DEPARTMENT OF
ENVIRONMENTAL SAFETY,
SUSTAINABILITY & RISK

Radiation Protection Training Manual & Study Guide For Radiation Producing Devices

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May 1994

Lesson Plan Outline

Instructional Subject:	Interactions of Fundamental Particles with Matter ° Interaction of Particles · Photons · Electrons · Heavy Charged Particles · Neutrons ° Radiation Dose Units
Instructor:	To be determined
Instructional Goal:	To provide the participant with basic knowledge of radiation concepts
Instructional Objectives:	Upon completion of the instructional period, the participant should be able to accomplish the following: ° Recognize the differences of radiation producing particles ° Know where to go for information ° Understand the interactions of particles with matter and energy transfer mechanisms ° Be able to identify and use radioactive dose units
Training Support Material:	Handouts Study Guide
Video Tapers:	None
Slides:	As determined by the instructor
Equipment Required:	As determined by the instructor
Reference Material:	Radiation Protection Training Manual and Study Guide - Chapter 1

Lesson Plan Outline

Instructional Subject: Accelerators and their Ionizing Radiations

- Primary Radiation
- Secondary Radiation

Instructor: To be determined

Instructional Goal: To provide the participant with a basic knowledge of accelerator and x-ray radiation potentials

Instructional Objectives: Upon completion of the instructional period, the participant should be able to accomplish the following:

- Recognize potential radiation hazards

Training Support Material: Handouts
Study Guide

Video Tapers: As determined by the instructor

Slides: As determined by the instructor

Equipment Required: As determined by the instructor

Reference Material: Radiation Protection Training Manual and Study Guide - Chapter 2

Lesson Plan Outline

Instructional Subject: Sources and Effects of Radiation

- Biological Effects of Radiation
- Radiation Exposure Limit
- Radiation from Background Medical and Consumer Products

Instructor: To be determined

Instructional Goal: To provide the participant with information concerning the effects and limits of radiation exposure

Instructional Objectives: Upon completion of the instructional period, the participant should be familiar with the effects and limits allowed for radiation exposure in the use of radioisotopes and/or equipment and:

- Be familiar with methods of protection

Training Support Material: Handouts
Study Guide

Video Tapers: None

Slides: As determined by the instructor

Equipment Required: As determined by the instructor

Reference Material: Radiation Protection Training Manual and Study Guide - Chapter 3

Lesson Plan Outline

Instructional Subject: Radiation Detection and Measurement

- Survey Instruments
- Use of Radiation Survey Instruments
- Calibration of Survey Instruments
- Personnel Monitoring Instruments
- Proper Use of Personnel Monitors

Instructor: To be determined

Instructional Goal: To provide the participant with a basic knowledge of instruments available and how they are used

Instructional Objectives: Upon completion of the instructional period, the participant should be able to accomplish the following:

- Identify the different types of instruments and detectors
- Be able to perform surveys with the appropriate instrument
- Understand how instruments are calibrated and how to determine the efficiency
- Have basic understanding of statistics

Training Support Material: Handouts
Study Guide

Video Tapers: None

Slides: As determined by the instructor

Equipment Required: As determined by the instructor

Reference Material: Radiation Protection Training Manual and Study Guide - Chapter 4

Lesson Plan Outline

Instructional Subject: Radiation Protection and Control of Exposures

- External Radiation Protection
- Hazards Associated with Accelerators
- Radiation Safety Procedures – Warning and Interlock Systems
- Radiation Survey Procedures
- Control Measures for Radiation Levels
- Planning in Emergencies – Radiation Accidents

Instructor: To be determined

Instructional Goal:

- To provide the information to the participant on the requirements of radiation protection methods
- How to determine shielding needs
- A view of possible hazards
- A view of protective and cautioning devices
- Methods of surveys and controls

Instructional Objectives: Upon completion of this instructional period, the participant should be able to accomplish the following:

- Be knowledgeable of the required safety warning and control devices
- Be able to identify hazards associated with accelerator and x-ray equipment

Training Support Material: Handouts
Study Guide

Video Tapers: As determined by the instructor

Slides: As determined by the instructor

Equipment Required: As determined by the instructor

Reference Material: Radiation Protection Training Manual and Study Guide - Chapter 5

Lesson Plan Outline

Instructional Subject: Radiation Protection Program

- Rules and Regulations
- Course Review
- Course Evaluation
- Examination

Instructor: To be determined

Instructional Goal:

- ° To provide the information to the participant on the requirements of a radiation protection program
- ° Review all material covered and provide RSO with an evaluation of the course

Instructional Objectives: Upon completion of this instructional period, the participant should be able to accomplish the following:

- Be knowledgeable of the rules and regulations and the requirements to have a radiation training program
- Be able to demonstrate acceptable knowledge of the information presented to easily pass the test for the course

Training Support Material: Handouts
Study Guide

Video Tapers: As determined by the instructor

Slides: As determined by the instructor

Equipment Required: As determined by the instructor

Reference Material: Radiation Protection Training Manual and Study Guide - Chapter 6

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Introduction

This Training Manual and Study Guide serves as the main text for the UMD Radiation Safety Office Training Course entitled "Basic Radiation Safety for Radiation Producing Devices". This manual is subdivided into two parts - one for the accelerator users and the other for X-ray diffraction unit users. This manual only covers the basic radiation protection, the training for operation of each unit will be conducted by the Principal User of that unit. The regulations governing the registration and/or certification of radiation producing devices are included in the Supplement to Radiation Safety Manual. The radiation protection training course is offered periodically in conformance with State regulations requiring that individuals working with radiation producing devices be adequately trained.

The concepts and ideas presented in the text require a fundamental understanding of biology, physics and mathematics. While the material is presented in its most basic form, undoubtedly some ambiguities will remain. A bibliography is provided for the interested student to further his or her knowledge in this area.

The Radiation Safety Office is available to answer any questions or aid any user in the radiation science field. We welcome all inquiries and would appreciate comments and suggestions on how to improve this Study Guide, Training Course or our Radiation Safety Program.

Radiation Safety Office

The Radiation Protection Training Course has been established to satisfy the training requirements for University of Maryland personnel who use radiation producing devices.

The course will be presented periodically. Personnel who are unable to attend the formal lecture presentation may pursue a course of study on their own by using the Accelerator Radiation Protection Training Manual and Study Guide.

Upon completion of the study course or lecture, an examination will be given to authenticate completion of the program requirements. Receipt of the completed examination by the Radiation Safety Office will be the only completion documentation accepted.

A Certificate of Achievement will be presented to those who have successfully completed the course and a permanent record of training completion will be on file in the Radiation Safety Office.

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Chapter I

Interactions of Fundamental Particles with Matter

The primary cause of biological damage from ionizing radiation is the production of ions in living tissues. For establishment of techniques in radiation protection, it is necessary to understand the manner in which radiation interacts with matter and transfers its energy. This chapter deals with the various mechanisms of energy loss by radiation while traversing through matter.

Energy from radiation is transferred to matter via two major ways: Ionization and Excitation. Ionization is the process of removal of an electron from an atom whereby the atom is left with a net positive charge. In excitation, the energy of incoming radiation is added to the atomic system, transferring it from the ground state to an excited state.

The interaction of all types of radiation with matter will ultimately have the same effect. However, the initial stages of energy loss for each type of radiation are different. In an accelerator, there are four principal types of radiation of concern:

a. Electromagnetic radiation (photons, e.g x or gamma)
b. Electrons including positrons
c. Charged heavy particles, e.g protons, deuterons and alpha particles
d. Neutrons

The electrons, positrons, protons, deuterons and alpha are grouped as the charged particulate radiation while the x-ray, gamma and neutrons are the uncharged radiation.

A. Interaction of Photons:

Since photons are chargeless, they do not interact by electrostatic forces as is the case with charged particles. Charged particles cause ionization of matter directly along their path of travel and as such are directly ionizing radiation whereas photons are indirectly ionizing radiation. That is, photons have sufficient energy to release high energy secondary charged particles (electrons) from matter through one of three basic interactions:

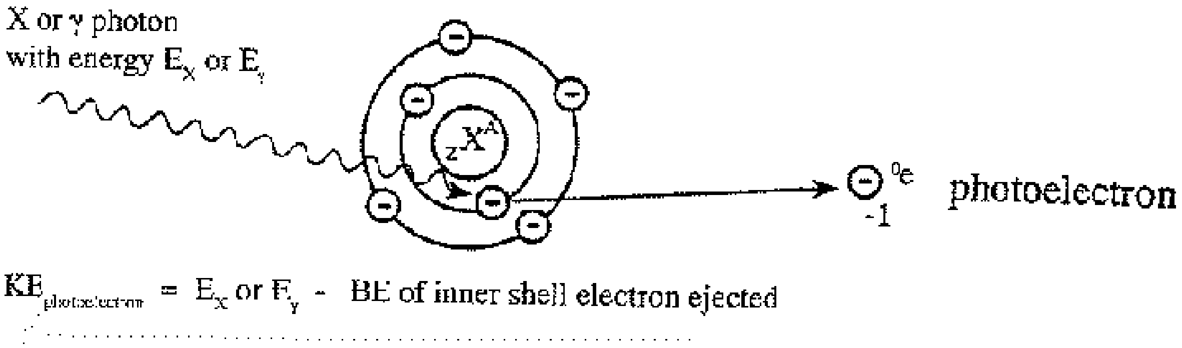
- The Photoelectric Effect
- The Compton Effect
- Pair Production

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

1. The Photoelectric Effect

The Photoelectric Effect is the interaction of low energy photons*** with matter, whereby all of the energy of the photon is transferred to an inner shell electron (usually the K shell). The electron is ejected from the atom and the atom is left with an inner shell vacancy. This shell vacancy creates an excitation energy which corresponds to the

Binding Energy (BE) of the ejected photoelectron.



KEphotoelectron = EX or Eg - BE of inner shell electron ejected

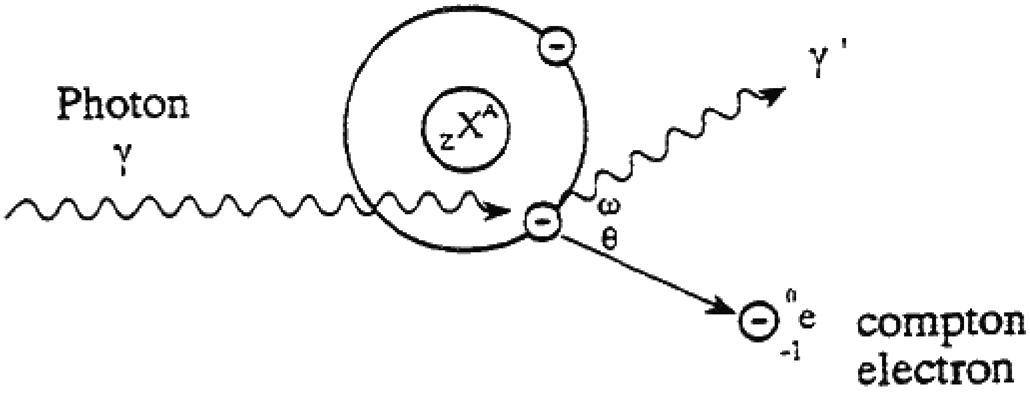
The resultant atom is now in an excited state and will decay to the ground state by emission of X-rays and fluorescent radiation with the total energy equal to the BE of the photoelectron. The energies of the secondary radiations are usually much lower than the primary photon energy.

For this reaction to occur, the photon must have sufficient energy to knock the inner shell electron.

*** A photon, as described by the Quantum Theory, is a "particle" or "quantum" that contains a discrete quantity of electromagnetic energy which travels at the speed of light, or 3 X 108 meters per second.

2. The Compton Effect

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

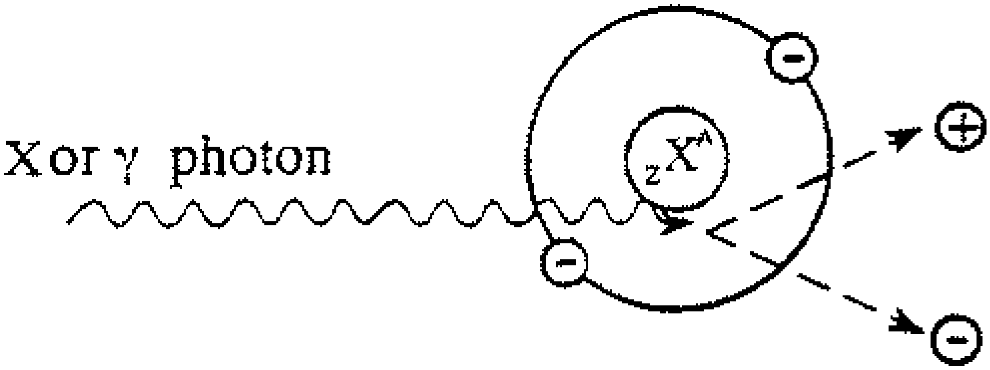


The primary g loses part of its energy to the Compton electron which gets scattered at an angle q from the original direction of the incident g, while the compton scattered g (g') is scattered at an angle w. In this process, the scattered photon and Compton electron share the energy of the incident g.

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

3. Pair Production

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



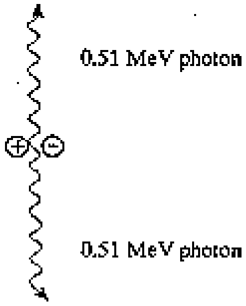
$Eg = KE_+ + KE_- + 2\ m_oc^2$

m_oc^2 represents the rest mass energy of an electron (0.51 MeV)

Since both particles are created from energy supplied by the incident photon, the process is energetically possible only if Eg or EX is greater than 1.02 MeV.

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

E = energy of two 0.51 MeV photons
m = the rest mass of two electrons (1/1840 amu)
c = the velocity of light (3 X 108 m/sec)



B. Interaction of Electrons:

For electrons, two mechanisms contribute to the energy loss process. In addition to atomic collisions (that result in ionizations or excitations), radiation losses occur when an electron is deflected by the electromagnetic field of a nucleus. The total energy loss, (dE/dX)tot, is written as:

$$(dE/dX)_{tot} = (dE/dX)_{coll} + (dE/dX)_{rad}$$

The quantity (dE/dX) is also referred to as the stopping power of the medium for the particle. The first term is the energy loss due to collisions and the second term represents energy loss from radiation, primarily **bremsstrahlung**. At low energies, < 1 MeV, the energy loss due to ionization is predominant. At very high energies the radiative term dominates and gives rise to electron-photon cascade showers. As the high energy electrons are deflected from their path in the vicinity of a nucleus, high energy photons referred to as the bremsstrahlung photons are emitted. These high energy photons, in turn, produce Compton electrons and electron- positron pairs, which then produce additional bremsstrahlung photons, and so on. These repeated interactions result in electron-photon cascade shower.

The ratio of energy loss by radiation to energy loss by ionization in an absorber Z is approximately equal to EZ/800, where E is the electron energy. Thus, the probability of bremsstrahlung increases with the increasing atomic number of the absorber. As a result a low Z material is used for shielding these radiations.

The electrons lose a large fraction of their energy in single collisions with matter, undergoing large deflections in the matter and travelling in a zig-zag manner.

C. Interaction of Heavy Charged Particles:

The interactions of heavy charged particles are fundamentally similar to that of electrons. The positive ions or heavy charged particles loose energy by interacting with electrons of the matter causing ionization and excitation of atoms. Unlike electrons, a heavy charged particle transfers only a small fraction of its energy in a single electronic collision and its deflection in the collision is negligible. Thus, a heavy charged particle travels almost in a straight path through matter, losing energy continuously in small amounts. Generally, the rate of energy loss of all charged particles moving with the same velocity in a given absorber is proportional to the square of their charges. Heavy atoms or high Z absorbers are less efficient for slowing down heavy charged particles because many of their electrons are too tightly bound in the inner shells.

D. Interaction of Neutrons:

Like photons, neutrons are uncharged particles and can travel long distances in matter without interacting. Neutrons interact with an atomic nucleus via two basic processes; scattering and absorption. In this section we will deal with only scattering interactions: elastic scattering and inelastic scattering.

1. Elastic scattering: This is the most important process for slowing down neutrons. In this scattering, the total KE is conserved, i.e. the total energy lost by an electron is equal to the energy of recoil nucleus. The maximum energy that a neutron of mass M and kinetic energy E can transfer to a nucleus of mass m in a single (head on) elastic collision is given by:

$$Q_{max} = \frac{4mME}{(M+m)^2}$$

2. Inelastic scattering: In this process, the nucleus absorbs some energy internally and is left in an excited state. Thus, the nucleus emerges from the collision with a different amount of energy than before the collision. The excited nucleus subsequently decays by emitting gamma-rays, the inelastic gamma-rays. Typically, a fast neutron will lose energy in matter by a series of elastic interactions.

Radiation Dose Units

Radiation is measured in four basic units - the *rad*, the *gray*, the *rem* and the *Sievert*:

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

b. The *gray* (Gy) is the SI unit of absorbed dose and is equal to an absorbed dose of 1 J/kg (100 rad).

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

d. The *Sievert* (Sv) is the SI unit for dose equivalent and is equal to 1 J/kg (100 rem). Below is a table listing Quality Factors for various types of radiations: Quality Factor Absorbed dose equal to a unit Quality dose Radiation Factor Equivalent * X, g or b 1 1 Neutrons of 10 0.1 unknown energies Alpha 20 0.05 Protons 10 0.1 Thus, the rem allows us to add doses of different radiation types to obtain a total effective dose. * Absorbed dose in rad equal to 1 rem or the absorbed dose in gray equal to 1 Sievert. Example: What is an individual's dose equivalent from 10 mrad of gamma rays, 5 mrads of b- particles and 10 mrads of neutrons? (m = milli = 1/1000) Total Dose Equivalent = mrads x QF = mrems Gamma dose equivalent = 10 x 1 = 10 Beta dose equivalent = 5 x 1 = 5 Neutron dose equiv. = 10 x 10 = 100. Total 115 mrems

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Chapter II

Accelerators and Their Ionizing Radiations

An accelerator is used to impart kinetic energy to electrically charged particles. In general, relatively small amount of energy is required to accelerate the electrons to nearly the speed of light. The increase in kinetic energy increases solely the mass of the particle and has little effect on its velocity. The accelerating potential is produced by waves travelling at constant velocity. These waves are generated in radiofrequency, RF, waveguides. The RF power source which drives the waveguide supplies very high power in short pulses. For example, the accelerating waveguides in a linear accelerator consists of a circular tube containing a series of disks along its length. Each disk has a central hole through which the electron beam passes. In cyclotrons and synchrotron, the particles are repeatedly returned to the same accelerating electrode by means of a magnetic field which causes them to move in circular or nearly circular path.

Ionizing radiation from accelerators can be classified according to its source:

a. primary radiation
b. secondary radiation
c. stray radiation
d. induced radioactivity

The primary and secondary radiations are grouped under prompt radiation fields and are described in this chapter. The remaining two types of radiations: stray radiation and induced radioactivity are explained in Chapter V.

Prompt Radiation Fields

A. Primary radiation:

Primary radiation is the beam of particles accelerated by the particle accelerator and may comprise of electrons, protons, deuterons, alphas and other heavy particles. The primary radiation is always directed and is focused into a beam. Inside the machine or the vacuum chamber it exists as an "internal beam" and as it emerges from the chamber usually by passing through a thin metal foil it is referred to as the "external beam".

The accelerator beam is usually collimated and travels in a straight line unless deflected by a magnet. Thus, the primary radiation field occupies a very small volume, and its energy is concentrated to a smaller area. However, some accelerators such as industrial processing units, have the ability to spread primary radiation over a larger area with a scanning horn. In these units, the primary radiation intensity is also very high but is concentrated to a larger area.

In either case, any exposure to primary radiation, i.e. the beam itself, presents extreme external hazards. When the beam strikes a solid object, e.g. a target, target holder or beam stopper, the beam may scatter in the backward direction or produce secondary radiation, which may be very penetrating.

B. Secondary radiation:

Secondary radiation is produced when the primary beam strikes a target or other material. As a result of this interaction, either charged particles are created or electromagnetic radiation is produced. The charged particles such as electrons, protons and positive ions produced from the interaction have short ranges while the x-rays, gamma rays and neutrons created in the process are very penetrating and are responsible for thick shielding around the accelerators. Often this secondary radiation is the principal useful output of the machine, e.g. x-rays for radiography and neutrons for activation analysis.

1. X-rays:

X-rays are electromagnetic radiations which originate in the electron field outside the nucleus of an atom. A high energy electron knocks an orbital electron from the innermost shell of an atom thereby leaving the atom in an excited state. An X-ray is released when the electron from an outer shell fills the vacancy and the atom returns to the ground state. The X-rays can also be produced by rapid deceleration of fast moving high energy electrons in the vicinity of a nucleus. The electrons are deflected from their original path and while slowing emit x-rays, also known as the "bremsstrahlung radiation". Bremsstrahlung is a German word for "braking radiation".

The efficiency of conversion of kinetic energy of an electron into bremsstrahlung radiation increases with increasing electron energy and with increasing atomic number of the target material.

The fraction, f, of the electron's kinetic energy which is converted to x-ray energy is given by the following equation:

$$f = 1.1 \times 10^{-6} E Z$$

where Z: Atomic number of the target

E: Electron energy

For example, in a thick tungsten target, a 10 MeV electron converts about 30% of its energy into X-rays whereas a 100 MeV electron converts more than 75% of its energy.

The energy of x-rays is usually expressed as the maximum or peak energy of the impinging electrons. In a typical X-ray production process the X-rays are emitted in a broad energy spectrum ranging up to the maximum energy of the accelerated electron used.

2. Neutrons:

Neutrons are chargeless particles having a mass nearly equal to protons. Neutrons are classified according to their kinetic energies as follows:

epithermal
thermal
intermediate
fast

Neutrons are usually generated in all directions with a high energy component in the forward direction. As the accelerator energy increases, the high energy component becomes more important and is the basis of shielding around accelerators. In electron accelerator, an intermediate target is used to create bremsstrahlung beam which in turn, strikes a second target and neutrons are produced.

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Chapter III

Sources and effects of Radiation

1. Biological Effects of Radiation

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

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

A. Radiosensitivity of Cells

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

$$H_2O \text{ ----> } H_2O^+ + e^-$$

and the H2O+ is rapidly hydrated to form:

$$H_2O^+ + H_2O \text{ ----> } H_2O^+ \; OH^{\cdot}$$

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

$$e^- + H_2O^+ \text{ ---> } OH^- + H^{\cdot}$$

The overall reaction is thus:

$$H_2O \text{ ---> } H^{\cdot} + OH^-$$

with the products separated by a considerable distance so that immediate back reactions to form water are not favored. Such radicals can combine with each other and with dissolved oxygen to give a variety of potent oxidizing agents such as hydrogen peroxide, superoxide, molecular oxygen and the perhydroxyl radical.

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

In addition to the indirect effect, radiation may itself cause ionization in DNA or other biological molecules. The energy of ionization is far greater than the bond energy in organic molecules, thus causing bond breakage. The amount of this **Direct Effect** occurring depends on the number of a particular type of molecule in the cell, and its size. The larger the molecule, the better target it makes. Since DNA is the largest molecule in the cell as well as the site of all the genetic information, its response has a central role in the mediation of radiation effects.

Depending on how it is damaged, different results will occur. If the damage results in a strand break in its back bone (breaking the molecule in half), subsequent mitoses may fail resulting in cellular death. If the break is in one of its side groups (bases), it will then transmit different genetic data during subsequent division resulting in some kind of a mutation. Both direct and indirect effects contribute to the overall number of such damaging events to the DNA and will vary for individual cell types.

The radiosensitivity of a particular cell depends on a number of factors. An early observation of this difference is reflected in the "Law of Bergonie and Tribondeau" which states "the radiosensitivity of a tissue is directly proportional to the reproductive activity and inversely proportional to the degree of differentiation". Tissues consisting of rapidly dividing stem cells (like blood or sperm cell precursors) are quite sensitive to radiation whereas cells that do not divide or only rarely divide (like nerve or muscle cells) are considerably more resistant. From microscopic examination, cells appear to get stuck in the division process after radiation exposure, which is consistent with the "Law" above. Other factors involved include metabolic rate, state of nourishment, oxygen level and presence of particular enzymes within the cell. The latter are most likely involved with the repair of some of the radiation damage.

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

Type	Biological Response
	-**Extremely Radiosensitive** -
Blood-forming Organs lymph nodes, thymus, spleen, bone marrow	Exposures as low as 50 rad can affect the white cell population within 15 minutes. Red cell count falls 2 to 3 weeks later. Results in a feeling of general weakness, anemia, and a lower resistance to infection.
	- **Moderately Radiosensitive** -
Reproductive Organs female, male	Exposures below 100 rad can reduce fertility. Temporary sterility can occur lasting 12 to 15 months following 200-300 rad. On the average, a larger exposure is needed to produce sterility in the male than in the female. Damage to the germ cells can lead to somatic and/or hereditary

	changes.
	Radiosensitive -
Digestive Organs small intestine, lower intestine, pharynx, esophagus	Degenerative changes occur as soon as 30 minutes after exposure of 500-1000 rad. Initial effects are: impaired secretion of necessary fluids. Cell breakdown results in failure of food and water absorption leading to infection and dehydration from diarrhea.
	- **Moderately Radioresistant** -
Vascular System arteries (lg & sm) capillaries, heart,	Sensitivity varies for the vascular system. Damage is great only in the 600-1500 rad range. This damage by radiation veins contributes to some of the changes in other tissues.
	- **Radioresistant** -
Skin	Exposures between 500-1000 rad can produce skin changes. However, as little as 100 rad can cause cell death in the germinal layer.
Bone and Teeth	Some parts of bone can be damaged by 700-1500 rad. Regeneration can begin 2 to 6 weeks after exposure.
	- **Relatively Radioresistant** -
Respiratory System	Inflammation of the lungs can occur at 1000-2000 rad. Possible hemorrhaging due to changes produced in blood vessels.
Urinary System	Secondary effects can show up years after exposure in the 500-2000 rad range due to changes in blood vessels.
	- **Very Radioresistant** -
Muscle and Connective Tissues	Massive exposures (over 2000 rad) are needed to cause slight changes in these tissues.
	- **Extremely Radioresistant** -
Nervous Tissue	Massive exposures are required (over 3000 rad) to bring about morphological changes in these tissues.

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

B. Genetic and Somatic Effects

Biological effects of radiation may be subdivided into two categories; genetic effects and somatic effects.

Genetic effects: these effects occur in the reproductive cells and the damage is observable in subsequent generations.

Somatic effects: these effects arise from the damage to all the cells in the body and occur in the lifetime of an exposed individual.

Somatic effects may be further subdivided into two groups: short-term or acute effects, and long term or latent effects.

I. Short-Term Somatic Effects

Short term effects arise from large acute exposures in excess of about 100 rad, and are observed in a few days or weeks after exposure. These effects may be characterized by the following features:

- effects are observed only after integrated doses of 50 rad or more are delivered in a period of few hours or less.
- effects exhibit a threshold, i.e. there is some dose below which they never occur.
- effects show dose-rate dependence, i.e. for low-LET radiation the effect is greater and for high-LET it is smaller.
- generally, effects exhibit a nonlinear response-dose relationship.

Death, radiation sickness, prodromal response, central nervous system death, response of the skin and acute radiation syndrome are some of the examples where these characteristics can be observed.

a. Acute Lethal Response

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

Acute Lethal Responses

Species	**RAD**
Guinea pig	175-409
Dog	350
Goat	350
Man	350-450
Mouse	550
Rat	590-970
Monkey	600
Rabbit	800
Fowl	1000
Goldfish	2300

The ranges shown represent an uncertainty only in the case of man, where precise experimental data does not exist. Other ranges represent a difference depending on the particular strain of the species used. The cause of death at the $LD_{50/30}$ is due to response of the blood forming organs. Interestingly, at the tissue level, a given dose yields about the same observable damage in any species. Some species, however, are better able to cope with the damage and so survive. When organisms are exposed at or above the acute $LD_{50/30}$ value, characteristic physiological responses are seen. These responses are known as "radiation sickness" and "acute radiation syndrome". The following tables illustrate the symptoms and their timing from various whole-body dosages.

Expected Effects of Acute Whole-Body Radiation Doses

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

5000 Incapacitation almost immediately. All personnel will be fatalities within 1 week.

Summary of Clinical Symptoms of Radiation Sickness

Time after Exposure	Survival Improbable (700R or more)	Survival Possible (550R to 300R)	Survival Probable (250R to 100R)
1st week	· Nausea · Vomiting · Diarrhea In first few hours.	· Nausea · Vomiting · Diarrhea In first few hours.	· Possible nausea · Diarrhea On first day.
	No definite symptoms in some cases (latent period).	No definite symptoms (latent period).	· Fever No definite symptoms (latent period).
2nd week	· ·	·	
3rd week	· ·	· Epilation Loss of appetite and general · malaise · Fever · Hemorrhage · Purpura · Petechiae · Nosebleeds Inflammation of the mouth · and throat · Diarrhea · Emaciation Death in most cases (mortality 50 percent for 450R).	· Epilation · Loss of appetite and malaise · Hemorrhage · Petechiae · Pallor · Sore throat · Moderate emaciation · Recovery likely in about 3 months unless complicated by poor previous health or superimposed injuries
4th week	· Diarrhea Hemorrhage · Purpura Inflammation of the mouth and throat Rapid emaciation Death (mortality probably 100 percent).		

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

b. Acute Radiation Syndromes

Acute Radiation Syndromes

Response	Dose	Syndrome

	(rad)	
Hematopoietic Death	700 to 1000	Death in 10-21 days caused by blood changes resulting in infection or hemorrhaging.
Gastrointestinal Death	100 to 10000	Death in 4-7 days. Nausea, vomiting, and diarrhea; food and water intake depressed. Death by severe morphological changes in gastrointestinal tract.
Central Nervous System Death	10000 to 100000	Death within 2 days. Minutes after exposure, disorientation, incoordination, and semi-consciousness develops. Coma and death occurs from central nervous system damage.
Molecular Death	More than 100000	Immediate death. Death caused by inactivation of substances required for basic metabolic processes.

c. Skin Response to Radiation

Reddening of the skin was the first biological response to radiation noted in man; it still seems to be the most frequently observed injury in the sublethal range. The biological response of the skin, in order of increasing severity is:

- erythema
- dry desquamation
- moist desquamation
- sloughing of skin layers
- chronic ulceration

The total radiation exposure, the length of exposure time, radiation quality, the distribution of dose in the irradiated tissue and the region of the body exposed are all the variables that influence the progression and severity of radiation injury. The clinical observations of skin erythema in man may be summarized as follows:

a. Erythema may appear within minutes to hours after exposure. In general higher the exposures the quicker the appearance of reddening. The skin erythema dose is about 600 rad if delivered at a depth of at least 0.1 mm.
b. After doses of 1600-2000 rad to the skin, there is a more rapid appearance of erythema, followed by blisters, moist desquamation, and ulceration.

c. Temporary loss of hair from the scalp follows absorbed doses of about 300 rad at the hair follicle, and permanent baldness follows doses only 20 to 30% higher.
d. A dose of 500 rad to the hands or feet may result in loss of the nails.
e. Skin sensitivity varies, thus the face, trunk, arms, and legs are less sensitive than the backs of the hands, tops of the feet, scalp, eyelids, and perineum.

II. Long Term of Latent Somatic Effects

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

Types of Late Effect

Carcinogenesis

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

Tissue Effects

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

Hereditary Effects

Since controlled experimentation can only be performed in animals, which may or may not represent human response, the ultimate effect on us remains in question.

Lifespan Shortening

Chronic exposure results in about 7% lifespan shortening for every dose equivalent to the LD_{50} received.

The above late effects can only be predicted for large populations. For an individual in an irradiated group, the exact cause of death cannot be identified, either natural or from one of the many environmental agents capable of producing the same effect. That is because each agent will contribute to the risk in proportion to its amount and effectiveness, as well as factors related to the genetic resistance or sensitivity of the individual exposed.

B. Chronic Exposure Response

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

C. Comparison of Health Effects

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

Estimated Loss of Life Expectancy from Health Risks

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

Adapted from USNRC Regulatory Guide 8.29

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

2. Radiation Exposure Limits

A. Historical Review

Soon after the discovery of X-rays and radium, the dangers of radiation exposure became well known. Standard setting organizations like the International Council on Radiation Protection (ICRP) and the National Council on Radiation Protection and Measurements (NCRP) were formed to recommend limits on the exposure of radiation. Prior to 1928, the radiation exposure limit was based on the amount of radiation needed to produce reddening of the skin (erythema). When the Roentgen (R) was defined in 1928, this "erythema exposure" was calculated to range from 0.04 R - 2 R per day. In 1935, the NCRP's first recommendation for exposure limitation was 0.1 R/day (31 R/year). This was an arbitrary limit, based on no observable effects of three technicians' exposure to radium gamma rays. In 1949, the NCRP reduced the limit to 0.05 R/day (0.3 R/week; 15 R/year) because radiations then being used were more penetrating. A major revision adopted by both the NCRP and ICRP took place in 1957 and will be in effect until January 1, 1994. This limit allowed an individual to receive up to 3 Rem in 13 consecutive weeks, provided that the accumulated dose does not exceed 5(N-18) rem, where N is the individual's age. The latest revision, was completed in 1991, and will be effective on January 1, 1994 and eliminates what has been called a "bank" of available dose before exceeding the 5(N-18) dose.

B. Basis for the Current Radiation Exposure Limits

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

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

B. External Exposure

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

1. Total whole body exposures: (external + internal exposures)	5 rem/yr.
2. Any individual organ or tissue, other than lens of eye: (external + internal)	50 rem/yr.
3. Lens of eye:	15 rem/yr.
4. Skin or extremity: (shallow dose)	50 rem/yr.

C. Other Exposure Limits

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

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

2. Radiation from Background, Consumer Products, and Medical Exposure

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

A. Naturally Occurring Radiation

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

1. Cosmic Radiation

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

2. Terrestrial Radiation

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

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

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

Source: UNSCEAR 1977 Report

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

Naturally occurring radionuclides can give rise to external doses when contained in raw materials used to construct roads and buildings. Uranium and thorium are commonly found in cement, concrete blocks, and masonry products. For example, the possible annual dose near a granite wall at the "Redcap Stand" in Grand Central Station, New York is 200 mrem (assuming an occupancy of 8 hrs/day).

3. Internal Radiation

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

a. Tritium

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

b. Carbon-14

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

c. Potassium-40

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

d. Uranium and Thorium Series

The radionuclides that contribute to internal exposure from the uranium series are: U-238, Ra-226, Rn-222, and its decay products Pb-210, Bi-210, and Po-210. The major nuclides that contribute to internal exposure from the thorium series are. Th-232, Ra-228, Ra-220, and its decay products Pb-212, Bi-212, and Po-212. The major contribution to the natural internal dose is from the decay products of Rn-222. The major source of these alpha emitting nuclides is through emanation of Rn-222 from the ground. The decay products form in clusters with water, oxygen, and other gases and attach themselves to aerosol particles. They can be inhaled, ingested, and through direct deposition on plant leaves and root absorption enter the food chain. Cigarettes are estimated to contain 0.6 pCi of Pb-210 and 0.4 pCi of Po- 210. Brazil nuts and Pacific salmon have been found to contain larger concentrations(>5 pCi/kg) of Ra-226. There are areas in the world in which water concentrations of uranium and radium are high due to isolated deposits. Reindeer and caribou contain elevated levels of Pb-210 and Po-210 mainly because they feed on lichens in the winter which accumulate these isotopes. The Pb-210 in fish and mollusks range between 20-500 pCi/kg. The main source of radon indoors is from building materials such as by- product gypsum, used for internal walls and ceilings, and concrete. Increasing the ventilation of the room will significantly reduce the radon levels. The highest levels are found in poorly ventilated areas, such as basements, where radon diffuses out of the concrete walls and through cracks in the floor. Sealing the walls and floors with epoxy paint can reduce the emanation rate by a factor of four. Three layers of oil paint can reduce the emanation rate by an order of magnitude.

4. Summary

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

Source of Irradiation	mrad	
External Irradiation	Gonads	Lungs
Cosmic Rays:		
Ionizing component	28	28
Neutron component	0.35	0.35
Terrestrial Radiation: (g)	32	32
Internal Irradiation		
Cosmogonic radionuclides:		
H-3 (b)	0.001	0.001
Be-7 (g)	---	0.002
C-14 (b)	0.5	0.6
Na-22 (b+g)	0.02	0.02
Primordial radionuclides:		
K-40 (b+g)	15	17
Rb-87 (b)	0.8	0.4
U-238, U-234 (a)	0.04	0.04
Th-230 (a)	0.004	0.04
Ra-226, Po-214 (a)	0.03	0.03
Pb-210, Po-210 (a+b)	0.6	0.3
Rn-222, Po-214 (a) inhalation	0.2	30
Th-232 (a)	0.004	0.04
Ra-228, Tl-208 (a)	0.06	0.06
Rn-220, Tl-208 (a) inhalation	0.008	4
Total (rounded)	78	110

Source: UNSCEAR 1977 Report

B. Technologically Enhanced Exposures to Natural Radiation

Technologically enhanced exposure to natural radiation is defined as exposure to natural radiation to which man would not be exposed if some kind of technology had not been developed. For example, travel by air, using natural gas for cooking or heating, and living near a coal fired power plant increase an individual's exposure to naturally occurring radiations. Air travel increases the exposure due to cosmic rays and solar flares when flying at high altitudes. The following table shows calculated doses for various routes:

	Subsonic Flight at 11km		Supersonic Flight at 19km	
Route	Round trip Flight Duration (hr)	Dose (mrad)	Round trip Flight Duration (hr)	Dose (mrad)

Los Angeles to Paris	11.1	4	3.8	3.7
Chicago to Paris	8.3	3.6	2.8	2.6
New York to Paris	7.4	3.1	2.6	2.4
New York to London	7	2.9	2.4	2.2
Los Angeles to New York	5.2	1.9	1.9	1.3
Sydney to Acapulco	17.4	4.4	6.2	2.1

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

Source: UNSCEAR 1977 Report

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

Absorbed Dose in Chests of Astronauts on Space Missions

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

Source: UNSCEAR 1977 Report

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

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

1. Absorption of radionuclides by food crops.
2. External radiation from fertilizer storehouses and production plants.
3. Airborne radon decay products over land reclaimed after phosphate mining.
4. Radiation from gypsum used in building products.

C. Consumer Products

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

1. Radioluminous Products

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

2. Electronic and Electrical Equipment

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

3. Miscellaneous

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

   The following tables describe various consumer products containing radioactive materials and some annual population dose rates:

Selected Products Containing Radioactive Material

Product	Nuclides	Amount
Radioactive Material Contained in Paint or Plastic:		
Time Pieces	H-3	1-25 mCi
	Pm-147	65-200 µCi
	Ra-226	0.1-3 µCi
Compasses	H-3	5-50 mCi
	Pm-147	10 µCi
Thermostat Dials and Pointers	H-3	25 mCi
Automobile Shift Quadrants	H-3	25 mCi
Speedometers	Pm-147	0.1 mCi
Radioactive Material Contained in Sealed Tubes:		
Time Pieces, Marine Navigational Instruments	H-3	0.2- Ci
Exit Signs, Step markers, Public Telephone Dials, Light Switch Markers	H-3	0.2-3 Ci
Electronic and Electrical Devices:		
Fluorescent Lamp Starters, Vacuum Tubes, Electrical Lamps, Germicidal Lamps	Ra-226	1 µCi
	Natural Thorium	50 mg
Glow Lamps	H-3	0.01 mCi
High Voltage Protection Devices	Pm-147	3 µCi
Low Voltage Fuses	Pm-147	3 µCi
Miscellaneous:		
Smoke and Fire Detectors	Am-241	1-100 µCi
	Ra-226	0.01-15 µCi
	Kr-85	7 mCi
Incandescent Gas Mantles	Natural Thorium	0.5 gm
Ceramic Tableware Glaze	Natural Uranium or Thorium	20% by weight of the glaze

Adapted from UNSCEAR 1977 Report

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

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

Adapted from NCRP Report No. 56

D. Medical Exposures

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

Patient Skin Entrance Exposure, per Film

Technique	mrad
Sacral Spine	2180
Barium Enema	1320
Upper GI Series	710
Dental Bite-Wing	400
Skull	330
Chest	44

Source. Bureau of Radiological Health

E. Summary

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

Annual Dose Rates to Population in USA. BEIR III (1980)

Natural Background	mrem/yr.
Cosmic	28
Terrestrial	26
Internal - C-14, Ra-226, Pm-222, K-40	28
	82
Medical	
Diagnosis	77
Dental	1.4
Radiopharmaceutical	13.6
	92
Other	
Weapon Tests (Fallout)	5
Power Plant and Nuclear Industry	< 1
Building Materials (brick, masonry)	5
TV Receivers	0.5
Airline Travel	0.5
	12
Total	168

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Chapter IV

Radiation Detection and Measurement

The instruments used for measurement of radiation from accelerators can be subdivided into two groups; survey instruments and personnel monitoring instruments. The following sections describe these types in detail.

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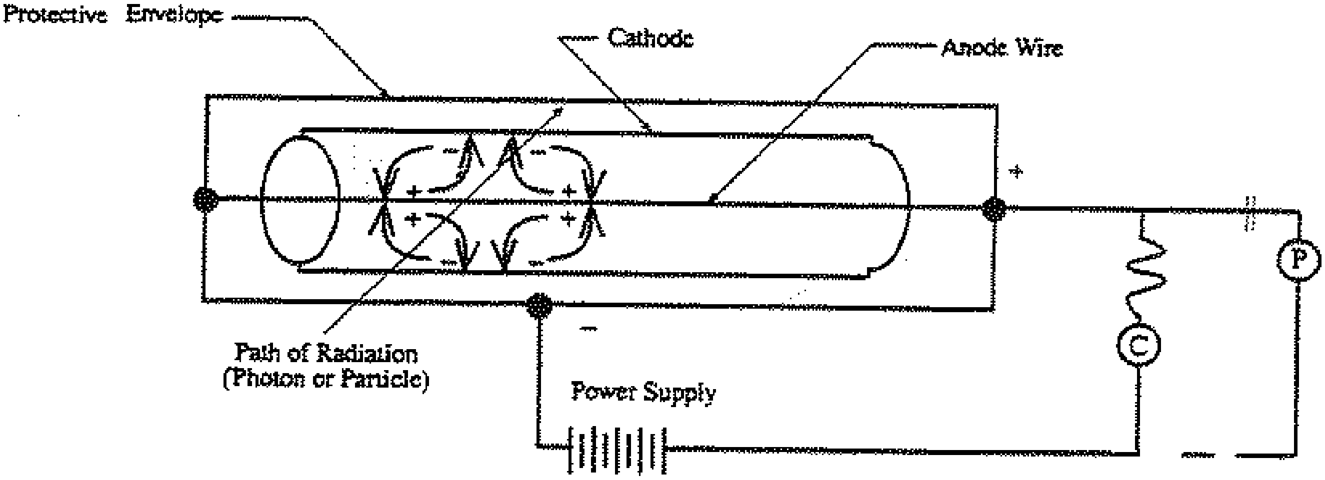
1. Survey Instruments

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

Basic Diagram of a Gas Filled Detector



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

Either a photon (X or gamma ray), producing primary electrons along its path, or a particle (alpha or beta) producing secondary electrons, will create ions that will travel to the electrodes and be collected. A sufficient potential must be applied across the electrodes to prevent ion recombination and make collection possible.

As the ions are collected, a current will flow. This will be measured on a sensitive measuring circuit "C" shown in the diagram above. Alternatively, the current may be measured as a pulse by a pulse counter "P" from the collection of each primary particle.

A. Ionization Chambers

Ionization chamber type instruments are designed to measure exposure rates of ionizing radiation (x- and gamma ray fields) in units of mr/hr or r/hr. The detector is usually cylindrical, filled with air and fixed to the instrument. When radiation interacts with the air in the detector, ion pairs are created and collected generating a small current. The amount of ionization charge deposited in air volume and the measurement of this ionization current will indicate the exposure rate. The ion chamber is the most useful instrument for measuring bremsstrahlung radiation. Counter-type instruments are limited in use for measurement of bremsstrahlung from pulsed accelerators.

B. Geiger-Muller Counter

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

C. Thermal Neutron Detector

The most useful instrument for measuring neutrons around accelerators is the BF3 proportional counter. The BF3 proportional counter is lined with polyethylene and is filled with ethylene or cyclopropane. The counter has a higher probability for thermal neutron detection and as such is an excellent monitor for such neutrons. The moderator lining the detector slows the fast neutrons to thermal energies which can then be detected.

2. Use of Radiation Survey Instruments

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

Read the instrument's operating manual. Gain familiarity with the controls and operating characteristics.

Check the batteries. Most instruments have a battery check indicator. Replace weak batteries. Turn off the instrument when not in use. When storing the instrument for extended periods, remove the batteries to prevent damage from battery acid leakage.

Check the operability of the detector. Pass the detector over a radioactive check source (sometimes attached to the side or end of the instrument) to verify that the detector responds to radiation.

Determine the instrument's response time. By passing the detector at varying speeds over a check source, you can determine how long it takes for the detector to respond to the radiation.>

Determine the operating background. Note the instrument's response in an area free of radiation levels. Subtract this background value from the "gross" reading to obtain the "net" results in the radiation area: $S_{net} = S_{gross} - S_{background}$.

When using portable instruments, caution should be used in extending the detector cord as this may generate electrical noise and register as "counts".

3. Calibrations

In order for the results of a survey instrument to be meaningful, the instrument must be calibrated. Calibrations should be performed yearly or when battery or test functions indicate a problem. Ion chambers are usually calibrated against Cs-137, Co-60, or an X-ray radiation field. The true exposure rate is determined by multiplying correction factors (if any) by the reading on the instrument.

4. Personnel Monitoring Instruments

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

A. Pocket Dosimeters

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

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

B. Film Badges

A typical film badge consists of a film packet and a holder. The film packet usually contains two pieces of film, one sensitive to X or gamma radiation in the energy range 15 keV to 3 MeV, and the other sensitive to beta radiation in the energy range from 200 keV to 1 MeV. Exposure to radiation causes the film to turn black, the degree of film blackening is then related to the amount of radiation exposure.

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

Advantages of film badges are:

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

Disadvantages are:

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

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

C. Thermoluminescent Dosimeters (TLDs)

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

Advantages of TLDs are:

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

Disadvantages are:

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

5. Proper use of Personnel Monitors

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

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Chapter V

Radiation Protection and Control of Exposures

1. External Radiation Protection

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

A. Time

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

Dose = Dose Rate x Time

mrem = mrem/hr. x hr.

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

`Stay Time =`

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

`Stay Time =  = 0.667 hr. = 4 minutes`

B. Distance

The amount of dose an individual receives will also depend on the distance between the person and the source.

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

`I proportional to`

To represent this in a more useful formula:

`I proportional to; I =`

$I_1 = K(1/d_1^2)$ Therfore,
$I_2 = K(1/d_2^2)$

$$\frac{I_1}{I_2} = \frac{\frac{K}{d_1^2}}{\frac{K}{d_2^2}}$$

$$\frac{I_1}{I_2} = \frac{d_2^2}{d_1^2}$$

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

```
                     I1        I2
source* ----------|------->|
        --------->|        |
```

I_1 = the radiation intensity at distance d_1 from the radiation source.
d_1 = the shorter distance from the source where the radiation intensity is I_1.
I_2 = the radiation intensity at distance d_2 from the radiation source.
d_2 = the longer distance from the source where the radiation intensity is I_2.

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

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

I_1 = 500 mrem/hr.
d_1 = 1 foot
d_2 = 3 feet

$I_2 = \ = \ = \ = 55.6$ mrem/hr.

C. Shielding

The shielding of electron accelerators depends on the energy and type of machine. Accelerator shield design involves two steps. For the prompt fields (primary and secondary radiations) very thick shields are required. The bremsstrahlung field is the major component in electron accelerators of all energies. Hence, the shielding in these accelerators is designed to minimize the bremmstrahlung radiation. In case of positive ion accelerators, neutrons are the dominant contributors to the radiation field, the material used for shielding should reduce the neutron intensity. Thus, the proper shielding material to use depends also on the type of radiation field and its energy.

1) Charged particles

Low-Z materials such as Al, or ordinary concrete are sufficient to minimize the production of x-rays as a result of electron interaction with matter. High-Z materials such as tantalum or platinum are used as ion-beam stoppers and for minimizing neutron production at energies below 5 Mev.

2) X and Gamma Radiation

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

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

where:

I is the intensity outside of a shield of thickness x I_o is the unshielded intensity
μ is the linear attenuation coefficient
x is the thickness of shielding material

The linear attenuation coefficient is the sum of the probabilities of interaction per unit path length by each of the three scattering and absorption processes; photoelectric effect, Compton Effect, and pair production. Note that μ has dimensions of inverse length. The reciprocal of μ is defined as the mean free path which is the average distance the photon travels in an absorber before an interaction takes place. Because linear attenuation coefficients are proportional to the absorber density, which usually does not have a unique value but depends somewhat on the physical state of the material, it is customary to use "mass attenuation coefficients" which remove density dependence:

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

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

$$\frac{\text{cm}^{-1}}{\text{gm/cm}^3} \quad \text{which} = \text{cm}^2/\text{gm}$$

Values of the mass attenuation coefficient for lead are given in Appendix IV.

Example: The intensity of a point source is 1 rad/hr. What would be the intensity on the outside of a 2 inches thick lead shield? Density of lead: 11.35 gm/cm³

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

$$I_o = 1 \text{ rad/hr}$$

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

$$I = (1 \text{ rad/hr.}) \times e^{-[(1.29 \text{ cm}^{-1})(5.08 \text{ cm})]} = 0.0014 \text{ rad/hr.} = 1.4 \text{ mrad/hr.}$$

3) Buildup Factor

In case of thicker shields, a phenomenon of buildup from scattering exists which must be accounted for. The thicker and taller the shield, the larger the buildup of scatter component. Also, the energy of the source affects the contribution of the scatter factor to the exposure rate. Thus, for a thick shield, we insert a build-up factor in the above equation:

$$I = B_x I_o e^{(-\mu x)}$$

where B_x is the buildup factor

In case of primary x-rays, the shielding calculations are conducted by the formula:

$$B_x = 1.67 \times 10^{-5} \frac{Hd^2}{DT} \qquad (1)$$

B_x = shielding transmission
H = max. permissible dose equiv. (mrem/h)
d = dist. between x-ray source and ref. pt (m)
D = abs. dose index rate (rad m2/min)
T = area occupancy factor

The value of B_x obtained is related to shielding thicknesses in terms of the number of tenth-value layers of the shielding material that is required to reduce the radiatio levels to dose- limit values. A tenth-value layer (n) is that thickness through which the x-ray dose equivalent is reduced by a factor of 10. Once the tenth-value lay r is known, the shielding-barrier thickness, S, can be estimated pretty conservatively. Thus

$$B_x = 10^{-n} \qquad (2)$$

$$S = T_1 + (n-1)T_e \quad (3)$$

T_1 = first tenth-value layer in shielding thickness
T_e = subsequent tenth-value layer

Values of T_1 and T_e for concrete, steel and lead are obtained from plots in Appendix I.

Example: Calculate the concrete shielding-barrier thicknesses for the forward directed (0°) and sideward directed (90°) x-rays from 1-cm diameter, 3 MeV, 2 mA electron beam incident on a thick high Z (tungsten) target at a distance of 5 m from the barriers. Assume occupancy factor of 1.

Solution: From equation (1),

$B_x(0°) = 4.7 \times 10^{-7}$

Using the Appendix I, the corresponding tenth-value layers are obtained; T_1 = 26 cm and T_e = 23 cm.

From equation (2), the number of these layers are:

n = 6.33
thus, S = 26 + 5.33 x 23 = 149 cm or 59 in.

A concrete thickness of 167 cm (66in) is recommended. Similarly, we can determine the barrier thickness for sideward directed beam. Once the calculations are done, the S value is found to be S = 126 cm or 50".

Thus, a concrete thickness of 137 cm (54in) is recommended. An additional thickness equivalent to at least one-half value layer is recommended in the above calculations. (NCRP-51)

2. Hazards associated with accelerators

Besides the prompt radiation from accelerators as discussed in Chapter II, other hazards such as stray radiation, induced radioactivity and skyshine also exists. These hazards are described as follows:

A. Stray Radiation:

Stray radiation may occur due to misalignment, back- streaming, or dark current. If parts of the accelerator are misaligned, a portion of the internal beam may strike the interior of the accelerator and cause stray radiation from an unusual area of the machine. In case of magnet failure or incorrect adjustment, the external beam may strike something other than the intended target and produce different types of secondary radiations. These sources of stray radiation may create a hazard even if the useful beam intensity is zero. Back streaming occurs when a stream of particles of opposite charge is released from the primary beam and is accelerated in the opposite direction. This process usually occurs in potential-drop accelerators.

Dark current is produced when poor vacuum conditions exist or when accelerator vacuum components are being outgassed. The name "dark current" is analogous with the current observed through a photo tube in the absence of light. When the machine voltage or radio frequency generating system is turned on, the dark currents of electrons are accelerated even if the electron source is not turned on. Electron linear accelerators and direct accelerators are prone to this phenomenon during warm-up or conditioning of accelerator components. In direct accelerator, radiation may be emitted due to capacitance until the charge has been brought to zero.

B. Skyshine:

When upward-directed radiation is scattered back toward the surface of the earth by collision with nuclei in the air.

The process of skyshine occurs. Skyshine is not a problem with the accelerators that are provided with adequate roof shielding. Wall shielding, in the absence of roof shielding, will reduce radiation levels near shield wall, but the radiation levels further away may be high because of the skyshine. It should not be assumed that if radiation doses are all within acceptable limits close to the shield of an accelerator that they are always lower further away. A survey made of the area close to the shield wall and further away from the wall may indicate the need for additional roof shielding.

C. Induced Radioactivity in Materials:

    1. Activation of targets and accelerator:

    If the beam strikes any material in the accelerator or if the material is exposed to intense secondary radiation, it will become radioactive. The beam in electron accelerator usually strikes other objects such as vacuum chamber walls and electrode supports. Radiation from these areas or sources does not become a personnel hazard until the machine is turned off and personnel enter these areas for accelerator maintenance, target changes or outine adjustments. Activation of cooling water and other cooling media in targets may be a problem. The major concern is the residual activity present on the water system. It may be hazardous during maintenance work after the accelerator is shut down. This means that shielding might be required around circulating pumps, heat exchanger and holding tanks. Surveys of activation of several locations around the accelerator should be made after each major beam current or energy change. The results obtained from these surveys can be helpful for maintenance work. The most radioactive parts of the accelerator must be removed and shielded.

2. Airborne Radioactive Materials: Air in the accelerator room and irradiation room may become radioactive in the following ways:
    A. if the beam passes through air, the elements in the air will become radioactive. The radiation intensity produced depends on the beam energy and intensity.
    B. radioactive gases produced internally in the targets may escape into the target area or accelerator room as a result of breach in the containment.

    These hazards are controlled by the installation of a separate ventilation system. The ventilation system is designed so that the accelerator room and the irradiation room are at lower pressure than other parts of the building. The airborne radioactive concentrations in the hazardous areas should be monitored with the beam on and off.

3. Tritium:

When particle accelerators are used for the production of intense beams of neutrons by bombarding with deuterium, tritium gas is released from the target. This tritium outgassing is the major cause of tritium contamination within the beam tube assembly, vacuum system and exhaust system. Tritium is usually present as tritium gas, tritium oxide or a mixture of both gas and oxide. It is not an external hazard due to its low range about 0.6 mg/cm2, however once inside the body there is no protection to the living tissues. With tritium in the body fluids, the entire energy may be absorbed within a single cell nucleus. It is eliminated by the body with an effective half-life of approx. 12 days. Tritium is not produced in significant amounts by accelerator. It is present only as a material absorbed in a tritium target or otherwise.

3. Radiation Safety Procedures-Warning and Interlock Systems
    A. Safety Interlocks

Interlocks are electrical systems which are used to turn off electrical power in hazardous situations. The most important part of an accelerator interlock system is the one that deals with radiation hazards. The radiation interlock system serves two functions: to prevent access to areas in which unsafe radiation levels are being produced by the accelerator; and to prevent operation of the accelerator if unsafe radiation levels will be produced in occupiable areas. This is accomplished by installing radiation detection and monitoring instruments in the control room and other occupiable areas. If the permissible levels have exceeded, the instruments turn off the beam and give a warning.

A part of the interlock system deals with extreme electrical hazards to personnel, particularly high-voltage DC power supplies. Interlock switches on the access doors to high- voltage compartments interrupt the input voltage to the compartment when the doors are opened, and discharge the capacitors.

One or more disabling switches in target rooms or experimental rooms are usually installed in case a person gets trapped in these areas and can turn off the accelerator. Also, in most accelerator facilities before the beam can be turned on, audible and light warnings are produced by the control circuit.

The last point to remember is that the interlocks are not to be used as a means of shutting down the accelerator. The accelerator should be turned on/off only and only from the control console.

B. Warning Lights and Cautionary Signs:

In addition to interlocks to prevent inadvertent entry into hazardous areas, warning devices are utilized to inform people of the machine status. For this purpose colored rotating lights, signs, and audible devices are used.

Lights:

The status lights located in the accelerator vault, irradiation rooms, and on the control console are used to indicate magnet status, beam status, and any other condition for the safe operation of accelerator.

Signs:

Signs are required to be posted under certain conditions as described below to warn other individuals in the area that radiation is present:

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

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

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

C. Handling Activated Materials

Store all bombarded targets and other radioactive items in shielded, labeled storage areas or storage containers. Any nuts, bolts and other small objects removed during maintenance should be also stored in marked containers.

4. Radiation Survey Procedures

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

5. Control Measures for Radiation Levels

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

A. Perform a radiation survey of the occupiable areas periodically to determine what kind of radiation levels exist and to detect any malfunctioning equipment.
B. If any adjustments are made to the machine, resurvey of the areas must be conducted.
C. Any shielding modifications, device maintenance or special procedures requiring bypassing of the interlocks must be authorized by the Radiation Safety Office.
D. Maintain records of all radiation surveys and any maintenance performed on the accelerator for review by the State inspectors.
E. To prevent unauthorized use, secure the accelerator when not in operation.

6. Planning in Emergencies - Radiation Accidents

In particle accelerators, the probability of lethal whole-body exposures is less than severe partial-body exposures. This section of the manual deals with some of the accidents that have occurred with the particle accelerators used in either research or industrial radiation facilities.

Accelerator Type:	3-MV Potential drop (industrial unit)
Date:	11 December 1991
Location:	Maryland
No. Individuals Exposed:	One
Esposure:	0.40 - 0.13 Gy/s
Primary Causes:	Failure to follow established operating and safety procedures. Inadequate training in radiation safety and nuclear physics.

Description of Accident:

The accident occurred during maintenance on the lower window pressure plate. The filament voltage of the electron source was turned "off", but the high voltage terminal was on full accelerating potential. The operator's body, especially his extremities and head were exposed to the electron dark current. Approximately 3 months after the accident, the victim's four digits on the right and left hand were amputated.

Accelerator Type:	Linear Accelerator
Location:	University
No. of Individuals:	Two
Exposure:	Not stated
Primary Causes:	Failure to follow established operating procedures. Target area not completely barricaded.

Description of Accident:

Two research assistants entered the target area of a LINAC without notifying the operator. They also failed to remove an interlock key and ignored warning lights, signs, and the sound of the accelerator klystron pulsars. One worker leaned over, adjusted the target by hand, and tried to make the alignment by eye. While aligning he noticed a bluish iridescence in his eyeglasses. Both realized what had happened and left target area immediately. No biological damage occurred.

Accelerator:	Linear Accelerator
Location:	California
No. Individual Exposed:	Six graduate students

Exposure: 920-2690 mrem - X-radiation

Description of Accident:
Six graduate students entered a high radiation area by overriding the interlocks on the doors that should have prevented access to the area. These students were involved in the initial tune-up of the LINAC. During the tune-up of the RF phase of the LINAC operation, the students were exposed to x-radiation.

From the above listed incidents, it's obvious that the accidents and overexposures occurred as a result of human errors - bypassing interlocks, failure to follow established safety and operating procedures and lack of sufficient safety training. It is vital that all operators participate in emergency drills and safety training.

It is essential to anticipate the possibility of an overexposure and a clear procedure should be established should any overexposure occur. A set of emergency procedures listing phone numbers of Radiation Safety Office and the Principal Investigator should be posted at the console. In case of an overexposure, the following steps should be taken:

1. Notify the Radiation Safety Office and your Supervisor immediately.
2. Notify the Health Center.
3. Do not change the configurations of the machine. Changing the machine configurations will make it impossible for others to verify any misalignments or equipment failures and prevent other accidents.

The above steps should be taken promptly even though symptoms of overexposure do not exist. Usually, some time must elapse before any indication of overexposure is observed.

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Chapter VI

Radiation Protection Programs

1. General

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

   A Radiation Safety Officer, and at the University of Maryland, a Radiation Safety Committee, has the responsibility to implement the radiation protection program. UMD's program includes:

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

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

2. UMD Radiation Protection Program

   A. Regulatory Agency

      Possession and use of radiation producing devices and radioactive materials at the University of Maryland, College Park is authorized under a license issued by the Maryland Department of the Environment, Center for Radiological Control as specified in Title 26 of the Official Annotated Code of Maryland, Chapter 26.12.01 - Ionizing Radiation Protection. Selected Sections of the State Code are shown below:

Part	Title
A	General Provisions
	Section A.1 - Scope
	Section A.2 - Definitions
	Section A.3 – Exemptions
	Section A.4 - Records
	Section A.5 - Inspections
	Section A.10 - Prohibited Users
B	Registration of Radiation Machine Facilities and Services
C	Licensing of Radioactive Material
	Section C.1 - Purpose and Scope
	Section C.3 - Source Material
	Section C.20 - Types of Licenses
D	Standards for Protections Against Radiation
	Section D.1 - Purpose and Scope
	Section D.101 - Radiation Protection Programs
	Section D.201 - Occupational Dose Limits for Adults
	Section D.502 - Conditions Requiring Individual Monitoring of External and International Occupational Dose
I	Radiation Safety Requirements for Particle Accelerators
J	Notices, Instructions and Reports to Workers and Inspections

B. Radiation Protection Services

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

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

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

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

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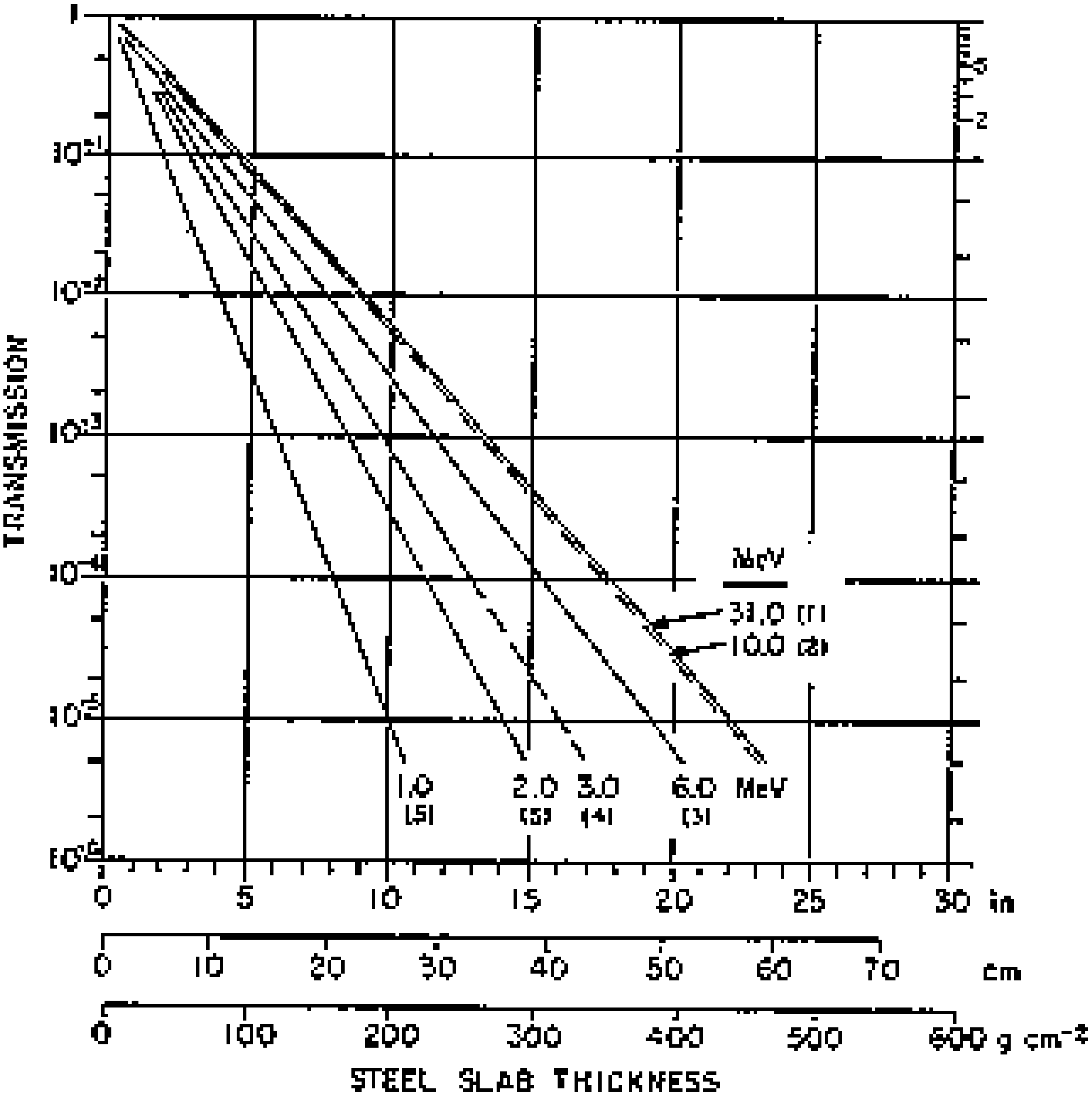
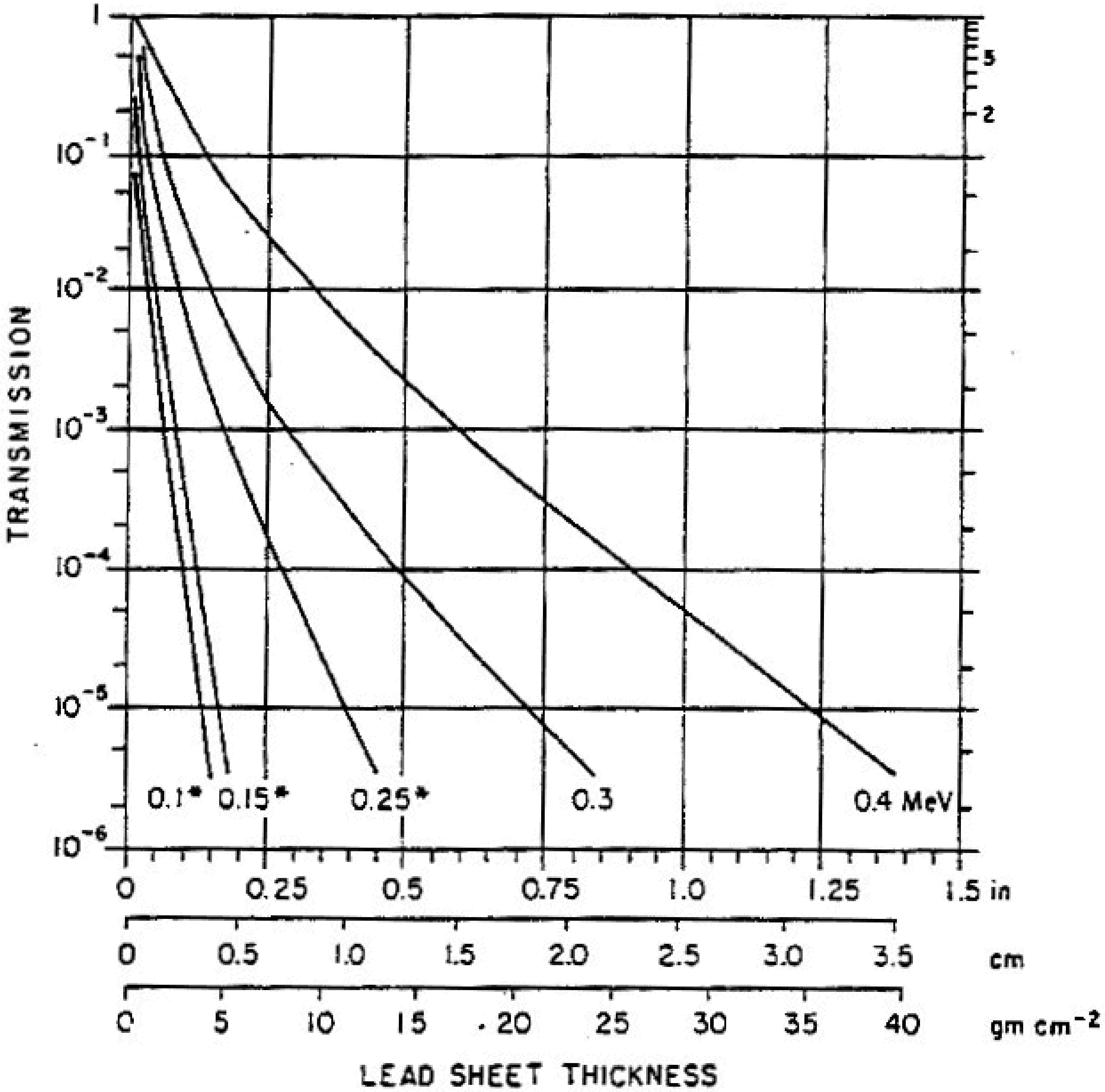
Appendix I

I.1. Broad-beam Transmisssion Through Steel of X Rays Produced by 1- to 31 MeV Electrons

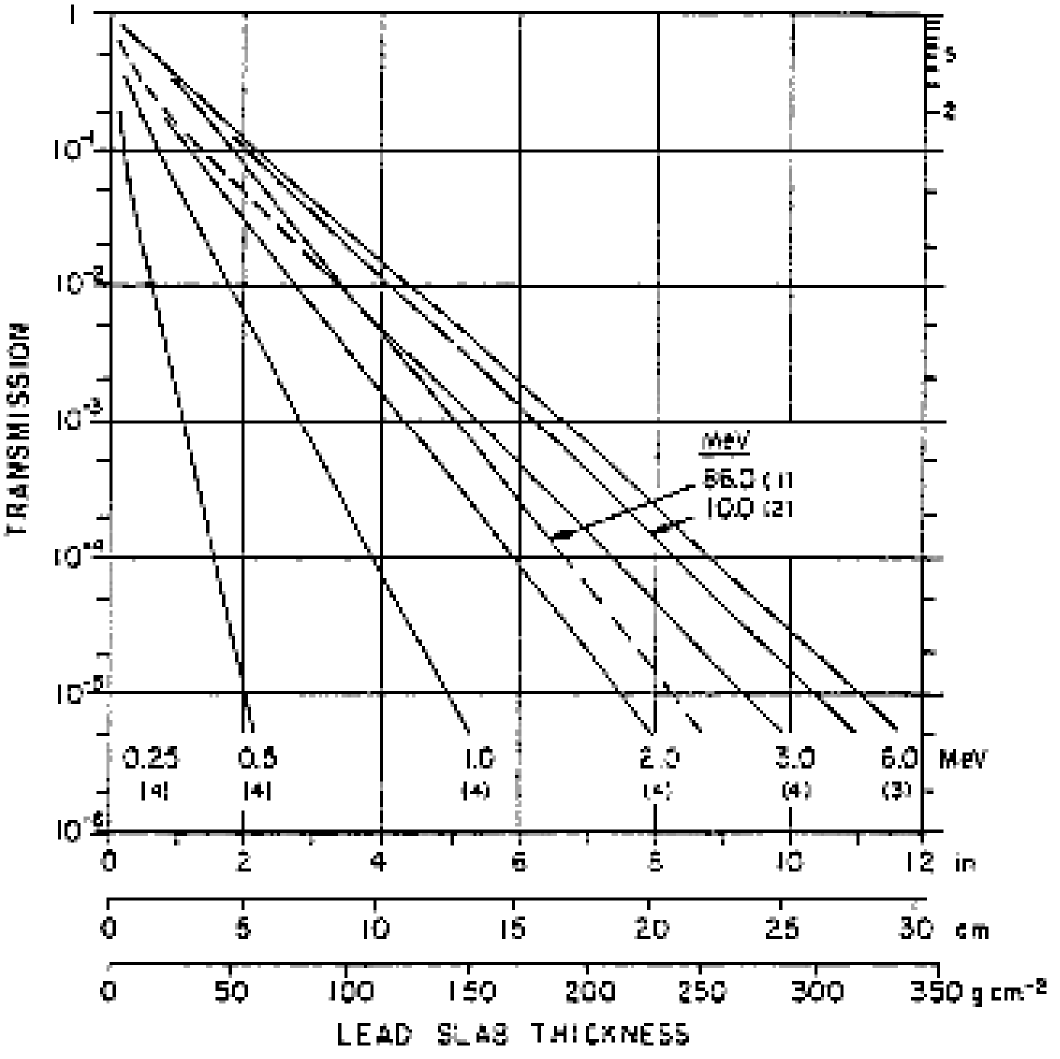


1.2. Broad-beam Transmission Through lead of X Rays Produced By0.1- to 0.4-MeV Electrons



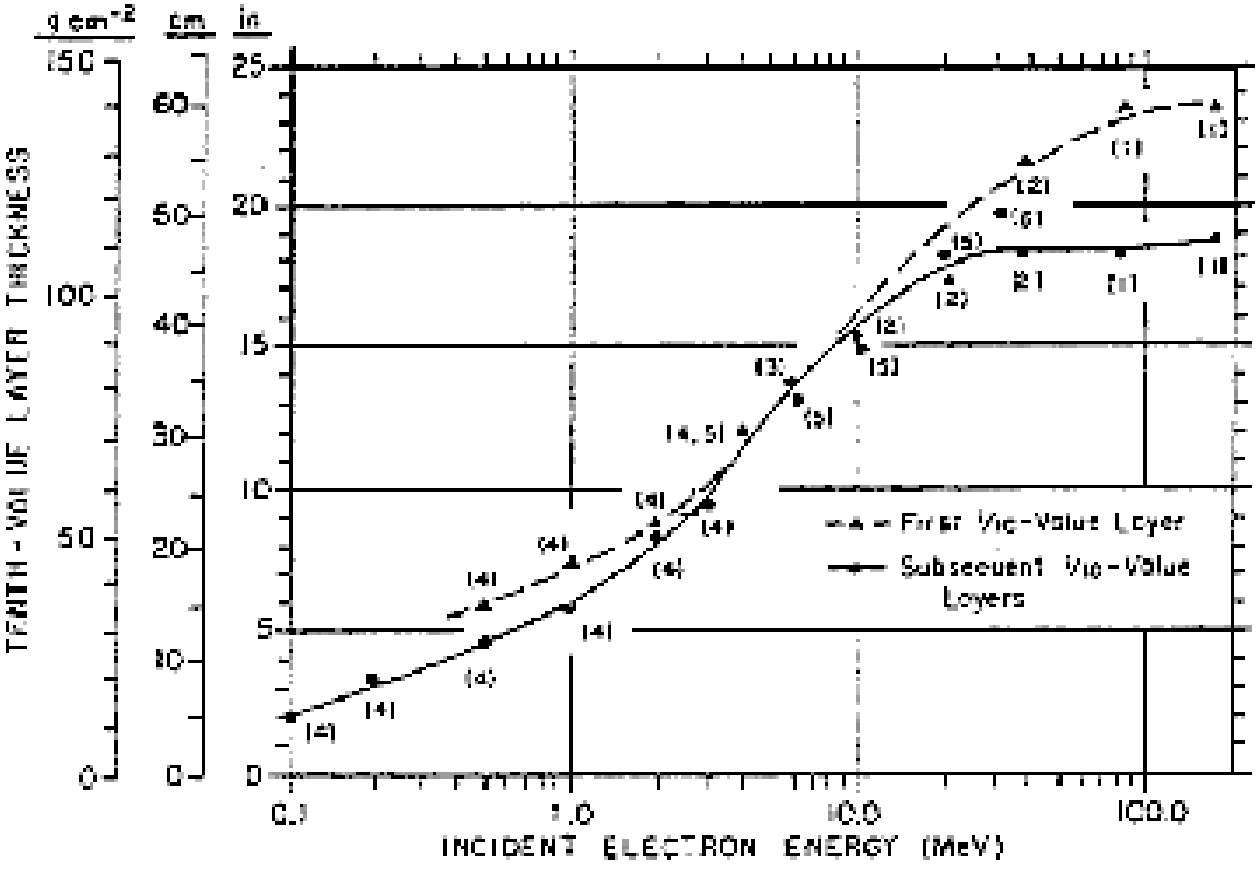
Transmission through lead (density 11.3 g cm^{-3}) of x rays produced by 0.1- to 0.4-MeV electrons, under broad-beam conditions. Electron energies designated by an asterisk (*) were accelerated by voltages with pulsed wave form; unmarked electron energies were accelerated by a constant potential generator. Curves represent transmission in dose-equivalent index ratio. (See Appendix E-14 for basis for interpolating between curves.) Curves were derived from NCRP Report No. 34 (NCRP, 1970a).

1.3. Broad -beam Transmission Through Lead of X Rays Produced By 0.5- to 86-MeV Electrons



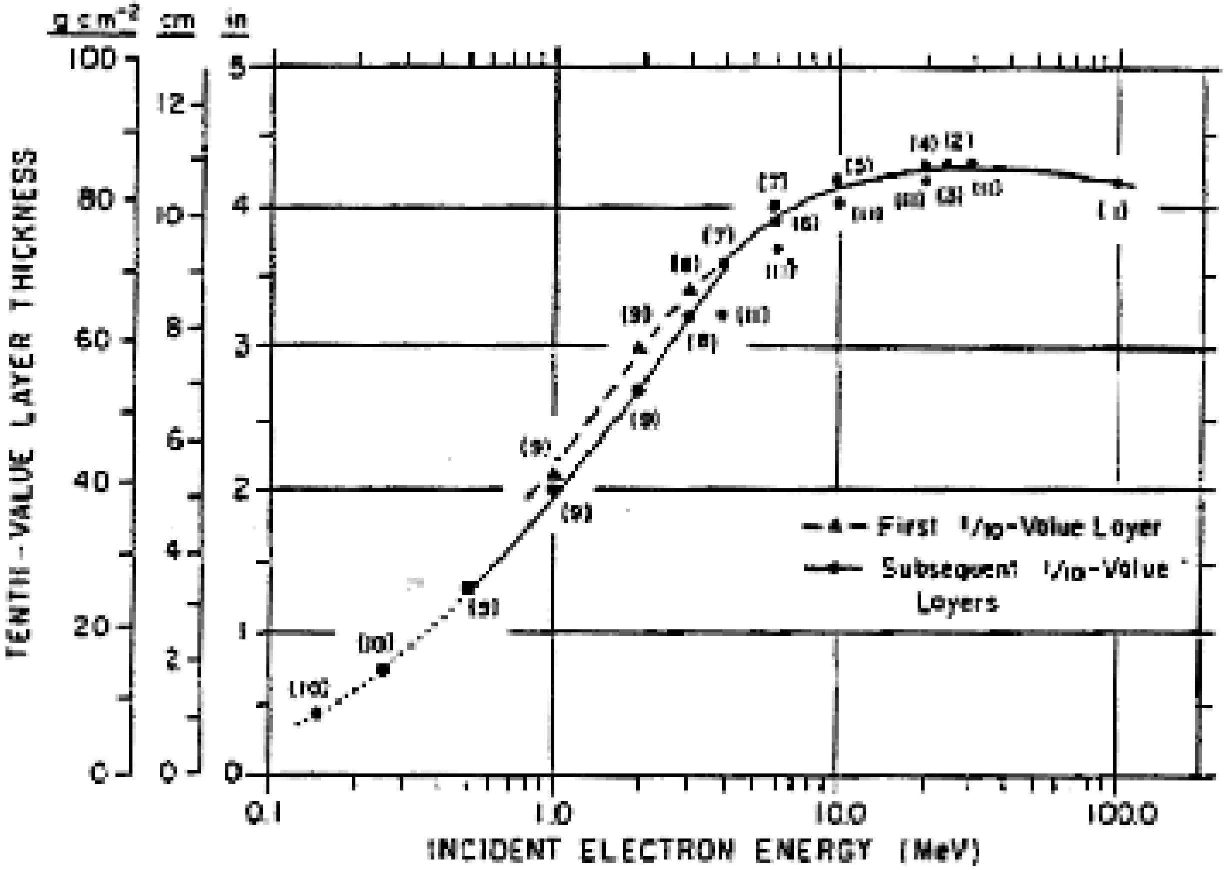
Transmission of thick-target x rays through lead (density 11.3 g cm^{-3}), under broad-beam conditions. Energy designations on each curve (0.5 to 86 MeV) refer to the monoenergetic electron energy incident on the thick x-ray producing target. Curves represent transmission in dose-equivalent index ratio. (See Appendix E-14 for basis for interpolating between curves.) Curves were derived from: (1) Miller and Kennedy (1956); (2) ICRP Publication No. 4 (ICRP, 1964); (3) Karzmark and Capone (1968); and (4) NCRP Report No. 34 (NCRP, 1970a) and NCRP Report No. 49 (NCRP, 1976).

1.4. Dose equivalent Index Tenth-Value Layers for Broad-Beam X rays in Concrete



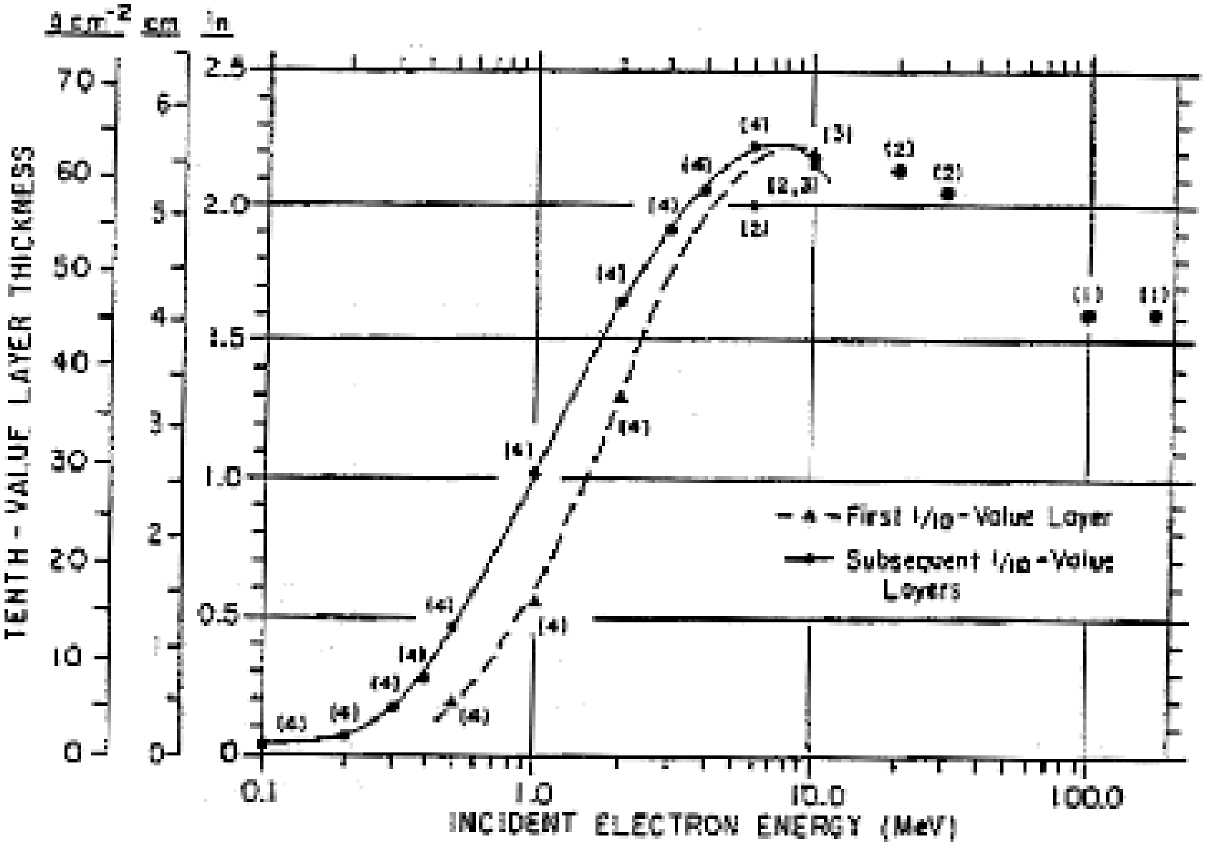
Dose-equivalent index tenth-value layers in ordinary concrete (density 2.35 g cm^{-3}) for thick-target x rays under broad-beam conditions, as a function of the energy of electrons incident on the thick target. The dotted curve refers to the first tenth-value layer, the solid curve refers to subsequent or "equilibrium" tenth-value layers. Both curves are empirically drawn through data points derived from the following references: (1) Miller and Kennedy (1956); (2) Kirn and Kennedy (1954); (3) Karzmark and Capone (1968); (4) NCRP Report No. 34 (NCRP, 1970a); (5) Maruyama *et al.* (1971). Studies by Lokan *et al.* (1972) on light Ilmenite-loaded concrete (density 2.80 g cm^{-3}) are in reasonable agreement with the solid curve above, on a mass thickness basis (g cm^{-2}).

1.5. Dose equivalent Index Tenth-Value Layers for Broad-Beam X rays in Steel



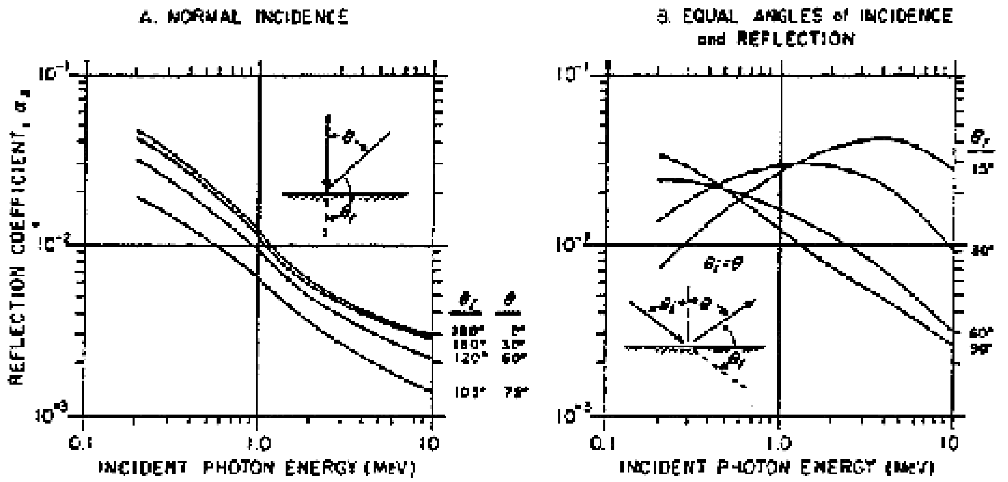
Dose-equivalent index tenth-value layers in steel (density 7.8 $g\ cm^{-3}$) for thick-target x rays under broad-beam conditions, as a function of the energy of electrons incident on the thick target. The dotted curve refers to the first tenth-value layer; the solid curve refers to subsequent or "equilibrium" tenth-value layers. Both curves are empirically drawn through data points derived from the following references: (1) Westendorp and Charlton (1945); (2) Widerøe (1963); (3) Scag (1964); (4) Adams and Girard (1946); (5) O'Connor *et al.* (1949); (6) Karzmark and Capone (1968); (7) NCRP Report No. 34 (NCRP, 1970a); (8) Goldie *et al.* (1954); (9) Buechner *et al.* (1948a); (10) estimated from Bly and Burrill (1959); and (11) Maruyama *et al.* (1971). Studies by Lokan *et al.* (1972) on heavy Ilmenite-loaded concrete (density 4.30) are in reasonable agreement with the solid curve above, on a mass thickness basis ($g\ cm^{-2}$).

1.6. Dose equivalent Index Tenth-Value Layers for Broad-Beam X rays in Lead

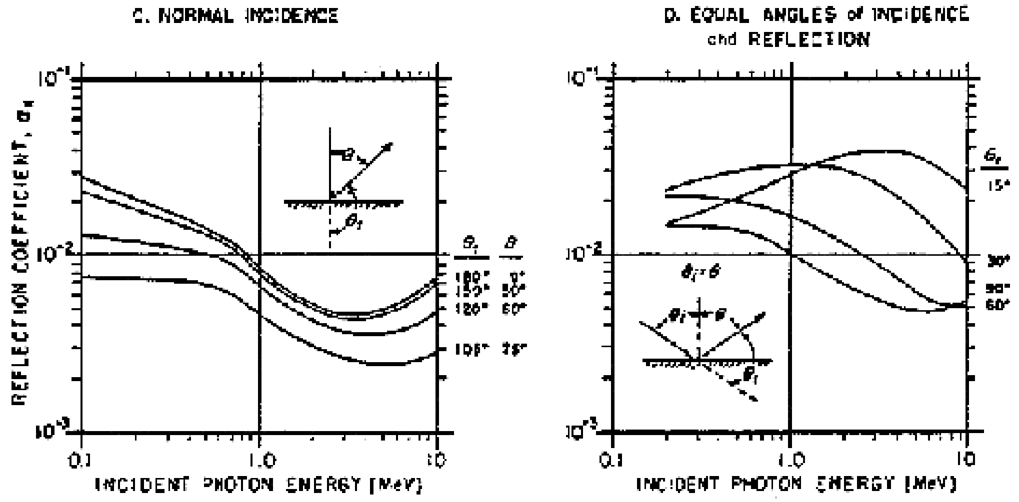


Dose-equivalent index tenth-value layers in lead (density 11.3 g cm^{-3}) for thick-target x rays under broad-beam conditions, as a function of the energy of electrons incident on the thick target. The dotted curve refers to the first tenth-value layer; the solid curve refers to subsequent or "equilibrium" tenth-value layers. Both curves are empirically drawn through data points derived from the following references: (1) Miller and Kennedy (1956); (2) Maruyama *et al.* (1971); (3) ICRP Publication No. 4 (ICRP, 1964); and (4) NCRP Report No. 34 (NCRP, 1970a). The empirical curve is not extended into the 10- to 100-MeV region because of uncertainties in the available data.

1.7. Reflection Coeffiicients for Monoenergetic X Rays in Concrete, Iron and Lead



PHOTONS ON ORDINARY CONCRETE



PHOTONS ON IRON

Reflection coefficients, α_x, for monoenergetic x rays on ordinary concrete, iron, and lead as a function of incident monoenergetic photon energy, for several angles of reflection assuming normal incidence and equal angles of incidence and reflection. Values are given for ordinary concrete and iron, based on existing available information, both theoretical and experimental, with particular emphasis on the following references: (1) Chilton and Huddleston (1963); (2) Chilton (1964); (3) Chilton (1965); and (4) Chilton *et al.* (1965). For photon energies higher than 10 MeV, the use of the 10-MeV values of α_x is expected to be safe.

Values of α_x for photons incident on lead are not as readily calculable, but a conservative upper limit is 5×10^{-3} for any energy and scattering angle.

The values of α_x for $\theta_r = 160°$ in Curve A are the same as for $\theta_r = 180°$ in Curve B.

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Appendix II

Rules of Thumb and Useful Equations

Alpha Particles

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

Beta Particles

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

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

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

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

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

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

Gamma Rays

The dose rate to tissue in rads per hour in an infinite medium uniformly contaminated by a gamma emitter is 2.12 EC/rho, where C is the number of microcuries per cubic centimeter, E is the average gamma energy per disintegration in MeV, and r is the density of the medium. At the surface of a large body, the dose rate is about half of this.

Radioactive Decay

The activity of any radionuclide is reduced to less than 1% after 7 half-lives.

For material with a half-life greater than six days, the change in activity in 24 hours will be less than 10%.

Useful Equations

Radioactive Decay: $A = A_o e^{-\text{gamma} \cdot t}$

Efficiency: observed cpm/actual dpm

Minimum Detectable Activity (MDA): $\text{Bkg cpm} \div (3 \text{ x } (\text{Bkg})^{1/2}/t) \div \text{Eff} = \text{dpm}$

Stay Time: limit (mR)/rate (mR/hr)

Inverse Square Law: $I_1 d_1^2 = I_2 d_2^2$

Gamma Exposure Rate: R/hr at one foot = 6 C Sum of en

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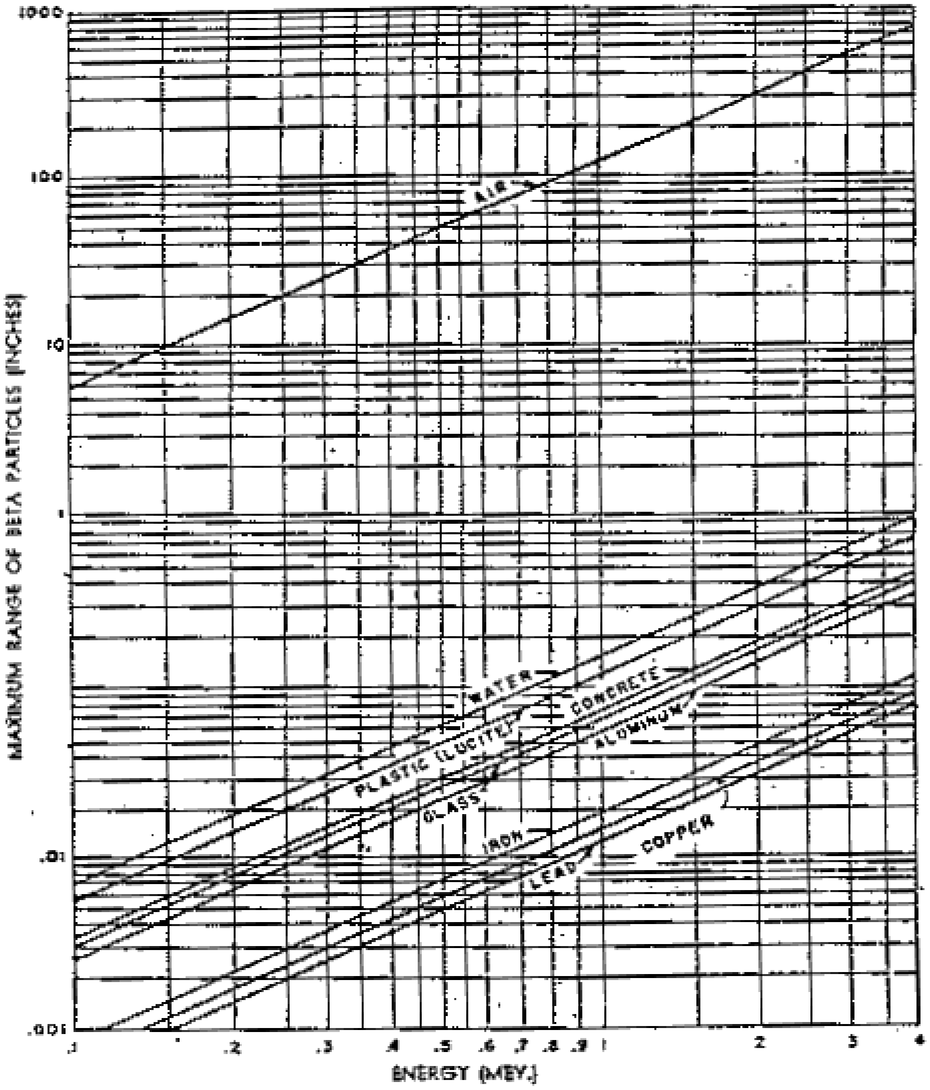
Appendix III

Penetration Ability of Beta Radiation



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Appendix IV

Reference Data for Selected Radioisotopes

		---BETA---			---GAMMA---							
Nuclide	Half-Life	Max Energy (MeV)	I%	AIR Range	PLASTIC Range	Energy (MeV)		I%	HVL (cm Pb)	Att. COEF (cm Pb)	Critical Organ (µCi)	Effective Half-Life (days)
Calcium-45	163 d	.257	100	20	.020	---	---	---	---	---	Bone (30)	17
Carbon-14	5730 y	.156	100	10	.01	---	---	---	---	---	Whole Body (400)	10
Cesium-137	30.17 y	1.173	5.4	150	.15	.33	.6616	89.9	.536	.114	Whole Body (30)	113.8
Chromium-51	27.7 y	---	---	---	---	.016	.3201	9.8	.165	.369	Lower Lg (800)	26.6 Inst.
Cobalt-60	5.27 y	.318	99.9	25	.03	1.32	1.17 1.33	99.9 99.98	1.035	.059	Whole Body (10)	9.5
Copper-64	12.71 y	.578	37.2	60	.06	.12	1.346	.49	1.11	.055	Whole Body (80)	.529
Hydrogen-3	12.33 y	.0186	100	.5	0	---	---	---	---	---	Whole Body (1000)	10
Iodine-125	60.14 d	---	---	---	---	.07	.036	6.67	.0029	21	Thyroid (.325)	42
Iodine-131	8.04 d	.606	89.4	60	.06	.22	.364	81.2	.178	.342	Thyroid (.14)	7.6
Potassium-42	2.36 h	3.521	82	600	.6	.14	1.524	17.9	1.174	.052	*	*
Phosphorus-32	14.28 d	1.71	100	250	.25	---	---	---	---	---	Bone (6)	13.5
Sodium-22	2.60 y	.546b+	89.8	55	.05	1.2	1.274	99.9	1	.061	Whole Body (10)	11
Sulfur-35	87.4 d	.1675	100	11	.01	---	---	---	---	---	Whole Body (400); Testes (90)	44.3
Zinc-65	243.9 d	.329b+	1.5	30	.03	.27	1.115	50.8	.925	.066	Whole Body (60)	193.2

I = Intensity   h = hours   d = days   y = years   G = Roentgen/hour at one meter per Curie