonionizing radiation to have a photochemical effect; i.e., chemical changes in the body caused by the radiation. An example of this would be the development of pigment in the skin from exposure to ultraviolet radiation; i.e., a suntan. It has also been shown that excessive exposure to ultraviolet radiation may catalyze or stimulate growth of carcinogenic cells (cancer).

Figure 6.1.2

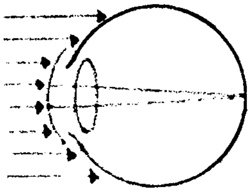
EYE SENSITIVITY



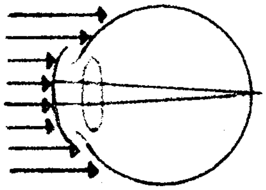
HIGH ENERGY X-RAYS; GAMMA RAYS; 99% PASS COMPLETELY THRU THE EYE, 1% ABSORBED.



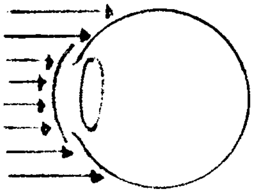
SHORT UV; ABSORPTION PRINCIPALLY AT CORNEA. (INTERMEDIATE UV; ABSORPTION AT CORNEA AND LENS.)



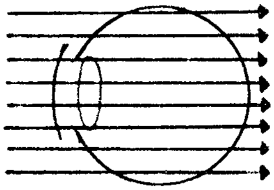
LONG UV, VISIBLE; TRANSMITTED THRU EYE AND FOCUSED ON RETINA.



NEAR IR; PARTIALLY ABSORBED BY LENS, IRIS, AND MEDIA, PARTIALLY FOCUSED AT RETINA.



FAR IR; ABSORPTION LOCALIZED AT CORNEA FOR SHARP H_2O ABSORPTION WAVELENGTHS, OTHER WAVELENGTHS ABSORBED ALSO BY LENS AND IRIS.



MICROWAVE; GENERALLY TRANSMITTED WITH PARTIAL ABSORPTION IN ALL PARTS OF THE EYE.

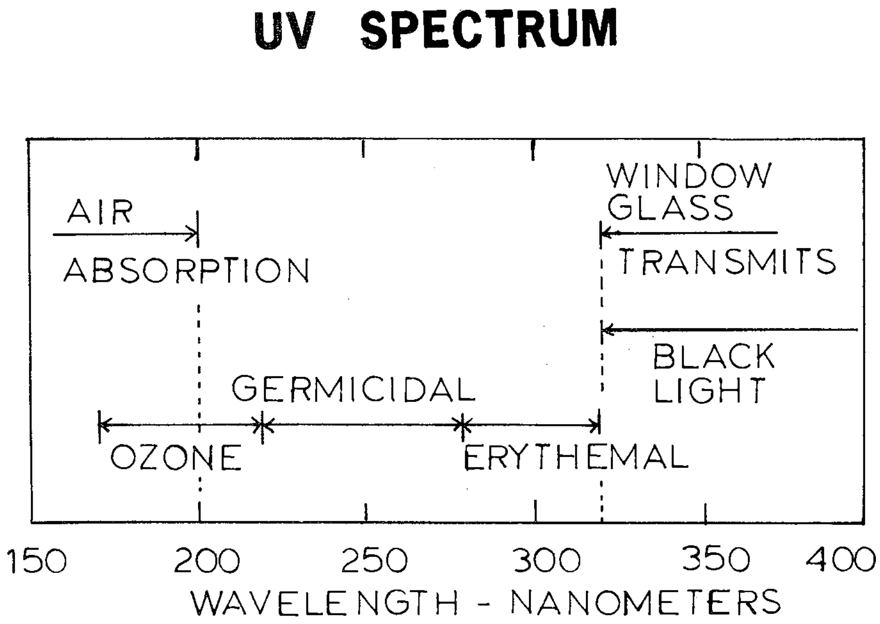
Nonionizing Radiation--Specific Regions

This section of the chapter deals with the characteristics, sources, biological effects, and permissible exposure limit values for ultraviolet, infrared, and radio frequency regions of the electromagnetic spectrum. Because of their wide use, the region of microwaves will be dealt with specifically, and the use of lasers will also be presented.

Ultraviolet Region. The ultraviolet region is the highest energy of the nonionizing radiation group. It is normally divided into three segments.

1. Vacuum--This region is representative of the ultraviolet radiation with wavelengths of less than 160 nanometers. Because this radiation is completely absorbed by air, the vacuum ultraviolet radiation can only exist in a vacuum.
2. Far--This region of ultraviolet radiation represents the region with a wavelength of 120 to 320 nanometers. For wavelengths less than 200 nanometers, the radiation is poorly transmitted through air. The radiation above 200 nanometers is absorbed by the ozone layer of the atmosphere.
3. Near--The final region is that which extends from 320 to 400 nanometers. This region transmits through air but only partially through glass. Figure 6.1.3 illustrates the ultraviolet spectrum as discussed.

Figure 6.1.3.



The most critical range is between 240-320 nanometers (actinic region) because ultraviolet has the highest biological affect in this range.

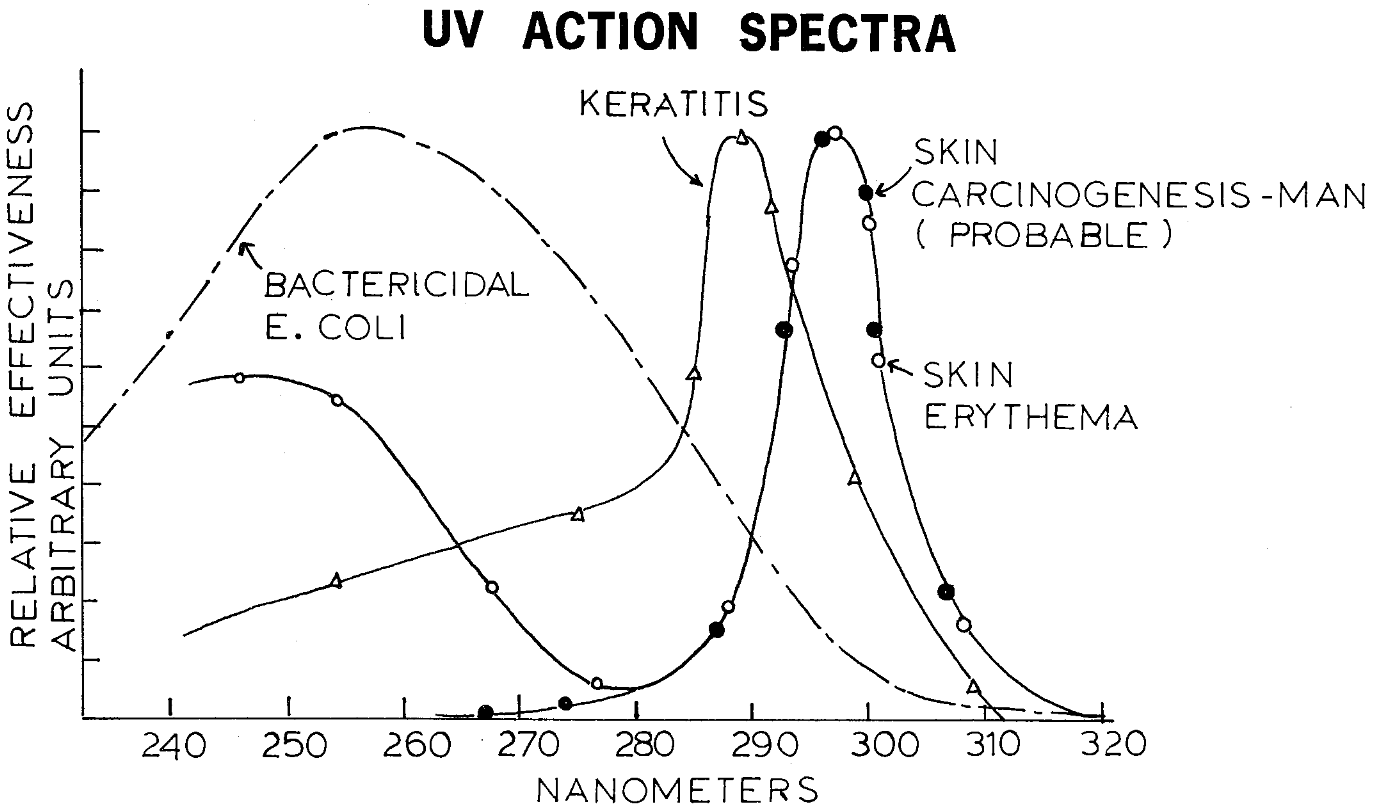
The primary source of ultraviolet radiation is the sun. Ultraviolet radiation is also emitted from incandescent or fluorescent lighting sources, welding operations, plasma torches, and laser operations. Typically, solar radiation on a midsummer day in the temperate latitudes causes a daily ultraviolet exposure (λ less than 400 nanometers) equal to approximately 2×10^{-3} J/cm^2. Of that, only 10^{-5} J/cm^2 is reasonably effective. (This concept will be further explained.)

Ultraviolet radiation has a number of uses because of its various properties. The most common application of ultraviolet radiation is in the production of visible light from fluorescent lamps. The fluorescent lamp bulb consists of a phosphor-coated glass tube that contains a small amount of mercury vapor. An electrical discharge occurs in the tube traveling through the mercury vapor, generating ultraviolet radiation. The ultraviolet radiation is absorbed by the phosphor coating on the inside of the tube, causing the phosphor to fluoresce. This fluorescence produces longer electromagnetic wavelengths (visible) energy. Because the ultraviolet radiation is absorbed by the phosphor coating, incandescent and fluorescent lamps used for general lighting purposes emit little or no ultraviolet radiation and are generally not considered any potential hazard.

Because of basic absorption properties of ultraviolet radiation with respect to certain bacteria and molds, ultraviolet radiation has been used as a germicide. As illustrated in Figure 6.1.4, the absorption properties of ultraviolet in E.coli is demonstrated. Because of this, ultraviolet has been used in the prevention and cure of rickets, killing of bacteria and molds, and for other therapeutic effects.

The "black light" properties of ultraviolet radiation have found use in industry in such things as blueprinting, laundry mark identification, and dial illumination of instrument panels. These applications generally are based on the same principle of fluorescence as described for fluorescent light. A substance (laundry marking) that is not visible to the eye in the presence of visible light, when exposed to ultraviolet radiation, will fluoresce, producing visible energy which then can be seen.

Figure 6.1.4



The most common exposure to ultraviolet radiation is from the sun. Men continually working in the sunlight are continuously exposed to ultraviolet radiation and may develop tumors. Electric welding lamps and germicidal lamps are the most common sources of ultraviolet radiation aside from the sun.

The primary biological effect of ultraviolet radiation is upon the skin and eyes. If the skin absorbs an adequate amount of ultraviolet radiation, the skin will redden (erythema). Different wavelengths of ultraviolet radiation have different effects. The general range of ultraviolet radiation that will cause erythema (skin reddening, blisters) is from 240 to 320 nanometers. The maximum effect is at a wavelength of 296.7 nanometers with a secondary peak effect at 250 nanometers. This is also illustrated in Figure 6.1.4 in what is known as the standard erythemal curve, indicated by the skin erythema scale.

The signs and symptoms that may be observed are dependent upon the dose received. Minimal dose may cause simple reddening, whereas a moderate dose may cause the formation of blisters or even peeling of the skin (disquamation). The time required for the onset of symptoms is also dependent upon the dosage. It may range from two to several hours. The peak effect is usually visible 12 to 24 hours after exposure. If the ultraviolet source is removed, the symptoms will subside. If the skin is exposed to continuous ultraviolet radiation, a protective mechanism develops for subsequent exposures. The skin increases the pigmentation in the upper layer which acts as a screen to the ultraviolet radiation. This is commonly known as the "suntan."

The dosage required to cause erythema varies according to the pigmentation content of the skin; for example, Negroid skin may require two to three times as much ultraviolet radiation as the average Caucasian skin to cause erythema. Further, untanned skin would require less ultraviolet radiation to cause erythema. In general, the erythemal-causing dose of ultraviolet radiation for the average Caucasian is in the range of 0.02-0.03 J/cm^2.

Ultraviolet radiation can also affect the eye. If the exposure is above the threshold limit value (TLV), inflammation of the conjunctiva (conjunctivitis) or inflammation of the cornea (keratitis) may occur. The cornea is probably the most vulnerable because of two factors. First, it is avascular, which means that there are very few blood vessels in the cornea. Because there are few blood vessels, the cornea has difficulty dissipating the heat that would be generated through the absorption of ultraviolet radiation. Second, there is an abundance of nerve endings in the cornea. This would increase the intensity of pain of the overexposure. It has been found that maximum damage to the eye occurs when the wavelength is in the area of 288 nanometers.

If an exposure above the TLV of ultraviolet radiation occurs, common signs and symptoms of the problem will be inflammation of the conjunctiva, cornea, or eyelid. The individual may also experience pain and an abnormal intolerance of light. It is also possible that as a reflex protective action the eyelids will close tightly (blepharospasms), and the individual will have difficulty opening his eyes. The time required for the onset of symptoms is dependent upon the dosage. It may take from 30 minutes to 24 hours for the symptoms to appear. Once the ultraviolet source has been removed, symptoms will regress after several days with no permanent damage.

A common example of ultraviolet radiation exposure to the eyes is welder's "flash burn." This occurs when, during a welding operation, a welder does not fully protect his eyes against the ultraviolet radiation. In this instance, the individual will exhibit signs and symptoms previously mentioned and will have difficulty with vision. However, as mentioned, the symptoms will regress after several days with no permanent damage.

Unlike the skin, the eye has no mechanism to establish an increased tolerance to repeated exposures of ultraviolet radiation. Therefore, it is possible for problems such as welder's flash burn to occur repeatedly if exposure levels are not reduced.

Another biological effect caused by ultraviolet radiation is the fluorescence of the vitreous fluid of the eye. If the wavelength of ultraviolet radiation approximates 360 nanometers, the vitreous humor fluoresces, causing diffuse haziness and decreased visual acuity. This "internal haze" is strictly a temporary condition and has no detrimental effects and should disappear when exposure ceases. However, because of the decreased visual acuity, the individual being affected by this problem may become anxious because of his reduced vision.

Although no case of industrially-induced skin cancer has been reported to date, it is presumed that continuous exposure to ultraviolet radiation is related to skin cancer. This is presumed because of the increased number of cases of skin cancers found in outdoor workers who are constantly exposed to ultraviolet radiation. Further, there is even a more significant increase in the number of cases of skin cancer when outdoor workers are simultaneously exposed to chemicals such as coal tar derivatives, benzopyrene, methylcholanthrene, and other anthracene compounds. It is further assumed that industrially-induced skin cancer cases have not been reported because the dosages required to cause cancer are in excess of the dosages required to cause skin and eye burns. Therefore, the pain would be intolerable; and the individual would remove himself from the source before an adequate dosage to cause cancer would be reached. With outdoor workers, however, the ultraviolet radiation is continuous over an extended period of time and may catalyze cancer development.

One final biological effect that has proved of value is that ultraviolet radiation in the range of 160 nanometers is absorbed by nucleoproteins, which in turn cause irreparable damage to certain types of bacteria. As previously discussed, low pressure mercury discharge lamps are used as bactericides. While this type of procedure provides an adequate method for destruction of bacteria in certain processes, the ultraviolet radiation which acts as a bactericide can also cause erythema and conjunctivitis.

Some indirect, nonbiological effects of ultraviolet radiation have also been discovered and are of concern. It has been found that certain wavelengths of ultraviolet radiation can dissociate certain molecular structures to form toxic substances. For example, ultraviolet radiation (λ less than 250 nanometers) can cause dissociation of molecular oxygen to form ozone (O_3). A wave of less than 160 nanometers can cause dissociation of molecular nitrogen, which in turn reacts to form nitrogen oxide; and if the wavelength is less than 290 nanometers, the ultraviolet radiation can cause decomposition of chlorinated hydrocarbons, e.g., carbon tetrachloride, trichloroethylene, to form toxic gases such as hydrochloric acid and phosgene. This is of value in that care must be taken to evaluate the substances which are being used in an area which may have ultraviolet radiation.

Exposure Criteria. The threshold limit values (TLV's) recommended by the American Conference of Governmental Industrial Hygienists (ACGIH) refer to the ultraviolet in the spectral region between 200 and 400 nanometers and represent conditions under which it is believed that nearly all workers may be repeatedly exposed without adverse effect. The values presented apply to ultraviolet radiation from arcs, gas and vapor discharges, fluorescent and incandescent sources, and solar radiation. The values present a guide in the control of exposure to continuous sources where the exposure duration is not less than 0.1 second.

The TLV for occupational exposure to ultraviolet radiation incident upon the skin or eye where irradiance values are known and exposure time is controlled are as follows:

1. For the near ultraviolet spectral region (320 to 400 nanometers), total irradiance incident upon the unprotected skin or eye should not exceed 1 mW/cm^2 for periods greater than 10^3 seconds (approximately 16 minutes), and for exposure times less than 10^3 seconds should not exceed 1 J/cm^2.

2. For the actinic ultraviolet spectral region (200 to 315 nanometers), radiation exposure incident upon the unprotected skin or eye should not exceed values presented in table 6.1.3. within an 8-hour period.

Table 6.1.3

RELATIVE SPECTRAL EFFECTIVENESS
BY WAVELENGTH

Wavelength (nm)	TLV (mJ/cm^2)	Relative Spectral Effectiveness Sλ
200	100	0.03
210	40	0.075
220	25	0.12
230	16	0.19
240	10	0.30
250	7.0	0.43
254	6.0	0.5
260	4.6	0.65
270	3.0	1.0
280	3.4	0.88
290	4.7	0.64
300	10	0.30
305	50	0.06
310	200	0.015
315	1000	0.003

In many instances, the individuals in the working environment will be exposed to a broad band source of ultraviolet radiation. Because the erythemal effect of ultraviolet radiation is not the same for all wavelengths within the spectrum, it is necessary to weight the exposure by wavelength according to the spectral effectiveness curve. The following weighting formula can be used to determine the effective irradiance of a broad band source.

$$E_{eff} = \Sigma E_{\lambda} S_{\lambda} \Delta\lambda$$

where

E_{eff} = the effective irradiance relative to a monochromatic source at 270 nanometers

E_{λ} = the spectral irradiance in W/cm^2 per nanometer

S_{λ} = the relative spectral effectiveness (unitless)

$\Delta\lambda$ = the band width in nanometers

Once the effective irradiance relative to a monochromatic source has been determined, the permissible exposure time in seconds for exposure may be computed by dividing 0.003 J/cm^2 by the effective irradiance in W/cm^2. The exposure time may also be determined by using Table 6.1.4 which provides exposure time corresponding to effective irradiance in μW/cm^2.

Table 6.1.4

PERMISSIBLE ULTRAVIOLET EXPOSURE

Duration of Exposure Per Day	Effective Irradiance, E_{eff} (μW/cm^2)
8 hrs	0.1
4 hrs	0.2
2 hrs	0.4
1 hr	0.8
1/2 hr	1.7
15 min	3.3
10 min	5
5 min	10
1 min	50
30 sec	100
10 sec	300
1 sec	3,000
0.6 sec	6,000
0.1 sec	30,000

Visible Light

Because Section 5 deals with visible light, it will not be discussed in this section. If there are any questions, please refer to the section on Illumination.

Infrared Radiation

Infrared (IR) radiation is found at the lower end of the visible spectrum. It includes the wavelength range of 750 nanometers to 0.1 centimeters. The IR region is divided into two regions; the near region represents the wavelength of 750 nanometers to 5.0 micrometers, and the far region represents the wavelengths from 5 micrometers to 0.1 centimeters.

Exposures to infrared radiation can occur from any surface which is at a higher temperature than the receiver. Infrared radiation may be used for any heating application where the principle product surface can be arranged for exposure to the heat sources. Transfer of energy or heat occurs whenever radiant energy emitted by one body is absorbed by another. The electromagnetic spectrum wavelengths longer than those of visible energy and shorter than those of radar waves are used for radiant heating. The best energy absorption of white, pastel-colored, and translucent products is obtained by using wavelength emissions longer than 2.5 micrometers. The majority of dark-pigmented and oxide-coated materials will readily absorb wavelength emissions from 0.75 to 9.0 micrometers. Water vapor and visible aerosols such as steam readily absorb the longer infrared wavelengths.

Sources of infrared radiation are primarily those pieces of equipment which are designed to provide a commercial heating source using infrared radiation. However, in any process which requires the extreme heating of metals or glass to a melting point, e.g., 2100^{o}F, infrared radiation will be formed. Examples of this include molten metals or glass or any type of welding arc process.

The basic application of infrared radiation is in the production of heat and heating materials. Depending upon the absorption qualities of the absorbing material and the surrounding environment, infrared radiation can be used to provide rapid rates of heating if desired. Typical industrial applications of infrared radiation include such things as:

1. Drying/baking of paints, varnishes, or enamels
2. Heating of metal parts for brazing, forming, thermal aging
3. Dehydration of textiles, vegetables, sand molds
4. Localized controlled heating of any desired absorbing material

Although not a direct application of infrared radiation, a common source of infrared radiation is from furnaces and similar heated bodies which are working with molten glass and metals. Most arcing processes (welding) also produce a significant amount of infrared radiation.

Infrared radiation is perceptible as a sensation of warmth on the skin. The increase in tissue temperature upon exposure to infrared radiation depends upon the wavelength, the total amount of energy delivered to the tissue, and the length of exposure. Infrared radiation in the far wavelength region is completely absorbed in the surface areas of the skin. Exposure to IR radiation in the region between 0.75 and 1.5 micrometers can cause acute skin burns and increased persistent skin pigmentation.

The short wavelength region of the infrared is capable of causing injuries to the cornea, iris, retina, and lens of the eye. Excessive exposure of the eyes to luminous radiation, mainly visible and IR radiation, from furnaces and similar hot bodies has been said for many years to produce "glass blower's cataract" or "heat cataract." This condition is an opacity of the rear surface of the lens. Generally, the signs and symptoms of infrared radiation exposure are similar to that of ultraviolet radiation exposure. The symptoms include skin burns, vasodilation of the capillary beds, erythema, blistering of the skin, pain, and potential increased pigmentation. The difference between the two, however, is that exposure to infrared radiation has no latent period, and symptoms will appear immediately. Because of this, extended exposure to intense infrared radiation is minimized because the pain produced by the exposure forces the individual to remove himself from that environment.

Threshold Limit Values. Because overexposure of infrared radiation to the skin causes pain and the individual will remove himself from the environment, the primary concern is overexposure of the eyes to infrared radiation. Further, it has been determined that the damage is dependent upon the wavelength absorbed, the intensity of the wave, and the duration of the exposure. As these relate to the threshold phenomenon, it would appear that a maximum permissible dose (TLV) of 0.4-0.8 J/cm^2 could limit the occurrence of acute infrared radiation effects. A further reduction by a factor of 10 should prevent the more chronic effects on the intraocular tissues.

Radio Frequencies

As with the other regions of radiation discussed, radio frequencies obey the general laws of electromagnetic radiation. The radio frequencies range from a frequency of 1×10^{-3} to 3×10^{13} Hertz or cycles per second. This would translate into a wavelength of 3×10^{-3} to $1 \times 10^{+8}$ meters.

Radio frequencies have the capability of inducing electrical currents in conductors. Further, they may also induce the displacement of current in semi-conductors, thus transforming radiant energy to heat. By transforming the frequency to an electrical current, patterned energy may be transferred such as with the radio or television. If the radio frequency encounters a semi-conductor, then the radio frequency can be used as a heat source.

Radio frequencies are generally polarized and form two zones or fields. The near field (Fresnel zone) is representative of the area around the source in which the radio frequency wave has a unique distribution because the waves emitted interact with the source itself. The size of the field is a function of the wavelength emitted and the area of the source (antenna). The radius of the Fresnel zone can be calculated using the formula

$$R = \frac{A}{2\lambda}$$

where

R = radius of the field (cm)
A = area of the antenna (cm^2)
λ = wavelength (cm)

In the Fresnel zone, the energy is transmitted by both the electric and magnetic vectors. This energy can be measured in terms of volts/meter for the electric vector and amps/meter for the magnetic field. However, measurement of field strength in the Fresnel zone is a very complicated process because of the interaction with the source.

The far field (Fraunhofer zone) is the outer field. Energy in this field is transmitted by the electric vector only and is measured in terms of volts/meter. Because there is no interaction with the source, measurements in the Fraunhofer zone are more easily taken. Generally, meters are calibrated in the Fraunhofer zone.

Threshold limit values for radio frequencies are usually expressed in terms of power density (watts/m^2). The field strength (volts/m) can be converted to power density using the formula

$$P = \frac{E^2}{120\ \pi}$$

where

P = power density (watts/m^2)
E = energy density (volts/m)

The common sources of radio frequency include telecommunications, high radio frequency heating instruments, and scientific instruments.

The application of radio frequency radiation can be divided into two basic areas, that of heating absorbing materials and communications. Radio frequency heating is used in a wide variety of industrial applications. For example, radio frequency radiation may be used for such things as hardening gear teeth, cutting tools, and bearing surfaces. It may also be used for soldering and brazing. Applications in the field of wood working include such things as bonding plywood, laminating, and general gluing procedures. It is also used for such applications as molding plastics, vulcanizing rubber, and setting twist in textile materials.

There are basically two types of radio frequency heaters, induction and dielectric. Induction heaters are used when the absorbing material to be heated is some type of conductor. In the induction heater, the absorbing material is brought near an induction coil which is connected to a source of high frequency power. The absorbing material will resist the flow of induced high frequency current and thus be heated. The dielectric heater is used for nonconducting materials; e.g., rubber, wood, plastics, leather. With this type of heater, the absorbing material is placed between plates of a capacitor connected to a source of high frequency power. In the radio frequency field developed, the molecules of the absorbing material become agitated and the material heats because of molecular friction. The most commonly used application of the radio frequency capability is the microwave oven.

Radio frequency radiation is also commonly associated with communications. The radio frequency wave is used to carry a signal which can be received and converted to some form of discernible message. All radio communications, broadcasting, and even the use of radar, fall in the spectrum of radio frequency electromagnetic radiation.

The effect of radio frequency varies greatly in individuals. The primary effect of radio frequencies on an individual is the thermal effect. For the radio frequency to have an affect on the body, the body must have a diameter of at least 1/10 of the wavelength. Therefore, any wavelength greater than 20 meters will have no thermal effect on the body. The body acts as a semi-conductor. As discussed, the electromagnetic radiation is transformed to heat in a semiconductor. The absorption and transformation of the radiation to heat is dependent upon the water content, and the depth of penetration of the radio frequency is dependent upon the fatty tissue content. Radio frequencies display an interesting property in that they may be reflected at interfaces of dielectrically nonhomogeneous layers, giving rise to "a standing wave." This causes a concentration of the energy. An example of this is the various layers of the skin. Because the layers are dielectrically nonhomogeneous, it is possible that standing waves would be produced and the energy of the waves concentrated. Further, the rate of energy absorption and heat accumulation is dependent upon such factors as field strength and power density; the length of exposure; the environmental temperature and humidity; the type of clothing worn; the type of body layers, e.g., fat versus muscle; and the reflection of the waves.

Specific regions of the body that are sensitive to temperature are more critically affected by radio frequency radiation. For example, the lens of the eye can be affected because of its difficulty in dissipating heat. Thus, cataracts may form from radio frequency exposure. Radio frequency exposure to the male reproductive organs causes a temperature increase which critically affects the sperm cells in the testes. Less androgen is produced and, thus, a decrease in sex hormones. Finally, because the central nervous system consists of thick bones and has a high fatty content, the penetration of radio frequency is facilitated, but heat dissipation is hindered. Further, the spherical shape of the spinal column and skull cavity may cause reflections and concentration of the energy. Therefore, radio frequency radiation must be monitored in areas where the energy and power density could reach TLV.

Radio frequency radiation can also have nonthermal effects that may be detrimental. First, because of the effect of the electric and magnetic fields in combination, particles greater than 15 micrometers in diameter having an electrical charge will polarize in the Fresnel zone. Because there are no histological structures in the body that are greater in diameter than 15 micrometers, polarization does not occur in human tissue; but the potential does exist. Radio frequency radiation can also demonstrate a demodulating effect. This effect involves organs of the body that display modulating electrical activity; e.g., heart, central nervous system. The exposure of these organs to radio frequency causes a change in amplitude and peak frequency in electrocardiograms and electroencephalograms. This effect does not appear to have any permanent effects and is eliminated when the radio frequency exposure is removed. Finally, radio frequency radiation can have an effect on molecular structure. In essence, the radiation causes excitation of molecules and there exists a potential for molecular polarization. Although the molecular structure is not changed, this effect can exert a catalytic action upon some chemical and enzymatic reactions; i.e., making molecules more receptive to certain types of chemical reactions.

A number of safety limit standards have been established by various organizations with respect to radio frequency radiation. These limits are based upon the potential thermal and nonthermal effects of this radiation and take into consideration individual sensitivity toward radio frequency radiation. Standards accepted in the United States are continuous across all frequencies and state that a power density of 10 milliwatts/cm^2 should not be exceeded if the exposure is for 0.1 hours or longer. If the exposure period is 0.1 hours or less, the energy density of 1 milliwatt/cm^2 should not be exceeded.

Experts in the USSR have established more rigid health standards with respect to radio frequency radiation. Their standards have discriminated between various radio frequencies. For example, for radio frequencies between 3 and 30 megahertz, any radio frequency radiation source which is used for inductance heating should not exceed 20 volts/m (electrical field) or 5 amps/m (magnetic field). If the source is being used for dielectric heating or broadcasting in that given frequency range, the energy density should not exceed 20 volts/m. For the range of 30 to 300 megahertz, the energy densities should not exceed 5 volts/m. Finally, for the range of 300 to 300,000 megahertz, exposure should not exceed 10 microwatts/cm^2 for a continuous exposure over an average working day; 100 microwatts/cm^2 for a 2-hour exposure per 24-hour period; or 1 milliwatt/cm^2 for a 15- to 20-minute exposure per 24-hour period. Although the Russian standard is more specific, it seems appropriate to use the American standard as our basis for evaluation of radio frequency radiation exposure.

Each of the regions of nonionizing radiation have been briefly presented in the previous section. The remaining two sections will deal with nonionizing radiation that is not specifically presented on the electromagnetic radiation spectrum. First will be the use of microwaves. Microwaves are essentially a subgroup of the radio frequencies just discussed. The second section will deal with lasers. Lasers are essentially a special application of electromagnetic radiation and as such are not specifically represented on the electromagnetic spectrum. However, lasers play an increasing important role in the industrial environment and present some special potential health and safety hazards that should be presented.

Microwaves

Radio frequencies above 1,000 megahertz are classified as microwaves. Microwaves demonstrate the basic properties of all other electromagnetic radiations. They have the capability of being transmitted over long distances through air and rain. They follow a quasi line-of-sight path with minimal diffraction spreading. Microwaves may be readily generated with high power densities. Because of their unique absorption properties in dielectric insulators, microwaves lead to the uniform heat disposition in many materials. Microwaves are strongly reflected and can be contained by metallic surfaces.

There are basically two types of microwave units. The first type is a continuous wave microwave unit. This type of unit generates a microwave on a continuous basis with no interruptions in the production of the wave. The second type is a pulse wave unit. In this unit, the wave is produced for a short period of time (10^3 microseconds). The advantage of the pulsed wave unit over the continuous wave unit is that greater power levels can be obtained with the pulsed wave unit.

Specific uses of microwave frequencies have been established by the Federal Communications Commission. Typical uses of microwave radiation are presented in Table 6.1.5.

Table 6.1.5

MICROWAVE BAND DESIGNATIONS

Designation		Wave-Length	Frequency	Application
Very high frequency (VHF)	Ultra-short (meter)	10-1 m	30-300 MHz	FM broadcast, television, air traffic control, radionavigation
Ultra high frequency (UHF)	Decimeter	1-0.1 m	0.3-3 GHz	Television, citizens band, microwave point-to-point, microwave ovens, telemetry, tropo scatter, and meteorological radar
Super high frequency (SHF)	Centimeter	10-1 cm	3-30 GHz	Satellite communication, airborne weather radar, altimeters, shipborne navigational radar, microwave point-to-point
Extra high frequency (EHF)	Millimeter	1-0.1 cm	30 GHz 300 GHz	Radio astronomy, cloud detection radar, space research, HCN (hydrogen cyanide) emission

The FCC has also established specific frequencies for use in communication. General bands have also been established. For example, three common bands have been designated "S," "X," and "K" bands; and these bands have a wavelength of 10, 3, and 1.2 centimeters respectively.

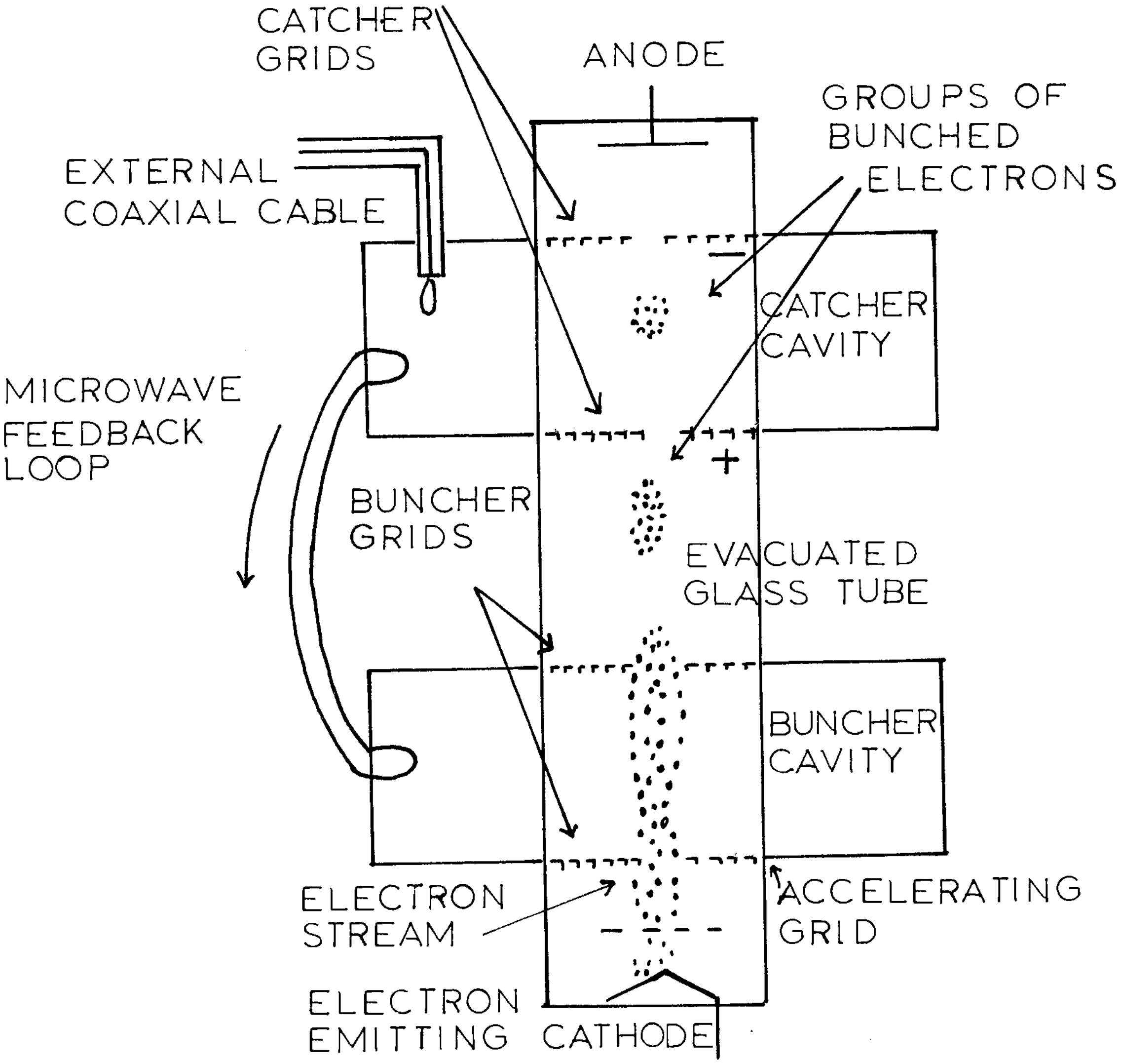
The two practical sources of the microwave are the klystron and the magnetron. The klystron is designed to generate low power levels in the neighborhood of 1 watt. The magnetron has the capability of generating much higher power levels in the neighborhood of 1 kilowatt on a continuous wave basis. Microwaves are produced by the deceleration of electrons in an electrical field. As the electrons slow down, kinetic energy is released in the form of microwaves.

The klystron has six basic components (see Figure 6.1.5). These components include a vacuumized glass tube, electron-emitting cathode, accelerating grid (anode), two metal ring-like microwave cavities referred to as a "buncher" and a "catcher," an accelerating grid, and coaxial feed line.

The operation of the klystron is relatively simple. A stream of high speed electrons is produced at the cathode. The electrons travel toward the anode; and as they pass through the accelerating grid, they increase their speed. In the buncher cavity, the electrons are modulated by a microwave field into bunches.

Figure 6.1.5

KLYSTRON MICROWAVE SOURCE

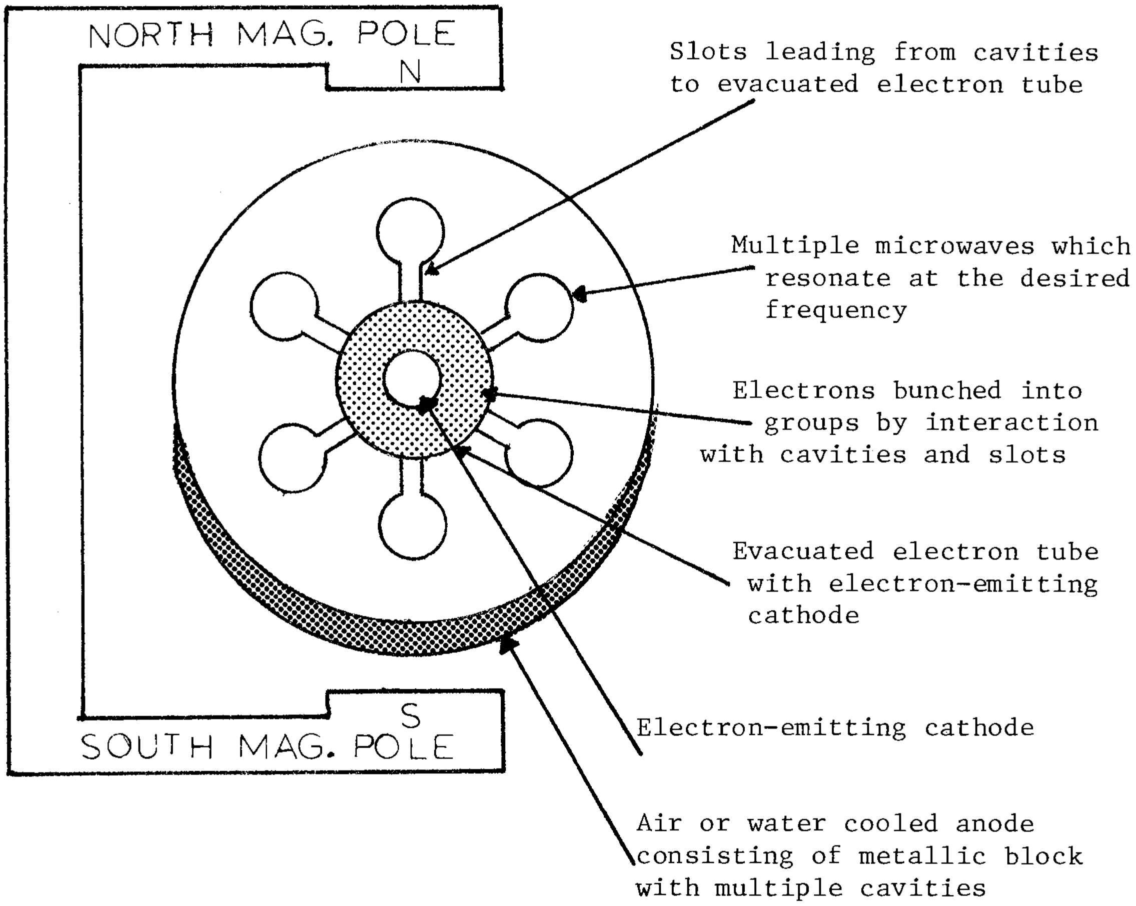


When the bunched electrons pass the catcher grid, the electrons slow down and microwave radiation is released; and the microwaves are removed by the coaxial cable. Finally, the electrons are captured at the anode. The specific radiation released is dependent upon the dimensions of the tube, the dimensions of the cavity, and the velocity of the electrons.

The magnetron operates on the same principle as the klystron but is a much higher energy source. With the magnetron, the electron beam travels in a circular orbit within a magnetic field. In the magnetron, there are a multiple number of cavities (6 or more), and the same cavities bunch the electrons and catch the electrons (Figure 6.1.6). The ability of the magnetron to function with high currents and with many cavities gives it greater power capability than the klystron. It is also easier to cool, which is a limiting factor in the klystron.

Figure 6.1.6

MAGNETRON · MICROWAVE GENERATOR



Biological Effects. The biological effects attributed to microwaves are similar to the biological effects caused by radio frequency. One special concern is that the thermal heating of an exposed tissue takes place throughout the volume and does not originate from the surface as with some of the other electromagnetic radiations discussed. The depth of penetration is dependent upon the frequency of the wave and the type of tissue relative to water content. For example, fat layers and bone have low water content and therefore low absorption of microwave energy. However, the skin and muscles have high water content and therefore high absorption of energy. With microwaves, the thermal effects are more significant than nonthermal effects. However, in any case, both the thermal and nonthermal effects of microwave radiation are the same as for radio frequencies.

Threshold Limit Value. The threshold limit value established for microwaves is presented in terms of power density versus the exposure time which would be allowed at that given power density. Table 6.1.6 lists the power densities and exposure time allotted.

Table 6.1.6

TLV LEVELS/MICROWAVES

Power Density	Exposure Time Allowed
Less than 10 milliwatts/cm^2	8 hrs. (continuous exposure)
Between 10 and 25 milliwatts/cm^2	10 minutes per every 60-minute period during 8-hour day
Greater than 25 milliwatts/cm^2	No exposure allowed

The TLV established for microwave radiation exposure should prevent any type of acute or chronic problems arising from microwave exposure.

Lasers

The term "laser" is an acronym for "light amplification by stimulated emission of radiation." The laser can use ultraviolet, infrared, visible, or microwave (maser) radiation.

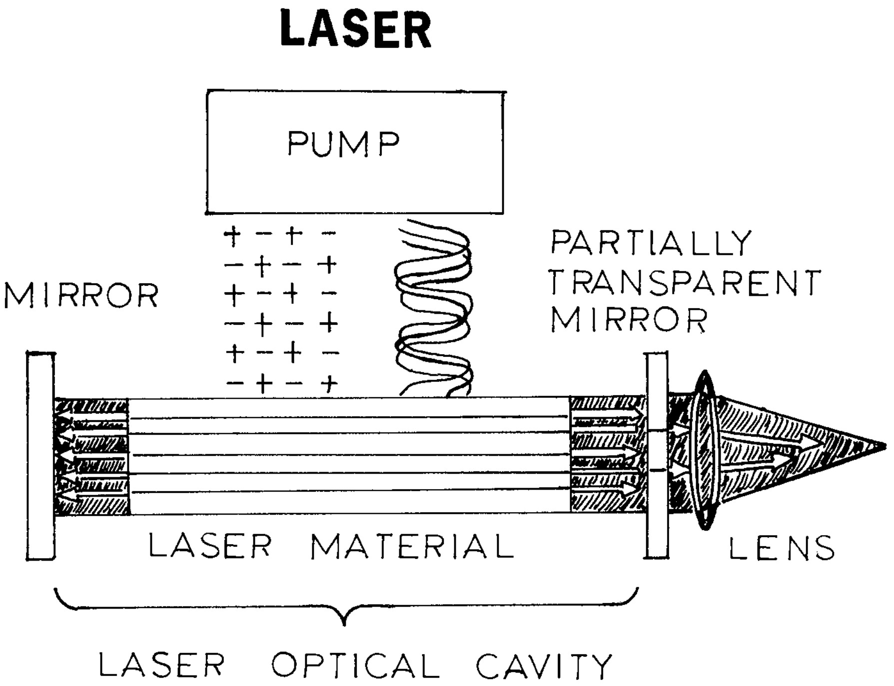
The laser is a device that produces a concentrated light beam with the following properties. First, the light beam is coherent. This means that the beam is highly uniform in phase over an extended area, allowing for a narrow directional beam over long distance. Second, the beam is monochromatic, meaning that the emitted radiation has a very narrow wavelength band. Finally, the power density can be very high. This comes about because the beam is coherent and monochromatic.

There are a variety of laser sources available, depending upon the power and wavelength of interest. These sources are usually categorized according to the type of instrumentation used, whether it be ruby crystal, gaseous, or injection-type laser.

In general, every laser has three basic elements. The first element is an optical cavity, consisting of at least two mirrors, one of which is partially transmissive. The second component is some type of active laser medium. This is a material that can be excited from an unenergized ground state to a relatively long-lived excited state. The third element of a laser is some means of "pumping." This pumping procedure is necessary for supplying the excitation energy to the active laser medium.

As an example, the ruby laser, as shown in Figure 6.1.7, will be presented. This consists of a high voltage power that feeds into an electrical pulse-forming network. This pulse-forming network produces short pulses of very high electrical current that feed into a xenon flash lamp. A flash lamp trigger pulse is also produced. The flash lamp produces a short and very intense optical pulse that is absorbed by the ruby rod.

Figure 6.1.7



The ruby rod is a crystal of aluminum oxide with about 0.05% chromium oxide. It is the chromium oxide that gives the ruby its pink color and acts as the active laser material.

The ruby laser is excited by optical pumping which lifts the system from the ground state of the chromium ion to one of the wide absorption bands. These absorption bands are optically wide in comparison to the sharp photon wavelength later emitted.

Once these absorption bands are excited, they quickly drop to a lower energy level by a radiationless transition. This lower energy level is actually split into two levels which are close together in energy. One of them is very long lived with a life of T = 3 milliseconds. One photon can be emitted by each state. The longer wavelength photon, which comes from the long-lived state, is more numerous. It is these photons that are emitted in a rapid pulse much shorter than the lifetime of the state that gives the high power of the ruby laser.

The ends of the ruby crystal act as the optical cavity. Once the critical level is reached, the presence of photons stimulates emission of other photons, and chromium ions return to their ground state again. Simultaneous emission of the photons forms the coherent light. This light is then transmitted through the transmissive mirror-like end of the ruby crystal tube. The entire sequence described requires approximately one-thousandth of a second. The coherent wave is produced because the critical level of photons required for stimulated emission is reached.

The ruby crystal is but one type of laser; i.e., solid crystal with impurities. Depending upon the wavelength or obtainable power of interest, a variety of types of lasers are available. Table 6.1.7 lists the common types of lasers.

As with microwave units, laser units may also operate in the pulse or continuous wave mode. Again, as with microwaves, the advantage of the pulse mode is the tremendous increase in power density that is obtainable.

Table 6.1.7

MOST COMMON TYPES OF LASERS

Laser Type	Example	Mode of Operation	Power per Pulse	CW Power
Solid host	Ruby (Chromium)	Pulsed or Rapid Pulse Mode	1000 megawatts	1 watt
	Neodymium YAG		10 megawatts	100 watts
	Neodymium Glass	Same		
Gas Laser (Neutral Atom)	Helium Neon	CW		up to 100 milliwatts
Ion Gas Laser	Argon	CW		1 to 20 watts
Molecular Gas Laser	Carbon Dioxide	CW		10 to 5000 watts
Molecular Gas Laser	Nitrogen	Pulsed or Rapid Pulse Mode		250 milliwatts
Semiconductor Diode	Gallium Arsenide	Pulsed or CW	1 to 20 watts	
Chemical Laser	HCl	CW or Pulsed		
Liquid Laser	Organic Dye Laser (tuneable)	Pulsed	1 megawatt	

The power produced by the laser is measured in terms of joules per second or watts. If the time of the pulse is decreased, then the watts or energy is increased Further, if the power density is defined as the power per unit area, then if the area is reduced, power density increases. Assume that a laser produces a peak power of 1 Joule. (Note: One Joule is enough energy to operate the average home iron for approximately three-tenths of a second.) Further, assume that the pulse of the power is reduced to 10^{-3} seconds and that through a series of lenses the power is focused on a one square millimeter area. With the capability of shortening the pulse and focusing on a minute finite area, then the power density (W/m^2) becomes

$$\frac{1 \text{ Joule}/10^{-3} \text{ sec}}{10^{-3} \text{ m}^2} - 1 \times 10^9 \frac{\text{Joules sec}}{\text{m}^2} = 10^9 \text{ W/m}^2$$

which is equal to 10^9 watts/m^2. As can be seen, the ability of the laser to focus on a finite area with a short pulse of energy increases the power density generated

As mentioned, the capability of the laser to present a coherent beam that may be focused on a small spot is of great advantage. Aside from the coherence, the ability of the laser beam to maintain in a parallel beam is what increases its great potential. For example, a laser beam may be divided into two regions based upon its beam divergence (Figure 6.1.8). The first region is the parallel region and is defined as:

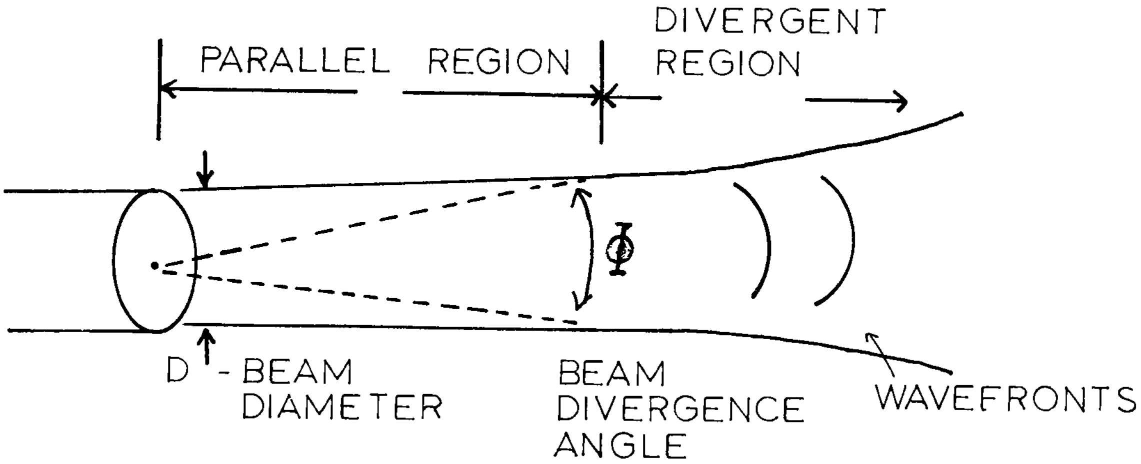
$$L = \frac{D^2}{2.44\lambda}$$

where

L = the parallel region (cm)
D = the beam divergence (cm)
λ = the wavelength of the laser wave (cm)

Figure 6.1.8

BEAM DIVERGENCE

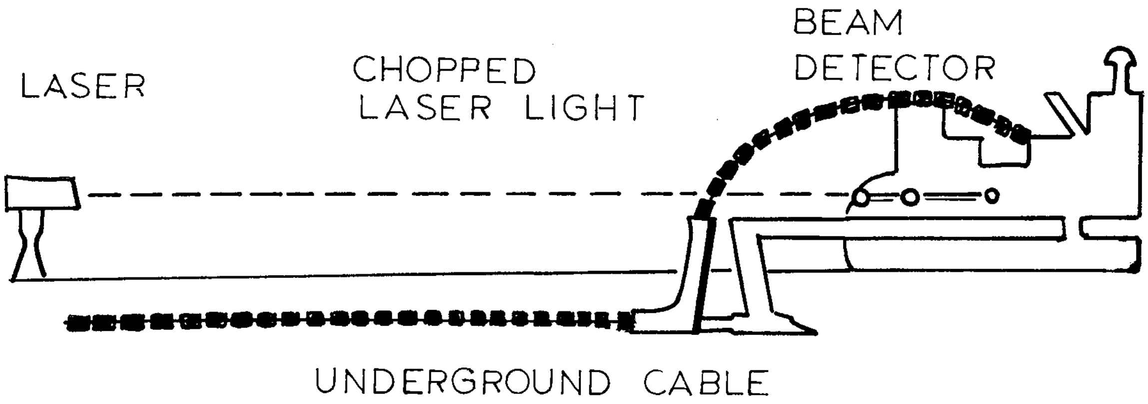


For example, if infrared radiation of a wavelength equal to 10^{-4} cm and a beam diameter of .1 cm was used, then the parallel region would be approximately 41 cm. The divergence region would then begin at that point. With beam divergence, the intensity of the wave begins to decrease. The energy lost, however, is very small in that, for the example wavelength, the beam divergence angle after the parallel region is only .85 milliradians. Therefore even over large distances, the laser beam will maintain its integrity to a great degree. The calculation of the parallel region and the divergent region is not so important as the concept that the laser beam has the capability of maintaining a coherent parallel wave over long distances.

The application of laser radiation is quite varied. The construction industry has found great use for the helium neon (He-Ne) gas laser. Because of the culmination of the beam, the laser can be used to project a reference line for construction equipment in such operations as dredging, tunneling, and pipe laying. Figure 6.1.9 illustrates a typical procedure for laying a pipeline with the laser providing a reference beam.

Figure 6.1.9

CABLE INSTALLATION



Because of the high energy content of the laser beam, it has been used also for such things as welding and machining of fine parts. Also, because of their tremendous energy, lasers have a potential use in the drilling of tunnels through rock.

The laser beam can also be used to transmit communication signals. Theoretically, it will be possible for a laser to transmit as many messages as all communication channels now in existence. The major obstruction to the use of lasers in this application is the lack of the laser's ability to penetrate fog, rain, or snow.

Biological Effects. Because of the high power density outputs of the laser, the eye and the skin seem most vulnerable. Effect to the eyes depends on the type of laser beam; namely, the wavelength, output, power, beam divergence, and pulse repetition frequency created by the unit. Damage to the eye caused by the laser beam is extremely critical because the lens of the eye further focuses the laser beam on the fovea. This focusing by the lens of the eye increases the power density of the laser to several magnitudes greater than the actual laser beam output. The general effect of laser beam radiation is thermal in nature. It may cause heating of the retina and cornea, depending upon the wavelength. Laser radiation which operates in the visible light spectrum affects the retina and retinal pigment. However, because the eye is sensitive to visible radiation, high intensities of laser radiation in this region will stimulate the protective reflex of the eye and will prevent long durations of exposure. However, when the laser operates in the infrared or ultraviolet regions, the eye is not sensitive to these wavelengths and therefore no protective reflex will be stimulated. Therefore, damage may be greater. In general, it can be stated that damage to the eye in the form of retinal burns may occur if the beam power density is greater than 1 milliwatt/cm^2.

Threshold Limit Values

The threshold limit values are for exposure to laser radiation under conditions to which nearly all workers may be exposed without adverse effects. The values should be used as guides in the control of exposures and should not be regarded as fine lines between safe and dangerous levels. They are based on the best available information from experimental studies.

The threshold limit values presented in Tables 6.1.8 and 6.1.9 provide the TLV for exposures from a laser beam based upon wavelength for a specified exposure time.

The tables present TLV's for skin exposure, and a correction factor for eye exposure must be included. All TLV's in these tables can be used as given for the wavelengths 400 to 700 nanometers as being the TLV for eye exposure. At all wavelengths greater than 1.06 but less than 1.4 micrometers, the TLV's are to be increased by a factor of 5 for eye exposure. The TLV at wavelengths between

700 nanometers and 1.06 micrometers are to be increased by a uniformly extrapolated factor as shown in Figure 6.1.10. For certain exposure duration at wavelengths between 700 and 800 nanometers, correction factors C_a and C_b are indicated. These correction factors are based upon the wavelengths of interest, and the approximate correction factor is indicated in the table.

Table 6.1.8

THRESHOLD LIMIT VALUE FOR DIRECT OCULAR EXPOSURES (INTRABEAM VIEWING) FROM A LASER BEAM

Spectral Region	Wave Length	Exposure Time, (t) Seconds	TLV
UVC	200 nm to 280 nm	10^{-3} to 3×10^{4}	3 mJ • cm^{-2}
UVB	280 nm to 302 nm	"	3 "
	303 nm	"	4 "
	304 nm	"	6 "
	305 nm	"	10 "
	306 nm	"	16 "
	307 nm	"	25 "
	308 nm	"	40 "
	309 nm	"	63 "
	310 nm	"	100 "
	311 nm	"	160 "
	312 nm	"	250 "
	313 nm	"	400 "
	314 nm	"	630 "
	315 nm	"	1.0 J • cm^{-2}
UVA	315 nm to 400 nm	10 to 10^{3}	1.0 J • cm^{-2}
	" "	10^{3} to 3×10^{4}	1.0 mW • cm^{-2}
Light	400 nm to 700 nm	10^{-9} to 1.8×10^{-5}	5×10^{-7} • cm^{-2}
	" "	1.8×10^{-5} to 10	$\left[\frac{1.8\ t}{\sqrt[4]{t}}\right]$ mJ • cm^{-2}
	" "	10 to 10^{4}	10 mJ • cm^{-2}
	" "	10^{4} to 3×10^{4}	10^{-6} W • cm^{-2}
Infrared A	700 nm to 1.06 µm	10^{-9} to 18×10^{-5}	0.5 C_a µJ • cm^{-2}
"	700 nm to 1.06 µm	18×10^{-4} to 10	$(1.8t/\sqrt[4]{t})C_a$ mJ • cm^{-2}
"	700 nm to 1.06 µm	10 to 100	10 C_a mJ • cm^{-2}
"	1.06 µm to 1.4 µm	10^{-9} to 1.0×10^{-4}	5µJ • cm^{-2}
"	1.06 µm to 1.4 µm	1.0×10^{-4} to 10	$\left(\frac{9t}{\sqrt[4]{t}}\right)$ mJ • cm^{-2}
"	1.06µm to 1.4 µm	10 to 100	50 mJ • cm^{-2}
"	700 nm to 800 nm	100 to $\left(\frac{10^{4}}{C_a}\right)$	10 C_a mJ • cm^{-2}
"	700 nm to 800 nm	$\left(\frac{10^{4}}{C_b}\right)$ to 3×10^{4}	C_aC_b µW • cm^{-2}
Infrared B and C	1.4 µm to 10^{3} µm	10^{-9} to 10^{-7}	10^{-2} J • cm^{2}
	" "	10^{-7} to 10	0.56 $\sqrt[4]{t}$ J • cm^{-2}
"	" "	$10 \times 3 \times 10^{4}$	0.1 W • cm^{-2}

$C_a = e^{(\lambda - 700/224)}$

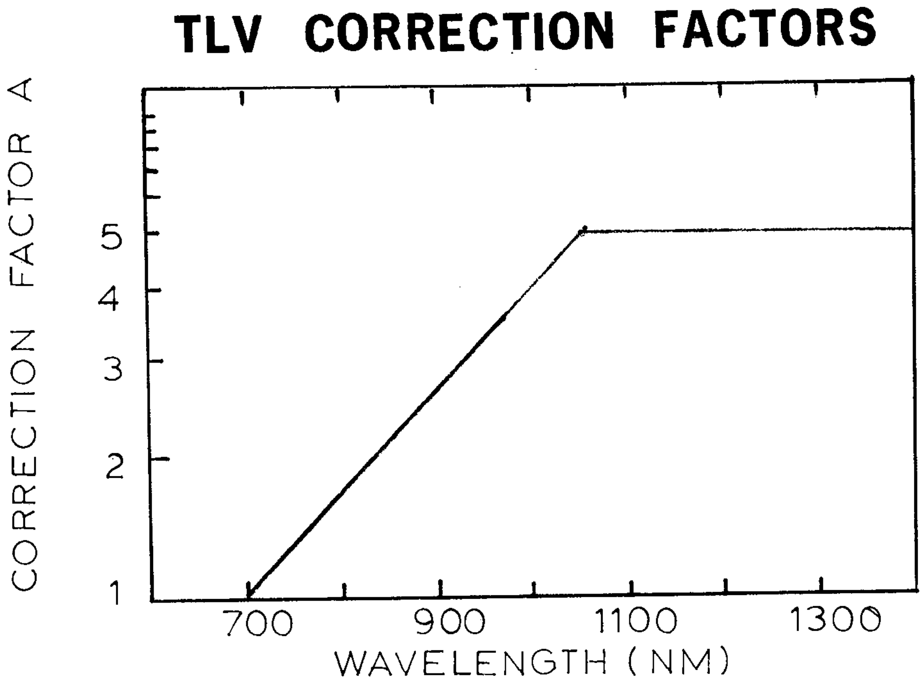
$C_b = (\lambda - 699)$

Table 6.1.9

THRESHOLD LIMIT VALUE FOR SKIN EXPOSURE FROM A LASER BEAM

Spectral Region	Wavelength	Exposure Time, (t) Seconds	TLV
UV	200 nm to 400 nm	10^{-3} to 3×10^{4}	Same as Table 6.1.8
Light and Infrared A	400 nm to 1400 nm	10^{-9} to 10^{-7}	2×10^{-2} J • cm^{-2}
"	" "	10^{-7} to 10	$1.1 \sqrt[4]{t}$ J • cm^{2}
"	" "	10 to 3×10^{4}	0.2W • cm^{-2}
Infrared B & C	1.4 µm to 1 mm	10^{-9} to 3×10^{4}	Same as Table 6.1.8

Figure 6.1.10



TLV CORRECTION FACTORS FOR LASER WAVELENGTHS (EYE)

In some instances, repetitive pulse lasers may of interest. The protection standards for irradiance or radiation exposure in multiple pulse trains have the following limitations:

1. The exposure from any single pulse in the train is limited to the protection standard for a single comparable pulse.
2. The average irradiance for a group of pulses is limited to the protection standards as outlined in the tables of a single pulse of the same duration as the entire pulse group. When the instantaneous pulse repetition frequency (PRF) of any pulse within the train exceeds 1, the protection standard applicable to each pulse is reduced as shown in Figure 6.1.11 for pulse durations less than 10^{-5} seconds. For pulses of greater duration, the following formula should be used:

$$\text{Standard (single pulse in train)} = \frac{\text{Standard (pulse NT)}}{N}$$

where

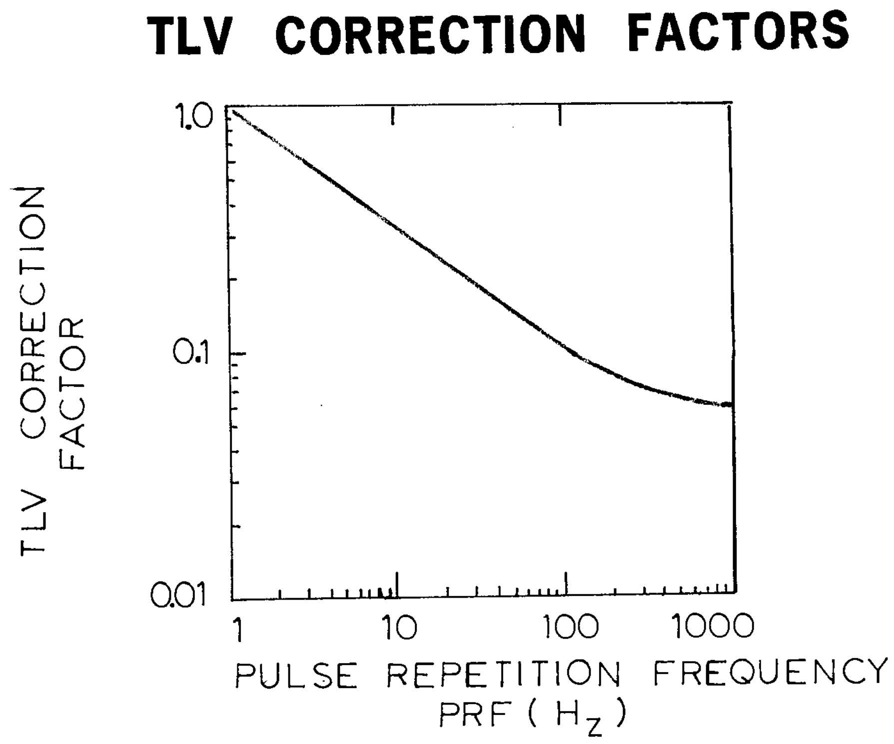
N = the number of pulses in the train

T = the duration of a single pulse in the train

Standard NT = protection standard of one pulse having a duration equal to NT seconds

In this manner, multi-pulse lasers may be evaluated with respect to the TLV.

Figure 6.1.11



Summary

In general, the discussion in this section has concerned the characteristics, sources, application, biological effects, and established threshold limit values for electromagnetic regions of the spectrum including ultraviolet, infrared, and radio frequency. The specific area of microwaves and lasers has also been discussed. Future sections will be devoted to the applications related to hazards and the control of these nonionizing radiations.

CHAPTER 2

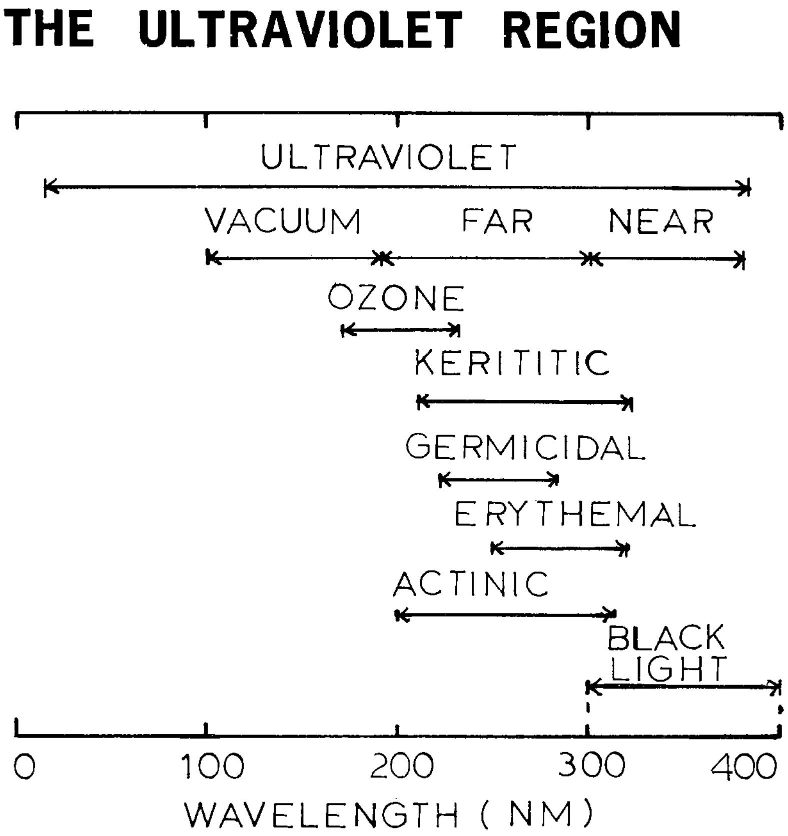
CONTROL OF NONIONIZING RADIATION

In this chapter, the recognition and control of ultraviolet radiation, microwave radiation, and lasers will be discussed. Because the measurement and control of the other types of electromagnetic radiation discussed in the previous chapter are similar to those for ultraviolet and microwave radiation, these specific types of radiation have been selected because of their common application in industry.

Ultraviolet Radiation

Ultraviolet radiation covers the range from 10 to 400 nanometers. This range has been divided into regions based upon their effect on man. Figure 6.2.1 illustrates these specific regions. For example, the keratitic region is those wavelengths that have the greatest effect upon the cornea. The erythemal region is those wavelengths that cause the pronounced skin reddening and blisters, and the actinic is the region (200-315 nanometers) that has a generally adverse effect on man.

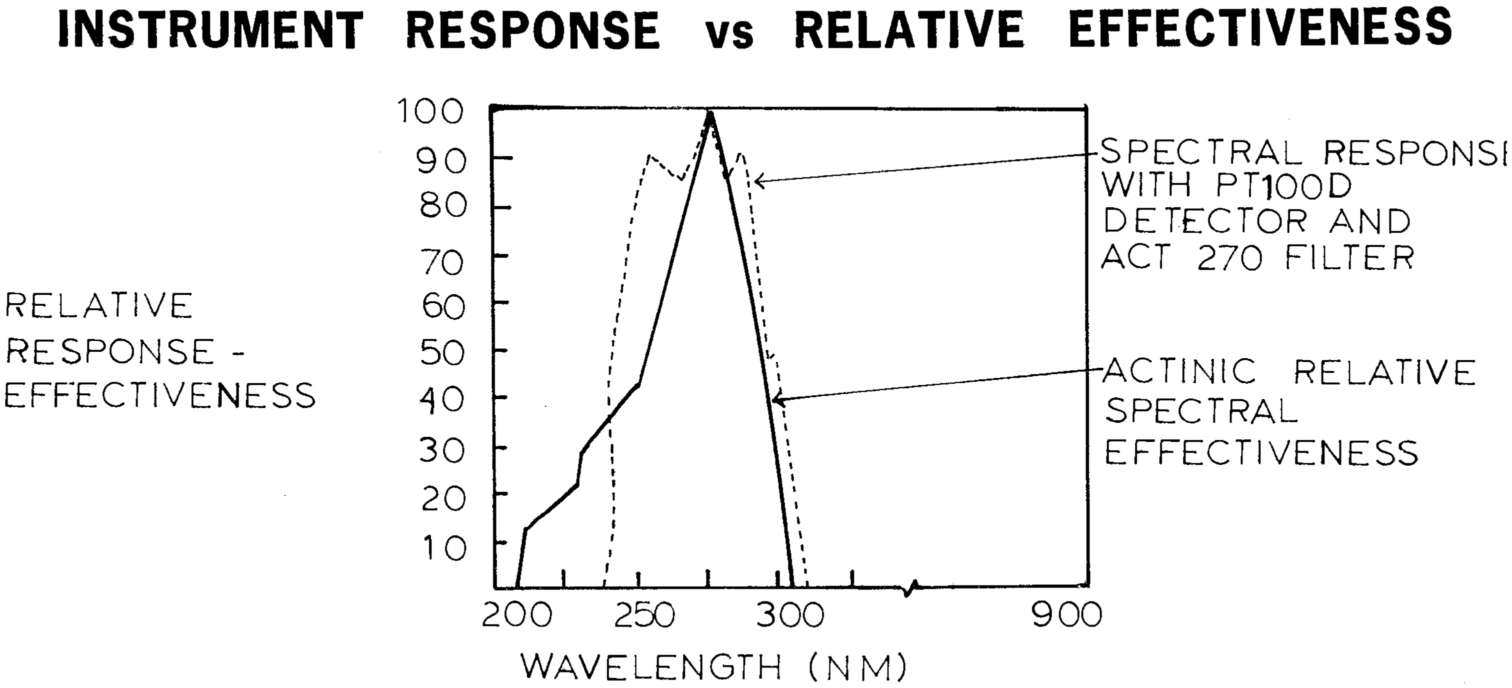
Figure 6.2.1



As discussed, the primary source of ultraviolet radiation is the sun. Industrial sources of ultraviolet radiation are from black light lamps, carbon arcs, welding arcs, high pressure mercury vapor, and low pressure mercury vapor sources.

When measuring ultraviolet radiation exposure, the measurements must reflect the relative effectiveness by wavelength of the ultraviolet radiation. This can be accomplished in two ways. First, a filtering system that mimics the actinic curve (Figure 6.2.2) will minimize the air and account for the relative effectiveness by wavelength.

Figure 6.2.2



The second procedure that can be used is, if the ultraviolet is a broad band source, it is possible to take measurements at specified wavelengths and then calculate the effective irradiance. This is done by measuring the specific band widths, then calculating the exposure for each, and finally adjusting according to the relative actinic spectral effectiveness. Once this is done, the sum of all exposures for all widths is calculated. The formula is as follows:

$$E_{eff} = \Sigma E_{\lambda} S_{\lambda} \Delta\lambda$$

where

E_{eff} = effective irradiance (W/cm^2)
E_{λ} = spectral irradiance ($W/cm^2/nm$)
S_{λ} = relative actinic spectral effectiveness (Value taken from Table 6.1.3)
$\Delta\lambda$ = band width (nm)

To date, broad based measuring devices for measurement of ultraviolet energy are not readily available. However, devices for measuring specific wavelengths are available. The two major classes of detectors are based upon the interaction of the ultraviolet radiation with the detector; namely, photon and thermal. Photoelectric monitoring devices use a phototube and photomultiplier to monitor ultraviolet radiation. When the ultraviolet radiation interacts with the metal target of the phototube, electrons are ejected and counted on the photomultiplier. The number of electrons ejected is proportional to the ultraviolet radiation present.

Photovoltaic measuring devices work on the principle of the production of a voltage difference in the device caused by ultraviolet absorption. The devices are usually semi-conductors, such as selenium photocells or silicon solar cells. Each of these devices is of value in that special consideration can be given to the type of target used, in that various metals have different reactive capabilities with various wavelengths of ultraviolet radiation.

One particularly useful device for measuring ultraviolet radiation is the thermopile. This device operates on the principle of the production of voltage by increased temperature caused by ultraviolet absorption. The change in voltage is proportional to ultraviolet radiation.

Since available photocells and filter combinations do not always closely approximate the ultraviolet biological action spectrum (Figure 6.2.2), it is necessary to calibrate each photocell and meter upon the specific use. Special care must be taken to control the ambient conditions during the calibration process. Filtering combinations may also allow for the discrimination of wavelengths. This discrimination is necessary because of the variation in effect of the various wavelengths of ultraviolet radiation.

Some instruments used will read the power density (W/m^2) directly, while others may give readings that require conversion to a power density value by a calibration factor. This calibration factor is instrument dependent and is supplied by the manufacturer, if necessary. Then, given the distance from the source of the reading and the average time of personnel exposure, exposure can be calculated and then compared to the threshold limit value. For example, using a photometer a reading of 0.5 microamps is taken at 90 cm. (90 cm is the mean body/eye distance of the worker.) If the worker is exposed to the radiation for approximately 15 minutes per 8-hour shift, is the TLV exceeded? (Assume the calibration factor = 90.6 microwatts/cm^2/μamp and the filters corrected to 270 nm.)

Solution

$$0.5 \text{ μamps} \times 90.6 \text{ μW/cm}^2/\text{μamp} = 45.3 \text{ μW/cm}^2$$

$$\frac{45.3 \text{ μJ}}{\text{sec-cm}^2} \times \frac{15 \text{ min}}{8 \text{ hr}} \times \frac{60 \text{ sec}}{\text{min}} = \frac{40.77 \text{ mJ}}{\text{cm}^2\text{-8 hr}}$$

$$\text{TLV} = 3.0 \text{ mJ/cm}^2 \text{ for 8 hr day}$$

$\therefore$ TLV exceeded

Extending this example further, what is the maximum exposure time per 8-hour period that the employee could work in this environment at the specified distance? The solution to this problem may be found by dividing the TLV, 3.0 mJ/cm^2, by the actual exposure rate, or 45.3 mJ/cm^2/sec. The calculation would be:

$$\frac{3.0 \text{ mJ}}{\text{cm}^2} \times \frac{\text{sec-cm}^2}{45.3 \times 10^{-3} \text{ mJ}} = 66.2 \text{ sec}$$

As previously mentioned, readings can be taken for specified band widths of ultraviolet radiation and then the effective irradiance calculated. The following example illustrates this procedure:

Example

Assume that the following exposure readings have been obtained. Is the TLV being exceeded if the average exposure is 30 minutes per 8-hour day?

Wavelength (nm)	Reading (μW/cm^2)
200	0.081
220	0.091
240	0.18
260	0.18
280	0.27
300	0.36

Solution

$$E_{eff} = \Sigma E_{\lambda} S_{\lambda} \Delta\lambda$$

$$E_{200} = \frac{0.08\ \mu W}{cm^2} \times \frac{0.03}{mm} \times 20\ nm \quad = 0.048\ \mu W/cm^2$$

$$E_{220} = \qquad = 0.216$$

$$E_{240} = \qquad = 1.080$$

$$E_{260} = \qquad = 2.340$$

$$E_{280} = \qquad = 4.752$$

$$E_{300} = \qquad = \underline{\ 2.160\ }$$

$$10.596\ \mu W/cm^2$$

Using the TLV table (Table 6.1.3), TLV = 1.7 $\mu W/cm^2$. Therefore, the exposure is 6.2 times the permissible level at the distance of the measurements.

When taking measurements for ultraviolet radiation exposure, certain factors must be considered to avoid errors of major magnitude. First, the monitoring instrument must match the spectral output of the ultraviolet radiation source. Further, the spectral output and measurement must be compared to the relative spectral efficiency as previously described. Second, certain types of devices require periodic calibration for the specified ultraviolet source. Solarization or aging of the lenses, especially with long usages or following measurements of high intensity ultraviolet radiation, causes shifts in the instrumentation. Third, atmospheric conditions must be considered. Water vapor in the atmosphere will reduce the readings of ultraviolet radiation by absorbing the ultraviolet radiation. Although there is no specific calibration or correction factor for atmospheric conditions, this must be considered when taking measurements. Fourth, the meters and probes used are directional, and it is necessary to insure that measurements are taken in all directions. Fifth, readings can be affected by the reflection of ultraviolet radiation from nearby sources or by high intensity visible light. Because of this, efforts must be made to reduce the presence of visible light and potential reflection of ultraviolet radiation when taking readings. Finally, readings should be taken at the approximate distance from the source that the personnel would be exposed. This is because of the "inverse square law" where the exposure rate is reduced by $1/\text{distance}^2$.

Personnel Protection. When protecting personnel against ultraviolet radiation, the primary concern is exposure to the skin and eyes. There are basically three protective tools that can be used: time, distance, and shielding.

The use of time as a protective tool is rather self-explanatory. By decreasing the time of exposure, the total exposure to the personnel is decreased. Therefore, when analyzing any potential ultraviolet radiation hazard, it is important to know the time of exposure per given workday or per week to calculate potential personnel exposure. In many instances, the analysis of the task being performed may indicate procedural changes which would reduce the exposure time to the personnel.

The second tool that may be used is distance. The intensity of the radiation is decreased by the square of the change in distance (inverse square law). For example, if a reading of 15 $\mu W/cm^2$ is taken at 1 meter, the reading would then be expected to be 3.75 $\mu W/cm^2$ at 2 meters or $15/2^2$. If one were interested in the reading at 3 meters, then the expected reading would be $15/3^2$ or 1.66 $\mu W/cm^2$. The distance may not be an important factor because of the type of work involved. For example, it would be difficult for a welder to be moved a greater distance from the potential source because it is necessary for him to be close to perform the welding. When working with distance as a tool, two factors must be considered. First, all measurements should be taken at the distance that approximates the worker distance. If, for example, the hands are normally closer to the ultraviolet source, measurements should be taken at various distances for hands and mean body distance. Second, efforts should be made to maximize the distance and thus minimize the exposure to personnel between the personnel and the ultraviolet source. This may be done through the use of tongs to handle materials, automation, etc.

Shielding. The use of shielding is a procedure whereby the exposure to the personnel is reduced by placing an absorbing material between the personnel and the ultraviolet source. With ultraviolet radiation, this can be done using three types of shielding--enclosures, protective clothing, and eye protection.

Enclosures minimize the exposure to persons working directly with an ultraviolet source and also to personnel in the vicinity of the ultraviolet source. The selection of enclosure material is dependent upon the wavelength and the properties of the wavelength involved; e.g., reflectance and absorption characteristics. For example, clear glass is opaque to ultraviolet radiation, yet transparent to visible light; while a red opaque filter is opaque to visible light, yet transparent to an ultraviolet source. Any area that includes an enclosure should be adequately marked and labeled as a radiation area.

Protective clothing can be worn to minimize ultraviolet exposure. In almost all instances, heavy clothing will absorb the ultraviolet radiation before it reaches the personnel. Examples of protective clothing are things such as gloves, coats, overalls, and face shields. Again, the type of clothing to be worn is dependent upon the radiation source and the type of radiation being emitted. In all instances, however, dark clothing should be worn to avoid the reflectance of the radiation.

Protective eye shields are commonly used to shield the eyes against radiant energy. The selection of filters is based upon the type, wavelength, and intensity of the radiation to be attenuated. Various filters transmit differently for different wavelengths. Table 6.2.1 illustrates the various types of filters that can be used for ultraviolet and infrared radiation, while Table 6.2.2 presents recommended filter lens for welding. Emphasis should be placed on the fact that most ultraviolet sources are broad band sources and that each band must be analyzed for the selection of proper filtering. In many instances, the filtering selected for a given wavelength may be inadequate for other wavelengths which are present.

Table 6.2.1

TRANSMITTANCES AND TOLERANCES IN TRANSMITTANCE OF VARIOUS SHADES OF FILTER LENSES

Shade No.	*Optical Density*			*Luminous Transmittance*			*Maximum Infrared Transmittance*	*Maximum Spectral Transmittance in the Ultraviolet and Violet for Four Wavelengths (millimicrons)*			
	Min.	*Std.*	*Max.*	*Max.*	*Std.*	*Min.*		*313*	*334*	*365*	*405*
				per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent
1.5	0.17	0.214	0.26	67	61.1	55	25	0.2	0.8	25	65
1.7	0.26	0.300	0.36	55	50.1	43	20	0.2	0.7	20	50
2.0	0.36	0.429	0.54	43	37.3	29	15	0.2	0.5	14	35
2.5	0.54	0.643	0.75	29	22.8	18.0	12	0.2	0.3	5	15
3.0	0.75	0.857	1.07	18.0	13.9	8.50	9.0	0.2	0.2	0.5	6
4.0	1.07	1.286	1.50	8.50	5.18	3.16	5.0	0.2	0.2	0.5	1.0
5.0	1.50	1.714	1.93	3.16	1.93	1.18	2.5	0.2	0.2	0.2	0.5
6.0	1.93	2.143	2.36	1.18	0.72	0.44	1.5	0.1	0.1	0.1	0.5
7.0	2.36	2.571	2.79	0.44	0.27	0.164	1.3	0.1	0.1	0.1	0.5
8.0	2.79	3.000	3.21	0.164	0.100	0.061	1.0	0.1	0.1	0.1	0.5
9.0	3.21	3.429	3.64	0.061	0.037	0.023	0.8	0.1	0.1	0.1	0.5
10.0	3.64	3.857	4.07	0.023	0.0139	0.0085	0.6	0.1	0.1	0.1	0.5
11.0	4.07	4.286	4.50	0.0085	0.0052	0.0032	0.5	0.05	0.05	0.05	0.1
12.0	4.50	4.714	4.93	0.0032	0.0019	0.0012	0.5	0.05	0.05	0.05	0.1
13.0	4.93	5.143	5.36	0.0012	0.00072	0.00044	0.4	0.05	0.05	0.05	0.1
14.0	5.36	5.571	5.79	0.0004	0.00027	0.00016	0.3	0.05	0.05	0.05	0.1

NOTE: The values given apply to class I filter glass. For class II filter lenses, the transmittances and tolerances are the same, with the additional requirement that the transmittance of 589.3 millimicrons shall not exceed 15 per cent of the luminous transmittance. Some of the headings in this table have been changed to conform with NBS Letter Circular LC857.

Spectral-Transmissive Properties and Use of Eye-Protective Glasses. *Reprinted from National Bureau of Standards, Circular 471, 1948.*

Table 6.2.2

FILTER LENS SHADE NUMBERS FOR VARIOUS WELDING AND CUTTING OPERATIONS (WELDER AND HELPERS)

Type of Operation	Recommended Shade Number
Resistance welding, and for protection against stray light from nearby welding and cutting (if persons are out of the danger zone)	Clear or filters up to No. 2
Torch brazing or soldering	3 to 4
Light oxygen cutting and gas welding (to 1/8 in)	4 or 5
Oxygen cutting, medium gas welding (1/8 to 1/2 in) and arc welding up to 30 amps	5 or 6
Heavy gas welding (over 1/2 in) and arc welding and cutting from 30 to 75 amps	6 or 8
Arc welding and cutting from 75 to 200 amps	10
Arc welding and cutting from 200 to 400 amps	12
Arc welding and cutting exceeding 400 amps	14

Note: Flash goggles should be worn under all arc-welding helmets, particularly for gas-shielded metal arc welding.

Adapted from <u>*Welding Handbook*</u>*, 5th ed, American Welding Society*

When evaluating an ultraviolet radiation source for hazards, associated nonradiation hazards must also be considered. First, instruments producing ultraviolet radiation may require high voltage for operation; thus, a possible electrical hazard. Further, the presence of high voltage may also precipitate the extraneous production of X-radiation (discussed in Chapter 3). Second, the ultraviolet radiation reacts with oxygen in the atmosphere to produce ozone (TLV O_3 = 0.1 ppm) which is an extremely toxic substance. Therefore, it is necessary to maintain adequate ventilation in areas where ultraviolet radiation is present. Ultraviolet radiation also reduces chlorinated hydrocarbons (trichloroethylene) to toxic substances. The ultraviolet radiation may also cause the formation of nitrogen oxides. Further, heating processes which form ultraviolet radiation may also form toxic fumes if the procedures involve base metals including elements such as zinc, fluorine, beryllium, lead, and cadmium. Because of this, efforts must be made to analyze materials that are involved in the procedure and chemicals that may be found in the work environment. Every effort should be made to minimize or eliminate potentially toxic substances from the working area. This can be done by evaluating the location of the ultraviolet source and also by providing adequate ventilation systems.

When surveying an area for ultraviolet radiation exposure, a diagram of the area should be prepared indicating:

1. The ultraviolet radiation source.
2. Personnel location.
3. Protective devices presently in use; e.g., signs, screens, ventilation systems.
4. Potential nonradiation hazards--location of ultraviolet source near degreasing area, lack of ventilation system.

When surveying an area, the sample form found in Figure 6.2.3 can be used as a basis for the survey.

Figure 6.2.3

ULTRAVIOLET RADIATION SURVEY

GENERAL INFORMATION

USING ORGANIZATION	ADDRESS
TYPE OF EQUIPMENT	INTENDED USAGE

MANUFACTURE	MODEL	SERIAL NUMBER	OTHER

WELDER ONLY	GAS	CURRENT	VOLTAGE	FILLER	MATERIAL	DUTY CYCLE

HAZARD DETERMINATION

MONITORING INSTRUMENT	PROBE	FILTER

ATTACHMENT

WAVELENGTH OR WAVELENGTH RANGE

DISTANCE TO SOURCE (METERS	D/R	KEY	INSTRUMENT READING ($\mu W/cm^2$)	EXPOSURE TIME 8/HR	EXPOSURE/DAY (3×10^{-3} J/cm^2) IRRADIANCE

ENVIRONMENT

PERSONNEL

BACKGROUND
SAFETY TRAINING
UNAWARE ONLOOKER
OTHER

PERSONAL PROTECTION

IN USE

SIGNS	SKIN CREAM	PARTITIONS
EYE PROTECTION	CLOTHING	OTHER
RESTRICTED AREA	CURTAINS	
GLOVES	ENCLOSURES	

RECOM-MENDED

SURVEYED BY

DATE

Although the form is specifically defined for use with a specific measurement device, the information to be collected on the form provides an adequate summary of the information needed to evaluate an ultraviolet radiation source. A summary of the components of the form is as follows:

1. USING ORGANIZATION--Company or division responsible for the ultraviolet source.
2. ADDRESS--Self-explanatory.
3. TYPE OF EQUIPMENT--Ultraviolet radiation source; e.g., welder, germicidal lamp, xenon lamp.
4. INTENDED USE--Purpose of the source; e.g., research, construction, material testing, etc.
5. MANUFACTURER--Model, serial number, and identification specifications of the ultraviolet source.
6. WELDER ONLY--Refers to the operating parameters if a welder is used.
    a. GAS--List gases used for welding operation.
    b. VOLTAGE/CURRENT--If electric welder is used.
    c. FILLER--Welding rods and material used.
    d. MATERIAL--Material being welded, including coating.
7. DUTY CYCLE--Operation time in 8-hour shift of any ultraviolet radiation source.
8. MONITORING INSTRUMENT--Device used to monitor ultraviolet source.
9. PROBE--Detector used.
10. FILTER--Type of filtering system used.
11. ATTACHMENTS--Attenuator, screen, beam splitters, etc.
12. WAVELENGTH RANGE--Sensitivity range of the monitoring system.
13. DISTANCE FROM SOURCE--Distance from measuring point to source.
14. D/R--Whether it is a direct or reflected reading.
15. KEY--Key location in diagram developed.
16. INSTRUMENT READING
17. EXPOSURE TIME--Average exposure per 8-hr day to exposure measured.
18. EXPOSURE/DAY
19. ENVIRONMENT--A drawing of the potential exposure area including ultraviolet radiation source, point of measurement, personnel location (time of exposure per day), nonradiation hazards, and protection devices.

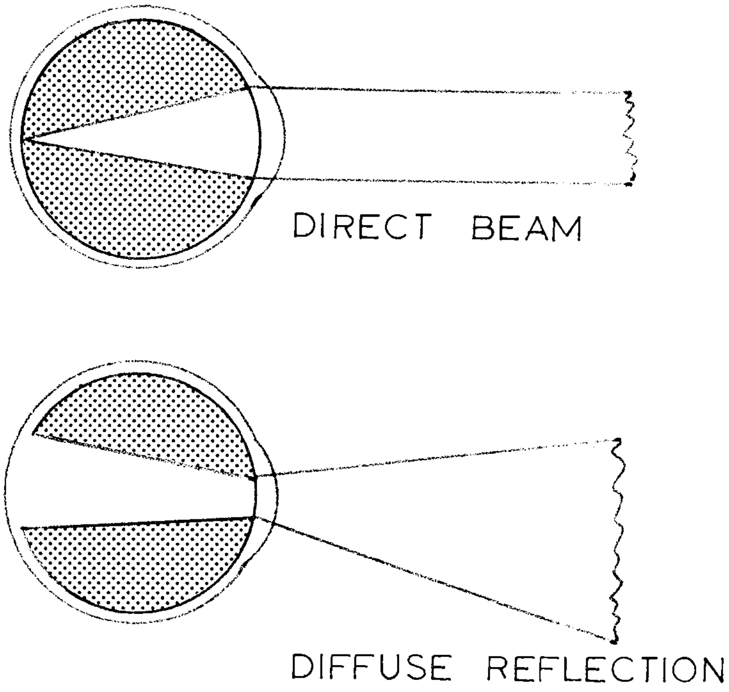
20. PERSONNEL--The type of personnel usually involved in the area of the ultraviolet source, their location, and exposure time per day should be recorded.
21. PERSONNEL PROTECTION--Existing protection devices which are presently being used and any recommended protection devices that could be added including such things as painting the walls to reduce reflection.
22. SURVEY BY/DATE--The signature and date of the surveyor conducting the analysis.

Lasers

Lasers provide a unique hazard because of the high concentration of energy that can be placed on a point target. As with ultraviolet radiation, the primary concern is with exposure to the skin and eyes. The eyes present an interesting problem in that the already concentrated ray of energy may be even more concentrated by the focusing capability of the lens of the eye, as presented in Figure 6.2.4. Part A of the figure illustrates parallel rays of a laser being focused to a point image by the eye. Part B illustrates rays from an extended source (as from a conventional lamp or rays from a diffuse reflection of a laser beam) produce a sizable (and less dangerous) image at the retina. Therefore, threshold limit values have been established for the eye and the skin.

Figure 6.2.4

OBSERVING LASER LIGHT



The requirements for periodic analysis and measurement of laser beams is minimized because of the accuracy of the manufacturers' specifications and design and engineering, the problems and complexity of radiometric measurement techniques, and, in general, the high cost of detectors. It is possible, however, to calculate the beam intensity (I-J/cm^2) at a selected range. To do this, the power output (E-Watts), the range of interest (r-cm), beam divergency (ϕ-radians), and initial beam diameter (a-cm) must be known. To calculate the beam intensity, the following formula is used:

$$I = \frac{Ee^{-ur}}{[\pi/4(a + r\ )]^2}$$

Note: e^{-ur} where r is the range of interest and u is an atmospheric attenuation factor (cm^{-1}) relates to atmospheric attenuation and can be ignored if the range is less than 10 kilometers.

Example

A typical laser has an initial beam diameter of 2.54 cm, power output of 5 mW, and a beam divergence of 0.1 mrad (10^{-4} rad). What is the beam intensity at 60 cm?

Solution

$$I = \frac{E}{[\pi/4(a + r\phi)]^2}$$

$$I = \frac{5.0 \times 10^{-3} W}{[(\pi/4)(2.54 + 60(10^{-4}))]^2}$$

$$= 1.25 \times 10^{-3} \ W/cm^2$$

$$= 1.25 \ mW/cm^2 \text{ at } 60 \text{ cm}$$

The calculation may then be further carried out to determine if the TLV level is exceeded if the wavelength and typical exposure time are known. If it is assumed that this particular laser beam operates at 312 nm and a typical exposure is for 1 minute, then the exposure may be found to be:

$\text{TLV} = 250\ \text{mJ/cm}^2$

$$\frac{250\ \text{mJ}}{\text{cm}^2} \times \frac{\text{sec-cm}^2}{1.25\ \text{mJ}} = 200\ \text{seconds}$$

$60\ \text{sec} < 200\ \text{sec}$

$\therefore$ TLV not exceeded

By using the same equation, (a) substituting the threshold limit value per unit time and (b) solving for time, it is possible to calculate the maximum viewing time at a given distance.

$$I = \frac{E}{\left[(\pi/4)(a + r\phi)\right]^2}$$

$$I = \frac{J}{\text{sec-cm}^2} \qquad \text{Assume } I_t = \text{TLV}$$

$$I = \frac{I_t}{t} \quad \text{where } t = \text{time (sec)}$$

$$\frac{I_t}{t} = \frac{E}{\left[(\pi/4)(a + r\phi)\right]^2}$$

$$t = (I_t/E)\left[(\pi/4)(a + r\phi)\right]^2$$

Further, if the equation is rearranged to solve for r, a minimum safe viewing distance can be calculated for a given exposure time.

$$t = (I_t/E)\left[(\pi/4)(a + r\phi)\right]^2$$

$$\frac{E}{I_t \cdot t} = \left((\pi/4)(a + r\phi)\right)^2$$

$$\left(\frac{E}{I_t \cdot t}\right)^{\frac{1}{2}} \times \left(\frac{4}{\pi}\right) = a + r\phi$$

$$r = \frac{\left[\left(\frac{E \cdot t}{I_t}\right)^{\frac{1}{2}} \cdot \frac{4}{\pi}\right] - a}{\phi}$$

To use any of the formulas, it is necessary to know the operational wavelength of the laser, the TLV, and the average viewing time or distance.

Example

A typical laser operating at 312 nm has an initial beam diameter of 1.5 cm, a power output of 2.25 mW, and a beam divergence of 0.1 milliradians. Calculate:

A. Maximum direct viewing time for an 8-hour period if the average viewing distance is 50 cm.

B. Minimum viewing distance if the average viewing time is 3 minutes per 8-hour period.

$\mathrm{TLV}_{312\ \mathrm{nm}} = 250\ \mathrm{mJ/cm^2/8\ hr}$

Solution

A. $t = (I_t/E)\left[(\pi/4)(a + r\phi)\right]^2$

$I_t = 250\ \mathrm{mJ/cm^2}$

$E = 2.25\ \mathrm{mW}$

$a = 1.5\ \mathrm{cm}$

$r = 50\ \mathrm{cm}$

$\phi = 10^{-4}$ radians

$$t = \frac{250\ \mathrm{mJ}}{\mathrm{cm^2}} \cdot \frac{\mathrm{sec}}{2.25\ \mathrm{mJ}} \quad \frac{\pi}{4} \quad 1.5\ \mathrm{cm} + 50\ \mathrm{cm}\ (10^{-4}) \quad {}^{2}$$

$= 155.2\ \mathrm{sec} = 2.59$ minutes

B.

$$r = \frac{\left[\left(\frac{E \cdot t}{I_t}\right)^{\frac{1}{2}} \cdot \frac{4}{\pi}\right] - a}{\phi} \qquad I = I_t$$

$I_t = 250\ \mathrm{mJ/cm^2}$

$E = 2.25\ \mathrm{mW}$

$a = 1.5\ \mathrm{cm}$

$t = 180\ \mathrm{sec}$

$\phi = 10^{-4}$ radians

$$r = \frac{\left[\left(\frac{2.25\text{ mJ}}{\text{sec}} \cdot \frac{\text{cm}^2}{250\text{ mJ}} \cdot 180\text{ sec}\right)^{0.5} \cdot \frac{4}{\pi}\right] - 1.5\text{ cm}}{10^{-4}}$$

$$r = \frac{(1.27\text{ cm} \cdot 4/\pi) - 1.5\text{ cm}}{10^{-4}} = \frac{1.62 - 1.5\text{ cm}}{10^{-4}} = 1200\text{ cm}$$

This example illustrates the importance of properly controlling laser operation. If the direct viewing time is increased by 25 seconds (180 sec - 155 sec), the safe viewing distance varies from 50 cm to 1206 cm; a 24-fold increase.

A variety of detectors may be used to monitor laser intensity. These detectors are selected based upon the laser wavelength, pulse duration, and power intensities generated by the lasers. Generally, the two categories of laser detectors are thermal and photon. The photon devices operate on the principle of measuring the rate at which light quanta are absorbed. Examples of this type of detector are the photoelectric, photoconductive, and photovoltaic monitoring devices. Thermal devices measure the effect of heat and temperature change on a material when absorbing light energy. Examples of this type of device include the calorimeter, bolometer, thermocouple, and thermopile.

Average power measurements of continuous wave laser systems are usually made with the conventional thermopile of photovoltaic cell. A typical thermopile will detect signals in the power range of from 10 mW to 100 mW. Many calorimeters and virtually all photographic methods measure total energy, but they can also be used for measuring power if the time history of the radiation is known.

When measuring laser intensities, the aperture stop of the device should closely approximate a pupil opening or 7 mm in distance. Calibration of the detector is required based upon the type of laser and wavelength involved. The spectral response of measurement devices should always be specified since the ultimate use of the measurements is the correlation with the spectral response of the biological tissue receiving the radiation insult.

The control of laser hazards is based primarily upon educating operating personnel, providing warnings to unsuspecting persons in the laser area, and general engineering designs that minimize hazards. For purposes of discussion, lasers have been classified based upon their potential hazard as identified in Table 6.2.3.

Table 6.2.3

NIOSH LASER CLASSIFICATION GUIDE

Class	Potential Hazard
I	Incapable of creating biological damage.
II	Low-power--Beam may be viewed directly under carefully controlled conditions.
III	Medium power--Beam cannot be viewed.
IV	High power--Direct and diffusely reflected beam cannot be viewed or touch the skin.
V	Class II, III, IV which are completely enclosed so no radiation can leak out.

General operating requirements have also been established for each of the classes. Generally, a protective housing and interlock system which prevents human access during operation must be included as part of the laser design. Classes III and IV must have a key-activated master control which prevents the laser from being operated unless the key-activated switch is used. Classes II, III, and IV must give some type of visible or audible indication when the laser is emitting. Further, Classes II, III, and IV must have controls which are located outside the beam area. Finally, the viewing optics used in any laser system must reduce emission to below the threshold limit value. More specific requirements by classes are presented in Figure 6.2.5.

Figure 6.2.5

SPECIAL REQUIREMENTS BY CLASS

Class of Laser			
I	II	III	IV
No requirement	Posting of signs in area Control of beam direction	Well-controlled area No specular surfaces Terminate beam with diffuse material and minimum reflection Eye protection for direct beam viewing	Restricted entry to facility--interlock Fail-safe system Alarm system Panic button Good illumination--150 footcandles Light-colored diffuse room surfaces Operated by remote control Designed to reduce fire hazard, build-up of fumes, etc.

Aside from the aforementioned guidelines, the following guidelines are presented for consideration when developing a laser facility.

1. The laser should be attended at all times during operation.
2. Only personnel educated in the operation of the laser and in potential hazards should be permitted in the laser area.
3. Noninstructed personnel should <u>not</u> be permitted in the laser area.
4. Laser equipment and the laser area should be properly posted.
5. Direct viewing of the laser should not be done using binoculars or telescopes.
6. The laser should not be aimed at occupied areas without appropriate shielding.
7. Methods of confining laser plumes and laser-induced vaporization should be used.

8. Nonreflecting surfaces should surround the laser area.
9. Any laser beam that must pass through glass should pass through perpendicularly to minimize the amount of beam reflectance.
10. The maximum range of the beam direction should be controlled and minimized to within the shielded area.
11. Combustible solvents and materials should be stored away from the laser.
12. Potential nonlaser hazards should be evaluated, including
    a. Voltage sources and leads
    b. X-radiation from high voltage sources
    c. Ozone generation from high voltage sources and ultraviolet radiation
    d. Ungrounded electrical equipment, including laser heads and work stations
    e. Toxic materials
    f. Combustible materials
    g. Chemically active materials
    h. Cryogenic fluids
    i. Inert purging gases
    j. Flash-lamp explosion
    k. Radiation other than laser beam
    l. Violent interactions during the interactions of the laser radiation and materials; e.g., explosions, fires, chemical reactions, brilliant plumes
    m. Mechanical failures
    n. Interlock failures
    o. Accidental discharging of the laser
    p. Invisibility of ultraviolet and infrared laser beams
    q. Potential human fallibility
13. Protective eyewear should be provided in any instance where the potential exposure is above 1 $\mu W/cm^2$.
14. Periodic (annual) medical examinations, including eye examination, should be performed on all personnel working with or near the laser.

Eye protection should be provided whenever exposure levels may exceed 1 $\mu W/cm^2$. The protective eyewear should prevent direct observation of the beam and also observation of the reflected beam; that is, side panels should be used. The protective eyewear should also be made of curved lens material such that the beam may not be reflected off the eyewear. Protective eyewear is developed based upon the wavelength of the laser beam, the optical density necessary to reduce the intensity of the beam to an acceptable level, the potential maximum output of the laser beam, the visible transmittance of the filtering system, and the filter damage threshold; i.e., level at which the filter is damaged by high energy lasers.

Generally, protective eyewear for lasers is based upon two concepts. First, the use of filters for absorption of specific spectral regions and second, selective reflection from a dielectric coating of a given percent of the beam. Figure 6.2.6 illustrates the method of construction of the eyewear using the dielectric coating procedure.

Figure 6.2.6

EYEWEAR CONSTRUCTION

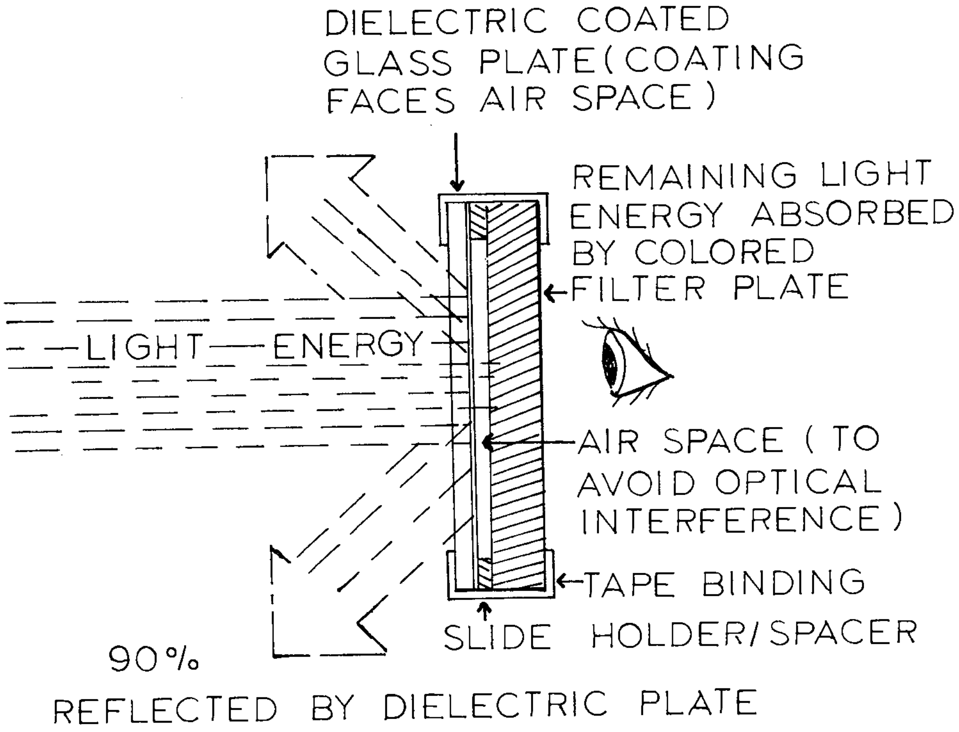


Table 6.2.4 illustrates typical laser eye protection goggles based upon the manufacturers' information. As can be seen, the appropriate eyewear is based upon the various factors previously described; e.g., wavelength, visible light transmission, and optical density.

Table 6.2.4

Laser Eye Protection Goggles
Based on Manufacturers' Information†

$$\text{OPTICAL DENSITY} = \log_{10} \frac{1}{\text{Transmittance}}$$

Manufacturer or Supplier	Catalogue Number	Argon 4880 Å	HeNe 6328 Å	Ruby 6943 Å	GaAs 8400 Å	Nd 10600 Å	CO_2 10.6 μ	UV <4000 Å >3000 Å	Coated Filter	Approx. Cost $	No. of glass filters & thickness of each	Visible Light transmission	Useful Range Å
American Optical Co.	SCS—437,*	0.15	0.20	0.36	1	5	High	No	No	55	1, 3.5 mm	90 %	10600
	SCS—440												10600
	580, 586*	0.2	2	3.5	4	2.7	—	>0.2	No	35, 25*	1, 3.5 mm	27.5%	—
	581, 587*	0.6	4.1	6.1	5.5	3	—	>1.6	No	35, 25*	1, 3.5 mm	9.6%	6328
	584	0	1	5	13	11	High	>0.6	No	55	2, 2 mm	46 %	10600
	585	0.3	2	8	21	17	High	>0.6	No	55	2, 2 mm	35 %	6943-10600
	598*	13	0	0	0	—	—	>14	No	25*	1, 3 mm	23.7%	4550-5150
	599	11	0	0	0	—	—	>14	No	35	1, 2.5 mm	24.7%	4550-5150
	680	0	0	0	0	0	50	No	No	35	1, 2.7 mm	92 %	10600
	698	13	1	4	11	8.5	High	>14	No	55	2, 2&3mm	5 %	10600 and 5300
Bausch & Lomb	5W3754	15	0.2	0	0	0	>35	20	Yes	39	1, 7.9 mm	4.3%	3300-5300
	5W3755	4	0	0	0	0.1	>35	10	Yes	39	1, 7.9 mm	57 %	4000-4600
	5W3756	0.8	12	15	5.6	4.8	>35	3	Yes	39	1, 6.4 mm	6.2%	6000-8000
	5W3757	0.9	4.5	7.7	12	5.7	>35	2	Yes	39	1, 7.1 mm	4.7%	7000-10000
	5W3758	1.9	1.8	2.2	4.8	7.5	>35	2	Yes	39	1, 7.6 mm	3 %	10000-11500
Control Data Corp.	TRG-112-1	—	5	12	30	30	—	No	No	50	1, 6 mm	22 %	6943
	TRG-112-2	10	0	0	0	0	—	No	No	50	1, 6 mm	31 %	4880
	TRG-112-3	5	2	6	15	15	—	No	No	50	2, 3 mm	5 %	6943-4880
	TRG-112-4	—	—	—	—	—	High	No	No	50	1, 5 mm	92 %	106000
Fish-Schurman Corp.	FS650AL/18	0.34	3.8	10	>10	>10	—	No	No	30	1, 6 mm	30 %	6943, 8400, 106000
Glendale Optical Co.	NDGA**	1	0.5	2	16	16	High	>20	No	25	Plastic	60 %	8400, 10600
	R**	0.4	2.2	6.3	0.4	0.0	High	5	No	25	Plastic	19 %	6943
	NH**	0.4	5	2.5	0.6	0.5	High	>10	No	25	Plastic	19 %	6328
	A**	15	0	0	0	0	High	>12	No	25	Plastic	59 %	4880, 5143
	NN**	0	0	0	0	0	High	>12	No	25	Plastic	70 %	3320, 3370
Spectrolab	—	8	5	9	13	12	0	8	Yes	115	2, 3.2 mm	<5 %	Broadband

*Spectacle Type. †See reference 24.

**Available in goggles or spectacle type.

CAUTION

1. Goggles are not to be used for viewing of laser beam. The eye protective device must be designed for the specific laser in use.
2. Few reliable data are available on the energy densities required to cause physical failure of the eye protective devices.
3. The establishment of engineering controls and appropriate operating procedures should take precedence over the use of eye protective devices.
4. The hazard associated with each laser depends upon many factors, such as output power, beam divergence, wavelength, pupil diameter, specular or diffuse reflection from surfaces,

Source: the Industrial Environment--its Evaluation and Control

Medical Surveillance. Medical examinations should be given to all personnel working with or near the laser unit. The examination should include opthomologic examinations and dermatologic examinations by experienced personnel. Persons with the following conditions should not be permitted to work near lasers: eye disease, skin problems, chronic pulmonary or cardiovascular disease, chronic emotional and mental illness, hypothyroidism, diabetes, and pregnancy. In general, strict guidelines should be established with respect to the medical surveillance of personnel working with lasers.

Microwaves

The general hazard in dealing with microwave and other radio frequency radiation is the absorption of microwave causing a general temperature increase at the exposure site or overall body temperature. Microwaves also have the capability of potential cataract formation, and some experts believe that microwaves have a potential effect on the central nervous system.

When measuring microwaves, the near and far fields of the microwave must be considered. In the near field, the electrical and magnetic field are perpendicular to each other and may potentially interact with the microwave source. In the far field, there is no interaction between the electric, magnetic, and the source of the wave. To calculate the radius of the near field or the distance from the antenna to the intersection of the near and far field is given as

$$\text{radius} = \frac{a}{2\lambda}$$

where

a = the antenna

λ = the wavelength

With microwaves, it is possible to calculate the power densities in the near and far fields and to calculate a minimum safe approach distance in the far field. To estimate the power density (W) in the near field, the following formula is used:

$$W = \frac{4P}{A}$$

where

W = power density ($\mathrm{mW/cm^2}$)

P = power output (mW)

A = effective area of the antenna ($\mathrm{cm^2}$)

If the above values are known, then the power density can be calculated. If the calculated power density is less than the TLV, then the near field is safe for occupancy. If the calculated W is greater than the TLV, then it must be assumed that the calculated level is present in all parts of the near field.

The far field power density is calculated by

$$W = \frac{AP}{\lambda^2 r^2}$$

where

W = power density (mW/cm^2)
A = effective antenna area (cm^2)
P = average power output (mW)
λ = wavelength (cm)
r = distance from antenna

Rearranging this equation, it is possible to calculate a safe distance.

$$r = \frac{(AP)}{\lambda^2 W}^{\frac{1}{2}}$$

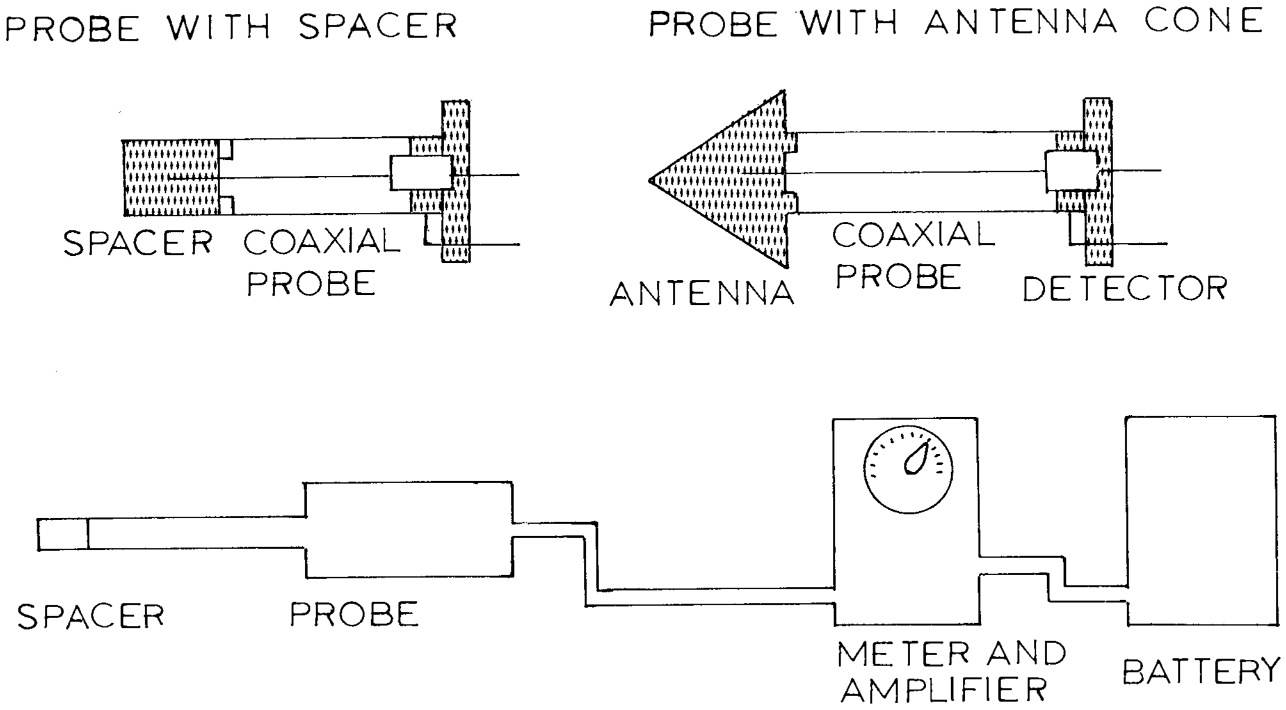
where

r = safe distance (cm)
A = effective antenna area (cm^2)
P = average power output (mW)
λ = wavelength (cm)
W = exposure criteria (mW/cm^2)

Most survey instrumentation is designed to measure the far field and is calibrated in units of milliwatts per cm^2. Generally, this type of calibration is adequate for the measurements being taken to evaluate microwave hazards. The actual measurement of microwave radiation in the near field is much more complicated.

Generally, microwave survey instruments consist of a probe, meter and amplifier, and a power source as illustrated in Figure 6.2.7. The microwave instrumentation should be portable, rugged, and easily readable; and the probe should be directionally independent.

Figure 6.2.7



MICROWAVE SURVEY INSTUMENTS

Microwave detectors are generally divided into two categories: thermal and electrical. Thermal detectors operate on the principle of absorption of microwave radiation causing a change in resistance (bolometer). For example, a thermistor is a semi-conductor in which resistance decreases as the temperature increases. A baretter operates on the same principle, only the resistance increases as the temperature increases. Another type of thermal detector is the thermocouple, which has been discussed previously. This particular device produces a voltage difference when heated. One final detector that has not been discussed is an air pressure system. This type of detector measures the pressure changes in a confined gas when exposed to microwave radiation and the gas is heated. The problem with thermal detection devices is that they are sensitive to ambient temperature changes.

Electrical detectors, such as a diode or rectifier, are used to convert radio frequency current into direct current. This type of system is extremely sensitive and is used where a low level of microwave radiation may be present.

Except for the air pressure system, all detectors require some type of antenna (probe) to convert the wave radio frequency to wire conducted radio frequency. The probes are typically wavelength specific; however, it may be possible to have a wide band detector. When used, the probe must be parallel to the field during the reading to avoid field disturbance caused by the probe. Usually, the instruments and attached probe are calibrated for specific use upon purchase.

When taking measurements and calculating the exposure for microwave radiation, a similar procedure as outlined for ultraviolet radiation may be followed. Measurements should be taken periodically in any area of potential wave leakage or personnel exposure. A floor plan and outline of the work environment, equipment and personnel involved should be prepared. The calculation of exposure is also done as for ultraviolet radiation and should include such factors as exposure level, time, and distance from the source. However, a spectrum of relative biological effectiveness does not exist for microwave radiation as with ultraviolet radiation. Therefore, the calculation of exposure is simplified.

Hazard Control. Hazards are generally best controlled by engineering design; e.g., location of the antenna, appropriate shielding within the device, and the preparation of safe operating procedures. When surveying for potential hazards, the following should be given consideration as potential hazard sources:

1. Improper installation.
    a. Poor location
    b. Lack of proper grounding of low frequency supply
    c. Inadequate or inoperative interlocks, controls, relays, and fuses
    d. Inadequate shielding of radio frequency areas and circuits
2. Unsafe operating practices.
    a. Unauthorized personnel operating equipment
    b. Unauthorized adjustments of control

- c. Lack of attention while operating equipment
- d. Reaching into hoppers and conveyors to adjust or extract pieces while microwave is in operation
- e. Failure to shut down equipment and report operating defects such as faulty operating sequence, relays that stick, circuit breakers that do not open or close properly, interlocks that fail or are blocked out
- f. Feeding of brazing or soldering alloys during the heating cycle

3. Failty maintenance practices.

- a. Poor maintenance schedule
- b. Unauthorized repairmen
- c. Failure to shut off power and use lockout procedures before servicing
- d. Not discharging capacitors
- e. Failure to short high voltage leads to ground before working on equipment
- f. Improper tools and failure to pick up tools after job
- g. Lack of final check, after repairs and adjustments have been made, before energizing equipment

The use of protective clothing as identified with ultraviolet radiation is not necessarily needed with microwave radiation except in special instances where engineering design does not provide adequate protection for the personnel. Shielding materials and enclosures may be considered in environments where microwave radiation is present. The calculation and development of the shielding is similar in principle as previously described for ultraviolet radiation. Sample attenuation of potential shielding material for microwave radiation may be found in Table 6.2.5. Finally, as with all potential radiation sources, areas with microwave and radio frequency radiation should be properly posted to advise unaware personnel.

Table 6.2.5

ATTENUATION FACTORS (SHIELDING)

Material	Frequency			
	1-3 GHZ	3-5 GHz	5-7 GHz	7-10 GHz
60 x 60 mesh screening	.01	.003	.006	.01
32 x 32 screening	.016	.006	.006	.016
16 x 16 window screen	.016	.01	.01	.006
1/4" mesh (hardware cloth)	.016	.032	.06	.1
Window glass	.63	.63	.50	.45
3/4" pine sheathing	.63	.63	.63	.45
8" concrete block	.01	.006	.002	.001

Presented at American Industrial Hygiene Conference, 1967; Palmisano, W., U. S. Army Environmental Hygiene Agency, Edgewood Arsenal, Md.

Summary

In this chapter, an introduction to the management and control of nonionizing radiation has been discussed. Specifically, ultraviolet radiation, lasers, and microwave radiation have been presented. The intent of this chapter was not to provide a comprehensive discussion of control of nonionizing radiation but merely an overview of the topic.

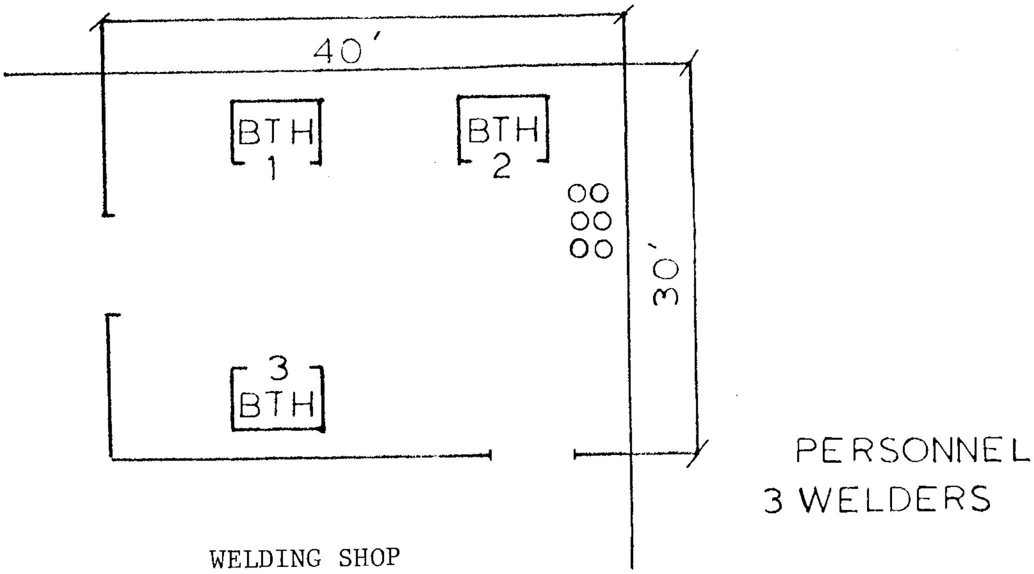
Practice Exercises

1. Referring to the welding shop defined in the Case Study presented in Section 1, Chapter 1, identify:

   a. potential radiation and nonradiation hazards

   b. a plan for measurement and evaluation of potential hazards

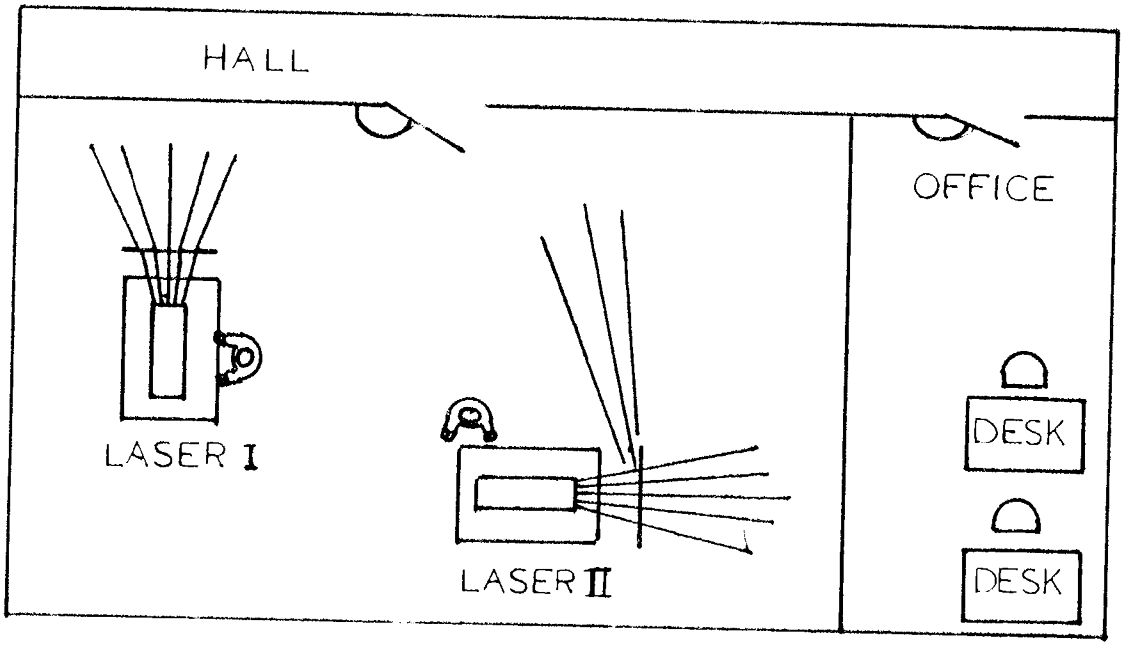
   c. procedure and equipment use which can be implemented to increase personnel protection



WELDING SHOP

Process Description

1. Parts are delivered to the welding shop by hand truck.
2. Welding is one bo specification on cleaned parts.
3. Some of the galvanized parts are sent to welding
4. Booths #1 and #2 are used for acetylene cutting and welding using an oxygen assist
5. Booth #3 is used for gas shielded metal arc welding. Carbon dioxide is used as the gas shield.
6. Parts are moved from welding by cart pulled manually or by forklift.



2. The above facility houses two laser systems. Laser I has been classified as a Class II laser, and the second laser is a Class III laser.

   a. What potential hazards exist?

   b. What changes should be made or what protective equipment should be used that would decrease the potential hazard of each of these units, both design and operation?

CHAPTER 3

PRINCIPLES OF IONIZING RADIATION

This chapter is dedicated to the basic properties of ionizing radiation. The discussion will include a review of atomic structure, radioactivity, the types of radiation, the biological effects of ionizing radiation, and the established maximum permissible doses for the various types of ionizing radiation.

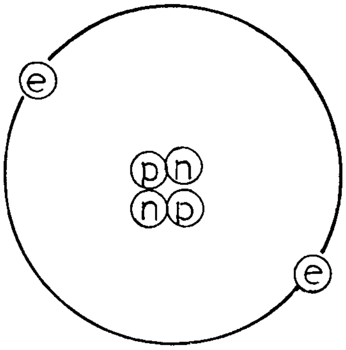
Atomic Structure

Over one hundred chemical elements exist on the earth. These elements provide the basic ingredients in all material things. An atom is the smallest particle of an element that posseses the chemical properties of that element. Each atom is composed of three fundamental particles that are most easily described in terms of two physical properties--electric charge and mass. The first particle is a proton. The proton has a positive charge (+1) and a mass of approximately one atomic mass unit (amu). The determination of the chemical element is based on the number of protons. The second particle is a neutron. This particle has no charge and a mass of approximately one amu. The proton and neutron contribute most of the mass of an atom and reside in a small volume called the "nucleus." The third particle is an electron. The electron has a negative charge (-1) and a mass of approximately 5.4×10^{-4} amu. The electrons exist in orbit around the nucleus. Each orbit represents a higher energy level for the electron.

An atom is said to be electrically neutral if the number of protons in the nucleus is equal to the number of electrons orbiting the nucleus. An atom with a surplus or deficit of orbital electrons will be negatively or positively charged respectively and is called an ion. The number of neutrons found in the nucleus is related to the number of protons, but there is not a direct correlation between protons and neutrons as there is in an electrically neutral atom. Figure 6.3.1 illustrates the particles of an atom for helium.

Figure 6.3.1

COMPONENTS OF AN ATOM



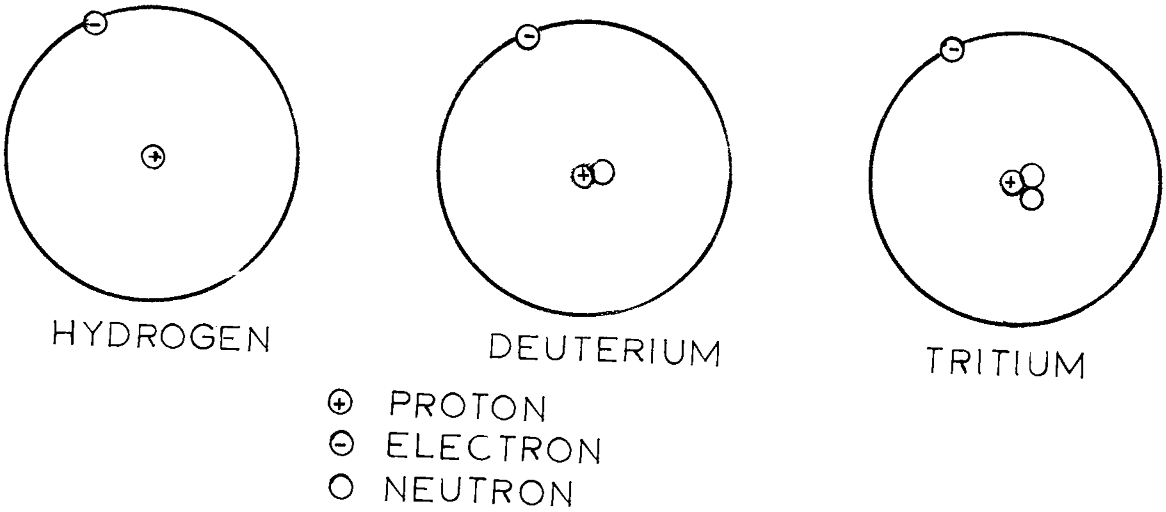
p = PROTON
n = NEUTRON
e = ELECTRON

Radioactivity

As stated, in the nucleus of an atom for a given number of protons, nuclear stability exists with a specific number of neutrons. It is assumed that the neutrons provide stability in the nucleus by acting as a "nuclear cement" that counteracts the repulsive forces and increases the attractive forces of the positively charged protons confined in a small area. It is entirely possible, however, than an atom exists having a different number of neutrons, other than the number that causes stability, for the same number of protons. When an element has the same number of protons but a different number of neutrons, the element with the excess neutrons is referred to as an isotope. An example of this principle can be seen in Figure 6.3.2 with the element hydrogen. As can be seen in each of the atoms--hydrogen, deuterium, and tritium--the number of protons and electrons remains the same (one of each) and the number of neutrons varies. As shown, hydrogen is the stable atom; deuterium is a stable isotope of hydrogen; and tritium is a radioactive isotope of hydrogen.

Figure 6.3.2

ISOTOPES OF HYDROGEN



With respect to nomenclature, the symbol for each of these isotopes is as follows:

Hydrogen: $_1H^1$

Deuterium: $_1H^2$--Hydrogen-2; ^2H

Tritium: $_1H^3$--Hydrogen-3; ^3H

In the first type of nomenclature, the subscript to the left of the element symbol indicates the number of protons in the element. The superscript to the right of the element symbol indicates the atomic weight of the isotope. Because the atomic weight attributed to the orbital electrons is usually considered insignificant (5.4 x 10^{-4} amu), the number of neutrons in the isotope being discussed can be calculated by subtracting the atomic weight from the number of protons. Therefore, using this approach, the number of neutrons in the isotope $_{92}U^{238}$ would be 146 neutrons. The remaining two nomenclature forms merely list the element and atomic weight. These are important concepts because many elements have a number of isotopes, and these isotopes are present in the literature in any one of the preceding formats.

Because the isotope of an element has an improper combination of protons and neutrons, the nucleus of the atom is at a higher energy level and is said to be unstable. The term, radioactivity, refers to this improper combination of protons and neutrons that is in an unstable energy state. In an effort to find a more stable state, the atom will spontaneously transform, emitting some type of radiation to release energy. This is analagous to an orbital electron going from a higher energy orbital to a lower energy orbital and, in doing so, giving off light energy. In the instance of radiation being emitted from the nucleus, however, the radiation (energy) may be emitted in the form of:

1. Alpha particle--A high energy particle composed of two protons and two neutrons. It has a mass of 4 amu and a charge of +2.
2. Beta particles--Electrons emitted by the nuclei which may be positively or negatively charged. The mass of a beta particle is insignificant.
3. Gamma radiation--Bundles (photons) of electromagnetic radiation.
4. A combination of the above emissions.

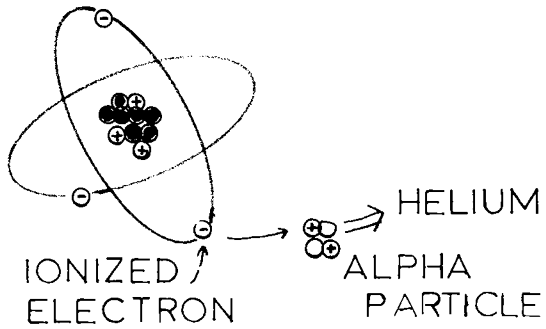
Alpha Particles. The alpha particle originates in the nucleus of a radioactive atom. It is composed of two protons and two neutrons. It has a mass of four atomic mass units (amu) and a charge of +2. Because of its structure, it is the same as the nucleus of a helium atom.

Depending upon the radionuclide source, the energy of an alpha particle varies and may occur up to 10 million electron volts (MeV). Because of its energy, the alpha particle causes more ionization (formation of ions in an absorbing material) than a beta or gamma radiation would in an absorbing material. However, because of its large mass and positive charge, the distance the alpha particle can travel is very short. For example, the general range of an alpha particle in air is approximately 4 inches. It can be stopped by a film of water, sheet of paper, or other paper-thin materials. Because of its short range, the danger in alpha particle radiation is not penetration through the skin but entrance of alpha particle emitters into the body through the respiratory or digestive systems.

The emission of alpha particles occurs through the radioactive decay of the larger elements. An example of an alpha source is Thorium-232 or Uranium-238. As discussed, if an alpha particle is emitted, the atomic weight and atomic number of the emitting radionuclide is altered. Referring to the sample radioactive decay (Figure 6.3.3), the alteration of the elements can be seen each time an alpha particle is emitted.

Figure 6.3.3

ALPHA PARTICLE INTERACTION



Once emitted, the alpha particle will attract two electrons to form a helium atom. Because the alpha particle causes the removal of two electrons from other atoms or molecules, the alpha particle is said to cause direct ionization (Figure 6.3.3).

Beta Particles. The beta particle, as with the alpha particle, originates in the nucleus of a radioactive atom. The beta particle is an electron emitted during radioactive decay. The beta particle can be positively or negatively charged; but in either case, the atomic mass of the beta particle is negligible when considering the change in atomic weight of the radionuclide. The energy level associated with a beta particle is usually in the range of 0.017 to 4.0 million electron volts (MeV).

As previously stated, the beta particle may be positively or negatively charged. If the beta particle has a positive charge, it is referred to as a positron. In the formation of a positron, a proton in the nucleus assumes the properties of a neutron, and the beta particle is emitted with a positive charge. Because a proton is lost in the process, when a positron is emitted the atomic number of the element decreases by one. However, because it is an electron being emitted, the atomic mass of the element remains the same. For example, when the element Zinc-65 ($_{30}Zn^{65}$) emits a positron, the new element which would be produced because of the loss of a proton would be copper ($_{29}Cu^{65}$). Once the positron is emitted, it will collide or interact with an electron in the medium and be annihilated. Upon annihilation, gamma radiation is emitted.

If the beta particle emitted is negative, then it is referred to as a negatron or high-speed electron. In the nucleus, a neutron assumes the basic properties of a proton, and a negatron is emitted. Because a proton is added to the nucleus, the atomic number increases by one, and a new element is formed. Once emitted, the high-speed electron will interact with the medium and cause direct ionization along with the formation of X-radiation. An example of beta decay that involves the emission of negatrons may be observed in the radioactive decay series (Figure 6.3.4). As shown in Table 6.3.1, each time a negatron is emitted, the atomic mass remains the same while the atomic number increases by one. Because each element is defined by its atomic number, each time a negatron is emitted, a new element is formed.

Table 6.3.1

POSITRON VERSUS NEGATRON

Beta	Description	Charge	Mass (amu)	Energy Level	Effect of Emission
Positron	High speed electron with positive charge	+1	0.00054	Up to several MeV	Z number decreases by 1
Negatron	High speed electron with negative charge	-1	0.00054	Up to several MeV	Z number increases by 1

The penetration capability of the beta particle is somewhat greater than the alpha particle. This is due to the smaller mass and charge of the beta particle. For example, the average range of a beta particle in air is less than six feet; in wood, 1.5 inches; in human tissue, 0.1-0.5 inches. Beta particles can be stopped by material of low atomic weight; e.g., aluminum. In general, this is the type of shielding material used when dealing with beta radiation.

As with alpha radiation, beta radiation causes direct ionization. Further, as discussed, the interaction of the positron with the medium causes the formation of gamma radiation; and the interaction of a negatron with the medium causes the formation of X-radiation. Because of its relatively short range, the beta particle provides a minimum hazard. However, because of the potential formation of secondary gamma and X-radiation and somewhat longer range, the beta particle is a greater external radiation hazard than the alpha particle.

Gamma Radiation. Gamma radiation is a short-wave electromagnetic radiation. It originates from the nucleus; but emission of gamma radiation does not cause any change in the element's properties, atomic number, or atomic weight. Gamma radiation is emitted because the nucleus is in an unstable, excited state; and the emission of gamma radiation releases energy and causes the nucleus to fall to a more stable energy level.

The energy level associated with gamma radiation is the highest electromagnetic radiation that will be discussed. The energy level of the gamma radiation is dependent upon the radionuclide source but usually falls within the range of 0.15 to 4 million electron volts. The source of gamma radiation is the radioactive decay of radioisotopes and the destruction of positrons as previously described.

Because gamma radiation has no mass or charge, is a wave, and has a relatively high energy content, gamma radiation has the potential for very deep penetration. This capability of deep penetration presents a tremendous health problem in the working environment. For example, to dissipate the energy of 1 millielectron volt of gamma radiation to one-half its original energy level, it would be necessary to have a shield of 0.5 inches of steel. When considering that potential energy levels of gamma radiation can reach one million times this value, the problem of gamma radiation becomes evident.

The photons associated with gamma radiation interact with atoms and molecules of the absorbing material in three ways.

1. Photoelectric effect--Incident photons cause the ejection of orbital electrons. These electrons possess energy equal to the difference between the photon energy and the electron binding energy. As shell vacancies are corrected, X-radiation is formed. Also, the resultant electron may interact to form X- or gamma radiation.

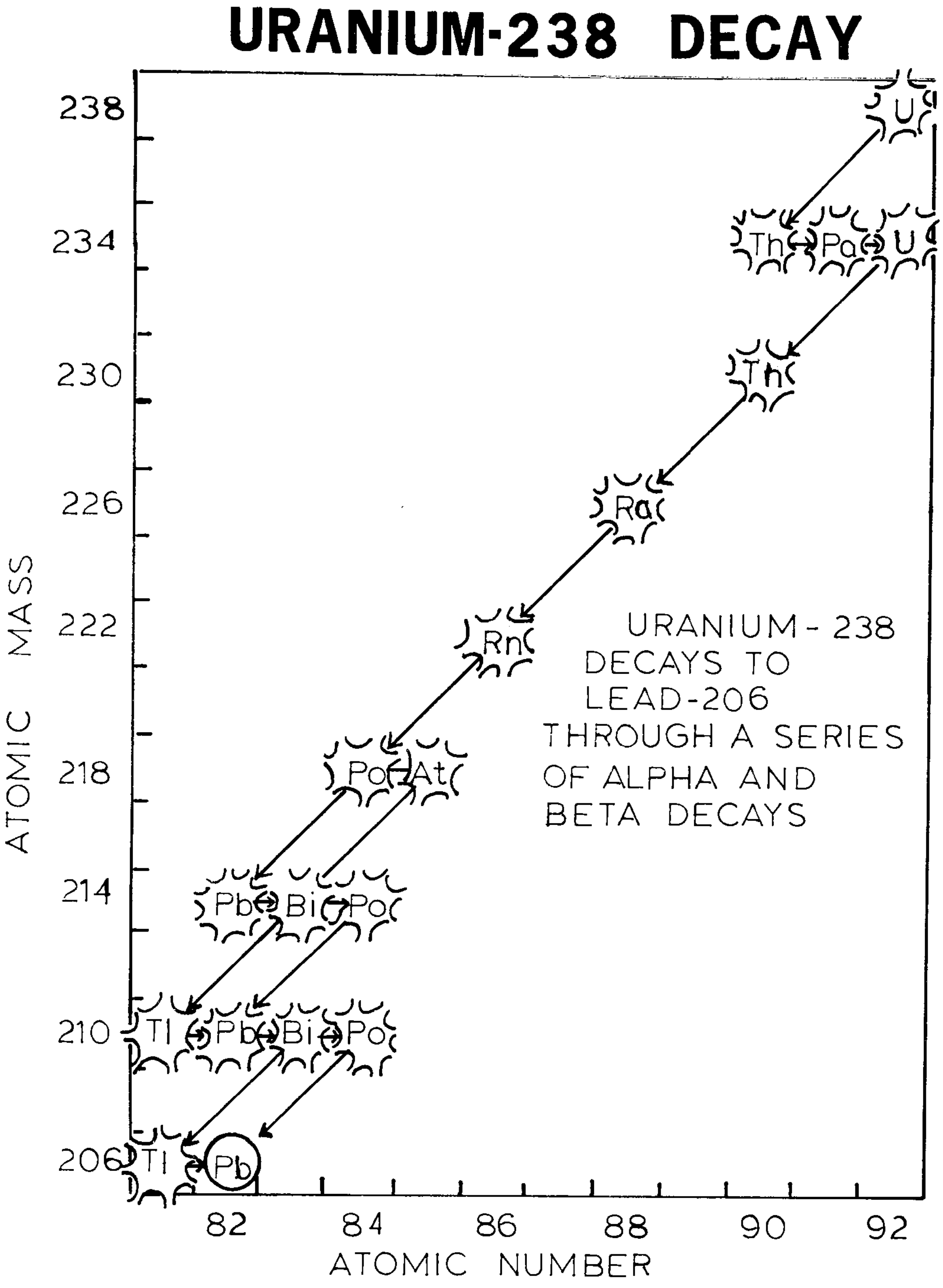
2. Compton effect--Incident photon gives up part of energy to orbital electrons. The electron may recoil and be rejected. Further, the degraded photon may interact further with other electrons.

3. Pair production--High energy photon interacts with electric field surrounding a charged particle (nucleus). The interaction causes the formation of an electron and positron of equal energy. When the positron and electron collide or slow down, X- or gamma radiation is formed.

There are approximately 240 radionuclides (radioactive isotopes) which undergo this spontaneous transformation (radioactive decay) to reach a more stable energy level. Depending upon the type of emission, the isotope may undergo a change and, in essence, form a new element or new isotope. If, for example, an alpha or beta particle is emitted, a new element would be formed because protons are either gained or lost. If a neutron is emitted, the element is the same; but a new isotope is formed. If gamma radiation is emitted, then the element would remain the same; but the energy level in the nucleus would be lower.

It is entirely possible that, as radioactive decay occurs, the new isotope that is formed is also in an unstable state. It too would then undergo a spontaneous transformation, emit some type of radiation, and form a new element. Each of the new radionuclides formed from the spontaneous transformation is referred to as a "daughter product." Spontaneous transformation and the production of daughter products will continue until the chain of events forms a stable isotope or element. The decay change presented in Figure 6.3.4 illustrates the decay of Uranium-238 (${}_{92}U^{238}$) to Lead-206 (${}_{82}Pb^{206}$) through a series of alpha and beta emissions.

Figure 6.3.4

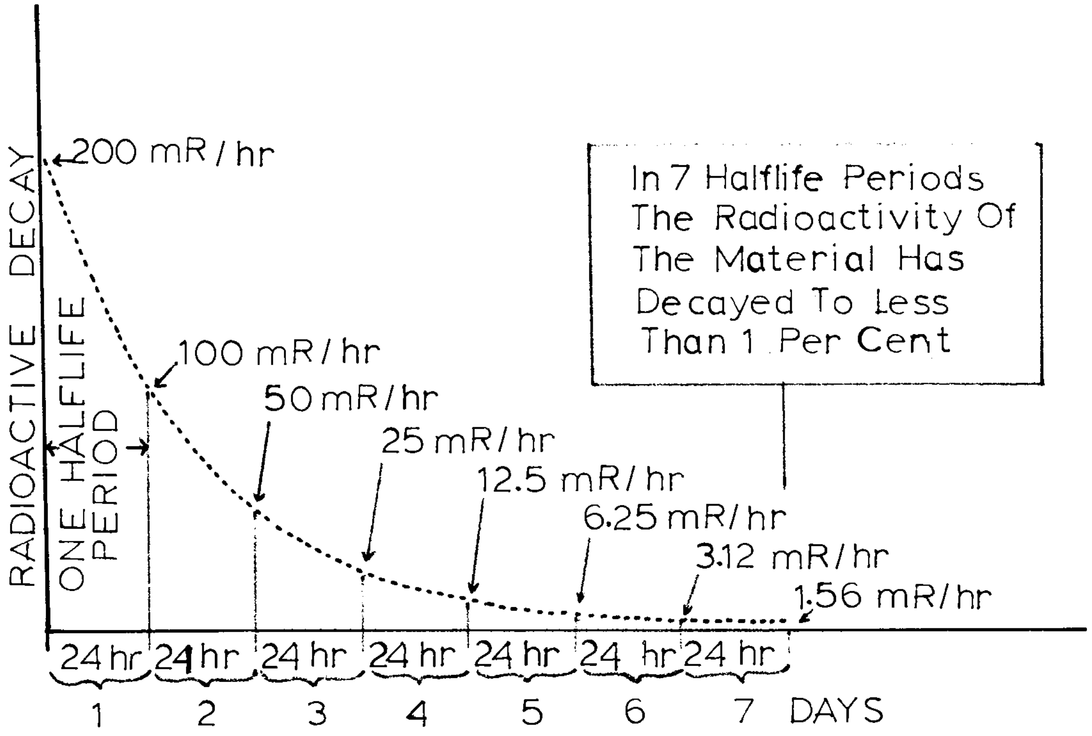

URANIUM-238 DECAY
ATOMIC MASS
238
234
230
226
222
218
214
210
206
ATOMIC NUMBER
82
84
86
88
90
92
U
Th
Pa
U
Th
Ra
Rn
Po
At
Pb
Bi
Po
Tl
Pb
Bi
Po
Tl
Pb
URANIUM-238 DECAYS TO LEAD-206 THROUGH A SERIES OF ALPHA AND BETA DECAYS

The steps in the decay process are shown in the diagram, where each nucleus that plays a part in the series is shown by a circle. The vertical column containing the circle indicates its atomic number, and the horizontal column indicates the atomic mass. Each arrow that slants downward toward the left shows an alpha emission (two protons and two neutrons), and each arrow that points to the right shows a beta emission (electron). Notice that some of the nuclei in the series can decay in more than one direction. This is but one of four similar radioactive series that can occur in nature. Because of this chaining effect of radioactive decay, it is possible for the total radioactivity to increase beyond the radioactivity present in the original isotope.

The radioactive decay rate of a radionuclide is measured in terms of a characteristic time, the half-life. The half-life of a radioactive material is the time needed for half of the active atoms of any given quantity to decay. Isotope X, for example, has a half-life of 24 hours. This means that half of any given specimen of Isotope X will be converted to some other element by the end of 24 hours. Then, in the next 24 hours, half of the remaining Isotope X will decay, leaving only one-fourth of the original number of Isotope X atoms. Therefore, the number of atoms decaying is proportional to the number of atoms present. This is constant for any radionuclide. Figure 6.3.5 illustrates a typical half-life scheme $(T^{\frac{1}{2}})$ for an isotope having a half-life value of 24 hours. As can be seen by the illustration, by the end of the third half-life, the radioactivity has dropped to approximately one-eighth of its original activity; and by the end of the seventh half-life period, the activity has decreased to less than one percent of the original activity. Using this illustration, one can see that the longer the half-life value, the smaller the amount of radiation that will be released at any given time.

Figure 6.3.5

DECAY OF RADIOACTIVE MATERIAL



There are two other types of ionization radiation which are important but are not formed by radioactive decay. The two forms of radiation to be discussed are X-radiation and neutrons.

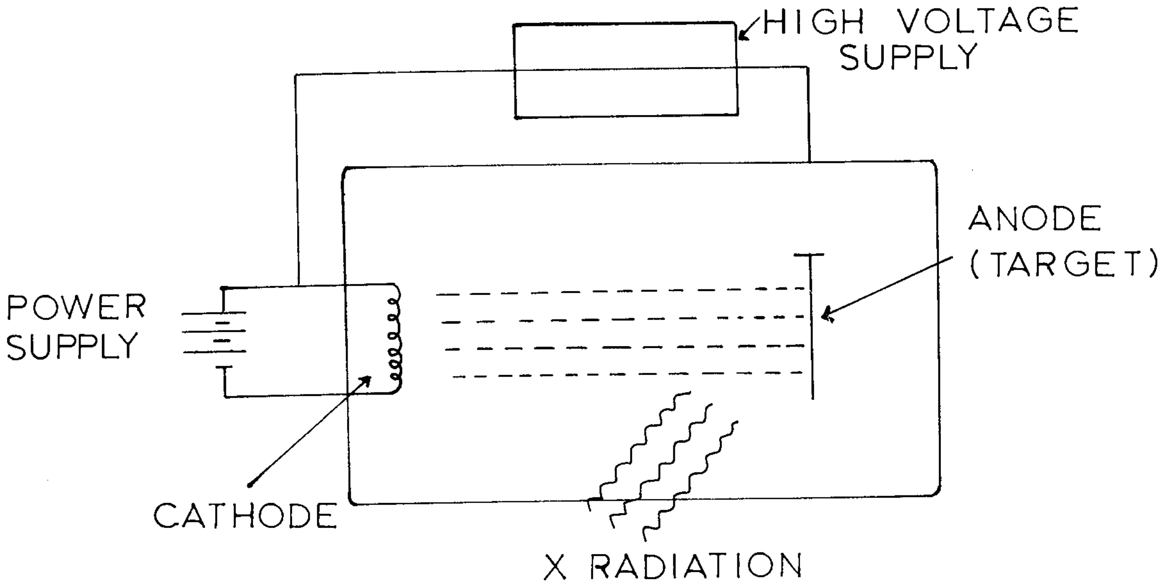
X-Radiation. X-radiation is also electromagnetic radiation. It is similar in property to gamma radiation and interacts with absorbing material in a similar manner, but it does not have as high an energy level as gamma radiation.

X-radiation originates outside the nucleus. In general, the principle behind the formation of X-radiation is that high speed electrons (negatrons) are slowed down or stopped. In the process of slowing down, the electrons give up energy in the form of X-radiation. The quantity of energy released is dependent upon the speed of the electron and the characteristics of the medium (striking target). Generally, there are two types of radiation formed: bremstrahlung, which is caused by deflection of electrons traveling near a nucleus; and characteristic, which is produced in energetic transitions between orbital electron levels.

X-radiation is generally produced by machine, although some X-radiation is emitted from the collision of negatrons during the process of radioactive decay. The machine necessary to produce X-radiation has basically three components (Figure 6.3.6): (1) cathode (electron source), (2) anode (target), and (3) potential difference between the cathode and the anode in a vacuum. In the machine, a potential difference is established between the cathode and the anode. The electrons travel through the vacuum at high speeds and then are stopped when striking the target (anode). When striking the target, the energy released is in the form of X-radiation.

Figure 6.3.6

THE X-RAY MACHINE



The penetrating capability of X-radiation is dependent upon the wavelength of the radiation. X-radiation with a short wavelength (approximately 0.001-0.1 nm in length) is referred to as "hard" X-radiation. This type of radiation has the capability to penetrate several inches of steel. X-radiation with longer wavelength (0.1-1.0 nm) is referred to as "soft" X-rays and is less penetrating than hard X-radiation. The range of penetration of X-radiation is dependent upon the energy of the radiation and the type of medium it is penetrating. For example, the half value layer (thickness required to reduce incident radiation by 0.5) is several inches of concrete. As previously discussed, the interaction with the target medium is the same for X-radiation as with gamma radiation.

Neutrons. The final type of ionizing radiation to be discussed is the neutron. The neutron particle originates from the nucleus. It has an atomic mass of 1 amu and a charge of 0. The energy level usually associated with neutrons is greater than gamma or X-radiation but is less than alpha or beta radiation. However, because of the zero charge on the neutron, the neutron has a greater penetrating capability than the alpha or beta particle.

Neutrons are formed in basically two ways. First, it is possible to bombard a light element, e.g., beryllium or lithium, with alpha particles or gamma radiation and, because of the increased energy in the nucleus, a neutron will be emitted. The second source is the fission of isotopes of uranium or plutonium. This fission is caused by neutron bombardment and results in the production of more neutrons. Because the reaction is produced by neutrons and results in the production of neutrons, a chain reaction may be established such that the neutrons resulting in the fission of a given uranium or plutonium isotope causes the fission of more isotopes. Because of this, the principle of criticality evolves. There is a minimum level of concentration required of the radioisotope to allow the chain reaction to begin. This is usually referred to as the "critical level." If the critical level is not exceeded, the chain reaction will not occur. If, however, the critical level is exceeced, a chain reaction may be produced by the fission of a single plutonium atom.

Neutrons are developed through nuclear reactions as described above or are mechanically produced through the use of accelerators such as the Van de Graff or the Cockroft-Walton generator.

The interaction of neutrons with a target medium is dependent upon the energy level of the neutron. Neutrons of a high energy level (fast neutrons) collide with the nuclei of the absorbing material and lose energy in a billiard-ball-like collision. Neutrons with less energy (slow/thermal neutrons) are captured by the absorbing nuclei. In either case, alpha, beta, or gamma radiation is emitted. Because ionization is secondary, the calculation of neutron dose is difficult.

The penetrating capability of the neutron is dependent upon the energy level, characteristics of the medium, and type of collision which occurs. The average distance the neutron of a given energy level will travel before some type of interaction is referred to as mean free path (mfp). The probability of an interaction in three mean free paths is equal to 0.95. As an example, in human tissue, the mean free path of a neutron may vary from 0.25 to several inches.

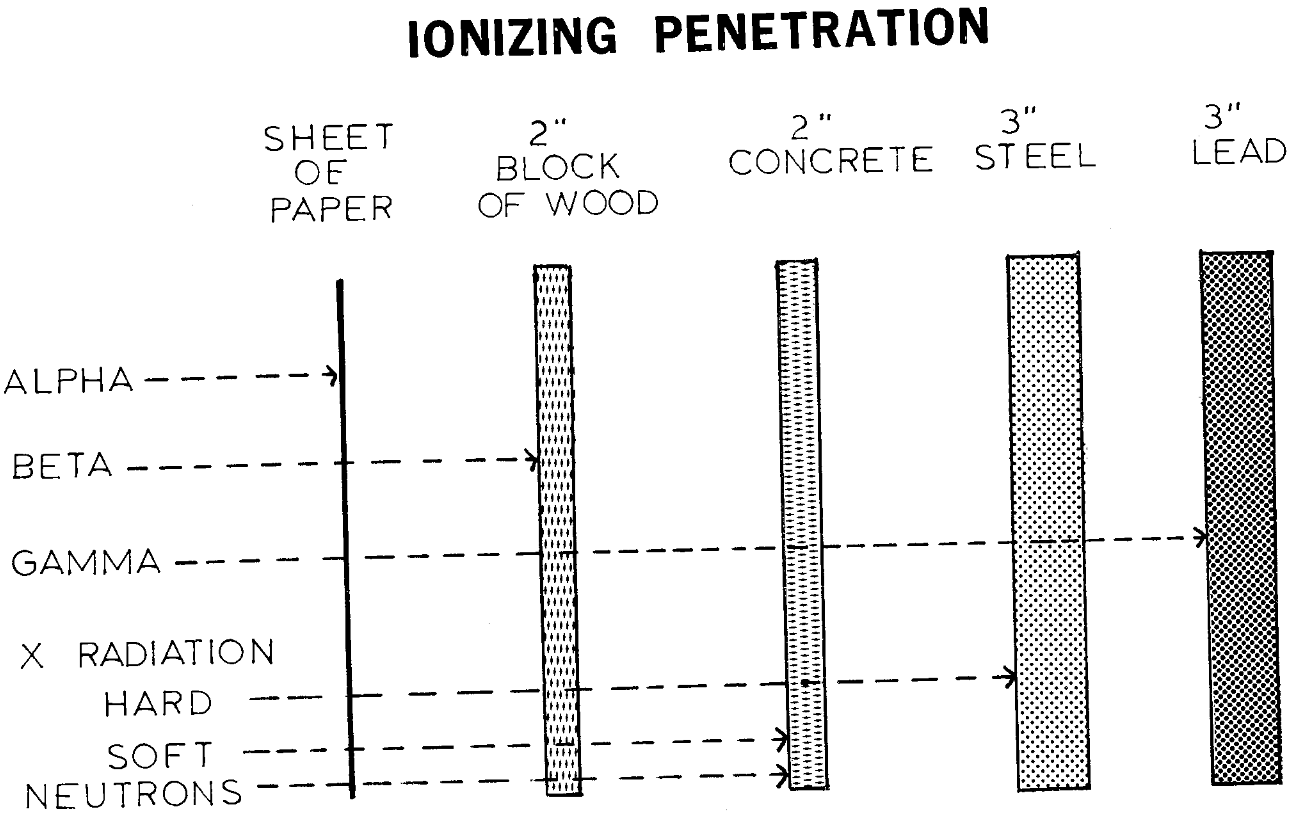
Table 6.3.2 summarizes the ionizing radiation discussed, and Figure 6.3.7 illustrates the relative penetrating capability of the types of ionizing radiation.

Table 6.3.2

PROPERTIES OF IONIZING RADIATION

Type	Source	Description	Charge	Mass (amu)	Energy	Radiation Hazard	Necessary Shielding
Alpha	Natural and manmade isotopes	Helium nucleus--causes direct ionization	+2	4	2-9 MeV	Internal hazard only	Thin sheet of paper
Beta	Most radioactive isotopes	Electron (+ or -) ionizes 1/100 as heavily as alpha	±1	.00054	Up to several MeV	Internal or external danger	Thick sheet of cardboard
Gamma	Natural isotopes-nuclear reactions	High energy electromagnetic radiation	0	0	Up to several MeV	Dangerous--deep penetration	Very heavy shielding--e.g., inches of lead
X	Slowing of electrons	High energy electromagnetic radiation--less than gamma	0	0	Up to several MeV	Dangerous--deep penetration	Heavy shielding
Neutrons	Nuclear reactions	Uncharged particles	0	1	Up to several MeV	Hazardous	Thick shielding composed of light elements

Figure 6.3.7



Units of Measure

When discussing radioactivity and the energies involved, the following units of measure will be of value. When reviewing the terms, place emphasis upon the concepts of each term rather than the actual numerical value.

Units of Energy. In physics, the standard unit of energy is the joule. The joule represents the work done when a constant force of one newton moves a body a distance of one meter in the direction of the force. Energies of atomic and nuclear phenomena are usually given in terms of electron volts (eV). One electron volt is the kinetic energy acquired by an electron after being accelerated through a potential difference of one volt. Energies encountered in radioactive decay processes are usually expressed in terms of thousands of electron volts (KeV) or millions of electron volts (Mev). For example, the energy of Cesium-137 gamma radiation is 0.667 million electron volts. If necessary, it is possible to convert joules to electron volts using the factor:

$$1{,}000{,}000 \text{ electron volts (eV)} = 1.602 \times 10^{-13} \text{ joules (J)}$$

Units of Activity. The measure of the rate of radioactive decay is given in terms of activity. The activity reflects the number of radioactive atoms emitting ionizing radiation. The special unit of activity is the curie (Ci) and is defined in terms of events per unit time, disintegrations per minute, or counts per minute. The numerical value for a curie is as follows:

$$1 \text{ curie (Ci)} = 3.7 \times 10^{10} \text{ disintegrations per second}$$

When discussing a quantity of radioisotopes, the quantity is discussed with respect to the amount of activity of that quantity. Therefore, it would be more appropriate to state that a quantity of uranium is "an amount of uranium with an activity of 500 curies" rather than "500 curies of uranium."

Exposure. The roentgen (R) is the special unit of exposure. This unit refers specifically to the measure of the amount of charge produced in air by gamma or X-radiation. Numerically, one roentgen is equal to 2.58×10^{-4} coulombs/Kg of air. The exposure of one roentgen corresponds to the production of about 2×10^{9} ion pairs per centimeter^3 of dry air at standard temperature and pressure. Exposure rate is the time derivative of exposure and is usually expressed in terms of roentgens per hour, roentgens per minute, or milliroentgens per hour, etc. The exposure rate constant (Γ) is the exposure rate per curie of radioisotope at 1 meter. The values of Γ are tabulated in the literature for many gamma emitters.

Absorbed Dose. The absorbed dose (D) is the energy imparted by ionizing radiation to absorbing matter per unit mass of absorbing material. The standard unit of absorbed dose is the rad and is defined as 1 rad = 10^{-2} joules/Kg. The absorbed dose rate is the time derivative of absorbed dose and reflects the given absorbed dose over a given period of time. It is usually expressed in terms of millirads per hour, rads per second, etc.

Dose Equivalent. Because of the specific biological effects and action of radiation upon human tissue, the measure of exposure or even absorbed dose does not present completely the measurement of ionizing radiation. For example, each type of ionizing radiation has a different penetrating capability. Alpha particles will have no detrimental effect to the body unless they enter the body through some other means than penetrating through the skin; whereas, gamma radiation easily penetrates the protective layer of the skin and can cause severe internal damage. Further, certain radionuclide sources, if introduced to the body, will migrate to certain areas of the body. An example of this is the radioisotope of calcium. Because of their properties and involvement in the development of bone tissue, most radioisotopes with properties similar to that of calcium will tend to concentrate in the body in the bone areas. Because of this, one cannot evaluate the problem of radiation based upon a whole body exposure. Finally, the effect of the various types of radiation on different parts of the body will vary. For example, areas of the hands, arms, and feet are less sensitive to radiation exposure than other areas such as the eyes, internal organs, or the reproductive organs.

To deal with these variations, a standard unit of dose equivalent has been developed. It attempts to take into consideration the above-mentioned factors. Generally, the unit, known as the rem, is equivalent to the exposure (R) or the absorbed dose (rad) multiplied by the quality factor. Although not absolute, it will be assumed that this quality factor (QF) corrects for the relative biological efficiency of the different types of radiation (RBE). The exact QF varies according to the source of radionuclide, area of exposure, and type of ionizing radiation. However, to calculate the dose equivalent, the following values may be used for purposes of determining the rem value, given exposure or absorbed dose.

Calculation of Dose Equivalent

rem = rad (or R) x QF

Type	QF
X-Radiation	1.0
Gamma Radiation	1.0
Beta Radiation	1.0
Alpha Radiation	20.0
Neutron (fast)	3.0
Neutron (slow)	10.0
Fission Fragments	20.0

An example of the calculation is as follows:

Example

If the absorbed dose reading from a $_{88}Ra^{226}$ (alpha emitter) is found to be 0.05 mrad/hr at a distance of 1 meter, what is the dose equivalent for an exposure lasting 8 hours?

Solution

$$\text{rem} = \text{rad} \times \text{QF}$$

$$= \frac{0.05 \text{ mrad}}{\text{hr}} \times \frac{20 \text{ mrem}}{\text{mrad}}$$

$$= \frac{1.0 \text{ mrem}}{\text{hr}}$$

$$\text{rem}/8\text{hr} = \frac{1.0 \text{ mrem}}{\text{hr}} \times 8 \text{ hr} = 8.0 \text{ mrem}$$

Although the quality factor (QF) is not exact, it can be used to calculate the dose equivalent given the exposure or absorbed dose rate for low level sources. In later sections, the importance of dose equivalent will be presented.

Fluence. When evaluating particulate radiation (alpha, beta, neutron) it may be of value to know the number of particles entering a cross section of a given area. The unit used to express this value is fluence (Φ) and is expressed in terms of "particles per centimeter^2." If the sum of the energies of the particles that enter the cross sectional unit is to be discussed, then the unit is energy fluence (Ψ) and is expressed in terms of "millielectron volts per centimeter^2."

Flux Density. If the fluence is to be determined over a given period of time and a rate calculated, then this rate of fluence per unit time is referred to as flux density (ϕ). This is usually expressed in terms of "particles per centimeter^2 per second"; e.g., neutrons per centimeter^2 per second. The energy flux density is the energy fluence of a given period of time and is expressed in million electron volts per centimeter^2 per second.

Each of the terms presented in this section will be used throughout the remainder of the sections on ionizing radiation. It is not necessary to memorize all numerical values, but it is important to understand the concept behind each unit of measurement.

Biological Effects of Ionizing Radiation

The fundamental property of ionizing radiation relates to the transfer of energy when the radiation passes through material. Absorption of the energy may cause ionization (the expulsion of orbital electrons from the atom or molecule) or excitation of the orbital electrons to a higher energy state. The ions formed in turn react with other atoms and molecules in the absorbing material, causing potential changes in those molecules and the absorbing structure. Because ionizing radiation causes changes at the atomic and molecular level, the effects of ionizing radiation to the cells will be discussed initially; and then the over-all systems function will be discussed.

The energy required to cause cell death is very small. A lethal dose of radiation dissipates approximately one-millionth the amount of energy dissipated by the cell during its normal daily function. Thus, a lethal dose affects only one of 2.0×10^7 molecules in a cell.

In the cell, ionizing radiation has two actions. First, if the ionizing radiation irradiates critical molecules of the cell, e.g., DNA, mitochondria, immediate cell death will occur. An indirect action can also occur by the irradiation of water molecules. This irradiation forms active products, e.g., H_2O_2, OH^-, O_2H^-, which react with other molecules within a cell and cause damage or death. Because irradiation is random at the cell level, the indirect action is more significant than the direct action. In general, radiation causes the following: immediate cell death, cell damage that prevents growth or causes the formation of cell mutations, or reduction of cell function and ultimately body function.

All forms of ionizing radiation produce some type of injury to the cell. Tissue reaction is dependent upon the density of the ionization in the radiation path; i.e., linear energy transfer. Particulate radiation (alpha, beta) produces more damage per energy absorbed, thus a high relative biological efficiency and a greater linear energy transfer factor (amount of energy transferred per linear penetration). Electromagnetic radiation, because of its high penetration capability, causes more diffuse ionization. It should be noted that the particulate radiation is more damaging if allowed to enter the body (internal radiation hazard). Because particulate radiation has a small penetrating capability, the protective layers of the skin tend to provide a barrier to prevent the penetration of particulate radiation through the skin.

The response of an individual to radiation is dependent upon the dosage of the radiation; the amount and type of tissue irradiated, e.g., localized versus whole-body irradiation; and the length of time of exposure. A localized exposure; e.g., to the hands and arms, will cause damage to the specific irradiated site or organ. However, it is possible for a local exposure to cause systemic changes. Whole-body irradiations tend to cause systemic-type illnesses. Signs and symptoms such as nausea, vomiting, skin erythema, intestinal bleeding, and diarrhea are common to whole-body irradiation. The following effects would be observed in man after acute whole-body doses of penetrating radiation:

1. 0-25 rad--no observable effect.
2. 25-50 rad--minor temporary blood changes.
3. 50-150 rad--possible nausea and vomiting, along with reduced white blood cell count.
4. 150-300 rad--exaggeration of above symptoms plus diarrhea, malaise, and loss of appetite.
5. 300-500 rad--exaggeration of above symptoms, plus hemorrhaging and loss of hair (depilation). About 50 percent of the untreated exposed population will die at 450-500 rad level.
6. Above 500 rad--Most of the above symptoms will appear sooner in more severe form. Survival chances diminish rapidly with higher doses.

Acute high level doses or moderate doses over longer periods of time can product effects later in life. The most notable effects include increased risk of cancer or leukemia; nonspecific life span shortening, i.e., acceleration of aging process; and harmful mutations that may be transmitted to future generations. In general, exposure to ionizing radiation causes a decrease in the efficiency of cell activity to the point that cell function is diminished and may ultimately cause cell death. To minimize the effect of ionizing radiation in the occupational environment, maximum levels of ionizing radiation exposure have been established.

Industrial Uses of Ionizing Radiation

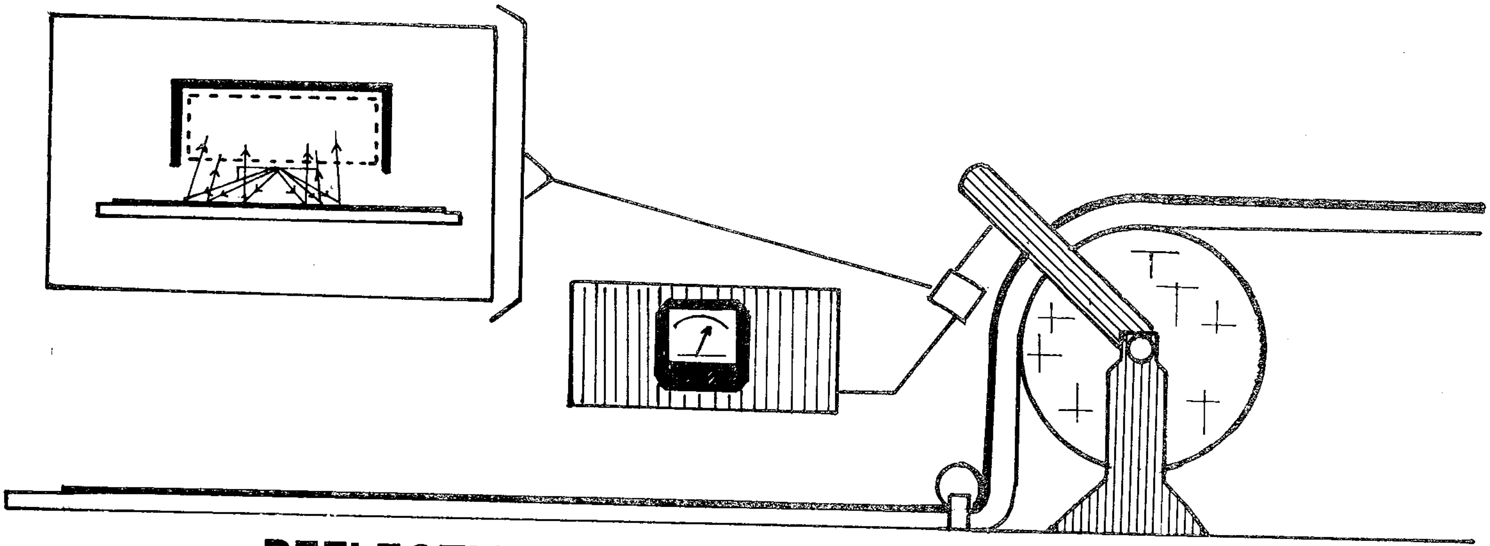
For many years following the basic investigations in the field of radioactivity, the primary use of ionizing radiation was in the medical field; and little progress was made in integrating ionizing radiation in industrial areas. Recent advances, such as fission and fusion techniques, have brought about the availability of economic radionuclides that are rapidly being introduced into the industrial field.

In most countries, only a small percentage of the total work force is involved in the industrial use of ionizing radiation. With few exceptions, the use of ionizing radiation has been remarkably free of radiation accident and injury. However, because of the potential hazard, much consideration must be given to the health and safety aspects as well as to the actual industrial applications of ionizing radiation. The following are examples of uses of ionizing radiation in the industrial environment.

Radiation Gauges. Ionizing radiation penetrates or is reflected by matter; and, with a suitable detector, it is possible to extract useful information from the transmitted or reflected beam. Because the intensity of radiation used is small, the beam is nondestructive and lends itself to automation. Some uses of a radiation gauge include the determination of sheet metal thickness, the density of metals or fluids, or the calculation of moisture content.

There are two types of gauges in use. The first is a transmission gauge that monitors the radiation penetrating a given substance. When using this type of gauge, the factors that will vary the transmission reading include the density and composition of the target material. The second type of gauge is a reflection-type gauge. It is more sensitive and in many instances may be the only practical solution. An illustration of a "backscatter" or reflection-type radiation gauge is given in Figure 6.3.8.

Figure 6.3.8



REFLECTION-TYPE THICKNESS GAUGE

In these gauges, beta emitters are used in conjunction with a reflecting r backing material such that the backscatter electron intensity is linearally roportional to the thickness of the substance to be checked over a given range. hese gauges are finding wide application because of the increasing industrial mportance of thin films and coatings.

If the gauges automatically control the process, e.g., metal sheet rolling, hen a greater accuracy can be obtained than with conventional control methods. able 6.3.3 illustrates the increase in quality control when using a radiation auge with automatic control versus a conventional type control sampling method.

Table 6.3.3

Industry	Application	Process Control (95% Correlation) Conventional Control (Normally sampling method)	Radiation Gauge With Manual Control	Radiation Gauge With Automatic Control
Paper	Fourdrinier paper machine	±12%	±10%	±3%
Metals	Tandem cold roll mill	±10%	±7%	±1.5%
Rubber	Sheeting calender	±10%	±6%	±3.2%
Rubber	Tire fabric calender	±6.5%	±5.5%	±3.5%
Plastics	Calender	±7%	±3.5%	±2.5%
Impregnation	Saturation dip coater	Automatic control provided an improvement factor of 2.5 over conventional		
Abrasive	Abrasive maker	Automatic control provided an improvement factor of 2 over conventional		

(From Crompton, C. E.)

The three types of ionizing particles in common use in radiation gauges are photons (X or gamma), beta (normally negative electrons), and neutrons (fast and thermal). A common source for industrial radiation gauge is a sealed source of Strontium-90 of up to 1 curie activity. All radiation sources made for such use must meet rigid specifications regarding resistance to temperature, pressure, impact, vibration, and puncture. Safety experience with such sources has been favorable; even gauges exposed to intense heat and fires have evidenced little or no leakage. Their locations and layout are normally such that external exposure of personnel is minimal. However, all sources should be periodically checked for leakage and maintained by qualified personnel.

Radiography and Fluoroscopy. Radiography is defined as the production of a shadow image of the internal structure of an object on a permanent record, usually some type of film or template. The primary types of ionizing radiation used include photons (X or gamma) or neutrons (fast or thermal).

Radiography provides a close inspection during and after fabrication of materials or structures. Welds in nuclear power plants or high pressure pipelines, critical joints in the foundations of large buildings, and engines in jumbo jet planes are only a few examples in which such a radiographic section plays a critical part. Industrial radiography comprises both field radiography and stationary radiography. Both are based on the same principle; but in field radiography the source of radiation is taken to the specimen, while in stationary radiography the specimen is taken to the source of radiation.

Fluoroscopy works on the same principle as radiography with the exception that the shadow image is presented temporarily on a screen. It is most appropriate in industry as a quality control tool for mass produced components, such as turbine blades and transistors, and for the inspection of such items as cables. Fluoroscopy is about four times less sensitive than radiography; therefore, it can be used only where such sensitivity can be tolerated and is usually backed up by radiography.

In either of the above techniques, the primary hazard is the radiation source that is being used as part of the procedure.

X-Ray Diffraction and Fluorescent Analysis. It has been known for many years that the planes in a molecular crystal lattice will diffract X-radiation in a set three-dimensional pattern. Using this information, if X-radiation is emitted through a molecular structure and the diffraction pattern determined, it is then possible to evaluate the crystal state of the material. Further, it is also possible to determine the actual content of the material based upon the absorption and emission properties of ionizing radiation of that material.

The production of crystals for broadcast transmitters, watch movements, silicone and germanium semiconductors are all aided by the determination of crystal structure through X-ray diffraction techniques. The determination of crystalline structure of a finished product, such as a turbine blade or nuclear reactor vessel, provides information on the soundness and freedom from stress which are important in predicting the useful life of the product.

The personnel hazards are of a specialized nature. The greatest hazard is associated with very fine, intense X-ray beams. Further, the electron accelerating voltage is normally in the range of 30,000 to 50,000 volts. It is possible, therefore, that the primary beam of X-radiation may have an intensity as high as

7,000 roentgens per second; and any part of the body held in the beam for only fractions of a second would receive such a dose. Beside the risk of exposure to the primary beam, a hazard also exists of exposure to a beam scatter off the specimen or analyzing crystal, which could be quite intense. Much less intense, but still strong enough to make further shielding precautions advisable, is the scattered radiation around joints, around shielding, and in general when the radiation is scattered at least twice.

The prime requisite for the safe operation of an X-ray diffraction and fluoroscent unit consists of proper training and supervision of operation personnel. Accidents frequently occur owing to operators placing their fingers and hands in the primary beam to remove samples, forgetting that the beam is on.

Electron Beam Equipment. The development of reliable electron guns and electron optics using electric and magnetic fields has led to many interesting and important industrial applications of electron beams. In two of them, electron beam evaporators and electron beam welders, advantages are taken of the unique ability of a defined electron beam to introduce into a specimen a large amount of heat at a specified point or area. In two other applications, electron microscopes and scanning electron microscopes, advantage is taken of the fact that the electron beam can behave like a light wave and is capable of an extremely high resolving power.

The electron beam evaporator makes use of the heat generated when an electron beam from a cathode strikes a target after being accelerated by application of a high potential and concentrated biomagnetic or electric field acting as an electromagnetic "lens." The power emitted by the electron beam is absorbed as heat at the surface of the target, causing the target surface to evaporate at a rate that may be controlled by varying the voltage and the current of the electron source. Metals such as tungsten and molybdenum and nonmetals such as quartz and aluminum oxide may be evaporated in this way. The evaporated metal is then used to provide thin coatings for antistatic coatings on glass or plastic and, in general, in the field of solid-state and laser technology. The hazards normally associated with electron beam evaporators are the production of X-radiation, the high energy levels of the electron beam, and the high voltage required to accelerate the electrons.

Electron beam welders operate on the same principle as electron beam evaporators with the addition of further focusing to concentrate the beam at a point on the target and in the use of higher voltages. The advantage of electron beam welding versus conventional welding is that the work piece is heated from the inside and thereby eliminates the distortion often associated with conventional welding techniques. The hazards associated with the electron beam welder are similar to those of the electron beam evaporator with the exception that the voltages required by the welder are in the range of 150,000 volts rather than the 13,000 to 20,000 volts required of the evaporator. Electron microscopes are used in research and industrial applications when resolving power approaching the ultimate possible is required. An optical microscope is limited by the wavelength of visible light which may be taken as 500 nm. In the electron microscope, however, the theoretical limit is a function of the electron beam accelerating voltage.

The basic components of an electron microscope are the electron gun, composed of a cathode and anode, and the condensing magnetic lens, specimen state, objective magnetic lens, projection magnetic lens, and viewing screen. The electron beam from the cathode is accelerated to the anode and concentrated into a parallel beam by the condensing lens. The beam then passes through the specimen. The energy of the electrons must be sufficient to penetrate the specimen, and accelerating voltages of 50,000 to 60,000 are commonly used. Passing through the objective lens, a magnified image is formed at the intermediate lens which converges the electron beam before passing through the final magnification stage. The final image can usually be viewed through observation ports on a fluorescent screen. Magnification as high as 200,000 times and a point resolution of 0.4 nanometers are now available on commercial models.

As with any of the electron beam devices, the hazards associated with the electron microscope are similar. The unit should be monitored for leakage of X-radiation, and precautions should be taken when dealing with the high voltage of the unit.

Activation Analysis. In this technique of chemical analysis, the test material is irradiated by one of several different types of uncharged or charged particles. A probability exists that in the reaction the target nuclei will be transformed into unstable or radioactive nuclei, the number of which depending upon the number of bombarding projectiles, the number of target nuclei, and the cross section of the reaction. Once radioactive, the target material will begin emitting ionizing radiation. Each radionuclide has a distinct pattern of X- and gamma radiation emission. Once an analysis of the emission is performed, then the identity and quantity of the elements present may be determined.

Radioactive Tracers. Isotopes have the same chemical properties whether they are radioactive or not. Therefore, it is possible to substitute a known quantity of radioactive isotope in a given material or process and then "trace" its progress. An example of the use of these tracers in product improvement is the study of the effect of various lubricating oil combinations on the wear of pistons in engines and cylinders. In this application, a piston ring was irradiated and was used on a piston in a cylinder of an internal combustion engine. The amount of activity in the lubricant was determined by counting, and the location of wear was determined by auto-radiography. This study permitted the development of improved lubricants in a relatively short time.

Another example of the use of tracers is to determine wetting, detergency, absorption, and durability. To improve the accuracy of a radiochemical separation, one can add a known quantity of radionuclide to a mixture with an unknown quantity of a radionuclide of the same element, for example Strontium-85 to a Strontium-90 mixture, and determine quantitatively the amount of Strontium-90 in the mixture.

Still another example of the use of tracers is in determining the volume of complex reservoirs in hydrology by utilizing a technique known as "isotope dilution." A known volume of radioisotope at a known concentration is added to a complex mixture or reservoir. If one assumes a perfect mixture and a sample is taken, it is possible to determine the volume of the reservoir by taking a known volume of sample and measuring its isotope concentration. From this, the actual volume of the entire reservoir or complex mixture may be extrapolated.

The tagging of a product in transit is an example of the use of radioactive tracers in the petroleum industry. In one application, various radioactive tracers are used to tag the input water in water flooding projects. Finally, in the field of solid-state technology, minute concentrations of metals and nonmetals can have profound effects on a semiconductor, and radioactive tracers are used as the only practical method of identifying behavior of trace elements found in reagents used in their fabrication.

Aerosol Fire Detectors. One of the most sensitive detectors of combustible gases and smoke relies on the use of radioactive materials. In this system, two ionization chambers, each containing a radioactive foil, are used. One is sealed and the other is open to the ambient air. These two chambers are connected to a cold cathode gas discharge tube. In the absence of air contaminants, the gas discharge tube does not fire. If the air becomes contaminated with combustible gases and smoke particles, the tube fires, actuating an electromagnetic relay which sounds the alarm. The hazard associated with this device is minimal because of the size of the sealed source.

Luminescent Dials. One of the oldest applications of ionizing radiation involves the use of radium as a source of radiation in a self-luminous compound. If a compound of phosphor (zinc sulfide) is bombarded with ionizing particles, the phosphor scintillates, causing it to "glow." The hazards associated with self-luminous compounds are present in all stages of the process, including the preparation of the compound, painting and assembly, and inspection. In each stage, steps must be taken to minimize personnel contact.

Large Radiation Sources. The use of large radiation sources has achieved practicality with the advent of inexpensive radionuclides and engineering design advances in accelerators. One application of large radiation source is radiation processing. This is the use of ionizing radiation to produce a biological or chemical change. Routine uses of radiation processing in industry include sterilization of medical supplies, an enzyme for laundry use, synthesis of ethyl bromide, controlled degradation of polyethylene oxide polymer, irradiation of wood-plastic composites, and control of anthrax bacillus in sheep hides and wool. Table 6.3.4 indicates industrial applications of radiation processing.

The second use of large radiation sources is a thermoelectric generator. The ionizing radiation is used as a heat source, and thermoelectric converters convert the heat to electricity. The primary hazards involved are the presence of gamma and X-radiation, and neutrons produced by the procedure.

A third potential use of large source radiation is in nuclear explosions. They may be used in the construction industry for excavating and tunneling, in the mining industry for breaking up ore, and in the petroleum industry for stimulation of gas fields. Although most industrial uses of radionuclides emphasize the safety and health protection of the working personnel, when using large radiation sources, protection of the general public must also be considered.

Table 6.3.4

SOME APPLICATIONS OF IONIZING RADIATION IN INDUSTRY

A = Research B = Pilot Plants C = Production	Sterilization	Pasteurization	Salmonella Control	Insect Disinfestation	Disinfection	Sprout Inhibition	Cross Linking	Polymerization	Scission	Free Radicals	Curing	Grafting	Testing and Evaluation
Sewage Treatment	A												
Semiconductors													A
Flooring							A	B		A		A	
Furniture							A	B		A		A	
Hides and Hair	C		C	C	C								
Textile							B	A		B	A	B	
Adhesives							A	A			A		A
Rubber							A	A		B	B		A
Spices		A	A	A	A								
Paints and Coatings								B		B	A	A	A
Membranes	A						A	A		B		B	
Chemical Synthesis								A	A	B			
Fuels									A				A
Lubricants									A				A
Wood-Plastic Composites							A	B		A		A	
Plastic Piping							A	A		A		A	
Heat Shrinking Tubing							B	B		A			
Enzymes		A	A		A								
Cosmetics	B	A	A		A								
Pharmaceutical	A	A	A		A								
Medical Supplies	C				A								
Foods	B	A	A	B	A	B							

Source: Gamma Industries, Inc.

Agricultural Uses

Agricultural uses of ionizing radiation may be categorized into two groups. The first use is the irradiation of living tissue with the intent of modifying the matter. Examples of this use include irradiation of potatoes to inhibit sprout production, the sterilization of fruit, or irradiation of seeds to cause mutations in an effort to develop various strains of the plant. With these uses, machine sources as well as naturally occurring radioisotopes are used.

Widely used radioisotope sources in agriculture and research include:

1. Multikilocurie gamma sources for food disinfection, pasteurization, and sterilization.
2. Beta and less intensive gamma sources used in radiography, thickness and density and level gauges.
3. Alpha sources used in electrostatic discharges, gauges, and electronic warning devices.
4. Isotope accelerators used for neutron activation analysis of soil metals, and protein.

As in industrial uses, tracers are used to evaluate biological phenomena. All types of radiation are used in agriculture. Alpha particles are used to study cellular disposition. Beta particles are used in evaluation of metabolic processes, pathways of fertilizer and nutrient deposition; and finally, X- and gamma radiation are used to evaluate processes similar to the use of beta particles. A list of common isotopes used for radiotracers in agriculture is found in Table 6.3.5.

Table 6.3.5

ISOTOPES FREQUENTLY USED AS RADIOTRACERS IN AGRICULTURE, CLASSIFIED ACCORDING TO RADIOTOXICITY

Isotope	Principal Radiation	Half-Life	Typical Application
Group 1 (Very High Toxicity)			
Strontium-90	β (β)	28	Uptake, metabolism and effect of radioactive fallout in food chains and animals
Lead-210	β,γ (α,β)	20	Cellular deposition and radiotoxicity of alpha emitters in farm animals
Polonium-210	α,γ	138 d	
Group 2 (High Toxicity)			
Calcium-45	β	160 d	Bone formation; calcium metabolism in biological systems, soil studies
Iron-59	β,γ	45 d	Uptake and metabolism of iron
Strontium-89	β,γ	54 d	Strontium movement and deposition in biological systems
Iodine-131	β,γ	8 d	Studies of fallout in soil, pasture, milk; thyroid studies in farm animals, blood volume measurement
Group 3 (Moderate Toxicity)			
Sodium-24	β,γ	15 h	Physiology and concentration of sodium in animals; underground water movements, leak detection
Phosphorus-32	β	14.3 d	Metabolism of phosphorus in fertilizers, pesticides, enzymes. Radiation effects in plants, insects, tagging of insects
Sulphur-35	β	87 d	Biochemistry of sulphur pesticides, fertilizers; wool and hair growth measurements
Chlorine-26	β	3.1×10^5 y	Uptake and metabolism of chlorinated pesticides; chloride ion balance
Potassium-42	β,γ	12.5 h	Fertilizer uptake; potassium distribution and biochemistry

Table 6.3.5 (Continued)

ISOTOPES FREQUENTLY USED AS RADIOTRACERS
IN AGRICULTURE, CLASSIFIED ACCORDING TO RADIOTOXICITY

Isotope	Principal Radiation	Half-Life	Typical Application
Group 3 (Continued)			
Manganese-54	γ	300 d	Trace-element studies in food chains; manganese metabolism
Iron-55	X	2.9	Labelling hemoblobin; studies of iron deficiency; blood circulation
Cobalt-58	β,γ	71 d	Labeled vitamin B12 metabolism
Cobalt-60	β,γ	5.2	Tagging of burrowing insects; vitamin B12; radiation effects; deficiency studies
Copper-64	β,β+,γ	12.5 h	Fungicide and trace-element studies
Zinc-65	β+,γ	245 d	Toxicology of fungicides; zinc metabolism
Selenium-75	X,γ	127 d	Muscular disease in sheep, toxicology
Strontium-85	γ	65 d	A less toxic substitute for Sr-90
Rubidium-86	β,γ	18.6 d	Fertilizer uptake; biophysiology studies (as potassium substitute)

Source: *Encyclopaedia of Occupational Health and Safety, International Labour Office*

Medical Uses

Medical uses for ionizing radiation may also be grouped into two categories. The first category is the application of X-radiation. Most people are familiar with its common use in the development of a film outline of bones, teeth, and calcified structures, along with the internal organs. Further, injection or ingestion of X-radiation opaque substance into the body provides outlines of the desired organ. For example, barium sulfate is ingested to provide a film of the intestinal tract.

The medical profession has also found various uses of radionuclides, primarily in diagnosis and therapy. Using the radioactive counterparts of isotopes that are normally found in various areas of the body, by introducing radioactive isotopes it is possible to chart the path and deposition of specific elements and compounds throughout the body. For example, if an analysis of the activity of the thyroid gland were of interest, then radioactive iodine would be used since iodine tends to migrate to the thyroid gland; if the kidney were of interest, radioactive mercury displays the same type of tendency towards migration to the kidney as iodine does to the thyroid gland. Certain types of cancers may be identified in that the cancerous cells does not absorb or use the same elements of the body as do normal, living tissues. Therefore, if a radioactive isotope were introduced into a given area and the cells did not absorb the radioisotope as would be expected, then the location of the cancer could be identified.

The uses of radionuclides in therapy are rather well known. Because of the biological effects of ionizing radiation, it is possible to expose nondesirable (cancerous) cells to specific types of ionizing radiation that will not affect normal tissue; and the effect of the ionizing radiation will be to cause cell damage and death to the cancerous tissues.

Hazards. In general, each of the industrial, agricultural, or medical uses has basically the same hazard. In those instances where a naturally occurring radioisotope is being used, specific exposures to that isotope is the primary problem. In those instances where high voltage equipment is needed to create the radiation, e.g., X-radiation, then an alternate problem of potential high voltage danger should be considered. Further, as can be seen on Table 6.3.5, radioisotopes may be used for specific types of radiation, e.g., alpha source, but the isotope selected may also emit gamma or beta radiation. Care must be taken to evaluate properly the extraneous as well as desired radiation.

Maximum Permissible Dose

In an effort to minimize the effect of ionizing radiation exposure, the following maximum permissible dose (MPD) levels have been established. The dose levels are presented in units of dose equivalents (rem).

Table 6.3.6

MPD EQUIVALENT RECOMMENDATIONS

	Maximum Weekly Dose (rem)	Maximum 13-Week Dose (rem)	Maximum Yearly Dose (rem)	Maximum Accumulative Dose
Occupational Exposure				
Whole Body	0.23	3.0	12.0	5(N-18)*
Skin		10.0	30.0	
Hands, feet		25.0	75.0	
Forearms, ankles		10.0	30.0	
Non-Occupational Exposure	0.01			
Emergency Situation				
Whole Body	100			
Hands and forearms	200 additional			

*Assume personnel age greater than 18

Using the MPD values presented in the table, it will be possible to calculate the exposure levels in the working environment that will not exceed the MPD level.

Efforts have also been made to convert the equivalent dose maximums to actual concentrations of radionuclides that may be present in the working environment, specifically in the air and water. Handbook #69, "Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and Water for Occupational Exposure," specifically identifies the maximum permissible burdens and permissible concentrations for each of the radionuclides presently being used in the working environment. The handbook also identifies the critical organ affected by that radionuclide. In essence, the handbook has converted the maximum permissible dose equivalent to a concentration of a specific radionuclide based upon the energy levels of the emissions of the nuclide. Table 6.3.7 is an excerpt from Handbook #69.

Table 6.3.7

Maximum permissible body burdens and maximum permissible concentrations of radionuclides in air and in water for occupational exposure—Continued

Radionuclide and type of decay		Organ of reference (critical organ in boldface)	Maximum permissible burden in total body $q(\mu c)$	Maximum permissible concentrations			
				For 40 hour week		For 168 hour week**	
				$(MPC)_w$ $\mu c/cc$	$(MPC)_a$ $\mu c/cc$	$(MPC)_w$ $\mu c/cc$	$(MPC)_a$ $\mu c/cc$
	(Insol)	**GI (LLI)**		**2×10^{-3}**	**4×10^{-7}**	**8×10^{-4}**	**10^{-7}**
		Lung			2×10^{-6}		6×10^{-7}
$_{34}$Se^{75}(ϵ, γ	(Sol)	**Kidney**	90	**9×10^{-3}**	**10^{-6}**	**3×10^{-3}**	**4×10^{-7}**
		Total Body	100	0.01	**10^{-6}**	**3×10^{-3}**	5×10^{-7}
		Liver	100	0.01	2×10^{-6}	4×10^{-3}	5×10^{-7}
		Spleen	200	0.02	3×10^{-6}	8×10^{-3}	10^{-6}
		GI (LLI)		0.07	2×10^{-5}	0.03	6×10^{-6}
	(Insol)	**Lung**			**10^{-7}**		**4×10^{-8}**
		GI (LLI)		**8×10^{-3}**	10^{-6}	**3×10^{-3}**	5×10^{-7}
$_{34}$Br^{82} (β^- γ)	(Sol)	**Total Body**	10	**8×10^{-3}**	**10^{-6}**	**3×10^{-3}**	**4×10^{-7}**
		GI (SI)		**8×10^{-3}**	2×10^{-6}	**3×10^{-3}**	6×10^{-7}
	(Insol)	**GI (LLI)**		**10^{-3}**	**2×10^{-7}**	**4×10^{-4}**	**6×10^{-8}**
		Lung			6×10^{-7}		2×10^{-7}
$_{36}$Kr^{85}m (β^-, γ)	(Immersion)	**Total Body**			**6×10^{-6}**		**10^{-6}**
$_{36}$Kr^{85} (β^-	(Immersion)	**Total Body**			**10^{-5}**		**3×10^{-6}**
$_{36}$Kr^{87} (β^- γ)	(Immersion)	**Total Body**			**10^{-6}**		**2×10^{-7}**

Reprinted from Handbook #69, "Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and Water for Occupational Exposure"

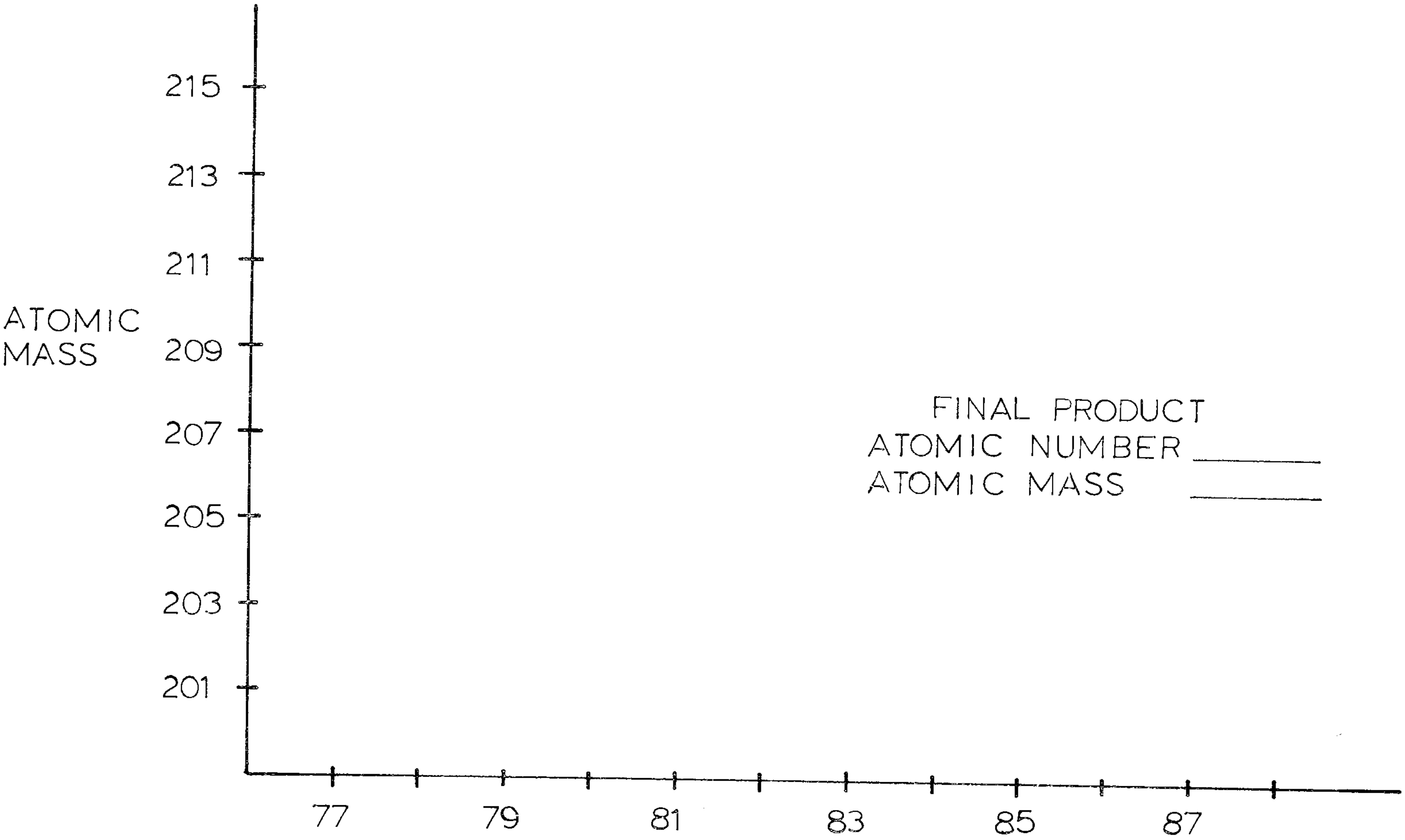
Summary

In this chapter, the atom, radioactivity, and the process of radioactive decay have been briefly discussed. Five types of ionizing radiation, including alpha, beta, gamma, X-, and neutron have been examined. The basic biological effects of ionizing radiation, applications of ionizing radiation, and the established maximum permissible dose levels for the working environment have been presented.

Practice Exercises

1. On the graph provided, chart the radioactive decay of radioisotope $_{85}Q^{215}$ if the following types of radiation are emitted in the sequence provided. What is the atomic number and mass of the element at the end of emission?

   1. Alpha particle
   2. Negatron
   3. Gamma radiation and alpha particle
   4. Positron
   5. Alpha particle



FINAL PRODUCT
ATOMIC NUMBER ________
ATOMIC MASS ________

2. Given that a quantity of Uranium-238 is decaying at the rate of 2.6×10^5 disintegrations per second, what amount of Uranium (in curies) would emit this activity?

3. How many disintegrations per second would be expected from a Strontium-90 with an activity of 500 curies?

4. A beta emitter has a monitor reading of 150 mrads/hr at 0.5 cm. Calculate the dose equivalent. How many hours per week could an employee be exposed and not exceed the MPD for hand exposure over 13 weeks?

5. Assume that a radioactive source is emitting beta and gamma radiation and that monitoring equipment has indicated an absorbed and exposed rate of 2.5 mrad/hr and 12.0 mR/hr, respectively. How many hours per week could the employee remain working in this environment and not exceed the MPD value for whole-body exposure over a period of 13 weeks?

CHAPTER 4
INSTRUMENTATION

Introduction

Radiation detection instruments monitor the effect of ionizing radiation on a given material. For example, the ions produced in a given volume of gas can be measured, and the ions will be proportional to the energy absorbed by the gas. No single instrument performs acceptably under all conditions and requirements. Therefore, no single instrument can monitor and discriminate between all types of radiation at the various energy levels. In this chapter, the most commonly used radiation detectors will be discussed, including:

Ionization chambers
Proportional counters
Geiger-Mueller (G-M) counters
Scintillation detectors
Photographic devices
Solid-state and activation devices

Specific applications of these detectors in personnel monitoring devices, including film badges, pocket dosimeters, and pocket ion chambers, will also be presented.

The obvious purpose of monitoring radioactivity in the working environment is to insure that the exposure rate and absorbed dose for any given individual are less than the maximum permissible dose (MPD) equivalents established as a minimum standard. However, the response recorded on a detector is due to the energy absorbed by the detector itself; and in some instances the detector does not have the same properties as human tissue. It is possible to select a detector and probe that can provide readings proportional to the absorbed dose that would be experienced by an employee in a given environment. Generally, however, the response of the instruments is not exactly equivalent to the response of human tissue receiving the same amount of energy. This is due primarily to the secondary ionization that would normally occur in human tissue but does not necessarily occur in the detector. For purposes of this discussion, however, it may be assumed that the response of the detector is equivalent to the absorbed dose unless otherwise stated.

The absorbed dose to an individual can rarely be determined directly, if at all. An estimation made by using some type of detector must be acceptable. Realizing the absorbed dose cannot be determined and that an estimation must be used, the maximum permissible dose equivalent values that have been previously presented take into consideration that an estimation will be used and, therefore, MPD values are conservative. These values have been conservatively established to the extent that an error in actual reading of ±30% could be tolerated. In most instances, the instruments selected, if appropriately matched to the environment and type of radiation of interest, will fall within this range. In general, the accuracy of the detectors for photon energies tends to be somewhat better than for particulate radiation.

If the detection instruments are calibrated according to the manufacturer's recommendation for the environment and radiation type of interest, no further effort is usually necessary to increase the accuracy of the instrument. However, if the readings should approximate the maximum permissible dose equivalent established, it is important that the most accurate readings possible be obtained. If the MPD value is approximated, the individual receiving this exposure may receive different medical treatment based upon the amount of exposure than has been calculated. Therefore, to insure appropriate treatment, the most accurate reading possible should be obtained. For readings that are well above or well below the MPD value, the need for accuracy is not as great.

Instrumentation

This section deals with the most common radiation detection and monitoring devices presently being used.

Ionization Chamber Instruments. The ionization chamber is an instrument that monitors the change in a gas caused by ionizing radiation. Ionizing radiation falls on the gas contained in the chamber and forms ions that migrate toward the cathode and anode within the chamber and are collected there. The potential voltage difference that is created because of the migration of the primary ions is measured. This potential difference is proportional to the quantity of ionizing radiation that falls upon the chamber.

This instrument can be used to measure relatively high levels of radiation. It can measure both particulate and electromagnetic radiation. The ionization chamber responds to any ionization produced in the chamber itself. It does not have the capability of discriminating between radiation types and specifically between particles of different linear energy transfer (alpha versus beta).

The ionizaton chamber is usually 190 to 320 cubic centimeters in volume. In general, the larger the chamber, the greater the sensitivity and required operational voltage. It can be designed to measure all types of radiation. The chamber is usually open to the atmosphere and requires corrections for ambient temperature and pressure. Sealed chambers are also available and do not require corrections for the ambient temperature and pressure but may have reading changes because of leakage or absorption and adsorption on inside surfaces of the gas within the chamber. The thickness of the wall of the chamber is of critical importance. The thickness must approximate the maximum range of the ionized particles produced by the ionizing radiation. Table 6.4.1 illustrates the various wall thicknesses required, based upon the energy of the radiation.

Table 6.4.1

THICKNESSES OF IONIZATION CHAMBER WALLS REQUIRED
FOR ESTABLISHMENT OF ELECTRONIC EQUILIBRIUM (ICRU, 1964)

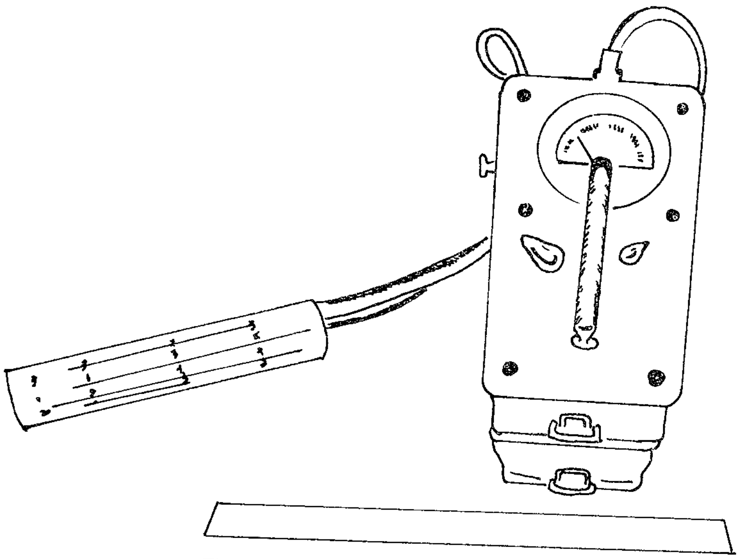
Photon Energy (MeV)	Thickness (g cm^{-2})
0.02	0.0008
0.05	0.0042
0.1	0.014
0.2	0.044
0.5	0.17
1	0.43
2	0.96
5	2.5
10	4.9

The chambers can also be designed to be air or tissue equivalent. If the chamber is designed to be air equivalent, then the readings reflect exposure rates. If the chambers are designed to be tissue equivalent, then the properties of the chamber simulate human tissue and the readings are calibrated to measure absorbed dose.

The primary advantage of the ionization chamber instrument is that it is a simple, rugged device that reliably determines absorbed dose or exposure. The disadvantage of this instrument is that special designs or modifications are required for the instrument to discriminate well between the types of radiation. Because of this, it is necessary to have a general knowledge of the radiation spectrum being evaluated.

Proportional Counter Instruments. The proportional counter (Figure 6.4.1) functions on the same principle as the ionization chamber. However, the voltage on the collection plates is increased such that as the primary ions approach the collection plates, secondary ionization occurs. This secondary ionization and the ions produced from it contribute to the ion current pulse that is registered on the meter. This process is referred to as "gas amplification." This gas amplification process increases the sensitivity of the proportional counter over a simple ionization chamber by a factor of 10^3 to 10^4 times. Even though gas amplification does occur, there still remains a proportionality between the counter current and energy fluence rate of the radiation which enters the proportional counter.

Figure 6.4.1



PROPORTIONAL COUNTER

The proportional counter is more useful in measuring particle radiation rather than photon radiation. It has the capability of measuring both alpha and beta radiation and can discriminate between the two types if they are simultaneously present. If the chamber is lined with a boron film or filled with BF_3 gas, then thermal neutrons can also be monitored. Fast neutrons of low energy level may also be measured with this instrument. Because of the proportionality between the counter and the energy entering the chamber, it is possible to use the proportional counter for spectrometry.

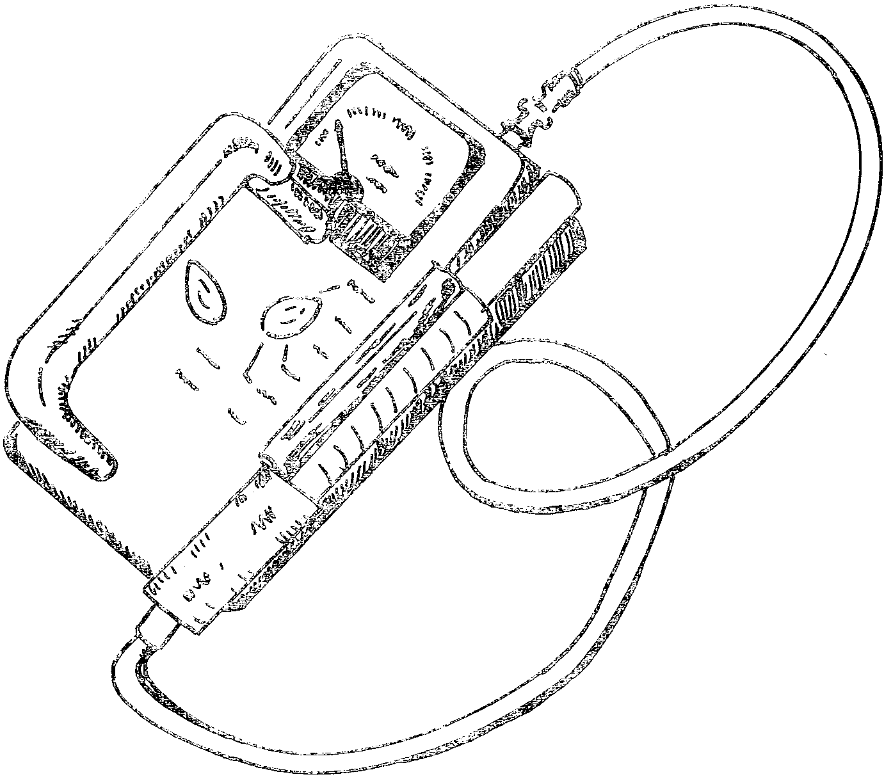
The selection of the type of gas and wall construction for the proportional counter chamber is dependent upon the purpose and type of measurements that are to be made. As with the ionization chamber, the proportional counter chamber can be designed to be air or tissue equivalent. Further, by changing the thickness of the wall, one can get an indication of the absorbed dose at various levels in human tissue.

The primary advantages of the proportional counter are its discrimination capabilities. For example, it is possible for the counter to eliminate the effects of gamma radiation while counting neutrons and to negate the effects of beta when counting alpha. Its primary advantage is its high sensitivity with relative high accuracy and counting efficiency. The disadvantages of this unit include the insulation requirements around the components to prevent miscellaneous radiation to enter the components. Also, in some instances inaccuracies in the readings may occur due to losses of absorbed energy. These losses may decrease accuracy by as much as 50%.

Geiger-Mueller (G-M) Counter. The Geiger-Mueller counter (Figure 6.4.2) is used extensively as a sensitive radiation detector. The G-M counter operates in a manner similar to the ionization chamber and proportional chamber with the exception that the applied voltage is increased still further so that secondary ionization occurs to all gas atoms in the chamber. Because of the extensive secondary ionization, the sensitivity is greatly increased. However, the electrical pulse current generated internally is not generally proportional to the type of ionizing event, and it cannot be directly related to either absorbed dose or exposure. Therefore, the G-M counter is used primarily as a detector of potential radiation hazard but cannot usually be used as a monitoring device.

Figure 6.4.2

GEIGER-MUELLER COUNTER



The G-M counter is used primarily to detect the existence of low level radiation, especially in the range of 0-20 milliroentgens per hour. Under special conditions, the G-M counter can be modified to yield a response that is proportional to the exposure over a limited range of photon energies, but primarily it is used as a detection device for low energy beta and gamma radiation. The G-M counter has the capability of monitoring gamma radiation in the presence of neutrons.

The G-M counter is made in a variety of shapes, sizes, and compositions. These factors must be matched to the environment and the type of radiation that is to be monitored. In some instances, the sensitivity to beta radiation is dependent upon the angle of incidence of radiation; that is, the G-M counter is direction dependent. This is important to note in that the survey procedures that are used to detect radiation must take into consideration the directional factor of the G-M counter.

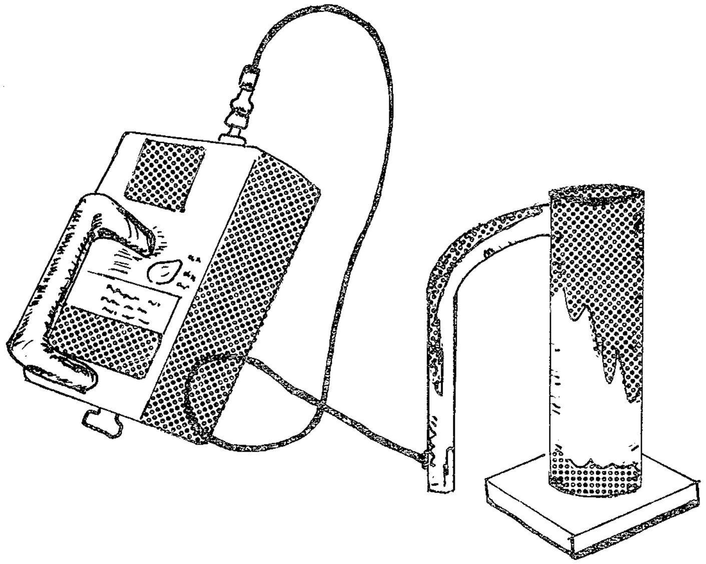
One characteristic of the G-M counter that also must be considered is the so-called "dead time." This dead time ranges from approximately ten to several hundred microseconds and is the time required for the ion avalanche to be initiated to travel along the anode and to be quenched, leaving the counter ready for a new count. Because of the design of the G-M counter and the massive secondary ionization that occurs because of the presence of ionizing radiation and the high voltage, time is required for the instrument to respond to the ionization in the chamber, initiate the avalanche, and then have the chamber return to a neutral state so that ionization may again occur. The halting of the avalanche is accomplished by the inclusion of an inert gas in the ion chamber. This gas is commonly referred to as a "quenching gas."

The G-M counter should <u>not</u> be used if it is anticipated that the count rate will be greater than 1,000 cpm (counts per minute). Because the G-M counter is energy dependent, an increased radiation level will cause a decrease or blockage of the meter reading. This occurs because the mechanics of a G-M counter cannot operate with such a high level of ionizing radiation. In this instance, the G-M counter may show a "no field" or no ionization radiation present when, in fact, the field is very high. In the instance where meter blockage occurs, no count will be registered. If the meter is not blocked, at least one count every few seconds will occur because of typical background radiation present in the environment. Therefore, if no counts register during the first few seconds, the counter is either inoperative or blocked. In this case, a less sensitive detector should be used, such as an ionization chamber. For the same reason, G-M counters should not be used for the measurement of short, high intensity pulses since this may also cause meter blockage.

The primary advantage of the G-M counter is that the unit is typically portable, generally stable and rugged, and has a high sensitivity. The disadvantages of this unit are that the readings cannot be directly related to absorbed dose or exposure but merely indicate the presence of ionizing radiation. Further, because of the presence of a high radiation field, the meter may block and read "no field" at 1000 cnts/min. Finally, most G-M counters have a directional sensitivity requiring a sweeping-type motion during any survey process.

Scintillation Detector. The scintillation detector (Figure 6.4.3) works on a different principle than the ionization chamber instruments previously discussed. With the scintillation detector, the ionizing radiation interacts with a phosphor or crystal that is capable of producing light. When the ionizing radiation falls on the scintillation counter, the crystal is excited and emits light. The light produced registers on a photomultiplier and is converted to electrical impulses. The electrical impulses are then magnified and registered on a microammeter. The number and size of the electrical impulses recorded are related to the energy deposited in the scintillator chamber.

Figure 6.4.3



SCINTILLATION-TYPE INSTRUMENT

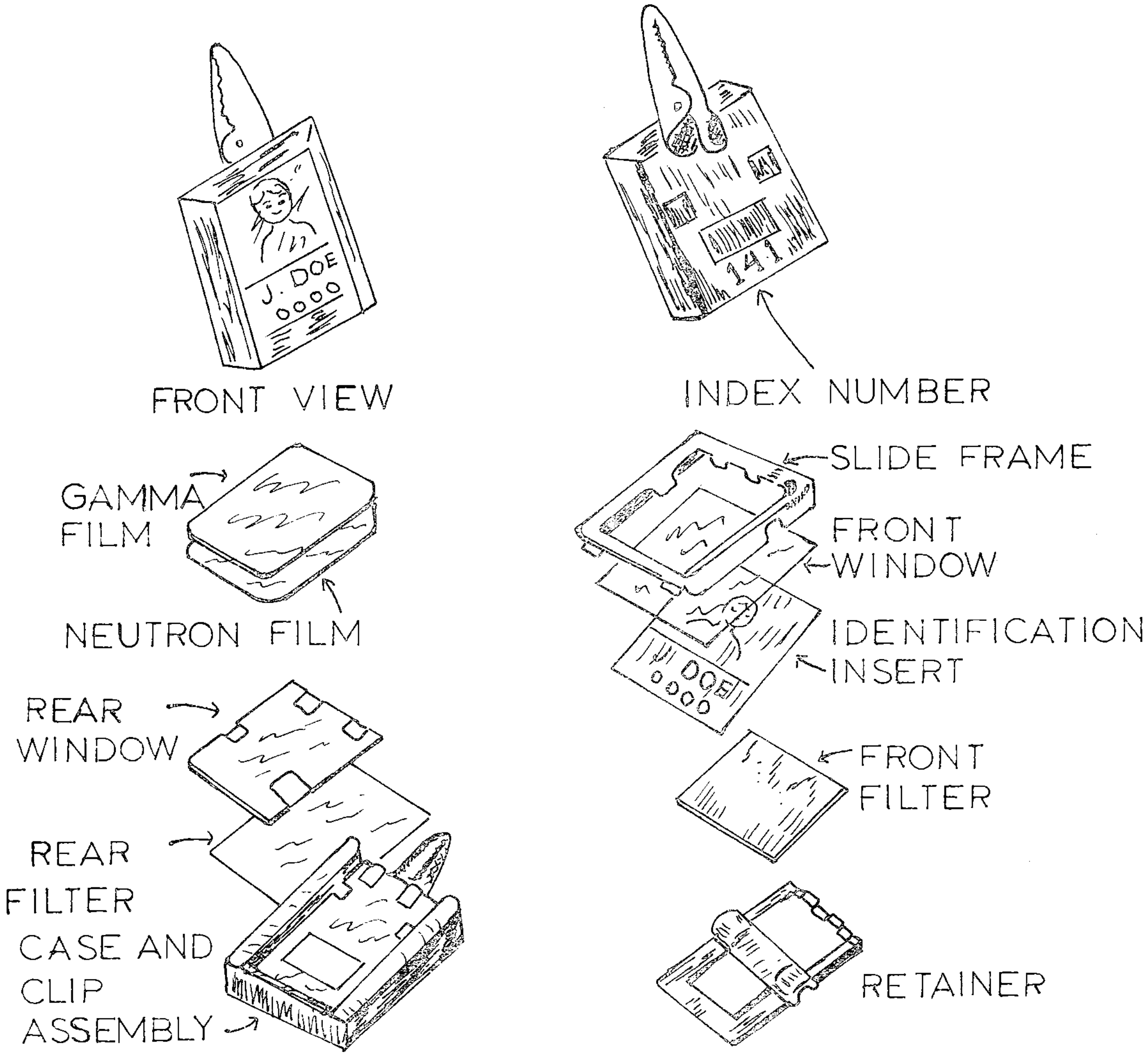
The scintillation detector has basically three components. The scintillator itself is a photo-sensitive crystal, plastic, or liquid that, when exposed to ionizing radiation, will emit light. The photomultiplier collects the light and converts it to electrical impulses. The final component of the system is the electronic counting equipment that registers and records the electrical current produced. The scintillation detector is most useful in the evaluation of alpha and low level gamma radiation. With a sodium iodide crystal, gamma radiation may be measured in the presence of beta. Also, the instrument may be modified so that beta radiation may be measured in the presence of high energy gamma. Further, soft X-rays may also be monitored using this instrument. Alpha particles using a cesium iodide crystal can be evaluated. To avoid the problem of the window of the chamber absorbing alpha particles, the radioactive sample can be placed in the scintillation chamber and a direct reading taken without interference from the window.

The primary advantage of this type of instrument is its sensitivity. It is possible to monitor low energy sources in the range of 5 μR/hr above background radiation. It has the capability of discriminating between different types and energies of radiation and has a relatively high counting efficiency; i.e., alpha and beta particle monitoring approaches 100% efficiency. Finally, the unit can be used as a spectrometer so that a mixture of several radionuclides can be analyzed quantitatively and qualitatively. This can be done because of the direct relationship between the pulse shape and height and the type and energy of the radiation being monitored.

One problem with this unit is that the photomultiplier and crystals are relatively fragile. Ths unit can be designed as a portable unit, but care must be taken not to damage the internal parts of the unit. Further, some crystals used are easily damaged by moisture and humidity and will cause erroneous readings because of environmental conditions. Care must be taken also to insure that the scintillator and photomultiplier are kept in a light-tight case to insure that erroneous readings are not taken. The instrument is usually designed to provide this light-tight case. However, because of wear and use, it is possible that extraneous light can enter the system and cause erroneous readings.

Photographic Devices. Photographic capabilities can also be used to monitor ionizing radiation. Photographic devices can be designed to provide a reasonably accurate and permanent record of cumulative exposure. Photographic films are available that are sensitive to the various types of ionizing radiation. The ionizing radiation interacts with the silver halide in the photographic emulsion on the film. The silver is ionized and then attracted to negatively changed sensitivity centers on the crystals in the film emulsion. At this point, the silver ions produced are reduce to a free silver compound. When the film is processed, the silver ions are removed; and the free silver stays attached to the film. The quantity of silver that remains is proportional to the exposure of ionizing radiation.

Figure 6.4.4



RADIATION FILM BADGE

The range of the film and the type of ionizing radiation to which it is sensitive are dependent upon the characteristics of the emulsion, the filtration that might be used, the processing technique, and the type and quality of exposing radiation. In general, the range of the emulsion is usually 10:1.

The primary use of the photographic device is in personnel monitors. These are commonly used as "film badges." Figure 6.4.4 is an illustration of a film badge.

Film badges generally are used to monitor beta, neutron, X-, and gamma radiation. Because the film must be maintained in a light-tight casement, only beta energy of greater than 0.2 MeV can penetrate the film casement. This also eliminates the possibility of using the film badge to monitor alpha radiation.

Usually the film badges are quite small. They require no power supply to operate, and special holders and packs have been devised to monitor various parts of the body; e.g., wrists and fingers. In many instances, larger film casements and film processes have been used to monitor ionizing radiation.

Using the photographic device as a monitoring process is relatively expensive and is not generally cost effective for less than two hundred people. Usually film badges are changed every two to four weeks and then processed. However, in some areas if radiation is either very critical or noncritical, they may be changed weekly or quarterly, as the system requires. A potential problem in using the film badge and not changing the badge on a biweekly or monthly basis is that high levels of accidental exposure may be undetected for long periods of time; e.g., if the film badges are changed on a quarterly basis.

Use of the film badge provides some distinct advantages. It provides a permanent record of radiation exposure and can be used on large populations of individuals. Film badges can be designed to discriminate between types of radiation and, because of their size and stability, can be used to monitor whole-body as well as individual parts of the body; e.g., fingers. However, there are some problems with using the film badge that should be considered. First, the film badge and exposure of ionizing radiation to the film badge is dependent upon the direction of the incident radiation. Therefore, if the film badge is not appropriately placed with respect to the potential source and the individual receiving the exposure, the readings on the film badge will be incorrect. Second, it is difficult to assess the absorbed dose and dose equivalent to within 20 to 50 percent for simple radiation fields. In those areas where a complex or multisource radiation field may exist, the error may be even greater. Third, calibration and processing of the film is somewhat complex. Because of the variations in the reactivity of the film emulsions from batch to batch, it is necessary to expose some of the film to a standardized radiation source and use this as the standard for that particular batch. This variation in sensitivity of the emulsions can cause problems in interpretation and calibration of the film system.

Finally, some film emulsions are reactive to water vapor, causing potential error in readings. Therefore, it is necessary to carefully contain all film badges in moisture-tight casements.

Solid-State and Activation Devices. Any solid material that, when radiated, exhibits a property whose response is a function of the energy absorbed may in principle be used as a radiation device. Aside from the properties already discussed, other physical properties that have been considered include coloration, photoluminescence, thermoluminescence, and photoconductivity. Of these, thermoluminescent, photoluminescent, and semiconductor detectors are also in common use. Therefore, they will be briefly discussed at this point.

Thermoluminescent detectors are useful in measuring X- and gamma radiation and high energy beta particles. The thermoluminescent material, when exposed to radiation, is ionized and "holes" develop in the lattice structure of the material. In essence, these "holes" are areas in the lattice where an electron has been removed by the ionizing radiation. When the material is heated, this provides adequate energy for the electrons to shift in the material and fill the holes. As this recombination occurs, light is emitted. The quantity of light emitted is proportional to the ionizing radiation exposure that originally caused the change in the lattice structure. Typically, materials such as calcium chloride, lithium chloride, and calcium phosphate are used for thermoluminescent detectors.

The advantage of these detectors is that they can be quite small; e.g., 0.01-1 gram. They are rugged and durable and provide monitoring over a wide range (10 milliroentgens, 10^5 roentgens). The reading provided usually is within ±5-10 percent, and the detector is reusable. The disadvantage of this type of detector is that an instrument is required to "read" the device. This reading device heats the detector and then records the light emitted. One problem that does exist with the use of thermoluminescent detectors if that of fading. The heat at room temperature may cause recombination and thus a reduction in the signal. For example, calcium sulphate readings may decrease by as much as 30 percent after eight hours and as much as 65 percent after eight days. Because of this problem, it is necessary to read the detector as soon as possible after potential exposure.

Photoluminescent devices work on a similar principle as the thermoluminescent devices, with the exception that rather than exposing the detector to heat to cause the emission of light, the photoluminescent device is exposure to ultraviolet light, thus causing light emission. Photoluminescent devices have the same advantages as the thermoluminescent devices including the long range and portability. They also share common problems in that a device is required to read the detector and fading may occur.

One final type of device that may be encountered is a device based upon the semiconductor principle. With this device, an exposure to ionizing radiation causes a change in conductivity of the subject material. This change in conductivity is then measured and, in some instances, is proportional to the exposure dose. This type of device can be used to measure alpha, beta, X-, or gamma radiation. In general, it acts as a solid ionization chamber with the exception that the range is from 10^{-6} to 10^{4} roentgens per hour. The major problem with this type of device is that the semiconductor may be temperature sensitive.

Personnel Monitoring Devices

Because of the importance of personnel monitoring, this section reviews the major types of detection devices used for personnel monitoring today.

Film Badges. Film badges were previously discussed. As mentioned, they are designed to provide a reasonably accurate and permanent record of cumulative exposure. They can be used to monitor whole-body or parts of the body as required. The primary problem as mentioned with the film badges is the complexity and time required for film processing.

Pocket Dosimeter. The pocket dosimeter is widely used in radiation monitoring. The dosimeter works on the principle of an ion chamber. It has the capability of indicating accumulated exposure to radiation at any given time and can be read by the individual without any type of reading instrument. However, the pocket dosimeter does not provide a permanent record of exposure; but it may be recharged which will reset the monitor to zero for reuse. The pocket dosimeter is prepared with a radiation scale to a maximum of 200 milliroentgens.

Pocket Chamber. The pocket chamber is also commonly used in monitoring radiation. It is similar in size and shape to a fountain pen. It, as with the pocket dosimeter, works on the principle similar to an ion chamber. The pocket chamber will indicate accumulated exposure to radiation at any time, but it requires a separate unit to read the device. As with the pocket dosimeter, it is calibrated in terms of milliroentgens and also requires recharging to reset the unit for repeated usages.

Choice and Use of Instruments

The factors that affect the selection of a particular instrument for use in monitoring ionizing radiation include the directional dependence of the instrument, the response rate and range, the susceptibility of the instrument to environmental interference, and the precision and accuracy of calibration as required by the user. Table 6.4.2 outlines generally the typical use of each of the devices discussed.

It will be necessary, however, to evaluate each individual setting to determine the specific instrument that would be appropriate for monitoring that environment.

Table 6.4.2

TYPES OF DETECTORS USED
FOR VARIOUS TYPES OF RADIATION

Type of Detector	Type of Radiation
Proportional or Scintillation Counter	Alpha
Geiger-Meuller Tube or Proportional Counter	Beta, Gamma
Ionization Chamber	X- and Gamma
Proportional Counter	N_f
Proportional Counter	N_t

CHAPTER 5

CONTROL OF IONIZING RADIATION

Identification of Radiation Safety Problems

Ionizing radiation cannot be felt, seen, heard, tasted, or smelled. This gives it a mysterious quality. Since, however, unknown radioactive isotopes can be identified and measured with the instruments described in the last chapter, ionizing radiation can be adequately monitored and controlled.

Areas where radiation dose rates may be excessive can be guarded during exposure time by suitable methods; such as the erection of barriers and warning signs, stationing of attendants to keep personnel out of restricted localities and, in extreme cases, complete closing of the areas. Safe exposure times and safe operating practices can be established through measurement and control and by profiting from experience.

Work with radiation can and should be so planned and managed that radiation exposure of employees and the general public is kept to a minimum. No radioactive material that can result in exposures above the established levels should be released through contaminated air or water, through loss of control over contaminated waste materials, equipment or shipments, or by employees unknowingly leaving the place of work with contamination of their persons, clothing, or shoes.

When examining the work environment for a potential radiation safety problem, many factors must be considered. First, the type of work in which the employee is involved must be evaluated. The potential level of exposure for working near the processing of feed materials for nuclear reactors is much greater than that which would be present in the area of an alpha-emitting static eliminator or beta ray thickness gauge. Further, radiation fields occurring with X-ray machines can be much more controlled than an unsealed radioisotope source. It is also dependent upon how involved the employee is with the process. For example, employees involved with the application of radioactive compounds, such as that applied to luminous instrument dials, would be in much closer contact with the radioactive source than an individual who is monitoring radioactive tracers used as labels in large pipeline distribution systems.

The second consideration that must be made is the source of the radiation. The amount and type of radiation is important. As mentioned, those radioactive sources that are instruments or machines can be turned off, whereas radioisotopes will emit radiation constantly. Also, each radionuclide has a radio toxicity per unit activity that varies from nuclide to nuclide. Further, sealed sources are not nearly so dangerous as unsealed sources. Finally, if the radioisotope is in the form of a radioactive metal that is going through some type of machining process, a major problem will be the spread of loose material--e.g., flaking, grinding chips--and the contamination of the employee.

If the operational factors are considered, the required level of radiation protection and potential problems that might arise can be determined. The operational factors that should be evaluated include such things as:

1. The area involved (square feet), number of rooms and buildings.
2. Number of employees potentially exposed to the radiation and the location of those employees.
3. The chemical and physical states of the radioactive material and its use.
4. Potential incidents that are likely to occur that would increase the potential exposure to the employees.
5. Nonradiation hazards that might be involved; that is, high voltage, toxicity of chemical substances.
6. The nature of the probable exposure to the employees; that is, whether or not the exposure would be a controlled or supervised release such as through some type of disposal procedure, accidental release that may not be sensed by warning devices, or a violent release of dust droplets or gases--such as through fire or explosion--that may carry radioactive contamination.
7. The inherent danger of the materials and procedure being implemented.
8. The probability of detection of a potentially harmful radioactive situation by routine surveys and monitoring.
9. Possible effects of a radiation accident on operation; for example, loss of production, loss of space, and cleanup costs.

Finally, consideration must be given to the potential employee exposure. Efforts should be made to calculate the maximum dosage, given a specific type of incident, that the employee might receive. This should be done for both external and internal radiation potentials.

If the above factors are given consideration in the development of an overall radiation safety analysis, then potential employee exposure will be minimized.

Authorization for Radionuclide Use

Generally, the use of radionuclides and radiation-producing instruments (X-ray machines) is licensed through the Federal government or state health departments. The Nuclear Regulatory Commission (NRC) has established guidelines for the licensing of radionuclide users. Table 6.5.1 indicates the minimum quantity for radioactive materials that must be licensed through the NRC. Because of the variation in state requirements, licensing procedures should be investigated if radionuclide sources are to be used.

In general, any request for license requires the following information. The type and potential use of the radionuclide must be indicated, along with the maximum quantities of radionuclide that would be involved. The application must also define the training and experience of the users. It must define the laboratory facilities, handling equipment, and the monitoring procedures that will be used with the radioactive source. If it is necessary to dispose of the radioactive waste, this must also be defined. Finally, an outlined radiation protection program must be identified.

Although the above requirements need to be met only if NRC licensure is being sought, these requirements for licensure provide a good general outline of the components of a radiation safety program the industrial hygienist should consider.

Table 6.5.1

SAMPLE LICENSURE

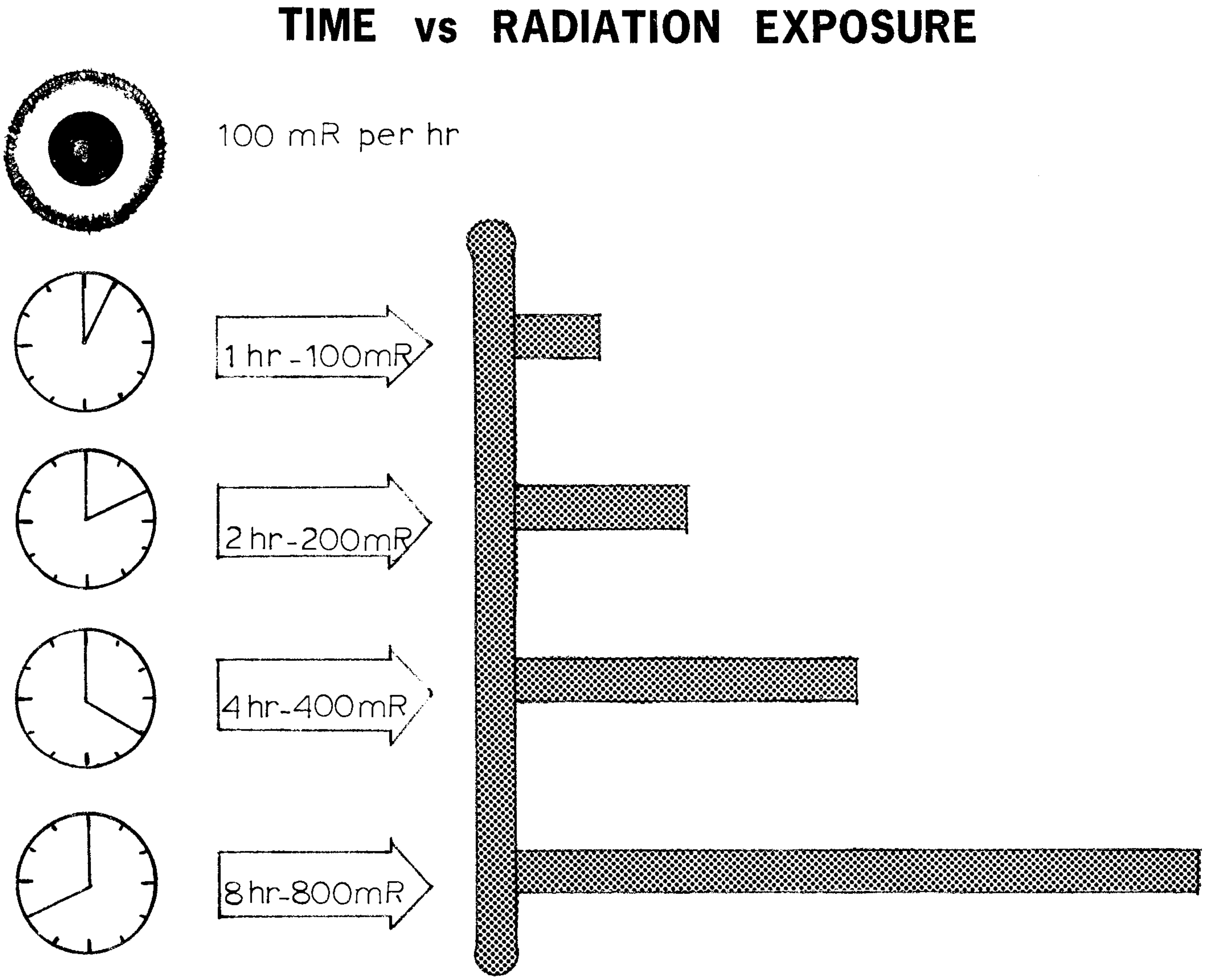
Radionuclide	Minimum Quantity for Radioactive Materials Sign in Room (μCi)	Minimum Quantity for Radioactive Materials Label (μCi)
Calcium-25	100	10
Carbon-14	1,000	100
Cesium-137 and Barium-137	100	10
Chlorine-36	100	10
Chromium	10,000	1000
Cobalt-60	10	1
Copper-64	1,000	100
Gold-198	100	100
Hydrogen-3	10,000	1000
Iodine-125	10	1
Iodine-131	10	1
Iron-55	1,000	100
Iron-59	100	10
Phosphorus-32	100	10
Potassium-42	100	10
Radium-226	0.1	0.01
Sodium-24	100	10
Strontium-90 and Yttrium-90	1	0.1
Zinc-65	100	10
Unidentified, but not α emitter	1	0.1
Unidentified α emitter	0.1	0.01

Protection from Radiation Hazard

There are three basic tools that can provide protection against a radiation source. These are time, distance, and shielding. The goal of the protection is to prevent overexposure from external radiation and to minimize the entry of radionuclides into the body, or minimize internal radiation.

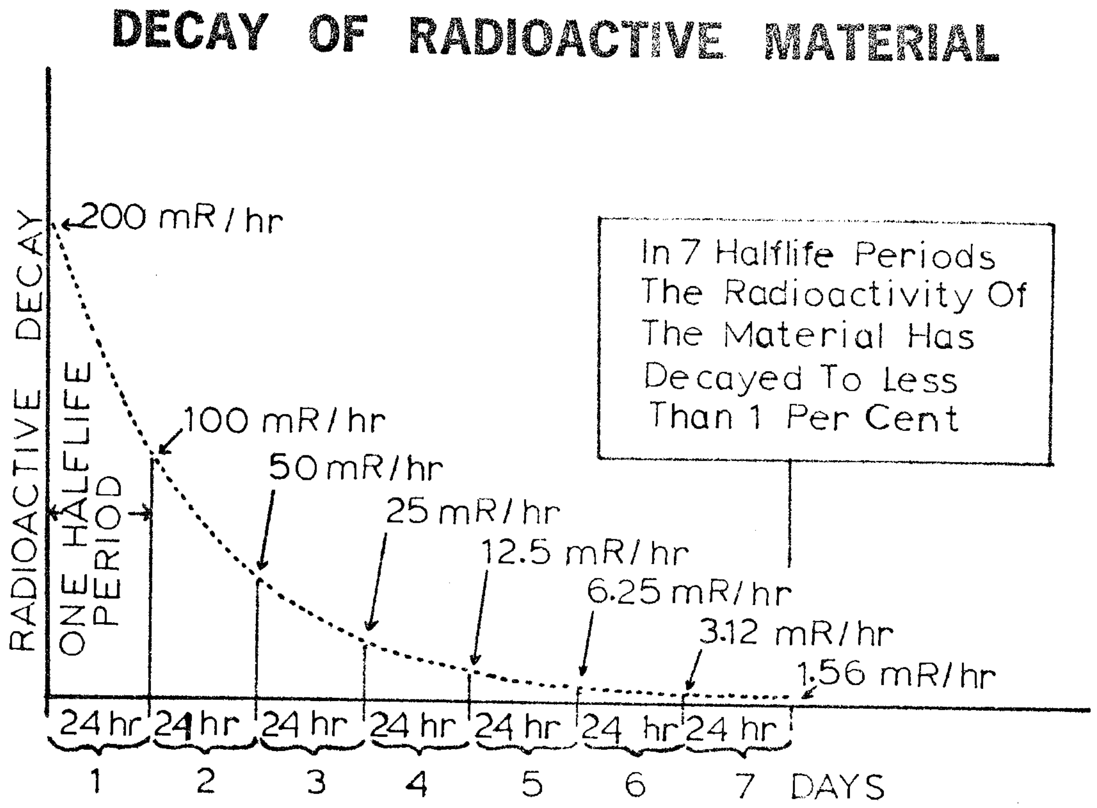
Time. As an element of protection, time is almost self-explanatory. Radiation occurs at a rate of roentgens (or rads) per hour. Therefore, the shorter the time of exposure, the smaller the radiation dose received by the personnel. Figure 6.5.1 illustrates this concept.

Figure 6.5.1



According to the figure, if someone is in an area where the radiation level from penetrating external radiation is 100 mR/hour, then in one hour he would receive 100 mR. If he stayed two hours, he would get 200 mR, and so on. Therefore, if work procedures can be reviewed and analyzed such that the time of exposure is minimized, then the exposure dose received by the employee is also minimized. Time also pays an important role with respect to protection when considering the factor of "half-life." If an exposure potential is high in a given area and the radioactive source has a short half-life, it is possible to just wait for radioactive decay to occur; and the activity of the radionuclide will be reduced. As demonstrated in Figure 6.5.2, at the end of seven half-lives the activity is reduced to one percent of the original activity. It is possible to calculate the loss of activity due to radioactive decay if the original activity and date of measure are known.

Figure 6.5.2



The decrease of activity is equal to $(1/2)^n$, where n is equal to the number of half-lives that have passed since the last known measurement.

Example

An isotope user acquired from a national laboratory a surplus Co-60 source in June, 1977. The source was last measured for activity in January, 1970. At that time, the source had an activity of 40 mR/hr at 10 cm.

What is the anticipated exposure rate at 10 cm in June, 1977?

Solution

January 1970 to June 1977 = 7.5 years

Half-life of Co-60 = 5.3 years

Half-life transpired = 7.5/5.3 = 1.415 half lives

Using $(1/2)^n \rightarrow (1/2)^{1.415} = 0.375$

Exposure rate (June 1977) $= \frac{40 \text{ mR}}{\text{hr}} \cdot 0.375 = \frac{15 \text{ mR}}{\text{hr}}$

For convenience, tables for $(1/2)^n$ have been developed for use as illustrated in Table 6.5.2.

Table 6.5.2

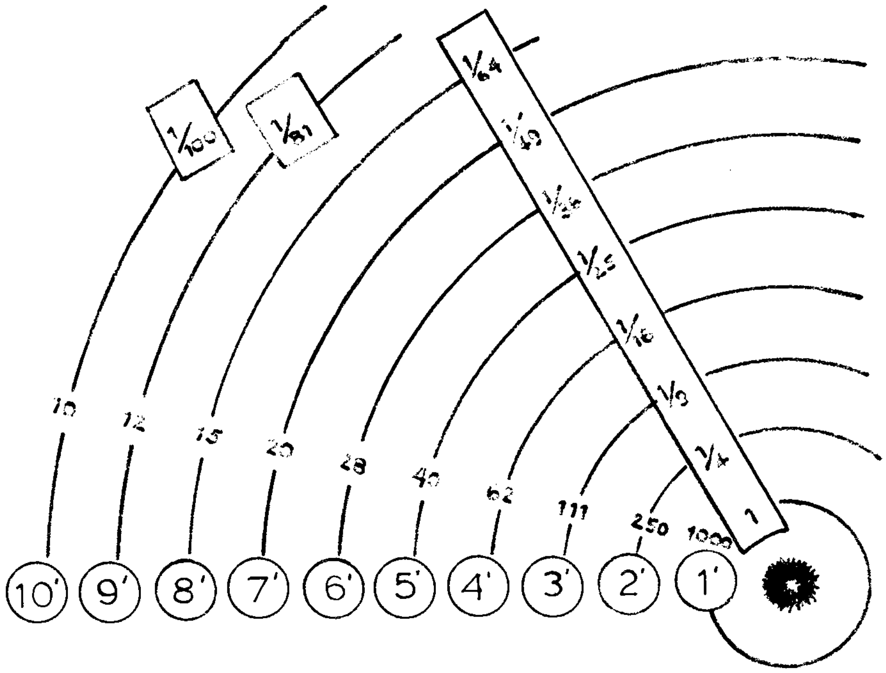
POWERS OF ONE-HALF FOR ATTENUATION AND DECAY CALCULATIONS, $(1/2)^n$

n	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	1.000	0.933	0.871	0.812	0.758	0.707	0.660	0.616	0.578	0.536
1	0.500	0.467	0.435	0.406	0.379	0.354	0.330	0.308	0.287	0.268
2	0.250	0.233	0.217	0.203	0.190	0.177	0.165	0.154	0.144	0.134
3	0.125	0.177	0.109	0.102	0.095	0.088	0.083	0.077	0.072	0.067
4	0.063	0.058	0.054	0.051	0.047	0.044	0.041	0.039	0.036	0.034
5	0.031	0.029	0.027	0.025	0.024	0.022	0.021	0.019	0.018	0.017
6	0.016	0.015	0.014	0.013	0.012	0.011	0.010			

"n" is the number of half value layers or half-lives.

Distance. The second tool used for protection against radiation exposure is distance. The exposure rate is reduced by a factor of one divided by the square of the distance between the employee and the course. This is referred to as the "inverse square law." Figure 6.5.3 demonstrates the effect of the inverse square law on the intensity of radiation.

Figure 6.5.3



DISTANCE vs RADIATION EXPOSURE

If there is a point source of radiation giving off 1000 units of penetrating external radiation at one foot, a worker would receive only one-fourth as much, or $1/2^2$, if the distance is doubled to two feet. If the distance is tripled, the dose is reduced to one-ninth, or $1/3^2$.

For example, if it is known that the radiation level is 1.0 R/hr at one foot, what would the exposure be if the worker was moved to a distance of five feet? Using the inverse square law, the radiation level at five feet would be equal to 1.0 R/hr divided by $(5)^2$, or 0.04 R/hr. The advantage of distance as a protective tool when working with radiation can be seen from this example. The example illustrates the valuable use of tools such as long tongs. One important point that must be mentioned is that the distance of measurement and the units used in the "inverse square law" must be equivalent; that is, if exposure levels are determined at X feet, the variations in distance must also be calculated in feet.

Shielding. The third tool to be used in protection against radiation is shielding. Shielding reduces radiation to the employee by placing a radiation absorbing barrier between the source and the employee to be protected. The selection of the shielding is dependent upon the type and quantity of the radionuclide present. Table 6.5.3 illustrates some typical shielding materials used for the various types of radiation. The arrangement of the materials in the table is in the general order of increased thickness required to be an adequate shield.

Table 6.5.3

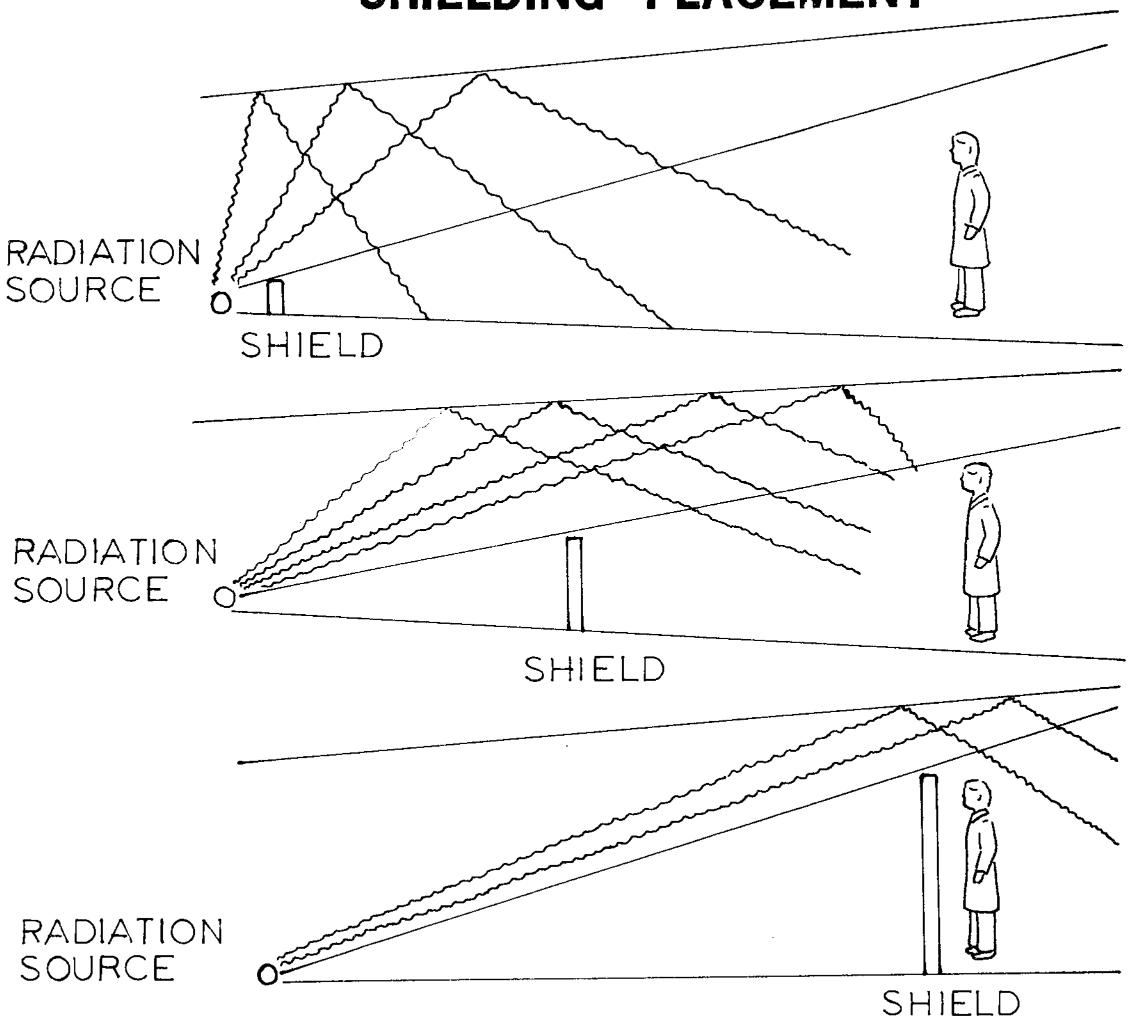
TYPICAL SHIELDING MATERIALS FOR RADIONUCLIDES

	Shielding Material		
	Permanent	Temporary	Additional Clothing
Alpha	Unnecessary	Unnecessary	Unnecessary
Beta	Lead, copper, iron, aluminum,	Iron, aluminum, plastics, wood,	Leather, rubber, plastic, cloth
Gamma, X-rays	Lead, iron, copper, lead glass, heavy aggregate concrete, aluminum, ordinary concrete, plate glass, wood, water, paraffin	Lead, iron, lead glass, aluminum, concrete blocks, water, wood	Lead fabrics (but not for "hard" gamma)

Care must be taken to insure that the location and shape of the shield limits radiation in all directions which may provide potential exposure to all employees; e.g., floor, ceiling. The thickness of the shielding required is relatively independent of the distance from the source or object. However, to minimize the size of the shield and to maximum protection, the shield should be as close to the source as possible as illustrated in Figure 6.5.4.

Figure 6.5.4

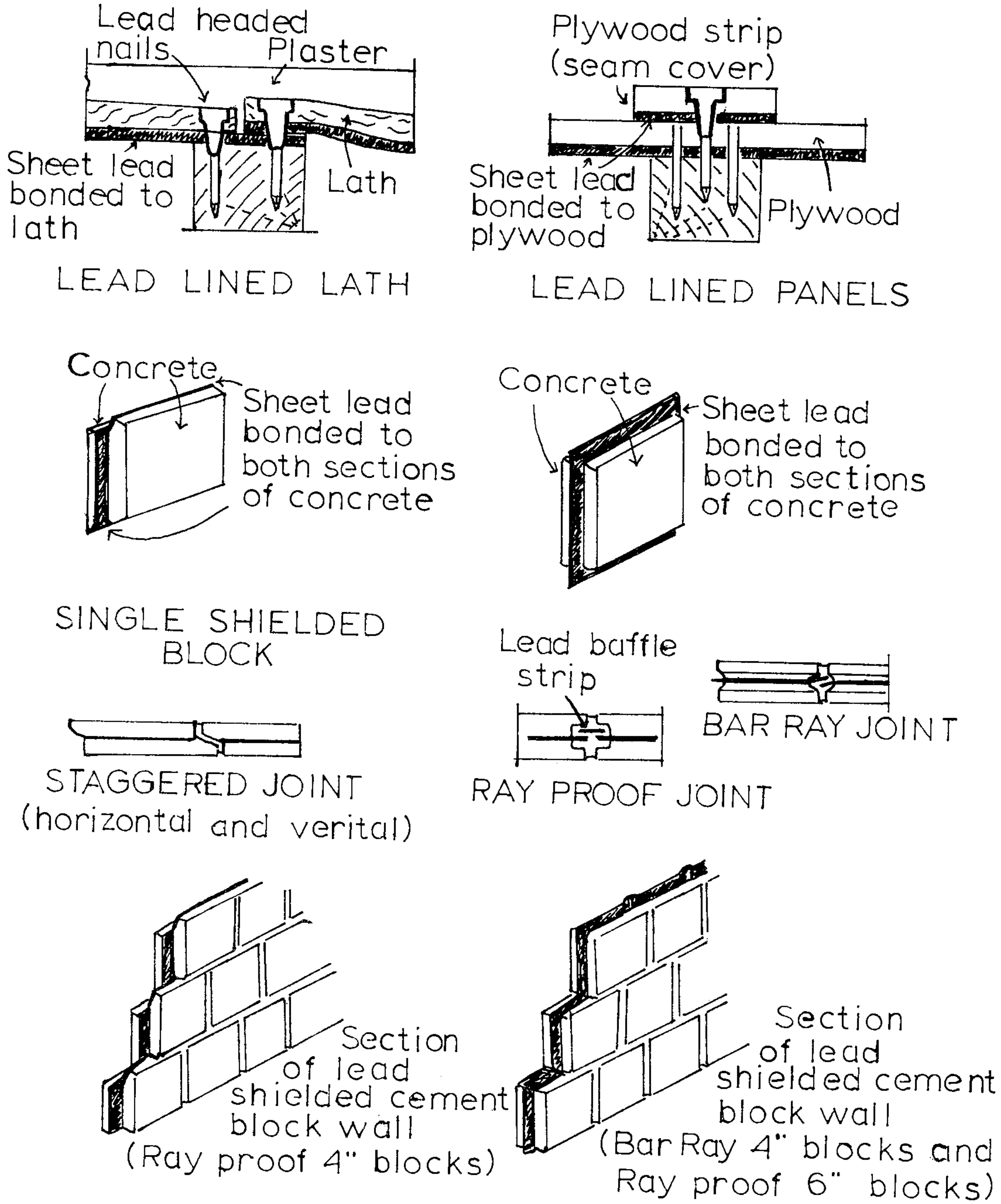
SHIELDING PLACEMENT



REDUCTION OF SCATTER BY PLACEMENT OF SHIELD CLOSE TO EITHER SOURCE OR PERSON TO BE SHIELDED

By placing the shield in close proximity to the source, incident radiation is minimized, and the expenditure for the shield is also reduced. Shields may be cylindrical or box shaped, depending upon local needs. Local shields are often built of lead bricks or concrete blocks, as presented in Figure 6.5.5.

Figure 6.5.5



LEAD LINED LATH

LEAD LINED PANELS

SINGLE SHIELDED BLOCK

STAGGERED JOINT (horizontal and verital)

RAY PROOF JOINT

BAR RAY JOINT

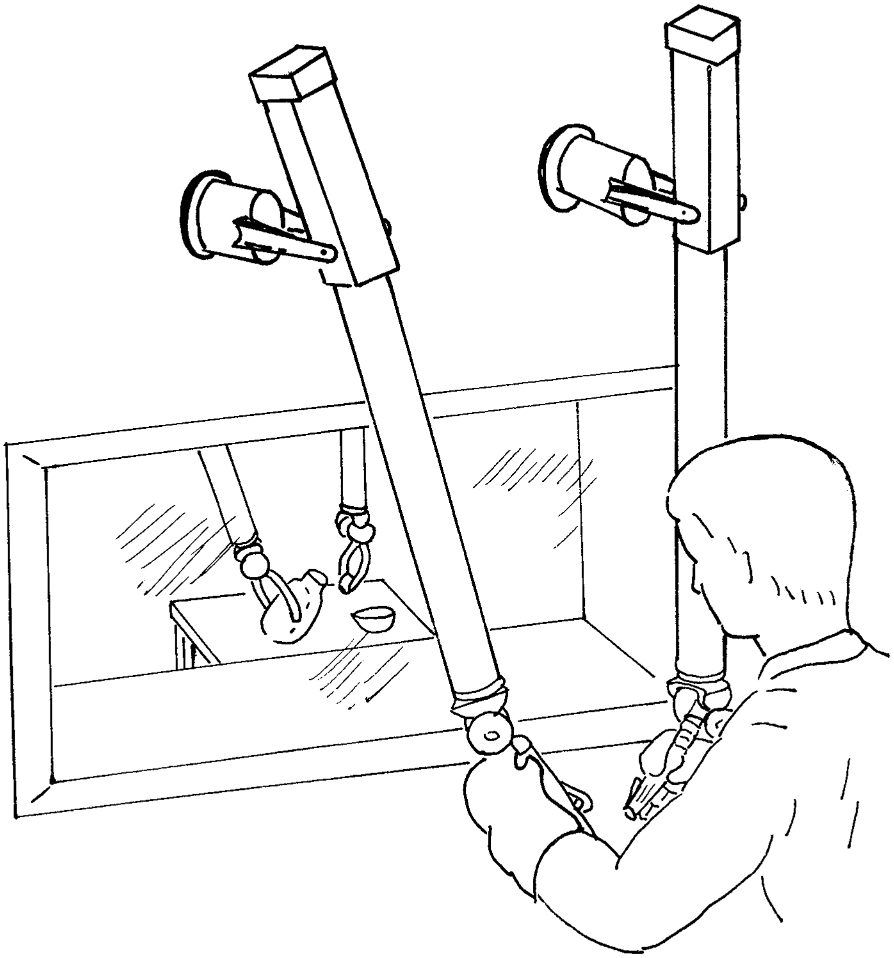
Section of lead shielded cement block wall (Ray proof 4" blocks)

Section of lead shielded cement block wall (Bar Ray 4" blocks and Ray proof 6" blocks)

MATERIALS FOR SHIELDING

A major concern in developing local shielding with any type of block or bricking is that radiation may leak through the cracks in the blocks, or incident radiation may be reflected off walls or even the shield itself. In many instances, the radioactive source is active enough such that the shielding limits the employee to approaching the radioactive source from a distance or by remote control. (Figure 6.5.6)

Figure 6.5.6



MASTER-SLAVE MANIPULATOR

Gamma Radiation Shielding. The purpose of shielding is to reduce the radiation exposure to an acceptable level; the shield absorbs the radiation. Gamma radiation is photon energy with a high penetrating capability; and, therefore, materials of high density--including lead, iron, and concrete--are used as shielding materials. The absorption of gamma radiation by a shield is an exponential function related by the equation

$$I = I_o e^{-ux}$$

where I is the exposure rate (R/hr) after passing through the shield, I_o is the initial exposure rate (R/hr) at the shield, u is the absorption coefficient of the shielding material (cm^{-1}), and x is the shield thickness (cm). The absorption coefficient is a function of the energy level of the radiation and the properties of the shielding materials. Often times the absorption coefficient is expressed as a mass attenuation coefficient (cm^2/g) (Table 6.5.4). To calculate u, given the mass attenuation coefficient, it is necessary to divide the mass attenuation coefficient by the density of the shielding material.

Table 6.5.4

MASS ATTENUATION COEFFICIENTS

Photon Energy	Mass Attenuation Coefficient in cm^2/g for--				
Mev	Aluminum	Iron	Lead	Water	Concrete
0.01	26.3	173	133	5.18	26.9
0.02	3.41	25.5	85.7	0.775	3.59
0.05	0.369	1.94	7.81	0.227	0.392
0.1	0.171	0.370	5.40	0.171	0.179
0.5	0.0844	0.0840	0.161	0.0968	0.087
1.0	0.0613	0.0599	0.0708	0.0707	0.0637
5.0	0.0284	0.0314	0.0424	0.0303	0.0290
10.0	0.0231	0.0298	0.0484	0.0222	0.0231

Source: "Radiological Health Handbook," U.S. DHEW, Public Health Service, 1970.

Therefore, shielding requirements or effects of a given shield can be calculated.

The effect of shielding is also often expressed in terms of half value layers (HVL). The half value layer is the thickness of a specified shielding material to reduce the exposure rate from a specific radiation source by a factor of 0.5. For example, in 2.6 half value layers, the number of photons will be reduced $(0.5)^{2.6}$ or 0.165 of the original number entering the specified shield. Using $(0.5)^n$ or Table 5.2, it is possible to calculate the number of half value layers required for a desired attenuation of the radiation. It also allows for the calculation of a given attenuation for a certain thickness of a shield. Table 6.5.5 illustrates some typical half value layers for five isotopes. The calculation of HVL is similar to the calculation of the effect of half life; i.e., attenuation shield = $(0.5)^{HVL}$.

Table 6.5.5

DATA FOR GAMMA-RAY SOURCES

Radioisotope	Atomic Number	Half Life	Gamma Energy (MeV)	Half-Value Layer Conc. in	Half-Value Layer Steel in	Half-Value Layer Lead cm	Tenth-Value Layer[a] Conc. in	Tenth-Value Layer[a] Steel in	Tenth-Value Layer[a] Lead cm	Specific Gamma-Ray Constant $R\ cm^3/m\ Ci\text{-}h$[b]
Cesium-137	55	27 y	0.66	1.9	0.64	0.65	6.2	2.1	2.1	3.2
Cobalt-60	27	5.24 y	1.17, 1.33	2.6	0.82	1.20	8.2	2.7	4.0	13.0
Gold-198	79	2.7 d	0.41	1.6	--	0.33	5.3	--	1.1	2.32
Iridium-192	77	74 d	0.13 to 1.06	1.7	0.50	0.60	5.8	1.7	2.0	5.0[c]
Radium-226	38	1622 y	0.047 to 2.4	2.7	0.88	1.66	9.2	2.9	5.5	8.25[d]

From "NCRP Report No. 34," National Council on Radiation Protection and Measurements, Washington, D.C., 1971

[a] *Approximate values obtained with large attenuation.*

[b] *These values assume that gamma absorption source is negligible. Value is R/millicurie-hour at 1 cm can be converted to R/Ci-h at 1 meter by multiplying the number in this column by 0.10.*

[c] *This value is uncertain.*

[d] *This value assumes that the source is sealed within 0.5 mm thick platinum capsule, with units of R/mgh at 1 cm.*

An example may further explain the shielding calculation.

Example

Calculate the thickness of a lead shield necessary to reduce the exposure rate from 10.0 R/hr to 2.5 R/hr from a Co-60 source.

Solution

HVL Method

$$\text{Attenuation required} = \frac{2.5\ \text{R/hr}}{10.0\ \text{R/hr}} = 0.25$$

Calculate HVL necessary

$$(0.5)^{\text{HVL}} = 0.25$$

$$\text{HVL} = \frac{\log 0.25}{\log 0.5} = \frac{-0.602}{-0.301} = 2\ \text{HVL}$$

$$2\ \text{HVL} \cdot \frac{1.25\ \text{cm Pb}}{\text{HVL}} = 2.48\ \text{cm Pb}$$

I/I_o Method

$$I = I_o e^{-ux}$$

$$x = \frac{-\ln(I/I_o)}{\mu}$$

$I = 2.5$ R/hr

$I_o = 10.0$ R/hr

Using table

$$\mu = \frac{0.060\ \text{cm}^2}{\text{g}} \times \frac{11.34\ \text{g}}{\text{cm}^3} = 0.680\ \text{cm}^{-1}$$

Note: Pb (density) = 11.34 g/cm^3

$$x = \frac{-\ln(2.5/10.0)}{0.68\ \text{cm}^{-1}} = 2.04\ \text{cm}$$

Example

An unshielded source of Cesium-137 has an exposure rate of 0.1 mR/hr. What would be the exposure rate if a 3 centimeter lead shield were placed around the source? (HVL: Cesium-137 = 0.64 cm lead (Pb)). MeV: Cs-137 = 0.66 MeV)

Solution

HVL Method

The solution to this example is rather straightforward. The HVL of these gamma photons is 0.65 cm. The number of HVL in a 3 cm shield would then be equal to 3.0 ÷ 0.65 or 4.62 half value layers. Using Table 6.5.2, n is equal to 4.62, which when extrapolated would indicate an attenuation coefficient of approximately 0.41. Therefore, the exposure rate with a 3 cm lead shield surrounding the source would be equal to 0.1 mR/hr x 0.041 or 4.1 μR/hr.

I/I_o Method

$I = I_o e^{-ux}$

$I = ?$

$I_o = 0.1$ mR/hr

$x = 3$ cm

$$u = \frac{0.105 \text{ cm}^2}{\text{g}} \times \frac{11.34 \text{ g}}{\text{cm}^3} = 1.19 \text{ cm}^{-1} \quad \text{(from table)}$$

$$1 = 0.1 \text{ mR/hr} \cdot e^{-(1.19 \times 3)}$$

$$= 2.82 \ \mu\text{R/hr}$$

In the previous example, the calculated values as determined by the two methods are somewhat different. More important, the effect as calculated by the I/I_o method is significantly less. This is because the formula, $I = I_o e^{-ux}$, does not take into consideration a "build-up" phenomenon. In matter being traversed by a beam of electromagnetic radiation, there is actually a higher intensity of photons at any point in the matter than would be predicted by the equation. This is true because of the presence of X-radiation and secondary or scattered photons produced as the radiation penetrates the matter. The increase in exposure rate, buildup (B), is not easily calculated but must be considered when determining shielding requirements. A factor B is included in the attenuation equation $I = BI_o e^{-ux}$, with the tablulated values of B for specific conditions available in the literature. Table 6.5.6 illustrates the dose build-up factor for a point isotropic source. Using such a table, the factor B can be included in the shielding calculation.

Table 6.5.6

DOSE BUILDUP FACTOR (B) FOR A POINT ISOTROPIC SOURCE

Material	MeV	μX*						
		1	2	4	7	10	15	20
Water	0.255	3.09	7.14	23.0	72.9	166	456	982
	0.5	2.52	5.14	14.3	38.8	77.6	178	334
	1.0	2.13	3.71	7.68	16.2	27.1	50.4	82.2
	2.0	1.83	2.77	4.88	8.46	12.4	19.5	27.7
	3.0	1.69	2.42	3.91	6.23	8.63	12.8	17.0
	4.0	1.58	2.17	3.34	5.13	6.94	9.97	12.9
	6.0	1.46	1.91	2.76	3.99	5.18	7.09	8.85
	8.0	1.38	1.74	2.40	3.34	4.25	5.66	6.95
	10.0	1.33	1.63	2.19	2.97	3.72	4.90	5.98
Aluminum	0.5	2.37	4.24	9.47	21.5	38.9	80.8	141
	1.0	2.02	3.31	6.57	13.1	21.2	37.9	58.5
	2.0	1.75	2.61	4.62	8.05	11.9	18.7	26.3
	3.0	1.64	2.32	3.78	6.14	8.65	13.0	17.7
	4.0	1.53	2.08	3.22	5.01	6.88	10.1	13.4
	6.0	1.42	1.85	2.70	4.06	5.49	7.97	10.4
	8.0	1.34	1.68	2.37	3.45	4.58	6.56	8.52
	10.0	1.28	1.55	2.12	3.01	3.96	5.63	7.32
Iron	0.5	1.98	3.09	5.98	11.7	19.2	35.4	55.6
	1.0	1.87	2.89	5.39	10.2	16.2	28.3	42.7
	2.0	1.76	2.43	4.13	7.25	10.9	17.6	25.1
	3.0	1.55	2.15	3.51	5.85	8.51	13.5	19.1
	4.0	1.45	1.94	3.03	4.91	7.11	11.2	16.0
	6.0	1.34	1.72	2.58	4.14	6.02	9.89	14.7
	8.0	1.27	1.56	2.23	3.49	5.07	8.50	13.0
	10.0	1.20	1.42	1.95	2.99	4.35	7.54	12.4
Lead	0.5	1.24	1.42	1.69	2.00	2.27	2.65	(2.73)
	1.0	1.37	1.69	2.26	3.02	3.74	4.81	5.86
	2.0	1.39	1.76	2.51	3.66	4.84	6.87	9.00
	3.0	1.34	1.68	2.43	2.75	5.30	8.44	12.3
	4.0	1.27	1.56	2.25	3.61	5.44	9.80	16.3
	5.1087	1.21	1.46	2.08	3.44	5.55	11.7	23.6
	6.0	1.18	1.40	1.97	3.34	5.69	13.8	32.7
	8.0	1.14	1.30	1.74	2.89	5.07	14.1	44.6
	10.0	1.11	1.23	1.58	2.52	4.34	12.5	39.2

*μX = mass absorption coefficient (μ/ρ) x shield thickness (cm) x shield density (g/cm^2).

Note: For concrete, use an average of aluminum of iron;
e.g., B (conc) = [B(iron) + B(Al)] ÷ 2.

Source: *"Radiological Health Handbook," U.S. DHEW, Public Health Service, 1970.*

Example

Calculate the exposure rate (I) for the previous example allowing for the buildup factor.

Solution

$I = BI_o e^{-ux}$

$I_o = 0.1$ mR/hr

$\mu = 0.105\ \text{cm}^2/\text{g} \times \frac{11.34\ \text{g}}{\text{cm}^3} = 1.19\ \text{cm}^{-1}$

$x = 3.0$ cm Pb

Using table 6.5.6 for

$\mu x = 1.19\ \text{cm}^{-1} \times 3.0\ \text{cm} = 3.57$

Cs-137 = 0.66 MeV

Interpolating, B = 1.79

$I = 1.79 \times \frac{0.1\ \text{mR}}{\text{hr}} \times e^{-(3.57)}$

$= 5.04\ \mu\text{R/hr}$

One final calculation that can be made when examining gamma radiation is that of projecting the potential exposure rate at a given distance of a gamma source. To make this calculation, it is necessary to know the type of radionuclide, the relative energies of that nuclide, and its activity. The formula will express exposure in terms of milliroentgens per hour and is as follows:

$$\text{mR/hr} = \frac{5000\ \text{CEf}}{d^2}$$

where

C = activity (in microcuries)

E = energy in million electron volts (MeV)

f = the fraction of disintegration emitting E

d = the distance in cm

If the distance is to be calculated in feet, then the constant, 5000, must be replaced with the constant, 6. Further, if more than one level of photon energy is given off, each energy level (E) times its fraction of disintegration (f) must be calculated and a cumulative total of the exposure made.

This formula has two values. First, if a new source is being introduced, it is possible to calculate the exposure rate of that source at any distance. Second, in an emergency, it is possible to calculate the approximate safe distance that will not exceed the maximum permissible dose (MPD) limits. Table 6.5.7 presents data on typical radionuclides as found in the literature. This information will be used in subsequent examples and practice exercises.

Example

A 50 microcurie source of Krypton-85 is to be used in a new industrial process being introduced in your facility. What is the exposure rate of an unshielded source at 25 cm?

Solution

$$\text{mR/hr} = \frac{5000\ \text{CEf}}{d^2}$$

where

C = 50 microcuries

E = 0.514 million electron volts

f = 0.43%

d = 25 centimeters

Therefore

$$\text{mR/hr} = \frac{5000 \times (0.514 \times 0.0043) \times 50}{25^2}$$

$$= 0.885\ \text{mR/hr at 25 cm}$$

It is also possible to perform the same calculation using the gamma ray constant (Γ) in the formula.

$$\text{R/hr} = \frac{\Gamma A}{d^2}$$

where

Γ = gamma ray constant (R-cm^2/hr-mci)

A = activity (mCi)

d = distance (cm)

Table 6.5.7

DATA ON RADIONUCLIDES REFERRED TO IN PROBLEMS

Radionuclide	Symbol	Half-Life	Major radiations, energies (MeV) and percent of disintegrations	Specific gamma ray constant, Γ R-cm^2/hr-mCi
Calcium-45	Ca-45	165 days	β-0.257 max; 0.077 av	
Carbon-14	C-14	5730 yr	β-0.156 max; 0.049 av	
Cesium-137	Cs-137	30 yr	β-1.174 max; (5.9%) 0.512 max; (94.1%) 0.188 av/dis ε-0.624 (7.8%); 0.656 (1.7%) γ 0.662 (85%) + low energy barium x-rays	3.3
Cobalt-60	Co-60	5.3 yr	β-1.49 max (0.12%) 0.318 max (100%) 0.087 av/dis γ 1.332 (100%); 1.173 (100%)	13.2
Gold-198	Au-198	2.70 days	β-0.961 max (99%) 0.28 max (1%); 0.32 av/dis ε-0.33(2.9%); 0.40 (1.4%) γ 1.088 (0.2%) 0.676 (1%); 0.412 (95%)	2.35
Hydrogen-3	H-3	12.3 yr	β-0.0185 max; 0.0057 av	
Iodine-131	I-131	8.05 days	β-0.807 max (0.7%) 0.606 max (90%) 0.33 max (7%); 0.18 av/dis ε-0.33 (1.7%); 0.046 (3%) γ 0.723 (1.6%); 0.637 (6.9%); 0.364 (82%) 0.284 (5.8%); 0.08 (2.5%)	2.18
Iron-59	Fe-59	45.6 days	β-1.57 max (0.3%); 0.47 max (53%) 0.27 max (46%); 0.188 av/dis γ 1.292 (44%); 1.099 (56%); 0.192 (2.8%) 0.143 (0.8%)	6.13
Krypton-85	Kr-85	10.3 yr	β-0.67 max; 0.246 av γ 0.514 (0.43%)	1.29

Table continued

Table 6.5.7

DATA ON RADIONUCLIDES REFERRED TO IN PROBLEMS

Radionuclide	Symbol	Half-Life	Major radiations, energies (MeV) and percent of disintegrations	Specific gamma ray constant, Γ R-cm^2/hr-mCi
Molybdenum-99	Mo-99	67 hr	β-1.23 max (80%); 0.454 max (19%)	1.29
+ Technetium-99m			γ 0.392 av/dis 0.78 (4.8%); 0.74 (14%) (4.8%); 0.74 (14%); 0.37 (1.5%); 0.18 (6.7%); 0.14 (90%); 0.04 (1.3%) 0.019 (12%); + low energy Tc-99 x-rays	
Phosphorous-32	P-32	14.3 days	β-1.71 max; 0.695 av	
Potassium-42	K-42	12.4 hr	β-3.52 max (82%); 2.0 max (18%); 1.43 av dis γ 0.31 (0.2%); 1.52 (18%)	1.50
Sodium-24	Na-24	15.0 hr	β-1.389 max; 0.55 av γ 2.754 (100%); 1.369 (100%)	18.8 (11.7 from 2.75 MeV and 7.1 from 1.37 MeV)
Sulfur-35	S-35	87.9 days	β-0.167 max; 0.049 av	
Technetium-99m	Tc-99m	6.0 hr	ε-0.138 (1.1%); 0.199 (8.8%); 0.0017 (98.6%); 0.017 av/dis γ 0.140 (90%) + low energy x-rays	0.70
Xenon-133	Xe-133	5.3 days	β-0.346 max (99.1%); 0.266 max (0.9%); 0.10 av ε-0.80 (2.4%); 0.075 (8.7%); 0.045 (52%) γ 0.081 (37%); Cs x-rays	

Sources: Martin and Blichert-Toft, 1970; Dillman, 1969; Hine and Brownell, 1956 (for values of specific gamma ray constants)

Using the tools of time, distance, and shielding, the exposure to employees can be minimized. By varying any of these factors, an increase or decrease in exposure can occur. In any instance, the exposure level can be minimized such that it is below established standards. The sample problems presented at the end of this chapter will provide you with an opportunity to apply the concepts just presented on the shielding requirements of gamma radiation.

X-Radiation Shielding

When evaluating the potential radiation hazard produced by an X-ray machine, the following three components must be considered. The first component is the useful beam itself. This is the beam and its energy directed at a specified target. The second component is scattered radiation. This is the incident radiation that is reflecting off the target, the walls, etc. Finally, leakage radiation must be considered. This is the radiation that penetrates the tube housing and is not part of the useful beam. The degree of shielding and protection required for an X-ray installation varies. X-ray shielding is based on the same principles as gamma shielding. However, direct calculations of half value layers for X-ray shielding are difficult. Factors such as the complexity of the X-ray spectrum, dependence upon the width of the beam and diffraction patterns, and factors contributing to the beam's scattering make HVL calculations difficult. Generally, when developing shielding patterns for the X-ray area, it is better to rely on calculated values in the literature that are based on experiments that have a similar design. For example, Table 6.5.8 illustrates the half value layers for diagnostic X-rays for two shielding materials from 50 to 100,000 volts. The shielding is designed to limit the maximum exposure to 0.1 roentgens per week at specified dose point.

Table 6.5.8

HALF VALUE LAYERS FOR DIAGNOSTIC X-RAYS

Tube Voltage	Lead (mm)	Concrete[a]
50,000	0.05	0.43
70,000	0.15	0.84
100,000	0.24	1.50
125,000	0.27	2.00

(*a*) The half value layer will vary in different kinds of concrete and is given for illustrative purposes only.

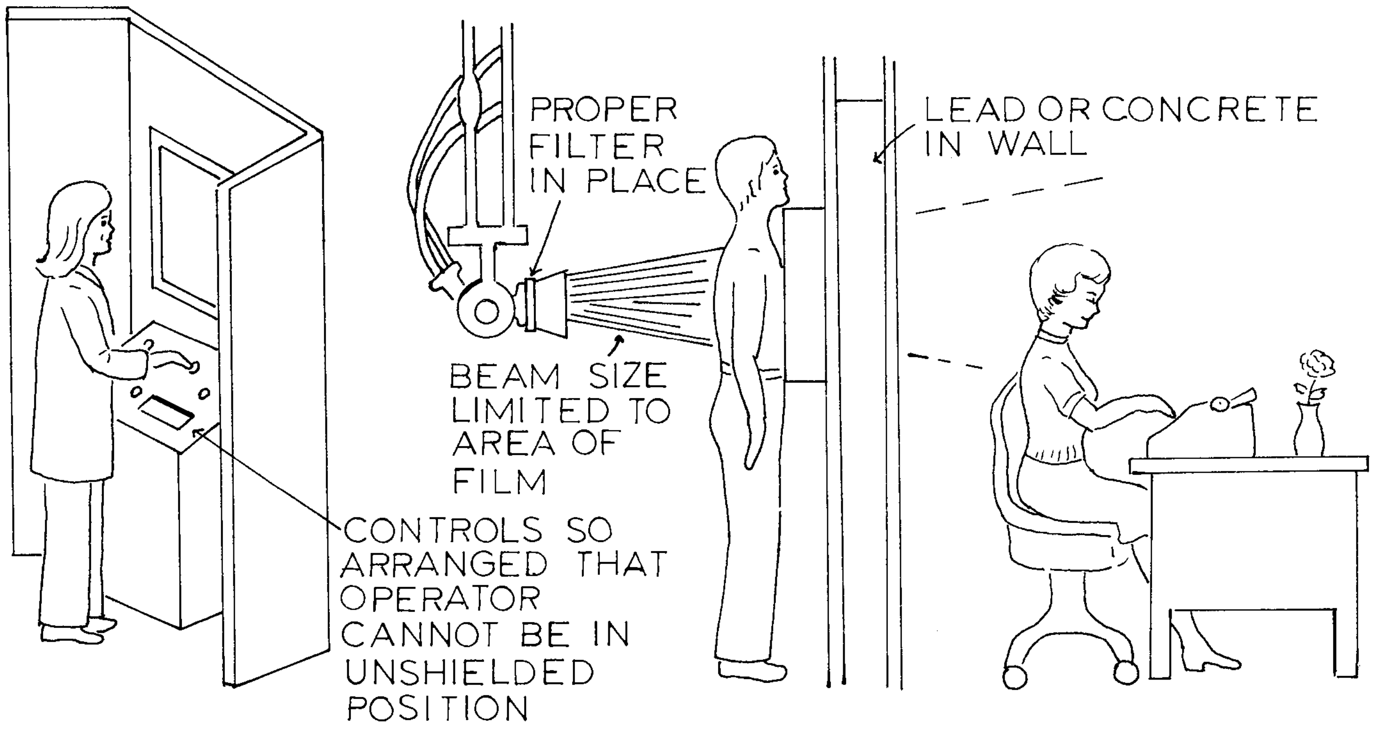
Source: NCRP 1970, Report 34

When evaluating the potential X-ray exposure that may be produced by a given installation, the following factors must be considered:

1. Work load (W)--The degree of use of the machine. This is usually expressed in terms of milliamps-minute per week (mamp-min/wk).
2. Use factor (U)--Fraction of work load during which radiation under consideration is pointed in the direction of interest; e.g., toward personnel.
3. Occupancy factor (T)--Factor of occupancy of areas of interest.
4. Output (P)--The output of the direct beam.
5. The distance from the beam source to the employees of interest.

Figure 6.5.7 illustrates a typical X-ray installation.

Figure 6.5.7



MEDICAL X-RAY PROTECTION

Table 6.5.9

AVERAGE RADIOLOGIC OUTPUT*

Target Distance		Tube Potential (ρ)						
		50 Kvp	60 Kvp	70 Kvp	80 Kvp	90 Kvp	100 Kvp	125 Kvp
in	cm	R/100 ma-sec						
12	30	1.8	2.8	4.2	5.8	8.0	9.8	15.2
18	46	0.8	1.3	1.8	2.5	3.4	4.2	6.7
24	61	0.4	0.7	1.1	1.4	1.9	2.3	3.8
36	91	0.2	0.3	0.5	0.6	0.9	2.1	1.7
54	137	0.1	0.1	0.2	0.3	0.4	0.5	0.7
72	183	0.1	0.1	0.1	0.2	0.2	0.3	0.4

* Measured in air with total filtration equivalent to 2.5 mm Al.
Source: NBS Handbook 76, 1961, Appendix A, Table 7

If the output, work load, use factor, and occupancy factor are known, shielding required can be determined. First, it is necessary to calculate the output from the tube (TO). This can be done using tables found in the literature such as illustrated in Table 6.5.9. Then, it is necessary to calculate the product of W x U x T. Then, the attenuation can be calculated by determining the product of the output specified for the distance from the target to the point of interest and the three factors, W, U, T. This product is divided into the permissible weekly dose. The shield thickness is then calculated in the usual way from the number of half value layers required to produce the desired attenuation. For convenience, as previously mentioned, the protection handbooks contain tables for determining shielding thickness at installations operated at a given kilovolt peak.

Example

Determine the thickness of lead required on the wall of a radiographic installation with personnel working 12 feet from the source on the other side of the wall with the following conditions:

Kvp = 70
W = 200 milliamp minutes per week
U = 1
T = 0.25

Solution

A. Calculate tube output (TO). (From Table 6.5.9)

at 1 ft and 70 Kvp

$$\text{TO} = 4.0 \text{ R/100 mamp-sec}$$

at 12 ft

$$\text{TO} = \frac{4.0 \text{ R/100 mamp-sec}}{(12)^2} = 0.028 \text{ R/100 mamp-sec}$$

B. Calculate W • U • T

$$W = 200 \text{ mamp-min/wk}$$

$$U = 1$$

$$T = 0.25$$

$$W \cdot U \cdot T = \frac{200 \text{ mamp-min}}{\text{wk}} \times 1 \times 0.25$$

$$= 50 \text{ mamp-min/wk}$$

C. Calculate attenuation

$$\text{att} = \frac{0.1 \text{ R}}{\text{week}} \times \frac{\text{wk}}{50 \text{ mamp-min}} \times \frac{100 \text{ mamp-sec}}{0.028 \text{ R}} \times \frac{\text{min}}{60 \text{ sec}}$$

$$= 0.12$$

D. Calculate HVL

$$(0.5)^n = 0.12$$

$$n = \frac{\log(0.12)}{\log(0.5)} = \frac{-0.9208}{-0.3010} = 3.06$$

From Table 6.5.8, it is found that 3.06 x 0.15 = 0.459 mm lead is required to shield this source.

The calculation for shielding requirements for incident radiation may also be calculated in the same manner. As previously mentioned, this procedure is somewhat simplified in the literature, but the same information is required to manipulate the data and calculate the shielding requirements.

The shielding requirements for beta radiation are somewhat less than for gamma and X-radiation because of the lesser penetrating capability of beta radiation. The range of the beta particle is a function of energy level of the beta particle and the composition of the absorbing material. The "range" of a beta particle refers to the thickness of material through which no beta particle emitted from a source can penetrate. Any shielding greater than the range specified for a given beta particle will prevent any emission of beta particles through the shield. In the literature, the range for the various energy levels of beta particles is given in terms of unit density material. Table 6.5.10 gives some properties of commonly used beta emitters including the unit density material. The range for the unit density material is based upon the assumption that the density of this absorbing material is one gram per cubic centimeter.

Table 6.5.10

PROPERTIES OF SOME COMMONLY USED BETA EMITTERS

	H-3	C-14	S-35	Ca-45	P-32	Sr-90
Half-Life	12.3 yr	5730 yr	88 d	165 d	14.3 d	28.1 yr
Maximum beta energy (MeV)	0.018	0.154	0.167	0.254	1.71	2.24*
Average beta energy (MeV)	0.006	0.050	0.049	0.077	0.70	0.93
Range in air (ft)	0.02	1	1	2	20	29
Range in unit density material (cm)	0.00052	0.029	0.032	0.06	0.8	1.1
Half value layer, unit density absorber (cm)	--	0.0022	0.0025	0.0048	0.10	0.14
Dose from 100 beta particles/cm^2-sec (mrad/hr)	--	64	60	43	12	11
Fraction transmitted through dead layer of skin (0.007 cm)	--	0.11	0.16	0.37	0.95	0.97
Dose rate to basal cells of epidermis from 1 µCi/cm^2 (mrad/hr)	--	2600	3600	5900	4300	3900

* From the Y-90 decay product

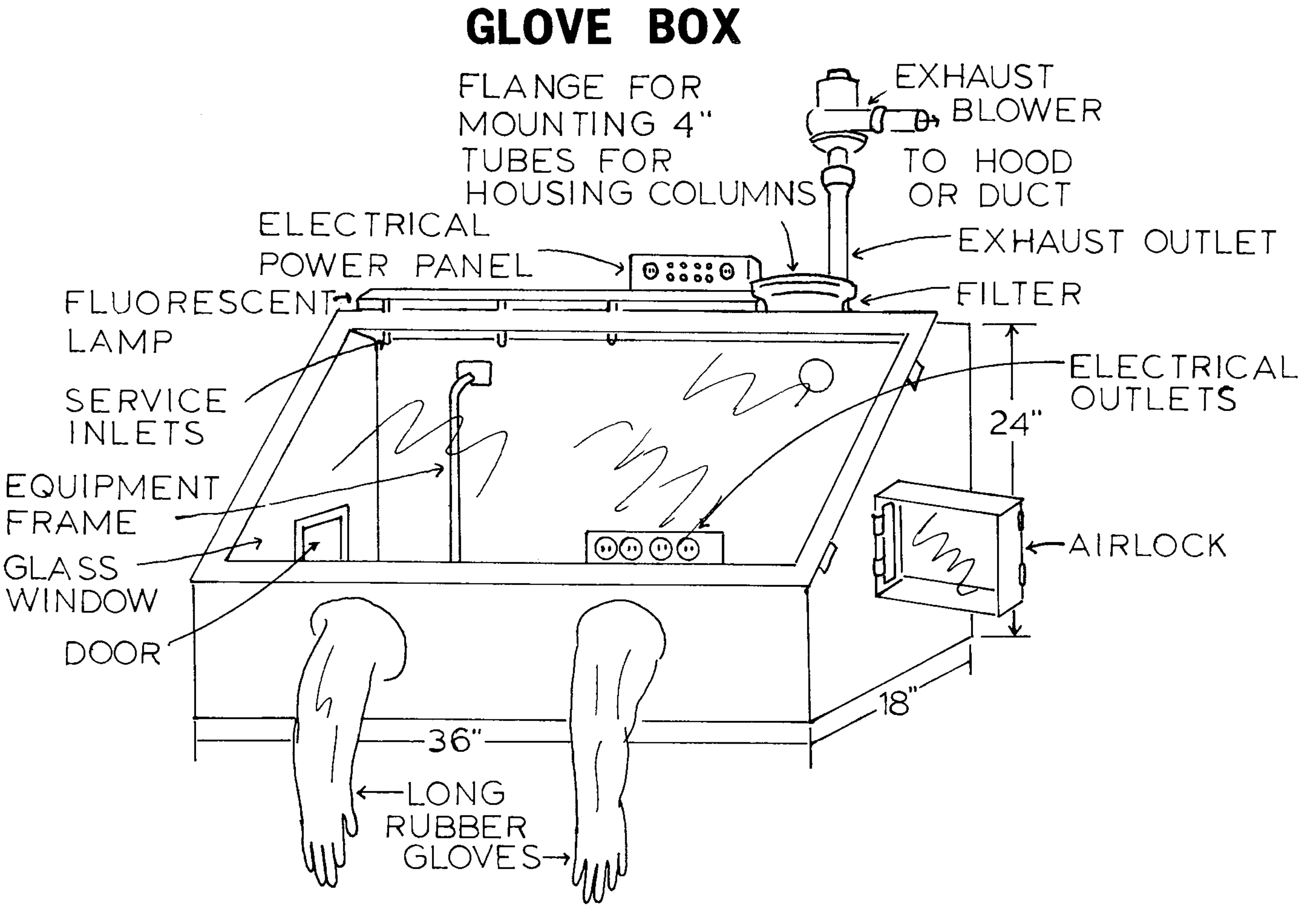
Source: Shapiro, Jacob. _Radiation Protection--A Guide for Scientists and Physicians_*, Harvard University Press, 1974.*

If an absorbing material with a density other than 1.0 gram per cubic centimeter is used, then the range can be calculated by dividing the unit density by the density of the shielding material. For example, if the minimal thickness of the wall of a glass test tube required to stop all beta particles from a Phosphorus-32 source is to be calculated, it is necessary to divide 0.8 cm (the unit density for P-32) by 2.3 grams/cm^3 (the density of glass) to get a value of 0.35 cm of glass as the range for Phosphorus-32 beta particles.

When considering the type of shielding material used for beta particle shielding, special consideration must be given to the atomic weight of the shielding material. Beta particles should be shielded by materials that are light or have small atomic weights; e.g., aluminum, water, glass. This is necessary because the beta particles convert to X-radiation which is more penetrating in those shielding materials that have large atomic numbers; e.g., lead. Because this production of X-radiation is more likely with heavier compounds, beta particle shielding should always be done with light atomic weight materials.

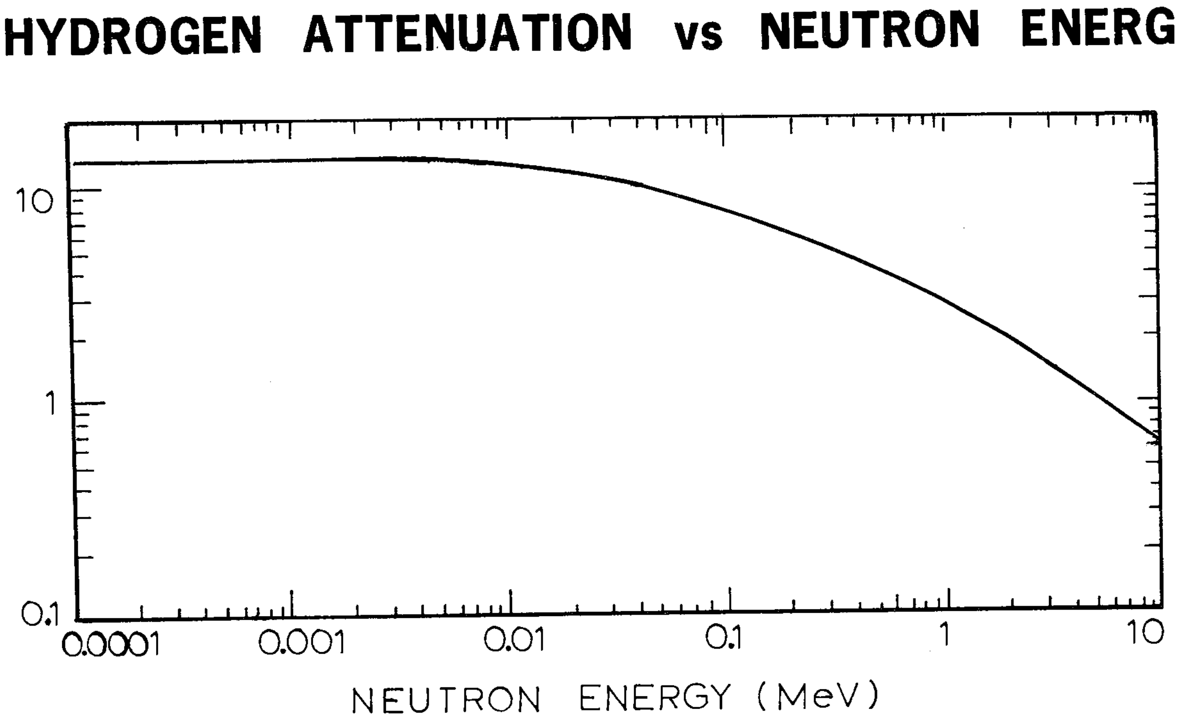
As with beta particles, alpha particles, because of their high atomic weight and charge, have a limited penetrating capability and range. This is true to the extent that alpha radiation cannot even penetrate the outer layer of dead skin of the body. However, the danger with alpha radiation is the potential of the alpha emitter entering the body. Therefore, containment more than shielding is required when working with alpha emitters. Figure 6.5.8 illustrates a typical installation used for the containment of alpha particles; e.g., the glove box. The glove box will be discussed in greater detail in this chapter.

Figure 6.5.8



The final radiation form that has been discussed, neutrons, can be shielded following the same concepts of half value layer and attenuation coefficients as described with gamma photon shielding. The most efficient absorption materials used for neutron shielding are high in hydrogen content; that is, hydrogen greater than 20%. Figure 6.5.9 illustrates the attenuation of hydrogen per energy level of neutrons.

Figure 6.5.9


HYDROGEN ATTENUATION vs NEUTRON ENERGY

To calculate the attenuation for other absorbing medium used as shielding, it is first necessary to calculate the hydrogen density in that medium and then multiply that by the attenuation coefficient found on the table. To calculate the half value layer, it is then necessary to divide the attenuation coefficient calculated into the constant, 0.693, so that

$$\text{HVL} = \frac{0.693}{\text{attenuation coefficient}}$$

The following is an example of the calculation of the attenuation due to hydrogen in a water shield 150 cm thick for 8 MeV neutrons.

Water is 11% hydrogen by weight. Therefore, the density of hydrogen in the medium, water, is 0.11 grams/cc. From Figure 6.5.9, for neutrons with 8.0 MeV energy level, the attenuation coefficient equals 0.68 cm^{-1}. Therefore, for water the attenuation coefficient would be 0.68 x 0.11, or 0.075 cm^{-1}. The half value layer would then be 0.693 divided by 0.75, equal to 9.24 centimeters. The number of half value layers would be equal to 150 divided by 9.24, or 16.2. The attenuation caused by 16.2 half value layers would be equal to $(0.5)^{16.2}$, or 1.3×10^{-5}.

Application of the previous formula can be used to calculate the effect of neutron shielding. However, neutron activity leads to the emission of gamma radiation. Therefore, neutron shielding requires gamma shielding. Because of the sophistication of this problem, it is beyond the scope of this text. Any situations that require neutron shielding should be investigated further in the literature.

Survey and Monitoring Procedures for Radiation Hazards

The purpose of surveying and monitoring areas with potential radiation hazards is

1. To indicate the general level of radiation in the working environment.
2. To monitor changes of level in radiation.

An area surveyed would include an initial examination of the facility, laboratory operating procedures, personnel habits, types of radiation sources being used, methods used in handling the sources, and radiation levels that are observed. Special emphasis should be placed on identifying and quantifying those factors that determine the exposure rate for the personnel. These things include the average time of exposure during the operating procedure, average distance of the employee from the potential source, and areas of the body that may come in closer contact to the source than others, e.g., the hand. Area surveys are generally more interested in analyzing potential radiation hazards and identifying existing hazards without actually quantifying the hazard.

These surveys should be scheduled on a routine basis. Shields should be checked for cracks, excessive surface and airborne contamination should be evaluated, the procedure use of radiation, and such factors as improper disposal of waste should also be considered. Special emphasis should be placed on unlikely or remote areas that typically are not included in any type of daily monitoring procedure.

Routine measurements should be made at intervals during the conducting of work. Measurements should be taken for all steps of the procedure and should include data such as the time of the procedure and exposure levels; distance from the source, including the mean body distance and specific areas of the body that are closer to the source, e.g., hands; the variations of exposure throughout the procedure to the employee, e.g., does the employee turn his back to the source during the procedure. From this information, a relative exposure rate for personnel can be determined and adjustments made accordingly. Care should be taken when taking these measurements to insure that all potential exposed areas are analyzed.

Efforts should be made, if appropriate, to analyze the contamination that may occur during any given procedure. Specifically, three areas are of concern. First, any radioactive contamination that may settle on any surface in the laboratory in the form of dust or particulate matter. This may be evaluated by taking a smear or wipe test. Its purpose is to determine the amount of loose radioactive material that may potentially become airborne or be transferred to personnel and carried outside the radiation facility. If a specific surface area, for example 100 cm^2, is wiped off with a clean cloth or adhesive tape each time a smear test is performed, then the results may be quantified. Smear samples, once taken, should be removed to areas of low background radiation and a reading taken. If surface contamination is found beyond established limits, corrective action should be taken as necessary.

The second form of contamination that should be monitored is that of air contamination. Air samples may be collected by standard procedure, such as using filters, electrostatic precipitators, impingers, or impactors. Care must be taken to insure that all particles of appropriate size are collected. Samples of 10 m^3 are usually adequate. Direct counting from the surfaces where air samples are collected is appropriate. Care must be taken when counting alpha particles because the alpha particles may be absorbed by the sample-collecting filter. In this instance, a correction factor must be determined. Assuming that the radionuclide is known, the concentration of radioactive contaminant in the air can be calculated in terms of microcuries per cubic centimeter (μCi/cc). This value is then compared to the maximum permissible concentration (MPD) for unrestricted areas. These values may be found in Handbook 69. (See References.) Once the concentration has been calculated, the quantity of nuclide taken in by personnel can be roughly estimated by determining the exposure time and then determining the product of the exposure time, concentration, and the conversion factor of 10^7 cc per eight hours. This value can be compared to the maximum body burden, also found in Handbook 69. If the nuclide source is not known, arbitrary limits can be established such that gamma and beta sources should not exceed 10^{-9} μCi/cc, and alpha sources should not exceed 10^{-12} μCi/cc. In any instance where air contamination is a possibility, respirators should be used until radiation levels have been adequately determined. In some instances, naturally occurring radon and thoron may interfere with readings; specifically when counting alpha particles. In this instance, adjustments must be made for the interference.

Water sample analysis is similar to that of air analysis. The sample should be of 100 to 500 ml. In analyzing the sample, the water is evaporated and a reading is taken. The concentration in microcuries per cubic centimeter is then calculated and the results compared to the maximum permissible concentration (MPC) values, also found in Handbook 69. If the nuclide is not known, qualitative tests can be performed to determine the source. In either the air or the water sample analysis, the minimum level for the critical organ should be used as a basis for comparison.

Personnel Monitoring

Personnel monitoring is the most direct method of calculating personnel exposure. As previously discussed, the common equipment used for personnel monitoring includes film badges, pocket ion chambers, and pocket dosimeters. Personnel monitoring should be used in any situation where it is possible that 25% of the MPD value for a 13-week period may be exceeded. Because of the potential liability of the instruments, the personnel devices should always be used in pairs.

The location of the personnel monitor is critical. If the whole-body radiation dose is of interest, the monitor should be worn between the waist and the neck, somewhere on the chest. It should be unshielded; that is, the monitor should not be covered by several layers of clothing. To maximize the value of the monitor, it should be at a point of maximum exposure. If, for example, the process requires the employee to handle the radioactive source with leaded gloves on, the monitor should be placed on the hands rather than somewhere on the body. Although the MPD value is greater for the hands and a body exposure may give a relative indication of exposure to the hands, the most accurate reading is necessary. The configuration of the employee's body to the radiation source must also be considered. If, for example, the person works 50 percent of the time with his left side facing the radiation source and 50 percent of the time facing the source directly, then the monitor should be placed such that readings are being taken at the points of maximum exposure and at no time does the worker's body shield the monitor from the radiation source.

Special effort must be made to insure that the monitors selected match the type and energy level of the radiation being monitored. The use of monitors and dosimeters that are not correctly matched will give erroneous readings. Records on each employee should be maintained concerning cumulative doses received.

In some instances, it may be of value to receive a continuous recording of dose rate at a fixed location. In these instances, fixed monitors are used. These monitors may be equipped with visible or audible alarms that warn of increased radiation levels. If contamination is possible, a fixed monitor may be placed in the doorway of the radiation facility so that personnel are monitored for contamination of clothing before leaving the facility. Special monitors have been developed that survey the hands and shoes, including the soles. This type of monitoring capability is of value when large numbers of personnel are involved at the change of shifts. It limits the possibility of radioactive contamination outside the designated facility.

Controls can be designed into the system that minimize personnel exposure. These include warning systems, such as previously discussed, for high exposure levels. Also, it is possible to develop interlock systems so that radiation-producing equipment (X-rays) cannot be operated unless shielding is in place, or shielding cannot be moved until personnel are a designated distance from the source.

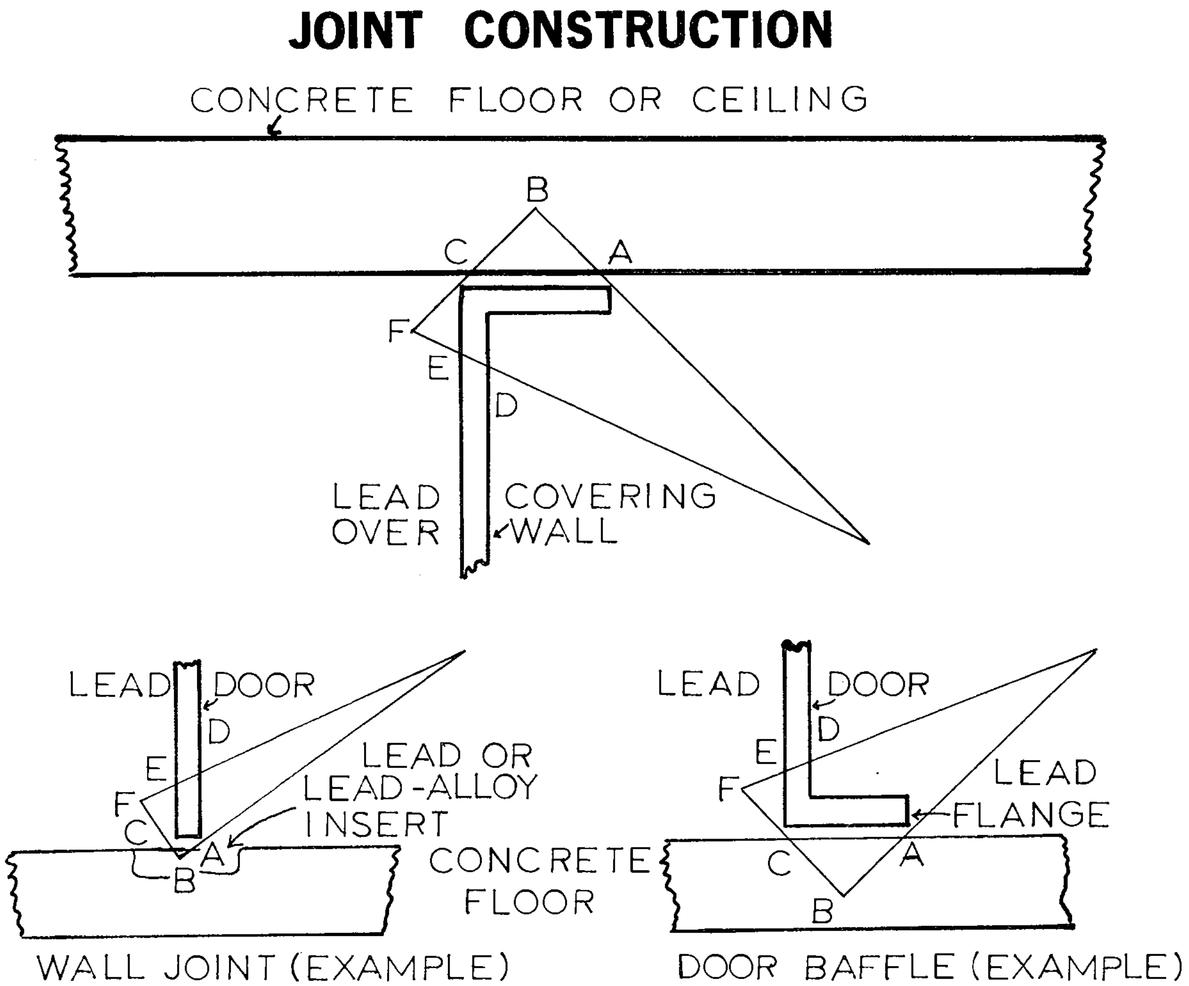
Facilities

When examining the design of the facility to be used for a radioactive procedure, steps must be taken to maximize containment of the radiation and to allow for the ease of cleanup in the event of contamination within the facility. Certain design factors can maximize this.

All surfaces involved in the radiation area should be smooth and nonporous; e.g., shelves, floors, sinks. It is unacceptable to have surfaces--such as uncoated wood, concrete, or soapstone--that would provide a porous surface for the collection of contaminants. Such surfaces as tile, polished stainless steel, and plate glass are acceptable. Although paints, varnishes, and lacquers do provide a somewhat nonporous surface, they are not recommended for use in radiation areas.

Any area that could be a dust collector should be eliminated. This includes things such as suspended lighting, suspended pipes, and roof trusses. Any shelving or storage areas should be enclosed by doors. Cove corners between the wall and floor will facilitate cleanup and reduce possible gathering of contaminated particles.

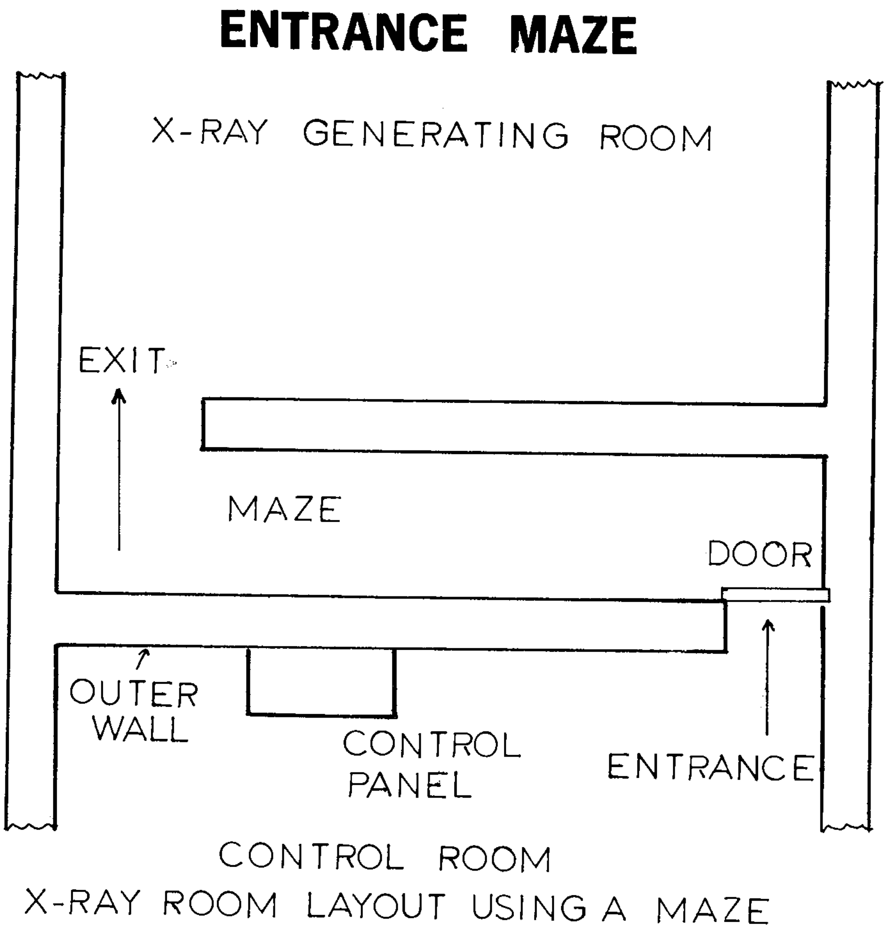
Figure 6.5.10



Any special piping or drainage systems that are necessary for the procedure and are involved in the radiation area should be plainly labeled, especially if used for radioactive waste.

The design of the facility and shielding should prevent any type of radiation leakage from from the facility. For example, Figure 6.5.10 illustrates special precautions that must be taken in the construction of joints to prevent the leakage of incident radiation. Figure 6.5.11 illustrates a typical doorway maze that is used to minimize leakage.

Figure 6.5.11



Within the facility, special equipment is often required. For example, long-handled tools such as tongs and forceps are often used to increase the distance between personnel and the source and decrease the exposure rate (inverse square law). In those instances when the radiation source is of a high activity, it may be necessary to use remote control devices with protective lead glass windows such as displayed in Figure 6.5.6.

With respect to the facility design, there are two areas that should be given special consideration, First, when working with unsealed radioisotopes, hood and exhaust systems are needed to minimize airborne contamination. The airflow in the hood system should be a minimum of 100 lfm. If highly toxic radioisotopes are being used, then the flow rate should be adjusted to approximately 125 to 150 lfm. The hood should have its own exhaust system with appropriate filtering and decontamination systems. The air contamination should be monitored to insure that it does not exceed established levels. (Note: The calculation of air contamination will be discussed later.) Airflow should also be monitored for cross drafts and leaks in the system. The development of the hood and exhaust system should follow the principles discussed in the Ventilation section.

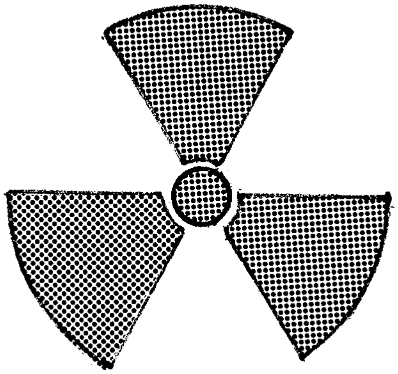
When working with alpha and low energy beta radiation, glove boxes, as shown in Figure 6.5.8, offer sufficient protection. This type of system prevents air contamination while allowing the employee to work closely with the radioisotope. As seen in the figure, hermitically sealed ports go into the box and allow for manipulation of the box contents using the glove. Air locks are also provided to allow for insertion and removal of samples without air contamination. For high energy beta rays and gamma radiation, it is necessary to replace the gloves with some type of remote mechanical manipulator. Frequently, the glove boxes have exhaust ports and filters with exhaust volumes in the area of 20 to 30 cubic feet per minute. The personnel should be positioned so that any explosion would not be directed at them through exhaust and inlet ports.

Posting the Area

Warning signs are essential in radiation areas since individuals might otherwise be unaware of the presence of the radiation field. Areas need to be posted only if the radioactivity is to be present in that area for longer than eight hours. Each symbol or label should bear the three-bladed radioactive caution symbol, either magenta or purple on a yellow background, as shown in Figure 6.5.12.

Figure 6.5.12

RADIATION SYMBOL



The labels and signs that accompany the radiation symbol are dependent upon the potential exposure in that given area. The following types of signs are required in areas where significant levels of radiation or radioactivity are present:

1. "CAUTION RADIATION AREA"--This sign is used in areas accessible to personnel in which a major portion of the body could receive in any one hour a dose of 5 millirems, or in any 5 consecutive days, a dose in excess of 100 millirems.
2. "CAUTION RADIOACTIVE MATERIAL"--This sign is required in areas or rooms in which radioactive material is stored or used in an amount exceeding the quantities listed in Table 6.5.1.
3. "CAUTION RADIOACTIVE MATERIAL" (Label)--A durable, clearly visible label is required on any container that is transported, stored, or used for a quantity of any material greater than the quantity specified in Table 6.5.1. When containers are used for storage, the labels must state also the quantities and kinds of radioactive materials in the containers and the date of measurement of the quantities.

4. "AIRBORNE RADIOACTIVITY AREA"--This sign is required if airborne radioactive activity exceeds at any time concentrations in excess of the maximum permissible for 40 hours occupational exposure, or if the average over a number of areas in any week during which individuals are in the area exceeds 25 percent of the maximum permissible concentration. (Table 6.5.1.)

5. "HIGH RADIATION AREA"--This sign is required if the radiation dose to a major portion of the body to a person in the area could be in excess of 100 millirems in any one hour. These areas also require the audible or visible alarm signals that were discussed previously.

As stated, because radioactivity cannot be sensed by the human body, it is essential that signs be present in areas where radioactivity may exist. On the other hand, the signs should not be used when they are not needed.

In many instances, the handling procedures for radioisotopes or the operation of radiation-producing instruments has been specifically defined. In those instances, it may be of value to post the operating/handling procedures as illustrated in Figure 6.5.13.

Figure 6.5.13

HOW TO HANDLE RADIOISOTOPE SHIPMENTS

An Outline of Recommended Procedures to be Followed When Receiving Radioactive Shipments

Open and inspect packages immediately upon receipt.

Radioactive solutions inadvertently stored upside down may gradually leak and cause contamination problems; furthermore, vendors often will not accept claims for shipments not inspected within 15 days after delivery.

Monitor package for radiation field.

It is suggested that plastic gloves be worn while processing the received package.

To Process Soft Beta, Hard Beta, and Gamma Emitters

1. Wipe and test package for removable contamination.
2. Note radiation units stated on package, verify and record in receipt log. (Hard beta and gamma only.)
3. Place package in vented hood.
4. Open outer package and remove packing slip. Open inner package and verify that the contents agree in name and quantity with the packing slip.
5. Measure radiation field of unshielded container--if necessary, place container behind shielding to reduce field to allowable limits and proceed with remote handling devices. (Hard beta and gamma only.)
6. Check for possible breakage of seals or containers, loss of liquid, or change in color of absorbing material.
7. Wipe test inner contents and document any pertinent findings on packing slip. Note: The liner, shield, and isotope container may have surface contamination; they should be discarded in hot waste disposal containers.
8. Record type of activity, quantity present, and location of delivery in receiving log.
9. Deliver processed package to proper laboratory. If delivery is delayed, notify recipient of its arrival and clearance.
10. If material has been packaged in dry ice, refrigerate or deliver immediately to ultimate user.
11. If contamination, leakage, or shortages are observed, notify the vendor's Customer Service Department immediately.

Trays and Handling Tools. When working with radioisotopes, any procedure that may result in the contamination of a table top should be performed in a tray. This would negate the problem of having to replace counter tops rather than the contaminating trays. Also, even small amounts of radionuclides should not be handled directly, but tweezers and/or tongs should be used whenever possible to minimize exposure. This will reduce the potential of contamination on the hands and gloves and also decrease the exposure rate through the inverse square law of distance.

Storage and Disposal of Radionuclides

Radionuclides should be stored in designated areas, protected against fire, explosion, or flooding. They should be stored in suitable containers that provide adequate shielding. In any type of storage situation, the radiation level should not exceed 5 millirems per hour at one foot in the storage area.

When concerned with disposal of radioactive wastes, there are only four possible alternatives: release into the atmosphere, release into tidal or sewage waters, burial, or a contract arrangement with a commercially licensed radiation disposal firm. Each of these is controlled by the Nuclear Regulatory Commission.

The release of radioactivity in the air is limited by the Nuclear Regulatory Commission. The concentration released through exhaust systems should not exceed the maximum permissible concentration (MPC) at the point of discharge. The exact concentration can be calculated, including the release of different nuclides at once.

Example

A radio chemist released 1 curie of tritium (titrated water) through a hood while performing a synthesis. The airflow rate was 100 feet per minute with a 1 foot by 4.5 foot hood opening. If the concentration is averaged over one week, was the MPC value exceeded?

Solution

Assuming 40 hours per week, the flow rate for the hood can be calculated to be 0.612 x 10^{10} cc/day or 3.06 x 10^{10} cc/week. From Table 6.5.4, the maximum permissible concentration for titrated water (Hydrogen-3) is equal to 2.0 x 10^{-13} curies/cc. The radioactive release from the hood is equal to 1 Ci/week ÷ 3.06 x 10^{10} cc/week = 3.26 x 10^{-11} Ci/cc. Therefore, the MPC has been exceeded.

Table 6.5.11

MAXIMUM PERMISSIBLE CONCENTRATIONS OF RADIONUCLIDES IN AIR AND WATER

	Unrestricted Areas		Restricted Area (40 hr/wk)	
Radionuclide	Water (pCi/cc)	Air (pCi/cc)	Water (pCi/cc)	Air (pCi/cc)
C-14	80	0.1	20,000	4
H-3	3,000	.2	100,000	5
S-35	60	.009	2,000	0.3
I-131	0.3	.0001	60	0.009
I-125	0.2	.00008	40	0.005
P-32	20	.002	500	0.07
Ca-45	9	.001	300	0.03
Na-24	30	.005	800	0.1
K-42	20	.004	600	0.1
Cr-51	200	.08	50,000	2
Kr-85	--	.3	--	10
Xe-133	--	.3	--	10
Br-82	40	.006	1,000	0.2
Cl-36	60	.008	2,000	0.02

Source: U. S. Code of Federal Regulations, Title 10, Part 20, as of December 10, 1969

Note: The maximum permissible concentration depends upon several factors, including the degree of solubility of the contaminant. The lowest concentrations specified in the regulations have been listed.

Limited amounts of liquid radioactive waste can be deposited in unrestricted water or in sewage systems. Again, levels have been established by the NRC and must be met. Unlike the calculation of maximum level for air contamination, when calculating liquid disposal, both daily and monthly MPC values must be met. Further, disposal may not exceed 1.0 curies per year. An example of this is as follows:

Example

Determine how much Iodine-125 and Phosphorous-32 can be dumped into the sewage system if the water flow to the sewage (based on water bills) is 1.2×10^7 cubic feet per year.

Solution

From Table 6.5.11, the MPC value for Iodine-125 is 40×10^{-12} Ci/cc/wk, and the MPC value for Phosphorous-32 is 5.0×10^{-10} Ci/cc/day. The average daily water flow can be calculated based on the water bill to be equal to 9.31×10^8 cc/day (assume 365-day operation). Therefore, the daily limits for Iodine-125 and Phosphorous-32 would be equal to the product of the MPC value times the daily water flow, or 37.24 millicuries and 466 millicuries respectively. Therefore, these daily limits would be the maximum amount of radioactive waste that could be dumped into the sewage system. However, this daily disposal rate could only continue until a maximum of 1 curie/yr limit for the disposal of gross activity has been reached.

When disposing of solid waste, the alternatives of incineration, burial, or the commercial disposal firm are available. Incineration is a good bulk-reducing method. Again, this method is regulated by the NRC. The rule of thumb to follow is that the concentration released to the unrestricted areas should not exceed limits specified for continuous exposure. When calculating the release, the concentration may be averaged over a maximum of one year. The procedure for calculation is similar to that for air contamination, and to complete the calculation, the type of radionuclide, the quantity of radionuclide, and the airflow of the incinerator must be known. An important fact is that any ash left over after incineration must also be treated as radioactive waste.

The NRC rules for burial are fairly simple. Each organization is permitted twelve burials per year. Burials must be at least six feet apart and a minimum of four feet deep. The total quantity of radionuclide buried at any location may not exceed 1,000 times the level established in Table 6.5.1. If several nuclides are buried in a single burial, the sum of the radionuclide fractions cannot exceed one. For example, a user of radionuclides plans to dispose of 2 millicuries of Iron-59, 10 millicuries of Chromium-51, and 20 millicuries of Iodine-125 by burial. Is this possible?

Solution

He would be permitted to bury single (1,000 times value in Table 6.5.1, third column):

Iron-59 = 10 millicuries
Chromium-51 = 1000 millicuries
Iodine-125 = 1 millicurie

Immediately it can be seen that the amount of Iodine-125 which is to be buried exceeds the limit. However, the Iron-59 requires only 20 percent of the allotted limit, and the Chromium-51 requires only one percent of the allotted limit. Therefore, being sure that the sum of the nuclide fractions does not exceed 1, 0.79 of the Iodine limit, or 0.79 millicuries, could be buried in the same burial. However, the remaining 19.21 millicuries of Iodine would have to be buried in 19 separate burials. Because this exceeds the limit, it would seem more advisable to have the Iodine disposed of by a commercial firm.

In many instances, the guidelines for storage and disposal of wastes established by the NRC vary somewhat from state regulations. Therefore, state health departments must also be contacted when working with radioisotopes in production lines.

Personnel

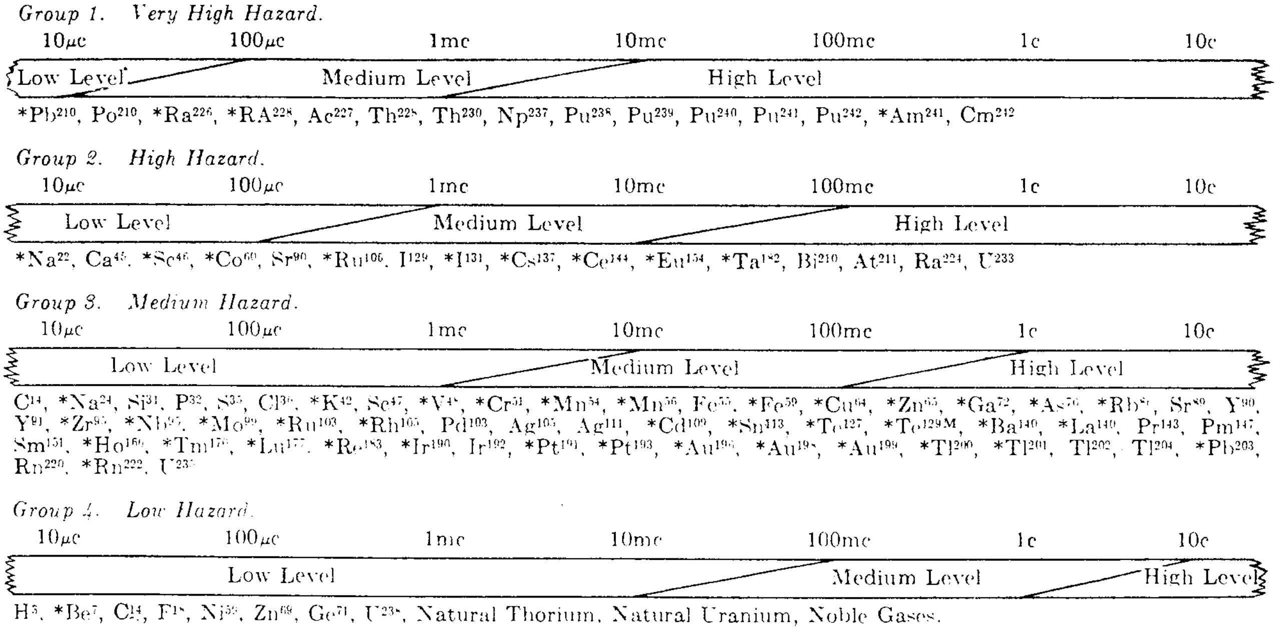
Personnel have a responsibility to minimize their exposure to ionizing radiation. Although maximum exposure levels (MPD) have been established, every effort should be made to minimize exposure.

The Nuclear Regulatory Commission has established training requirements for those personnel directly involved with the use of radioisotopes or radiation-producing machinery. Each person, however, potentially exposed to radioactivity should receive training in the potential dangers of radiation, operational procedures that minimize exposure, and procedures in case of accidents.

The protective clothing that is required of personnel is dependent on the level of radio toxicity of the nuclide. Specifically, the clothing should be such that it can be easily laundered or disposed of should contamination occur. The degree of protection that is required of the clothing is a function of the quantity and type of radioactivity, the nature of the operation, and the design of the laboratory. Sealed containers do not usually require protective clothing for use. In general, protective clothing of any kind is not required if the MPD value for the most critical organ (as defined by Handbook 69) is not and will not be exceeded. The amount of protective clothing, as previously mentioned, is dependent upon the radio toxicity. Figure 6.5.14 generally groups the radioisotopes according to toxicity.

Figure 6.5.14

HAZARD FROM ABSORPTION INTO THE BODY



Group 1: *Pb^{210}, Po^{210}, *Ra^{226}, *RA^{228}, Ac^{227}, Th^{228}, Th^{230}, Np^{237}, Pu^{238}, Pu^{239}, Pu^{240}, Pu^{241}, Pu^{242}, *Am^{241}, Cm^{242}

Group 2: *Na^{22}, Ca^{45}, *Sc^{46}, *Co^{60}, Sr^{90}, *Ru^{106}, I^{129}, *I^{131}, *Cs^{137}, *Ce^{144}, *Eu^{154}, *Ta^{182}, Bi^{210}, At^{211}, Ra^{224}, U^{233}

Group 3: C^{14}, *Na^{24}, Si^{31}, P^{32}, S^{35}, Cl^{36}, *K^{42}, Sc^{47}, *V^{48}, *Cr^{51}, *Mn^{54}, *Mn^{56}, Fe^{55}, *Fe^{59}, *Cu^{64}, *Zn^{65}, *Ga^{72}, *As^{76}, *Rb^{86}, Sr^{89}, Y^{90}, Y^{91}, *Zr^{95}, *Nb^{95}, *Mo^{99}, *Ru^{103}, *Rh^{105}, Pd^{103}, Ag^{105}, Ag^{111}, *Cd^{109}, *Sn^{113}, *Te^{127}, *Te^{129M}, *Ba^{140}, *La^{140}, Pr^{143}, Pm^{147}, Sm^{151}, *Ho^{166}, *Tm^{170}, *Lu^{177}, *Re^{183}, *Ir^{190}, Ir^{192}, *Pt^{191}, *Pt^{193}, *Au^{196}, *Au^{198}, *Au^{199}, *Tl^{200}, *Tl^{201}, Tl^{202}, Tl^{204}, *Pb^{203}, Rn^{220}, *Rn^{222}, U^{235}

Group 4: H^{3}, *Be^{7}, C^{14}, F^{18}, Ni^{59}, Zn^{69}, Ge^{71}, U^{238}, Natural Thorium, Natural Uranium, Noble Gases.

*Emits gamma radiation in significant amounts.

Source: *Safe Handling of Radioactive Materials, Handbook 92, National Bureau of Standards*

For those personnel working with low level radioisotopes, laboratory coats or coveralls are recommended. Simple cloth or plastic bags on the shoes to reduce the potential contamination of the shoes is also recommended. Rubber or plastic gloves should be worn, and handling of the radioisotope without gloves should be avoided. Any isotope that is classified in the medium level requires the personnel to wear coveralls, caps, gloves, and shoe covers. Every effort should be made to minimize contamination of the personnel's own clothing. Should the individual be exposed to high level radioisotopes, a multi-layer of coveralls, shoes, etc., would be required. In most instances, high level radioisotopes should not be encountered during normal operation.

When the recommended MPC level is exceeded, it is required that some type of respiratory protection be used. The type of respirator employed may vary from a simple respirator, which merely filters out particles, to some type of self-contained breathing appratus, which is a closed ventilatory system for the employee. Typical respirators are illustrated in other chapters. One limitation of respiratory equipment must be mentioned; that is, in all instances the mask will leak approximately 1 to 2 percent. A growth of the beard or a mustache may further affect the mask fit and leakage. Therefore, this potential leakage must be taken into consideration when the personnel are equipped with respiratory protection.

Shielding garments are somewhat different from protective clothing in that they not only serve to prevent and reduce contamination, but also they act as an absorbing or shielding material. They should be used for close contact work with radiation of low penetrating power. For example, leather or rubber gloves are often effective against most beta radiation. Fabrics loaded with high atomic material are used for shielding against X-radiation. Shielding garments should not be used solely for high level beta or gamma radiation because the shielding cannot be designed to stop radiation of high penetrating power. Personnel hygiene is also essential in minimizing exposure. Eating, smoking, storage of food, pipetting by mouth should be prohibited in radioactive areas. Any work with unsealed sources requires a "wash up" before eating, smoking, or leaving the work area. Written procedures for personnel should include basic hygiene practices as mentioned.

Personnel monitoring has been discussed previously. As a review, though, any personnel who potentially may be in an area of radiation level that is

25 percent of the maximum permissible dose should carry personnel monitoring devices; e.g., film badges, dosimeters. As mentioned, these devices should be used in pairs at a minimum to insure adequate coverage of the personnel.

Because of the physical hazards of ionizing radiation, medical supervision is essential. Each potential employee should have a pre-employment examination to identify his or her general physical condition. Efforts should be made at the pre-employment examination to quantify, if possible, previous radiation exposures including those involving medical examination; e.g., dental X-rays. Efforts should also be made to identify possible problems that may be magnified or potentially dangerous to the employee in a radioactive environment. Such problems might include dermatological diseases, impairment of pulmonary ventilation, or even cataracts. The decision of employment and placement should consider the above-mentioned factors. Once the employee has been hired and selected to work in a radioactive area, periodic medical examinations should be performed. They should occur at appropriate intervals based on the general health of the employee and the nature of work. These examinations should provide insight to any medical changes. However, the periodic examinations should not be used as a reliable method for monitoring radiation hazard. The examination should include a review of the occupational hazard records and the assessment of exposure doses. Medical advice should be followed with respect to continued radiation exposure for the employee.

In the event of a radiation accident, or even if the MPD value has been exceeded only slightly, it is important that follow-up examinations continue. This is true even if the examinations must occur after the employee has resigned from the organization. This type of follow-up examination will provide extended coverage for the worker, along with adding information of the effect of radiation on the general population. Records should be established and maintained for each employee working in some type of radioactive environment. These records should include medical and radiation exposure history. Job assignments and hazards involved should also be recorded.

Radiation Accidents

Maximum effort should be made to minimize accidents. For example, periodic review of operational procedures for potential hazards should be implemented.

Further, equipment used in the handling and operation dealing with radioactive sources should also be checked periodically. For nonroutine or high level operations, a trial run of the operation should be performed. This trial run will evaluate the adequacy of the procedure and determine the exposure time to the personnel.

In the event of an accident, loose contamination should be minimized whenever possible. All spills should be cleaned up promptly. Cleaning tools should not be removed from the radiation area without being decontaminated. Any level of contamination is difficult to determine, and the impact of the contamination is also very complex.

When monitoring for contamination, a G-M counter is used for beta and gamma radiation, and a proportional counter is used when alpha contamination is suspected. The wipe or smear test is often performed when contamination is suspected.

When employees' hands, body surfaces, clothing, or shoes become contaminated, loose contamination should be removed as soon as possible. Care must be taken to minimize the spreading of the contamination. Initially, washing with mild soap or detergent is a good step. This may be followed up with a mild abrasive soap, complexing solution, or mild organic acid, whichever is appropriate. When the hands are involved in some type of contamination, clipping the fingernails may reduce contamination. In any instance, medical personnel should be notified and the employee examined. Because of potential medical treatment being based on the level of dose received and contamination involved, a relatively accurate determination of the level of exposure is necessary. With respect to specific procedures for decontamination, the following section provides a general overview for radiation accidents.

Emergency Instructions in the Event of Release of Radioactivity and Contamination of Personnel

Objectives of Remedial Action. In the event of an accident involving the release of significant quantities of radioactive material, the objectives of all remedial action are to:

a. Minimize the amount of radioactive material entering the body, by ingestion, inhalation, or through any wounds.

b. Prevent the spread of contamination from the area of the accident.

c. Remove radioactive contamination on personnel.

d. Start area decontamination procedures under qualified supervision. Inexperienced personnel should not attempt unsupervised decontamination.

Procedures for Dealing with Minor Spills and Contamination. Most accidents will involve only minor quantities of radioactivity (i.e., at the microcurie level).

a. Put on gloves to prevent contamination of the hands. (Wash hands first if they are contaminated as a result of accident.)

b. Drop absorbent paper or cloth on the spill to limit spread of contamination.

c. Mark off contaminated area. Do not allow anyone to leave contaminated area without being monitored.

d. Notify the radiation protection office of the accident.

e. Start decontamination procedures as soon as possible. Normal cleaning agents should be adequate. Keep cleaning supplies to a minimum needed to do the job and place into sealed bags after use. (Recommendations for difficult jobs may be found in the Radiological Health Handbook, listed in the References.) Proceed from the outermost edges of the contaminated area inward, reducing systematically the area that is contaminated. (This principle may not apply in decontamination of highly radioactive areas, which would require supervision by a radiation protection specialist.)

f. Put all contaminated objects into containers to prevent spread of contamination.

g. Assign a person equipped with a survey meter to follow the work and watch for accidental spread of contamination.

Personnel Decontamination. If personnel contamination is suspected, first identify contaminated areas with a survey meter. Do not use decontamination methods that will spread localized material or increase penetration of the contaminant into the body; e.g., by abrasion of the skin. Decontamination of wounds should be accomplished under the supervision of a physician.

Irrigate any wounds profusely with tepid water and clean with a swab. Follow with soap or detergent and water (and gentle scrubbing with a soft brush, if needed). Avoid the use of highly alkaline soaps (may result in fixation of the contaminant) or organic solvents (may increase skin penetration by contaminant).

Use the following procedures on intact skin:

a. Wet hands and apply detergent.

b. Work up good lather; keep lather wet.

c. Work lather into contaminated area by rubbing gently for at least 3 minutes. Apply water frequently.

d. Rinse thoroughly with lukewarm water (limiting water to contaminated areas).

e. Repeat above procedures several times, gently scrubbing residual contaminated areas with a soft brush, if necessary.

f. If the radiation level is still excessive, initiate more powerful decontamination procedures after consulting with the radiation protection office.

Reporting Radiation Accidents. Those accidents involving radiation must be reported to the Nuclear Regulatory Commission. Reports must include information such as number of individuals exposed, names of individuals exposed, level of exposure, nuclides involved, and/or the concentration of nuclides released. The NRC has established notification requirements such that if an accident meets the following criteria, it must be reported immediately:

a. Whole-body exposure of individual exceeds 25 rems.

b. Skin exposure exceeds 150 rems.

c. Exposure of hands, feet, ankles exceeds 375 rems.

d. Release of radioactive materials exceeding 5,000 times the specified limits over a 24-hour period.

e. Loss of one or more working weeks due to radiation accident.

f. Damage to property in excess of $100,000.

If the accident does not meet the above levels but meets the criteria below, the accident must be reported within 24 hours.

a. Whole-body exposure in excess of 5 rems.

b. Skin exposure exceeding 30 rems.

c. Exposure of hands, feet, ankles exceeds 75 rems.

d. Release of radioactive materials exceeding 500 times the specified concentration limits over a 24-hour period.

d. Loss of one or more working days due to a radiation accident.

f. Damage to property in excess of $1,000.

Responsibilities of the Industrial Hygienist

In some instances, the industrial hygienist has direct responsibility for radioactive sources. In fulfilling his responsibilities, he should perform the following activities:

1. Comply with all government regulations.
2. Insure adequate supervision and training of personnel working with radioactivity.
3. Maintain inventory of radioactive sources being used, including type and amount.
4. Review operational procedures to evaluate potential:
    a. personnel exposure
    b. accidents causing a radiation release
5. Periodically survey radioactive areas for radiation levels.

6. Evaluate laboratory facility for proper design, construction, shielding, posting, labeling, etc.
7. Design alternative plans for containment and decontamination in the event of an accident.
8. Monitor the disposal of wastes.
9. Supervise the monitoring system, including personnel monitoring procedures.
10. Maintain accurate records, including personnel cumulative exposure, radiation surveys, instrument calibration, waste disposal, and radiation incidents.

Summary

The last three chapters have presented an overview of the theory, use, monitoring, and control and management of ionizing radiation. Because of the potential health hazard of ionizing radiation, it is essential that the industrial hygienist minimize the potential personnel exposure when working with radiation sources. These chapters were not intended to provide the reader with a complete and comprehensive understanding of ionizing radiation, but the material presented was designed to provide an initial understanding of the concepts of ionizing radiation.

Practice Exercises

1. Because of an accident, the shielding around a 500 mCurie Co-60 source has been destroyed. What is the minimum distance to the source a person can approach if a 2.5 mR/hr level is not exceeded?
2. Determine the thickness of concrete required to reduce the intensity of a Co-60 (gamma radiation) to 1/100 its value when unshielded. (Note: HVL Co-60 is 6.6 cm concrete.) Use HVL method.
3. Determine the thickness of lead (Pb) required to reduce the dose rate from a 30 mCi Cs-137 source to 5 mrem/hr at 30 cm from the source.

4. A technician in a pharmaceutical company routinely handles

   1. 500 mCi of I-131
   2. 100 mCi of Au-198
   3. 25 mCi of K-42

   all stored together in a hood. When he works in front of the hood, his mean body position is 60 cm from the active materials.

   a. How long can the technician work in front of the hood per week without additional shielding?

   b. What would be the effect on permissible working time if the technician used tongs, extending the mean body distance to 150 cm?

5. An investigator is interested in releasing 200 mCi of Xe-133 through a hood. The air velocity into the hood is 150 ft/min through an opening 15 inches high and 3 feet wide. Determine the permissible release rate so that the concentration in the effluent from the hood stack does not exceed maximum allowable concentrations averaged over a 24-hour period.

6. In a new process being introduced in your plant, an I-131 (gamma source) with an activity of 300 mCi will be used. In the process, the personnel will be a mean distance of 70 cm from the source and be exposed to the source for an average of 15 minutes per day. Because of the new process, it is possible that some of the material (Fe-59) may become airborne as particulate matter. Calculate:

   a. Potential exposure of unshielded source.
   b. Lead shielding required to reduce exposure to below MPD level.

7. Prepare a list of activities that should be performed to evaluate and control the radiation hazard being introduced.

Self-Test

Nonionizing and Ionizing Radiation | **Section 6**

1. Define the following terms:
   a. Photon ________________________________
   b. Wavelength ________________________________
   c. Frequency ________________________________
2. Rank the following regions of the electromagnetic spectrum from highest to lowest frequency and indicate whether they are a form of ionizing or nonionizing radiation.

Rank	Region	Ionizing	Nonionizing
_____	a. Ultraviolet	_____	_____
_____	b. Radio frequency	_____	_____
_____	c. Infrared	_____	_____
_____	d. Visible	_____	_____
_____	e. Gamma	_____	_____
_____	f. X-Radiation	_____	_____

3. Describe the primary difference between ionizing and nonionizing radiation.

____

____

____

____

4. List a source and biological effect for each of the following types of radiation.

	Source	Biological Effect
a. Ultraviolet	____________ ____________	____________ ____________ ____________
b. Infrared	____________	____________
c. Radio Frequency	____________ ____________	____________

Self-Test	
Nonionizing and Ionizing Radiation	Section 6

5. Describe the operation of a klystron unit. (Draw a diagram.)

Self-Test	
Nonionizing and Ionizing Radiation	Section 6

6. Describe the operation of a typical laser unit. (Draw a diagram.)
   Describe the potential hazards of a laser unit.

Self-Test

Nonionizing and Ionizing Radiation

Section 6

7. What is the power density (W/cm^2) of a laser unit with

   a. power output--0.5 Joules
   b. pulse length--10^{-4} seconds
   c. focal size--0.5 mm^2

8. List at least three (3) hazards associated with ultraviolet radiation.

9. Why is it necessary for ultraviolet measurements to approximate the actinic curve?

10. Describe the procedure used to determine the effective irradiance of an ultraviolet band source.

11. List three (3) factors which affect the accuracy of ultraviolet source measurement.

12. Briefly describe the effect of time and distance upon exposure to electromagnetic radiation.

Self-Test

Nonionizing and Ionizing Radiation | Section 6

13. What is the beam intensity of a laser at 135 cm with

    a. power output--0.5 watts
    b. beam divergence--0.80 milliradians
    c. beam diameter--2.0 cm

14. For each class of laser, describe the criteria for classification and at least one example of an operational requirement.

Class	Criteria	Operational Requirement
I		
II		
III		
IV		
V		

15. What is the difference between the "near" and "far" fields of radio frequency radiation?

16. Calculate the radius of the "near" field for radio frequency radiation, given the area of the antenna is 100.5 cm^2 and the wavelength is 10.5 cm.

Self-Test

Nonionizing and Ionizing Radiation

Section 6

17. List at least five (5) causes of potential radio frequency hazard.

18. List at least two (2) types of detectors used for measurement of nonionizing radiation, their use, and basic principle of operation.

19. Define the following terms:

a. Atom

b. Proton

c. Neutron

d. Electron

e. Isotope

f. Radioactive Decay

g. Half-Life ($T^{\frac{1}{2}}$)

Self-Test

Nonionizing and Ionizing Radiation

Section 6

20. Complete the following table:

	Type of Radiation Particle/Photon	Charge +,-,0	Atomic Weight amu	Penetrating Capability	Source (Machine, Decay)
Alpha					
Beta					
Photon					
Negatron					
Gamma					
X-radiation					
Neutron					

21. Define each of the following units of measure:

a. Curie ____________________

b. Roentgen ____________________

c. rad ____________________

d. rem ____________________

22. Calculate the dose equivalent for an alpha source with a reading of 150.0 μrads at 10 cm, and the maximum exposure time which would not exceed 0.23 rems/week.

23. Describe the difference between an internal and external radiation hazard. Give an example of each.

____

____

____

____

Self-Test

Nonionizing and Ionizing Radaition	Section 6

24. List at least four (4) uses of ionizing radiation in the industrial setting.

25. List at least three (3) hazards associated with radiation use.

26. Describe the principle of operation of a G-M counter and the characteristic difference between the G-M counter, proportional counter, and ionization chamber.

27. Describe the principles of operation of the
    a. Scintillation detector
    b. Photographic device
    c. Thermoluminescent device

28. What is the primary difference between a pocket dosimeter and pocket ion chamber?

Self-Test

Nonionizing and Ionizing Radiation | Section 6

29. Describe the purpose of shielding and an example of an appropriate shielding material for each type of ionizing radiation.

30. Briefly describe the steps which can be taken to control
    a. Alpha
    b. Beta
    c. Gamma

31. Describe the procedure necessary to analyze
    a. Surface contamination
    b. Air contamination
    c. Water contamination

32. List five (5) potential design problems which may exist in a facility using radiation.

Self-Test	
Nonionizing and Ionizing Radiation	Section 6

33. What steps should be taken if a person has been splashed with a solution containing a gamma/beta emitter?

REFERENCES

American Conference of Governmental Industrial Hygienists. TLV's for Chemical Substances and Physical Agents in the Workroom Environment with Intended Changes for 1976. Cincinnati: American Conference of Governmental Industrial Hygienists, 1976.

Blaty, Hanson. Introduction to Radiological Health. New York: McGraw-Hill Book Company, 1976.

Department of the Air Force, AFM. Laser Health Hazards Control. Washington: 1971.

Departments of the Army and Navy TB Med 279/NAVMED P-5052-35. Control of Hazards to Health from Laser Radiation. Washington.

International Commission on Radiation Units and Measurements. Radiation Protection Instrumentation and Its Application, ICRU Report 20. Washington: 1971.

__________________. Radiation Quantities and Units, ICRU Report 19. Washington: 1971.

Morgan, K. Z. and Turner, J. E. Principles of Radiation Protection. New York: John Wiley and Sons, Inc., March 1973.

National Bureau of Standards. Safe Handling of Radioactive Materials, Handbook 92. Washington: U. S. Government Printing Office, 1964.

National Council on Radiation Protection and Measurements. Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and Water for Occupational Exposure, NCRP Report No. 22, National Bureau of Standards Handbook 69. Washington: U. S. Government Printing Office, 1959.

__________________. Medical X-Ray and Gamma-Ray Protection for Energies up to 10 MeV, Structural Shielding Design and Evaluation, NCRP Report No. 34. Washington: 1970.

__________________. Protection Against Neutron Radiation, NCRP Report No. 38. Washington: 1971.

__________________. Basic Radiation Protection Criteria, NCRP Report No. 39. Washington: 1971.

Olishifski, Julian B. and McElroy, Frank E., ed. Fundamentals of Industrial Hygiene. Chicago: National Safety Council, 1971.

Shapiro, Jacob. Radiation Protection--A Guide for Scientiest and Physicians. Cambridge: Harvard Univeristy Press, 1974.

U. S. Department of Health, Education, and Welfare, Public Health Service, National Institute for Occupational Safety and Health. the Industrial Environment--its Evaluation and Control. Washington: U. S. Government Printing Office, 1973.

U. S. Department of Health, Education, and Welfare, Public Health Service. Radiological Health Handbook. Washington: U. S. Government Printing Office, 1970.

☆ U. S. GOVERNMENT PRINTING OFFICE: 1978 — 657-061/1866