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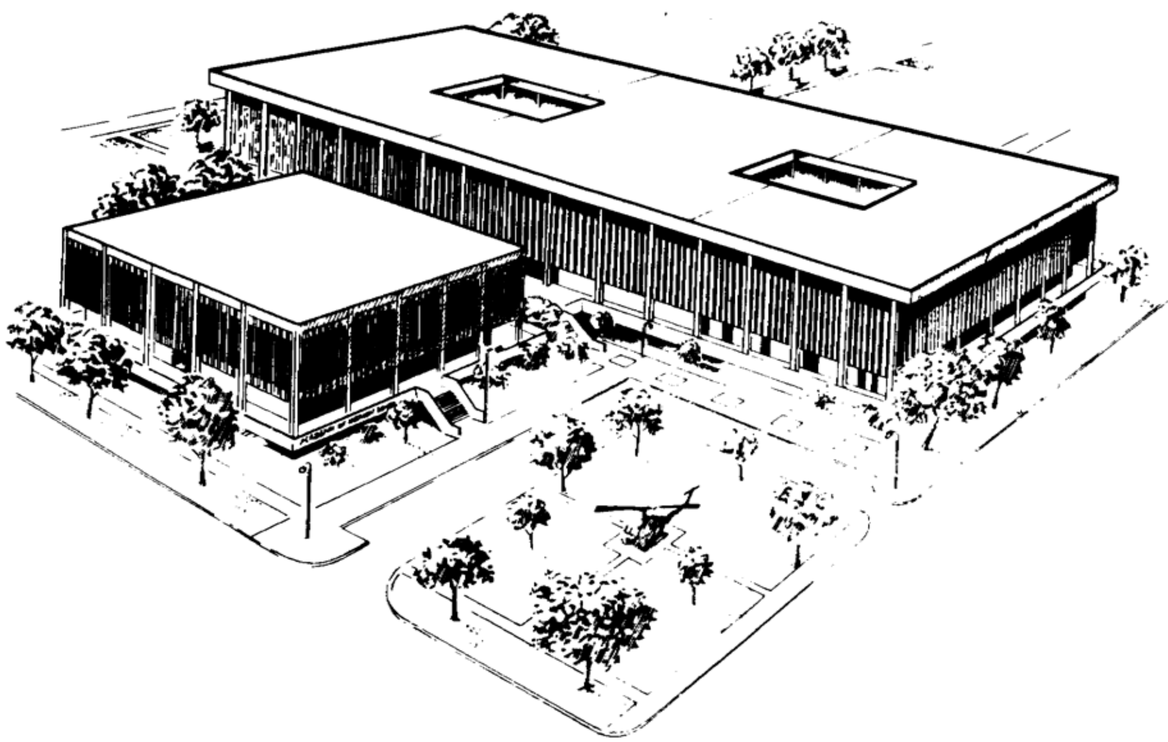

FUNDAMENTALS OF X-RAY PHYSICS

SUBCOURSE MD0950 EDITION 200

DEVELOPMENT

This subcourse is approved for resident and correspondence course instruction. It reflects the current thought of the Academy of Health Sciences and conforms to printed Department of the Army doctrine as closely as currently possible. Development and progress render such doctrine continuously subject to change.

ADMINISTRATION

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Be sure your social security number is on all correspondence sent to the Academy of Health Sciences.

CLARIFICATION OF TRAINING LITERATURE TERMINOLOGY

When used in this publication, words such as "he," "him," "his," and "men" are intended to include both the masculine and feminine genders, unless specifically stated otherwise or when obvious in context.

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CORRESPONDENCE COURSE OF THE
UNITED STATES ARMY MEDICAL DEPARTMENT CENTER AND SCHOOL

SUBCOURSE MD0950

FUNDAMENTALS OF X-RAY PHYSICS

INTRODUCTION

X-rays were discovered as a result of investigations relating to electricity and magnetism. When these electrical and magnetic phenomena are properly utilized and controlled, x-rays can be produced. If an x-ray specialist is to function efficiently, he needs a clear understanding of these factors. While you may be able to rely only on charts in routine work, unusual cases and situations will undoubtedly present themselves. When this happens, you will need to understand the principles involved. The purpose of this course is to acquaint you with those principles.

One lesson of this subcourse deals with basic concepts of atomic structure and energy. Another covers electricity, the general principles of electrical circuits, and various electrical devices. Another lesson covers x-ray machine circuits and the all-important x-ray tube. Knowledge of this material will enable the x-ray specialist to understand how these devices work together to produce and control x-rays so that good quality diagnostic radiographs will result. The final lesson discusses radiation safety for yourself and your patients.

<u>Subcourse Components</u>:

This subcourse consists of four lessons.

Lesson 1. Matter and Energy.

Lesson 2. Electricity, Magnets, and Circuits.

Lesson 3. X-Ray Circuits and Tubes.

Lesson 4. X-Ray Safety.

Appendix.

Study Suggestions:

Here are some suggestions that may be helpful to you in completing this subcourse:

--Read and study each lesson carefully.

--Complete the subcourse lesson by lesson. After completing each lesson, work the exercises at the end of the lesson, marking your answers in this booklet.

--After completing each set of lesson exercises, compare your answers with those on the solution sheet that follows the exercises. If you have answered an exercise incorrectly, check the reference cited after the answer on the solution sheet to determine why your response was not the correct one.

Credit Awarded:

To receive credit hours, you must be officially enrolled and complete an examination furnished by the Nonresident Instruction Section at Fort Sam Houston, Texas. Upon successful completion of the examination for this subcourse, you will be awarded 12 credit hours.

You can enroll by going to the web site http://atrrs.army.mil and enrolling under "Self Development" (School Code 555).

A listing of correspondence courses and subcourses available through the Nonresident Instruction Section is found in Chapter 4 of DA Pamphlet 350-59, Army Correspondence Course Program Catalog. The DA PAM is available at the following website: http://www.usapa.army.mil/pdffiles/p350-59.pdf.

LESSON ASSIGNMENT

LESSON 1	Matter and Energy.
LESSON ASSIGNMENT	Paragraphs 1-1 through 1-16.
LESSON OBJECTIVES	After completing this lesson, you should be able to:
	1-1. Define radiology and describe the discovery of x-rays.
	1-2. Describe the functions and structure of atoms and molecules.
	1-3 Describe the relationship of energy and work.
	1-4. Describe radiation the production and nature of radiation.
SUGGESTION	After studying the assignment, complete the exercises of this lesson. These exercises will help you to achieve the lesson objectives.

LESSON 1

MATTER AND ENERGY

Section I. INTRODUCTION

1-1. PURPOSE

The primary purpose of this subcourse is to discuss the fundamentals of x-ray physics that the enlisted x-ray specialist needs to know in order to understand the nature of the service that he is to perform. The secondary purpose is to acquaint the student with the history of radiography.

1-2. SCOPE

This subcourse includes a brief history of radiography and a discussion of fundamentals of physics, including the basic structure of matter and its relationship to energy; electricity; magnetism; generators; motors; rectification; x-ray tubes; x-ray machine circuits; and electrical and radiological hazards.

1-3. HISTORY OF RADIOGRAPHY

a. X-rays were discovered in 1895 by Wilhelm Conrad Roentgen, a German physicist, but many scientists before him paved the way for his discovery. Many major discoveries relating to electricity had been made during the three centuries that preceded the discovery of x-rays, but it was the study of electrical discharges under high voltage in vacuum tubes that led to the actual discovery of these rays. Scores of scientists had experimented with electrical discharges through different types of vacuum tubes and, no doubt, many of them had produced x-rays but had not recognized them as a new type of ray.

b. Roentgen himself was experimenting with cathode rays when he observed the presence of this new radiation. He was working with a certain (Hittorf-Crookes) vacuum tube through which a current under high voltage was being passed. The tube was entirely enclosed in black paper so as to exclude all the light emanating from it. During the experiment, Roentgen observed a fluorescence of some barium platinocyanide crystals coating a piece of cardboard lying nearby. It had been known for some time that these crystals would fluoresce in the presence of a vacuum tube activated by high voltage, but it occurred to Roentgen that the fluorescence of the crystals was due to some type of ray that could pass through the black paper around the tube. When he picked up the chemically coated cardboard, his fingers came between it and the tube, and he saw the bones of his hand. He realized that he had discovered the presence of a ray that would penetrate solid matter. By replacing the chemically coated cardboard with a photographic plate, he was able to record an image of the internal structure of his wife's hand. He also noted that the rays could not be reflected or refracted by the usual means and that they were not affected by electrical and magnetic fields as were the cathode rays that he was studying. Because he did not know the nature of these rays, he called them x-rays. Others have sometimes called them roentgen rays.

c. Modern medical science has profited greatly as a result of this important discovery. X-rays are utilized by the medical profession to diagnose illnesses, study bone fractures, locate foreign substances in the body, and treat cancer and skin diseases.

1-4. RADIOLOGY

Radiology is that branch of medical science dealing with the use of radiant energy in the diagnosis and treatment of disease. A radiologist is a physician who has special training and experience in radiology. In the Army, the principal duties of the radiologist are to conduct, interpret, and supervise x-ray and fluoroscopic examinations and to perform radiation therapy, which may include the use of x-ray, radium, and radioisotopes. Fluoroscopy is an examination conducted by observing the fluorescence of a screen caused by x-rays transmitted through an object.

1-5. THE ENLISTED X-RAY SPECIALIST

a. The x-ray specialist must have a comprehensive understanding of all the technical factors involved in operating x-ray equipment and in producing high-quality radiographs; he must have a good working knowledge of the characteristics, capabilities, and limitations of the equipment and accessories available to him; he must know how to operate the x-ray machines to obtain the best results possible, observing all safety rules.

b. The x-ray specialist must become proficient in the technical, clerical, and teaching areas of his duties and functions. In addition, he must be thoroughly familiar with the operational programs of his department. This will enable him to work effectively under different conditions, to substitute for others, and to cope with emergencies.

c. The continual introduction of new radiographic techniques that result in better diagnosis and treatment for the patient further requires the x-ray specialist to assume new responsibilities. The well-trained specialist is able to transfer learning derived from past experiences to new situations.

Section II. BASIC CONCEPTS OF MATTER AND ENERGY

1-6. INTRODUCTION

Certain fundamental concepts regarding matter and energy are required as a basis for an intelligent use of various types of radiation in diagnosis and therapy. Knowledge of the functional relationships between matter and energy helps one to understand how x-rays and other forms of radiation are produced, how they behave, and how they affect the human body.

1-7. MATTER

Matter has been defined as any substance that has mass and occupies space. There are three forms of matter: solids, liquids, and gases. Depending upon the temperature, some substances may occur in each of these forms. For example, water is a liquid under normal conditions; when exposed to freezing conditions, it becomes a solid (ice); and when boiled, it evaporates into a gas (steam).

a. All forms of matter are characterized by certain physical and chemical properties. Physical properties are characteristics such as density, solubility, color, and conductivity. Many of these properties are easily detected by one or more of our senses (sight, smell, touch, taste, and hearing). Chemical properties are characteristics that are shown during chemical interaction of one substance with another. When a substance undergoes a physical change, its composition is not altered. For example, the freezing of water is a physical change. However, when a substance undergoes a chemical change, its composition is changed, and one or more new substances are formed. For example, the burning of wood is a chemical change.

b. On the basis of their composition, substances may be classified as elements, compounds, or mixtures.

(1) Element. An element is a simple substance that cannot be decomposed by chemical means. The smallest unit of an element that still retains the characteristic properties of that element is an atom. An element is commonly designated by a symbol made up of one or two letters of its English or Latin name. For example, oxygen is designated by 0, hydrogen by H, mercury by Hg, and so forth. In general, all elements may be grouped into two classes: metals and nonmetals. Examples of metals are gold, magnesium, iron, lead and copper. Examples of nonmetals are nitrogen, oxygen, hydrogen, sulfur, and chlorine. Some characteristic metallic properties, such as luster, good conductivity (of heat and electricity), plasticity (malleability and ductility), and high density, are diametrically opposed to certain characteristic nonmetallic properties.

(2) Compound. A compound is a complex substance formed by a chemical union of two or more elements in definite proportions by weight. The smallest unit of a compound that still retains the characteristic properties of that compound is called a molecule. A compound exhibits properties different from the elements of which it is composed. For example, the elements that comprise the liquid water are the two gases hydrogen and oxygen (in a ratio of one to eight by weight). A molecule of water is composed of two atoms of hydrogen and one atom of oxygen. This relationship is often designated by the chemical formula H_2O. Further consideration of the structure of atoms and molecules will be found later in this lesson.

(3) Mixture. A mixture is made up of substances (in any proportion), each retaining its own physical and chemical properties. For example, salt and sand may be combined to form a mixture. These components are unchanged and can be separated by physical means, such as sorting or dissolving in solution.

1-8. ENERGY

Energy is inherent in all forms of matter. But unlike matter, energy is not a substance and does not occupy space. Energy is defined as the capacity to perform work. Two types of energy are recognized--potential and kinetic.

a. **Potential Energy**. Potential energy is the energy of position. It is the energy inherent in a body because of position. Thus, a car parked on a hill has potential energy. Water retained by a dam located upstream above a power plant also has potential energy. They represent stored energy waiting to be released under the right circumstances.

b. **Kinetic Energy**. Kinetic energy is the energy inherent in a moving body. Thus, when the brakes of a car are released and it begins to move, the potential energy becomes kinetic energy. When the dammed-up water falls to the power plant below, the potential energy in the water becomes kinetic energy. As the potential energy decreases in each of these instances, the kinetic energy increases, until finally the total kinetic energy at point of impact (when the car hits the bottom of the hill and keeps rolling, and when water from the dam begins to drive the turbines) equals the initial potential energy.

c. **Kinetic-Potential Energy Relationship**. A swinging pendulum (figure 1-1) also illustrates the kinetic-potential energy relationship. At the extreme upward end of each swing (A and C), the bob comes momentarily to rest, and all the energy then is potential. However, on its swing downward, the pendulum increases in kinetic energy (a) and all energy at the bottom of the swing (B) is kinetic. As it swings from the bottom upward toward the opposite end, the pendulum loses kinetic energy and gains potential energy (b) until its contained energy is all potential energy again (at C).

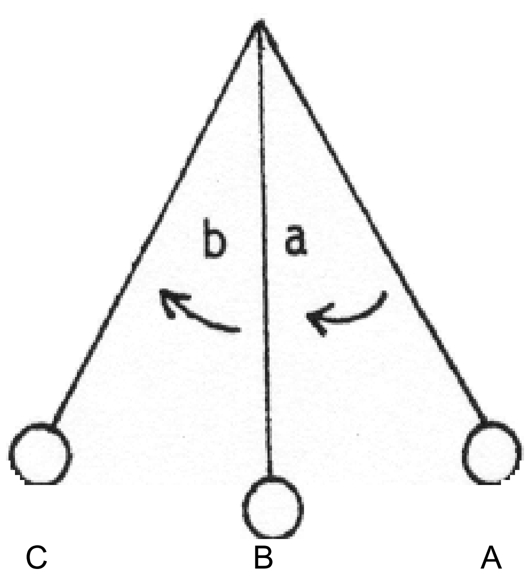


Figure 1-1. Pendulum used to illustrate kinetic and potential energy.

d. **Electron Volt**. The unit of energy used in radiology is the electron volt (eV). An electron volt is the amount of potential energy released when an electron is accelerated by a potential difference of one volt. A keV is equal to one thousand electron volts and a MeV is equal to one million electron volts.

e. **Energy Transformation**. Energy is constantly changing from one form to another. All changes in the universe involve the transformation of energy. Various forms of energy, such as mechanical energy (in steam engines), chemical energy (in storage batteries), radiant energy (from the sun), nuclear energy (in nuclear reactors), etc., are convertible, one to another. A boiler-steam engine generator hookup in a power plant illustrates this conversion. In this sequence, chemical energy stored in the fuel changes to heat energy that causes the water to boil, producing steam. The kinetic energy in the steam molecules is converted to mechanical energy as the engine moves. The mechanical energy is transformed into electrical energy as the steam engine drives the generator. Electrical energy is converted into light, sound, heat, and motion through such ordinary devices as electric bulbs, buzzers, toasters, motors, and so forth.

1-9. MASS-ENERGY RELATIONSHIPS

The quantity of matter in an object is often called its mass. Although frequently used interchangeably with weight, the term mass is usually more specifically used to designate the degree of inertia contained within an object. Inertia may be defined as the tendency of a resting body to remain at rest, or a moving body to remain in motion in a straight line.

a. To set a resting body in motion or to stop a moving body, a force must be applied. The greater the mass of an object, the greater the force needed to speed it up or slow it down. For example, it takes more force to stop an automobile in a given time than it takes to stop a bicycle when both are moving at the same speed.

b. When a force succeeds in moving a resting body, it is said that work is performed. The amount of work done is determined by the quantity of the force used and the distance the body moves in a straight line at a constant speed. Work is expressed by the following equation:

$$\boxed{\text{Work} = \text{force} \times \text{distance}}$$

c. The unit of work in the metric system is the joule (newton-meter). A joule is the amount of energy needed for a force of one newton to act through a distance of one meter. One watt is the unit of power equal to the work done at the rate of one absolute joule per second.

NOTE: A newton is the unit of force in the meter-kilogram-second system equal to the force that would give a free mass of one kilogram an acceleration of one meter per second.

1-10. THE LAW OF CONSERVATION

The law of conservation of matter and energy states that matter and energy can neither be created nor destroyed, though they can be changed from one form to another. In all chemical and physical processes of everyday living, the mass of end products obtained is equal to the mass of starting materials used. This will be well illustrated by later sections dealing with the structure of matter. The total amount of energy in the universe is constant. That is, matter can be transform into an equivalent amount of energy and vice versa. This is illustrated by Einstein's famous equation:

$$\mathbf{E = mc^2}$$

Where E = energy in ergs
m = mass in grams
c = speed of light in a vacuum in centimeters per second

In other words, mass and energy are mutually convertible. An atomic explosion illustrates how a tiny amount of matter is converted into a relatively large quantity of energy. The matter that seems to be destroyed is converted to energy. From this law, we can determine the following relationships for matter and energy.

a. Matter may be changed into another form of matter.

b. Energy may be changed into another form of energy.

c. Matter may be changed into energy.

d. Energy may be changed into matter.

1-11. ATOMIC STRUCTURE

a. **Components**. As the smallest unit of an element, the atom cannot be subdivided further by ordinary chemical and physical means. However, it can be broken down into even smaller particles by particle bombardment from nuclear reactors and particle accelerators. These smaller particles--protons, neutrons, and electrons--may be regarded as building blocks and have been found common to all elements. Differences in all atomic makeup are due primarily to different combinations of these building blocks.

b. **Bohr's Theory**. Different theories have been advanced and improved upon over the years to explain the structure of the atom. Bohr's theory, proposed in 1913, likens the atom to a miniature solar system (figure 1-2). According to this concept, a positively charged nucleus containing protons (positive particles) and neutrons (neutral particles) is located in the central core. It contains nearly all the mass (weight) of the atom. Revolving around the nucleus are almost weightless orbital electrons--planetary particles with negative charges. In the stable state (called the neutral state), these negative charges are balanced against the positive charges in the nucleus. Once this balance in atomic charge is disrupted (by the loss or gain of electrical charge, for instance), the atom is said to be <u>ionized</u>.

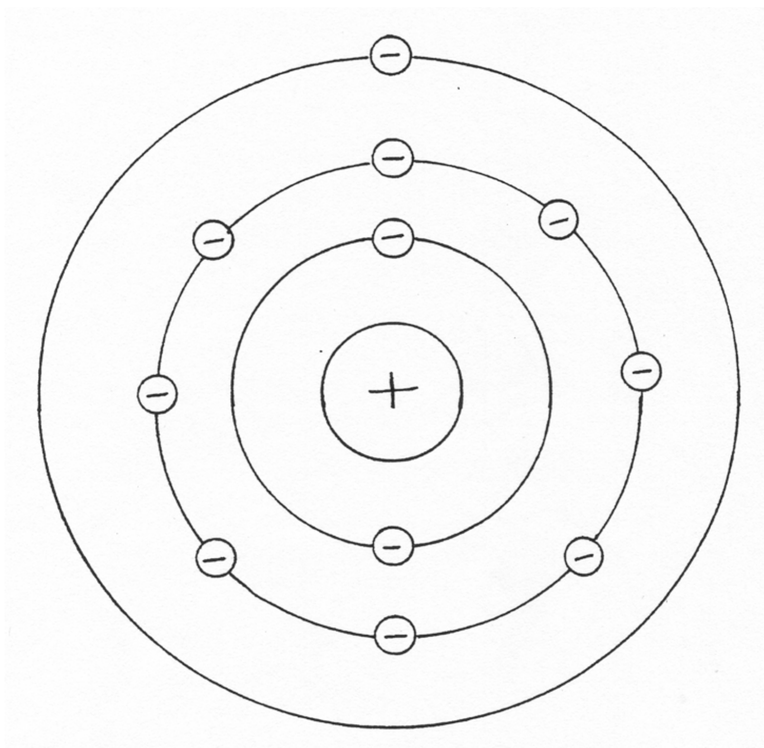


Figure 1-2. Atomic model as envisioned by the Bohr theory.

c. **Wave Theory**. The newer and more accepted theory of atomic structure based upon wave mechanics treats electrons as a kind of three-dimensional cloud spread around the nucleus as electron waves. Even though Bohr's concept of the atom with sharply defined electron orbits is now replaced by the electron cloud theory, the equation developed by Bohr on electron activity generally agrees with experimental observations. Therefore, for our purposes, the Bohr orbit concept will be used as it lends itself more effectively to visualization. Though the new electron wave theory may explain all known phenomena more satisfactorily, it is difficult to form a mental picture of what an atom might look like.

d. **The Nucleus**. The basic particles of the nucleus are protons and neutrons. Collectively, they are called nucleons.

(1) Protons. Protons are positively charged particles in the nuclei of atoms. A proton has a mass about 1,836 times that of an electron. While protons are identical for all elements, each element has its own characteristic number of protons. The number of protons contained in the atomic nucleus is the atomic number, represented by the symbol Z. The atomic number is also equal to the number of electrons in the neutral atom. It is what identifies a particular element and determines its place in the periodic table. It is usually designated at the lower left corner of a chemical symbol for an element (for example, ${}_{92}U$).

(2) Neutrons. Neutrons, as the name implies, are electrically neutral particles. A neutron has about the same mass as a proton. The number of neutrons in the atomic nucleus of a given element varies. Nuclear stability depends crucially on the number of neutrons associated with protons in the nucleus. The total number of protons and neutrons in the nucleus make up the mass number of an element that is represented by the symbol A. It identifies the isotopes of a particular element. It is usually designated at the upper left corner of a chemical symbol (for example, ${}^{238}U$).

e. **Extra-nuclear Structure**

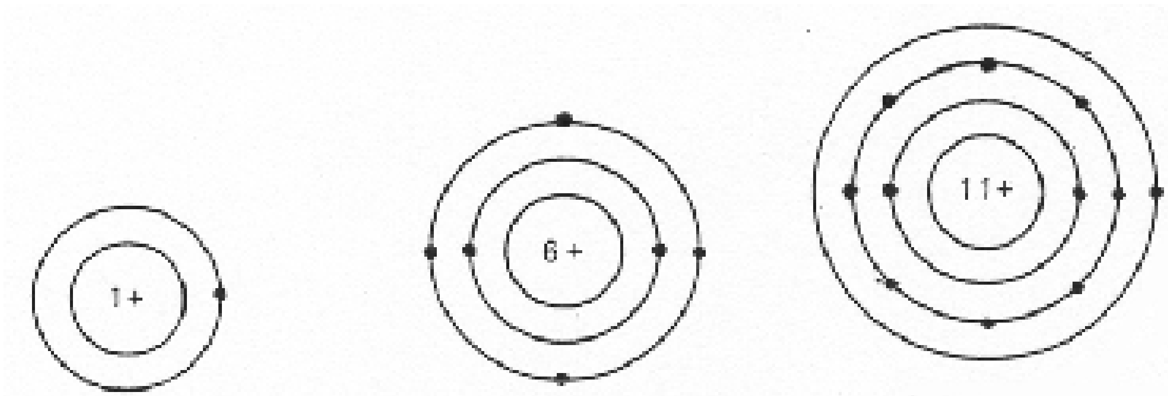
(1) The orbital electrons that whirl around the nucleus in continual motion are arranged in shells or energy levels around the nucleus. The number of electrons that each shell can hold is limited. The innermost shell (identified as K) holds only two electrons, but the next shell (L) may contain up to eight electrons. For elements with more than 10 electrons in their atomic structure, a third shell (M), which may hold up to 18 electrons, is present.

(2) The maximum number of electrons that may fill any Bohr orbital shell may be represented by $2n^2$, where n designates the number of the shell. For example, calculations for the first, second, and third shells, K, L, and M would be $2 \times 1^2 = 2$ (K-shell), $2 \times 2^2 = 8$ (L-shell), and $2 \times 3^2 = 18$ (M-shell).

(3) However, in the atoms of elements of higher atomic number, additional N, O, P, and Q shells are added. These shells may carry no more than 32 electrons ($2 \times 4^2 = 32$ for the N-shell), though they often carry fewer than 32. In many of these heavier elements, electrons are found in an outer shell when a shell closer to the nucleus is not completely filled. The extra-nuclear structure of uranium is an example of this. Two electrons are found in the seventh shell even though the fifth and sixth shells are not completely filled.

(4) In the neutral state, the number of orbital electrons is equal to the number of positive charges (the number of protons) in the nucleus. However, in some atoms the number of orbiting electrons may be less than the number possible for each orbit. In figure 1-3, note that the hydrogen atom (the nucleus of which contains one

proton) has a single orbiting electron. The carbon atom with a nucleus containing six protons has two "shells" of orbiting electrons, with two electrons in the inner and four in the outer energy level. Also, notice that the sodium atom has 11 protons in its nucleus and three shells of orbiting electrons with a single electron in its outermost shell.



Hydrogen atom 1 | Carbon atom 2, 4 | Sodium atom 2, 8, 1

(5) The use of orbits and shells to describe electron position indicates the relationship of different electron-energy levels. Generally speaking, an atom will tend to react with other elements more readily when its outer shell is not completely filled. This concept of interaction of elements will be further discussed later in this lesson under valence and molecule formation.

(6) Electrons are maintained in their shells by a combination of centrifugal force (which tends to propel them away from the nucleus) and electrostatic force, and the attraction between the positive nucleus and negative electrons. Since the electrons are bound to the nucleus by electrostatic force, a certain amount of energy is required to remove an electron from its shell to a point completely outside the atom. This is called the binding energy of that shell. The binding energy of the shell of an atom is greatest in the K shell and decreases as the distance of the shell from the nucleus increases. For example, the binding energies for tungsten shells are: K--69.5 keV, L--12 keV, M--2 keV, and N--0.8 keV. Consequently, it would require at least 69.5 keV of energy in an atom of tungsten to remove a K electron from its shell, at least 12 keV to remove an L electron from its shell, and so on. The binding energy is important in the production of characteristic radiation that is explained later in this lesson.

(7) The binding energy of a shell, and consequently of an electron in that shell, must not be confused with the potential energy possessed by that electron. The potential energy possessed by the electrons is least in the K shell and increases with distance from the nucleus.

(a) Binding energy. To illustrate the difference between binding energy and potential energy of the electrons, we will compare an atom to a metal ball and magnet. Suppose the ball was permitted to occupy three steps at different distances from the magnet as illustrated in figure 1-4. The magnetic force between the magnet and ball would be similar to the force of attraction between the nucleus and an electron since the force is inversely proportional to the square of the distance between the two. Thus, the ball on step A would be more firmly held (as a K shell electron) than the ball in step B (as an L shell electron) and, correspondingly, different amounts of energy would be required to remove them.

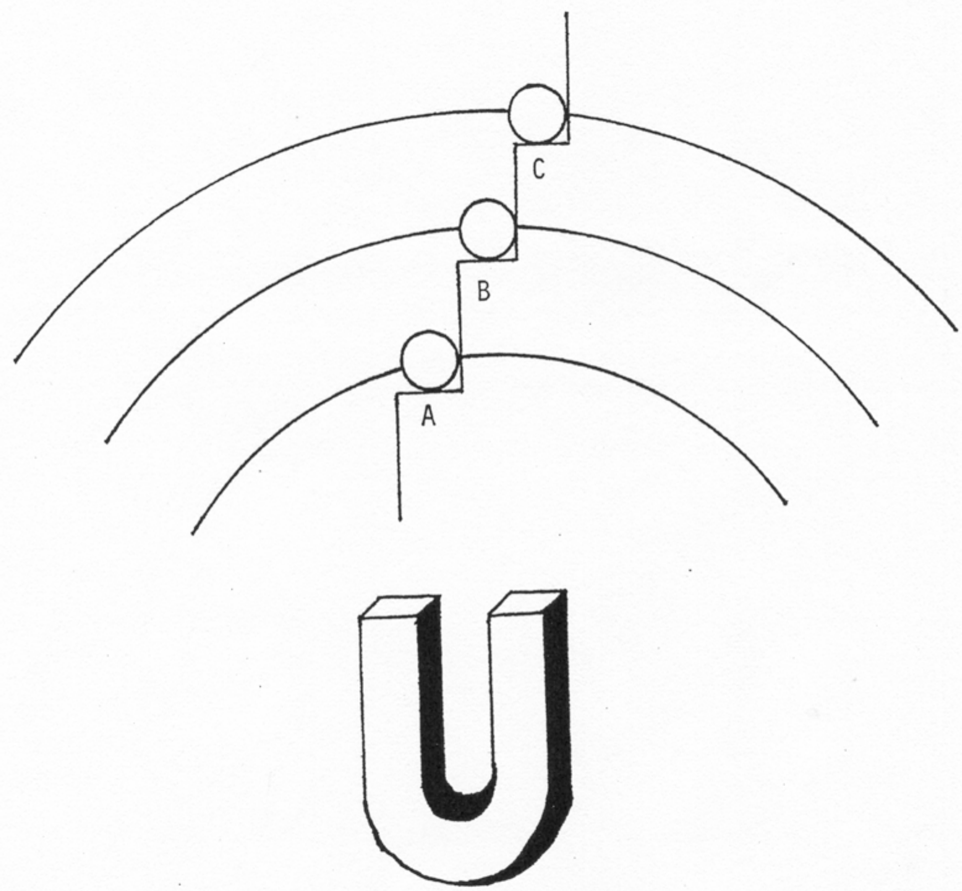


Figure 1-4. Binding and potential energy.

Binding and potential energy varies with object distance from a magnetic force. Thus, the distance between orbiting electrons and the atomic nucleus affects both the binding energy and the potential energy.

(b) Potential energy. The potential energy of the electrons is similar to the potential energy of the metal balls (figure 1-4). The ball on step C has more potential energy than the ball on step B because its position is more elevated. If the ball on Step C dropped to step B, it would release a certain amount of energy. Orbiting electrons also release energy in the same manner when they drop from a higher potential energy level to a lower potential energy level. Thus, the potential energy is higher when there are more electrons in shells farther from the nucleus.

1-12. ISOTOPES

a. Atoms of the same element (having the same atomic number) but having different mass numbers are known as isotopes. Isotopes have the same number of protons but a different number of neutrons in their nuclei. Consequently, the various isotopes have different atomic weights. Because an element consists of a group of isotopes, the atomic weight is an average and almost never a whole number.

b. For example, zinc with an atomic number of 30 has an atomic mass of 65.38, which is the average of a mixture of its five isotopes (^{64}Zn, ^{66}Zn, ^{67}Zn, ^{68}Zn, and ^{70}Zn) in definite proportions. The terms atomic weight and mass number are often used interchangeably because they are nearly equal to each other.

c. The term isotope does not always refer to a distinct species of atom, but the term nuclide does. It refers to a species of atom characterized by its nuclear configuration, and hence by the number of protons, the number of neutrons, and the energy content. We can say that the different isotopes of an element are composed of nuclides that have the same atomic number but different mass numbers.

1-13. VALENCE

a. The number of electrons in the outer shell of an atom determines its valence. Valence represents the capacity of an atom to combine with other atoms to form molecules. The hydrogen atom with a valence of +1 is the standard used for determining the valence of other atoms. Atoms with the same number of outer orbital electrons have similar chemical and physical characteristics.

b. For example, atoms of elements such as lithium, sodium, and potassium have only one electron in their outermost shells (figure 1-5). Their valence is +1, and they combine with other elements that may lack a single electron in the outermost shell. Atoms lacking one electron to complete their outermost orbit are said to have a valence of -1 (figure 1-6). These give-or-take electrons are called valence electrons.

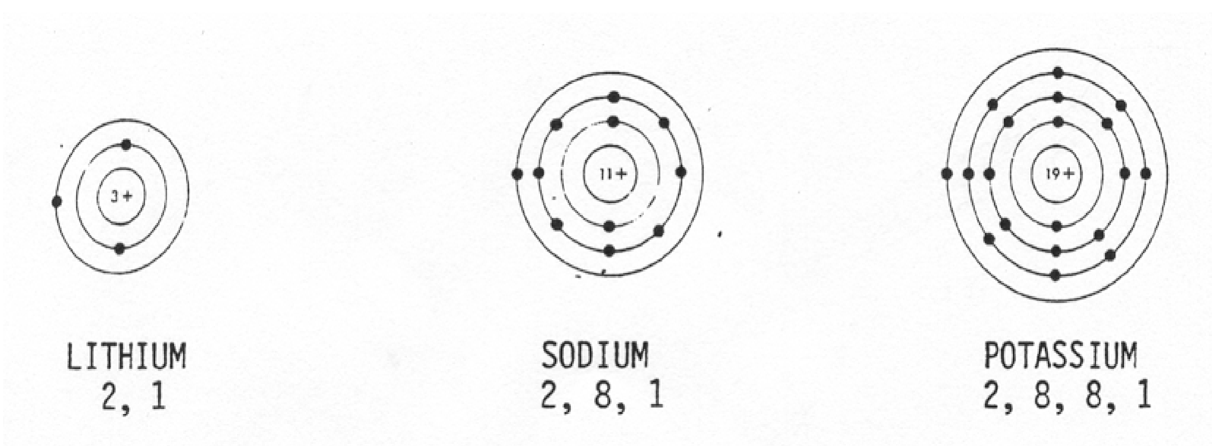


Figure 1-5. Atoms with a +1 valence.

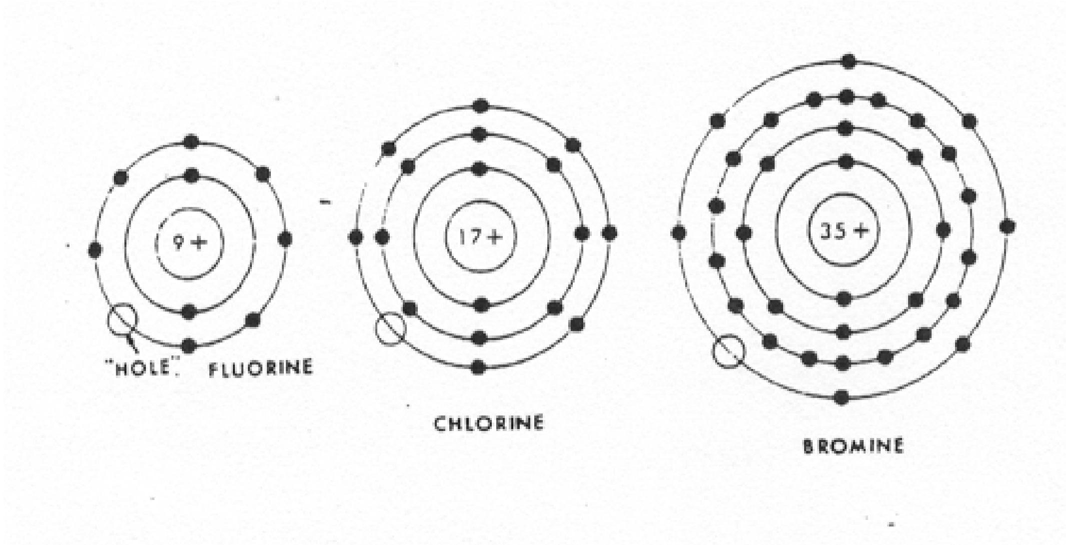


Figure 1-6. Atoms with –1 valence.

1-14. FORMATION OF MOLECULES

Molecules are formed of two or more atoms. Sharing of the outer valence electrons often occurs among atoms during molecule formation. This sharing is cemented by three kinds of bonds: the ionic or chemical bond, the convalent bond, and he hydrogen.

a. **Ionic Bond**. An ionic bond is formed with the direct transfer of an orbital electron from one atom to another in an electrostatic attraction. This type of valence, call <u>ionic polar valence</u>, is common to the formation of many inorganic compounds. For example, when a sodium atom and a chlorine atom are brought together, the single-valence electron in the outer shell of the sodium atom is transferred to the chlorine atom which has a "hole" in its outer shell and sodium chloride is formed (figure 1-7).

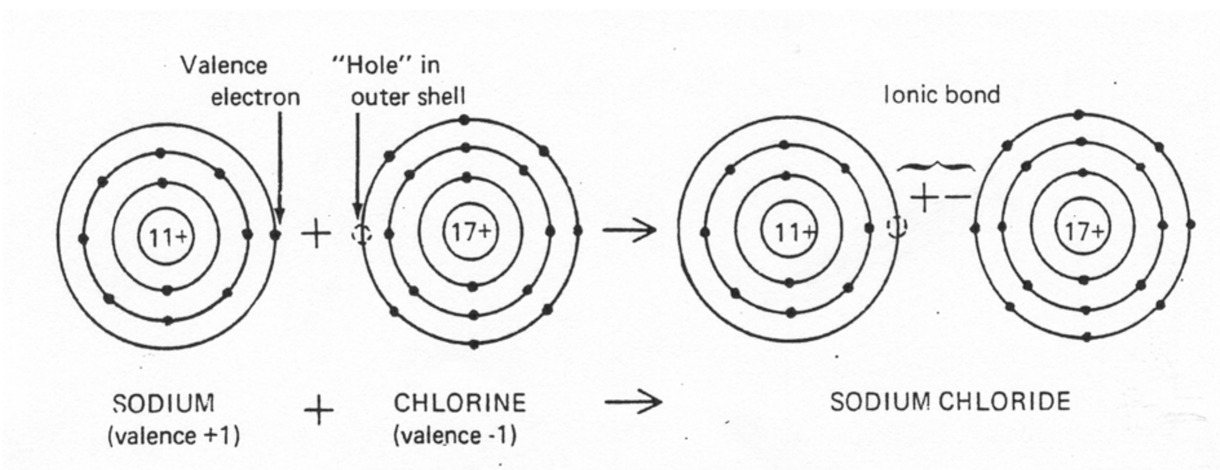


Figure 1-7. Ionic bond – sodium chloride.

b. **Convalent Bond**. In contrast, a convalent bond is formed by the sharing of valence electrons between atoms.

(1) A water molecule is an example (figure 1-8). Here, one oxygen atom is linked to two hydrogen atoms by the single electrons of the two hydrogen atoms to form a water molecule. Actually, the single electron from each hydrogen atom is paired with a single electron from the oxygen atom in this covalent relationship. For part of the time, each paired electron can be considered as circulating around the hydrogen nucleus and, for the rest of the time, around the oxygen nucleus. (Note: Slightly more time is spent around the electronegative oxygen atom.) By doing so, both the oxygen and hydrogen atoms have completed shells and established a more stable configuration.

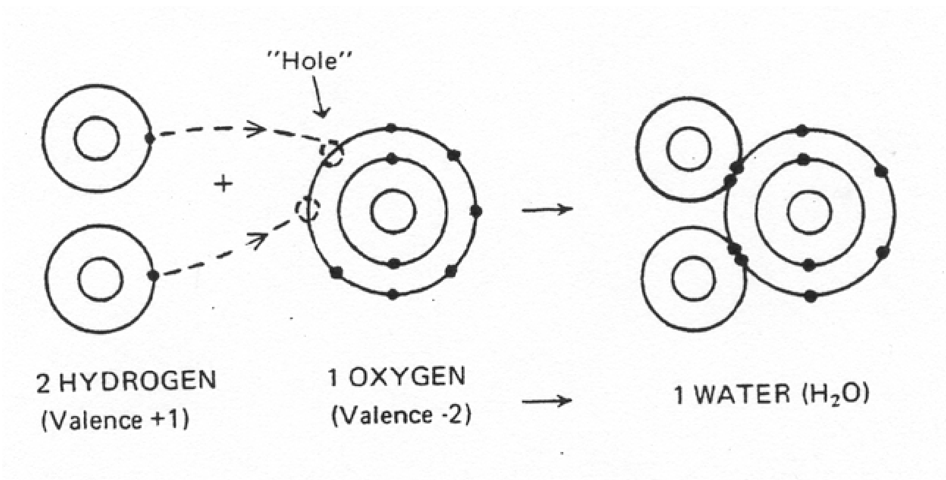


Figure 1-8. Covalent bond - water molecule.

(2) Another example is a molecule of carbon dioxide, which illustrates the double covalent bond (figure 1-9). Here two oxygen atoms are linked by the four electrons they share at each juncture with the carbon atom.

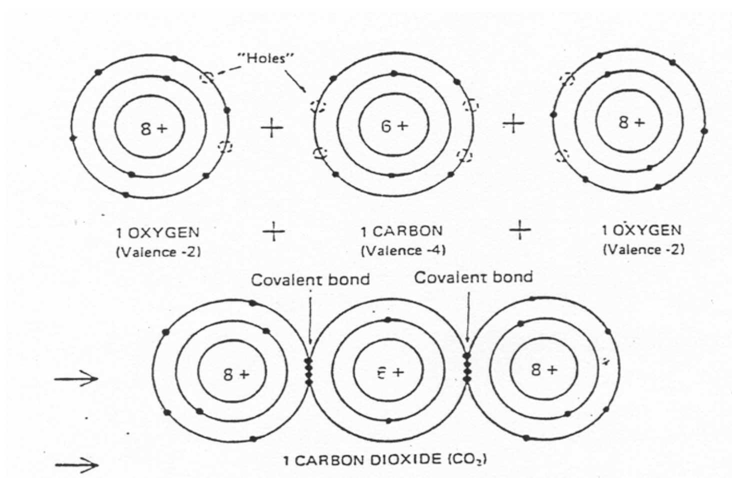


Figure 1-9. Double convalent bond – carbon dioxide molecule.

c. **Hydrogen Bond**. A hydrogen bond is an attraction between molecules that is weaker than ionic or covalent bonds.

(1) This may be illustrated by the intermolecular attraction between molecules of water (figure 1-10). In hydrogen bonding between water molecules, the angular placement of the hydrogen atoms on the oxygen atom sets up a polar magnetism. This polarity tends to draw the molecules together. Hydrogen bonding only establishes geometric arrangements and is an electrostatic phenomenon.

(2) Long chains of protein molecules containing nitrogen and oxygen atoms are also held together by hydrogen bonds.

__NOTE__: It will be noticed by now that the chemical reactions in molecule formation follow a pattern of definite proportions that may be explained by the concept of valence. Examples: sodium chloride is always formed by combining one atom of sodium with one atom of chlorine; water always by two atoms of hydrogen with one atom of oxygen.

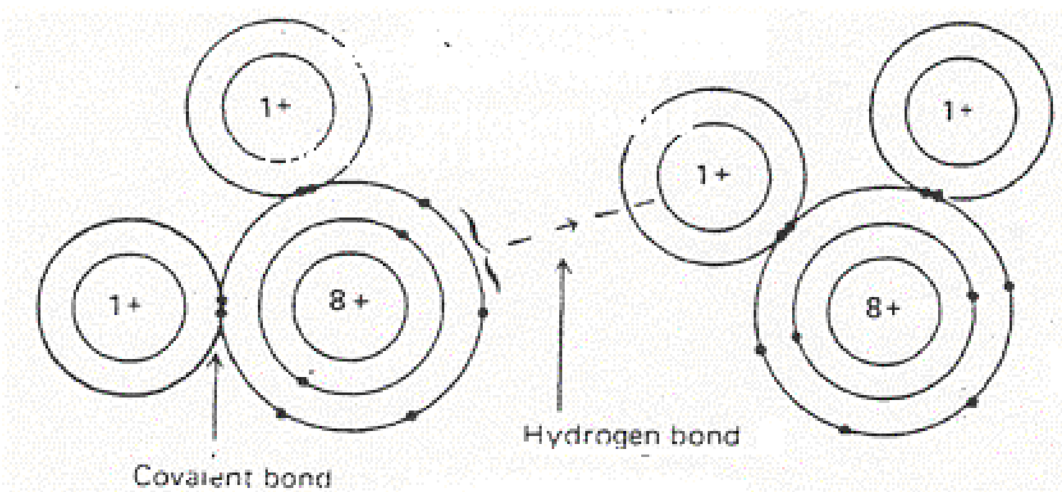


Figure 1-10. Hydrogen bond between two molecules of water.

1-15. RADIOACTIVITY

The spontaneous disintegration of radioactive substances in which the atomic nuclei undergo partial breakdown and give off penetrating radiation at the same time is described as radioactivity. It is a natural property of all existing elements with atomic numbers above 83. It is also possible to induce this property in all other known elements.

a. A factor contributing to nuclear disintegration in radioelements is the instability of their atomic nuclei. For these elements to reach a more stable or less energetic state, excess energy in the form of alpha, beta, or gamma radiation is released. This nuclear instability may occur from the natural configuration of the atoms of the element or it may be man-made.

b. Natural radioactivity, in which the nuclear disintegration is spontaneous, is exhibited in certain naturally occurring elements, such as radium. Artificial radioactivity is brought about by bombarding the atomic nucleus with various subatomic particles. Alpha and beta particles, protons (nucleus of the hydrogen atom), neutrons, and deuterons (nucleus of deuterium, or heavy hydrogen, atom) are most commonly used. However, the relatively small size of the atomic nucleus makes bombardment extremely difficult. To produce artificial radioactivity, the bombarding subatomic particle must deliver a direct hit to the atomic nucleus. With the proper bombardment technique, any stable atom or element can be made radioactive.

c. The radiation emitted with atomic nuclei disintegration may be in the form of corpuscular radiation or electromagnetic waves. The corpuscular radiations are the alpha and beta particles. The electromagnetic radiations include gamma radiation and x-radiation. Gamma radiation is emitted directly from the nucleus while x-radiation is produced by radiative and collisional interactions of electrons outside the nucleus.

(1) Alpha particle. The alpha particle is a stable combination of two protons and two neutrons, the same composition as the nucleus of the helium atom. When an element emits an alpha particle during nuclear disintegration, the particle is traveling at speeds of 9,000 to 20,000 miles per second, but it is slowed down rapidly in its passage through matter.

(a) Eventually, the alpha particle, which has a positive charge of +2, passes through matter causing many ion pairs by attracting the outer orbital electrons. The alpha particle becomes a stable helium atom when it has annexed two electrons. The Z number and A number of the nucleus of the element that gives up the alpha particle are reduced by 2 and 4, respectively.

(b) An alpha particle also has an extremely high ionizing ability. It may cause some skin damage, but its greatest danger lies in its penetrating abilities.

(2) Beta particle. A beta particle is an extremely high-speed electron (negative beta, $-^{0}_{1}e$) or positron (positive beta, $+^{0}_{1}e$) which is ejected from the nucleus of a disintegrating atom. Electrons emitted from the nucleus probably result from spontaneous conversion of a neutron into a proton and an atomic nucleus ordinarily does not contain free electrons. Except for its speed and origin, the electron is identical to the electrons that orbit about the nucleus of atoms. As a result of the neutron split which ejects an electron and retains a proton, the Z number of the element is increased by an addition of one, but its A number remains the same.

(a) In relation to the alpha particle, the beta particle has a smaller mass and travels at a much higher speed, almost as fast as light. Because of this, the beta particle exerts less force for a shorter period on the atoms of material through which it passes. Thus, its ionizing ability per unit path length is less than that of an alpha particle, though its range is greater.

(b) These factors normally make beta emitters a less serious internal hazard than alpha emitters. However, since the beta particle can penetrate skin and damage living cells, the beta emitter can also be an external hazard.

(3) Gamma radiation. Gamma radiation is identical to x-radiation except for its origin and method of production. It can be considered as bundles of pure energy (photons) generally expressed in keV or MeV.

(a) Gamma radiation results when protons and neutrons are rearranged in the nucleus of the unstable atom without emission of a particle. Because the components are found with different energies in different nuclear configurations, energy is released in the form of electromagnetic waves called gamma rays when the components are rearranged. Gamma radiation sometimes accompanies beta and alpha emission.

{b} Gamma radiation wavelengths are extremely short, and the radiation is the most highly penetrating. The A and Z numbers undergo no change in gamma emission.

(4) Half-life. Half-life is the time required for a given quantity of radioactive substance to disintegrate until one-half of its initial activity remains. For example, radium decays at such a rate that an initial amount of radium will decay to one-half its value in about 1600 years. Therefore, starting with 1 gram of radium-226, we will find its value to be only 0.5 gram after 1600 years. After another 1600 years, it will be only 0.25 gram in value. The other 0.75 gram will have been converted into daughter products of the decay family.

(a) Applied to dose rate, the concept of half-life takes on a new meaning. That is, the half-life of any radioactive nuclide is the time required for the dose rate from a sample of that nuclide to drop to one-half its initial value.

(b) Half-life values among nuclides will vary from a fraction of a second for one to several billion years for another. Each radioactive nuclide has its own half-life.

1-16. X-RADIATION

X-radiation (x-rays) and gamma radiation are identical to each other except for their origin and method of production. X-radiation is the result of the conversion of either the kinetic or potential energy of electrons into another form of energy while gamma radiation is emitted from radioactive nuclei. X-radiation is produced by radiative interactions of electrons with matter and collisional interactions of electrons with matter.

a. **Radiative Interactions**. When an electron (which is negatively charged) approaches the nucleus (which is positively charged), it may be deflected from its original direction by the attractive force of the nucleus. The change of direction causes deceleration of the electron or a loss of some of its kinetic energy. The energy lost by the electron is given off as an x- ray photon. This process is referred to as radioative interaction of an electron with matter. The radiation produced by this type of interaction is called bremsstrahlung (German for braking radiation), general radiation, or white radiation. The energy of the resultant photon depends upon: (1) the original kinetic energy of the electron, (2) how close the electron comes to the nucleus (see figure 1-11), and (3) the charge of the nucleus.

(1) Since in this type of interaction the electron loses only a portion of its kinetic energy, it may have one or more interactions with other atoms before expending all its energy. In this manner, it could produce several photons with various energies. Figure 1-12 shows now two electrons might interact with more than one atom to produce photons with a wide range of energies.

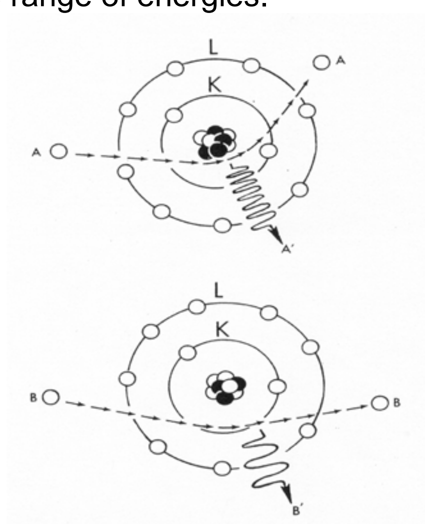


Figure 1-11. Variation of photon energy is partly dependent upon how close to the nucleus and intruding electron travels.

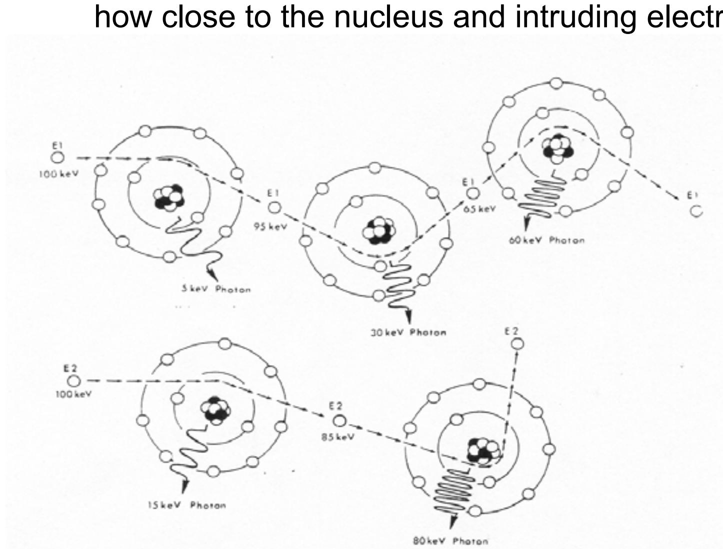


Figure 1-12. Typical paths of electrons producing bremsstrahlung radiation.

(2) A beam of bremsstrahlung radiation shows a continuous energy range from a very low energy to the maximum energy possessed by the electrons. The energy spectrum produced by 100-keV electrons in tungsten is illustrated in figure 1-13.

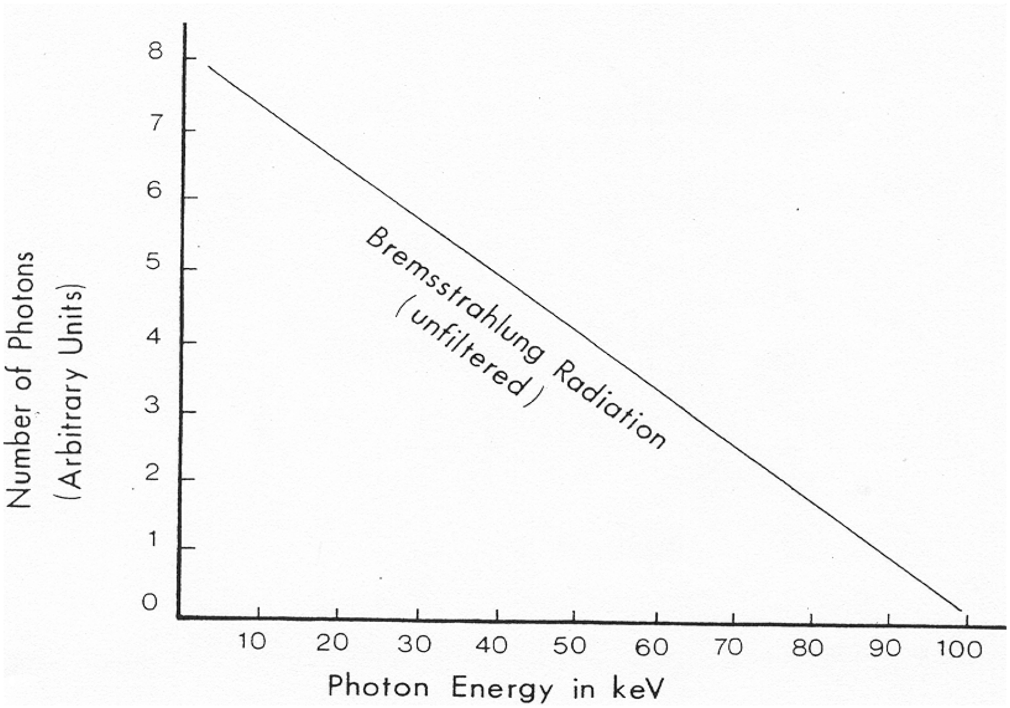


Figure 1-13. Energy spectrum produced by 100-keV electrons in tungsten.

(3) An electron, as well as being decelerated near the nucleus, may occasionally collide with the nucleus. In this case, the electron loses all its energy in the collision and that energy is given off as a photon. The energy of the photon would be equal to that of the electron. Figure 1-14 shows an interaction of this type. If the electron shown possessed 100 keV of energy, the resultant photon would also have 100 keV of energy.

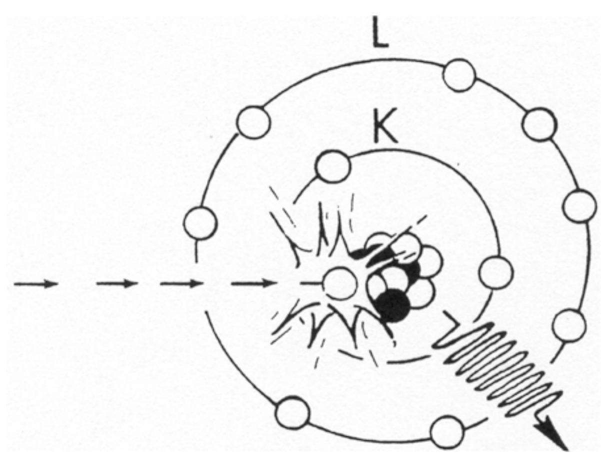


Figure 1-14. High speed electron in collision with atomic nucleus.

b. **Collisional Interactions**. The discussion to this point has demonstrated how x-rays are generated when electrons interact with the nucleus of an atom. X-rays are also generated when electrons interact with the tightly bound orbital electrons of a hard surface. This is called collisional interaction of an electron with matter and produces <u>characteristic</u> or <u>line</u> <u>radiation</u>.

(1) In the interaction, an approaching electron collides with a tightly bound orbital electron, such as an electron in the K shell of an atom of tungsten (figure 1-15). Because of the collision, the K electron is ejected from its shell and energy is absorbed by the atom equal to the binding energy of the shell. The atom is left in an excited state or with an excess of energy and an electron vacancy in a shell. Immediately after excitation, the atom returns to a normal state by emitting the energy it has absorbed in the form of x-ray photons. It does this as follows. Another electron, such as from the L shell, fills the vacancy. Since the potential energy of an electron in the L shell is higher than that of an electron in the K shell, the L electron loses energy in the transition. The energy lost is equal to the difference in the binding energies of the K and L shells and is given off as an x-ray photon.

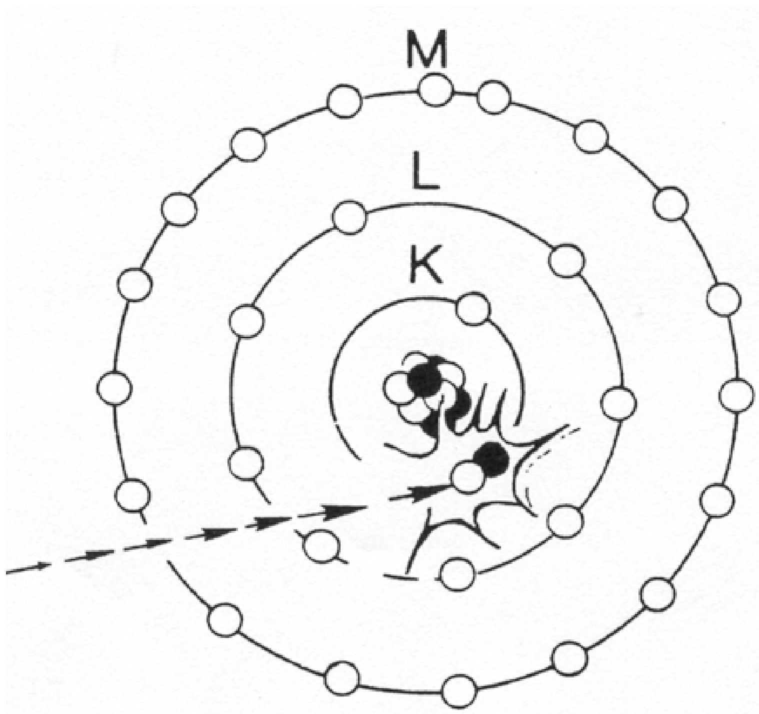


Figure 1-15. Collisional interaction in tungsten.

(2) Although a photon has been emitted, the process is not yet completed because there is now a vacancy in the L shell and the atom still has an excess of energy. This vacancy is also immediately filled by another electron such as one from the H shell and another photon is emitted equal to the energy of the difference of the transition. This chain reaction continues with a photon given off for each electron transition until the atom returns to a normal state.

(3) Figure 1-16 shows an atom of tungsten with only the K, L, and M shells demonstrated. The binding energy of tungsten's K, L, and M shells are 69.5, 12, and 2 keV, respectively. In the top illustration (figure 1-16A), the impinging electron has collided with and ejected a K electron from its shell and both electrons are seen leaving the vicinity of the atom. In the bottom illustration (figure 1-16B), as the electron transitions take place, two photons are emitted with energies of 57.5 keV (the difference in binding energies of the K and L shells) and 10 keV (the difference in binding energies of the Land M shells).

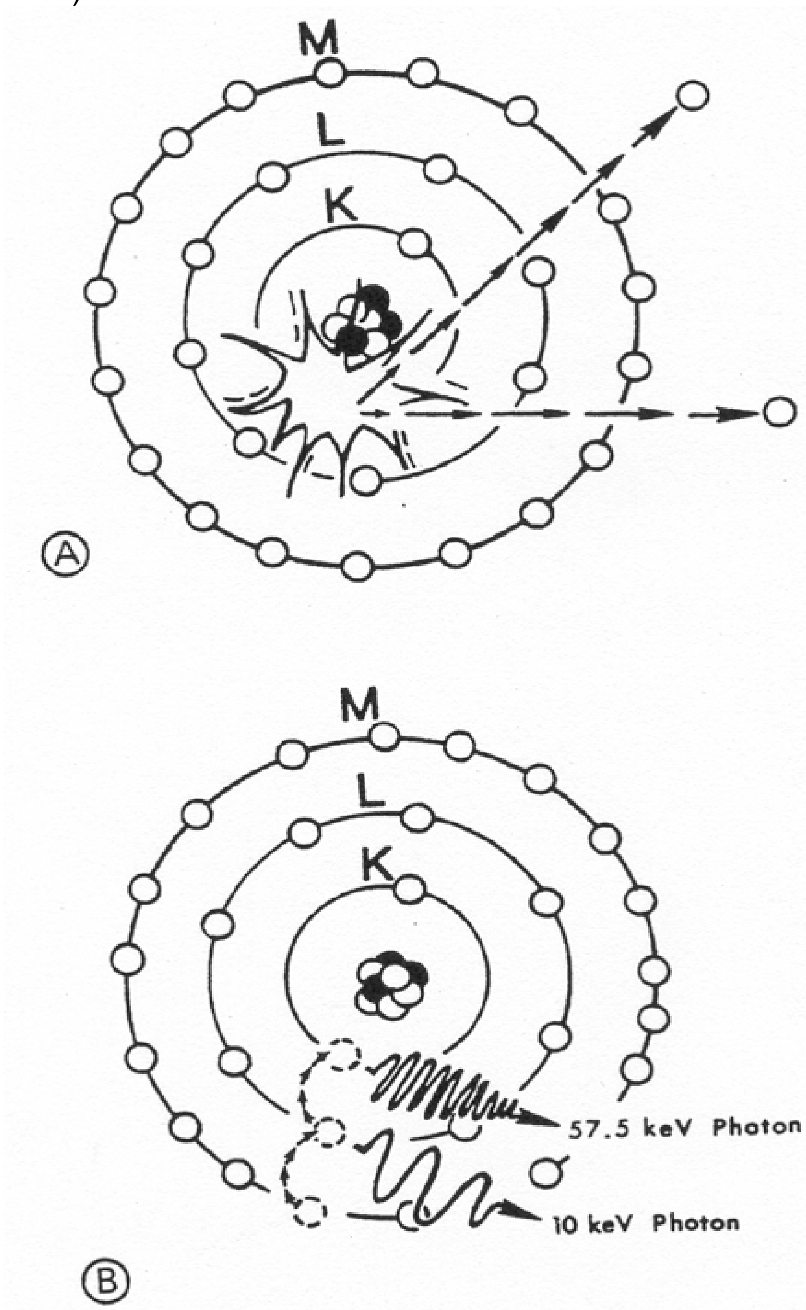


Figure 1-16. **A** Displacement of K electron.
B Replacement of displaced electron from shells L and M

(4) When a K shell electron is ejected, the vacancy need not be filled from the L shell. It can be filled from any shell with a higher potential energy level or even from outside the atom. In any case, the emitted photon is always equal to the energy of the difference of the transition. The combined energies of the photons from a collisional interaction are equal to the binding energy of the shell from which the electron was ejected because the atom initially absorbed that amount of energy. The maximum energy of a photon cannot be greater than the binding energy of the K shell of the atom (in the case of tungsten, 69.5 keV).

(5) The radiation produced in a collisional interaction is called <u>characteristic radiation</u> because its energy is characteristic of the shell of the atom from which it came. The binding energy of the K shell in copper is 9 keV; therefore, the maximum energy of characteristic radiation that could be generated in copper would be 9 keV, an amount that is not usable in radiology. Tungsten, however, can generate characteristic radiation with a maximum energy level of 69.5 keV, some of which can be useful in radiology.

(6) In order for characteristic radiation to be generated at all, an electron must be ejected from its shell. The energy required to remove an electron from its shell is equal to or greater than the binding energy of the shell. Since the binding energy of tungsten's K shell is 69.5, it would require an electron with at least 69.5 keV of energy to eject the K electron and thus generate useful characteristic radiation from tungsten. It should be noted at this time that 12 keV of electron energy can eject an L electron from tungsten, thereby producing characteristic radiation. However, this radiation's maximum energy would be 12 keV, which is not considered useful in radiology.

c. **The Electromagnetic Spectrum**. Gamma radiation and x-radiation are two of several types of electromagnetic radiation that make up the electromagnetic spectrum illustrated in figure 1-17. Notice that visible light waves, radio and television waves, and infrared waves are also electromagnetic radiation. The main difference between visible light and x- radiation is in their wavelength and, consequently, their energy.

d. **Wavelength, Energy, and Frequency**. Electromagnetic waves, including x-rays, all travel at the same speed in a vacuum--about 186,000 miles per second. They have the same general characteristics, but differ in the length of the waves. This is illustrated in figure 1-18, which shows two different wavelengths. The longer wavelength is less penetrating, has less energy, and, of course, has a lower frequency. The shorter the wavelength, the higher the energy, frequency, and the more penetrating the beam. X-rays have quite short wavelengths as compared to many other electromagnetic waves, but they do vary somewhat. Aluminum filters are used in x-ray machines to filter out the longer, less penetrating rays which otherwise would expose the patient to radiation with an energy level too low to be useful in radiography.

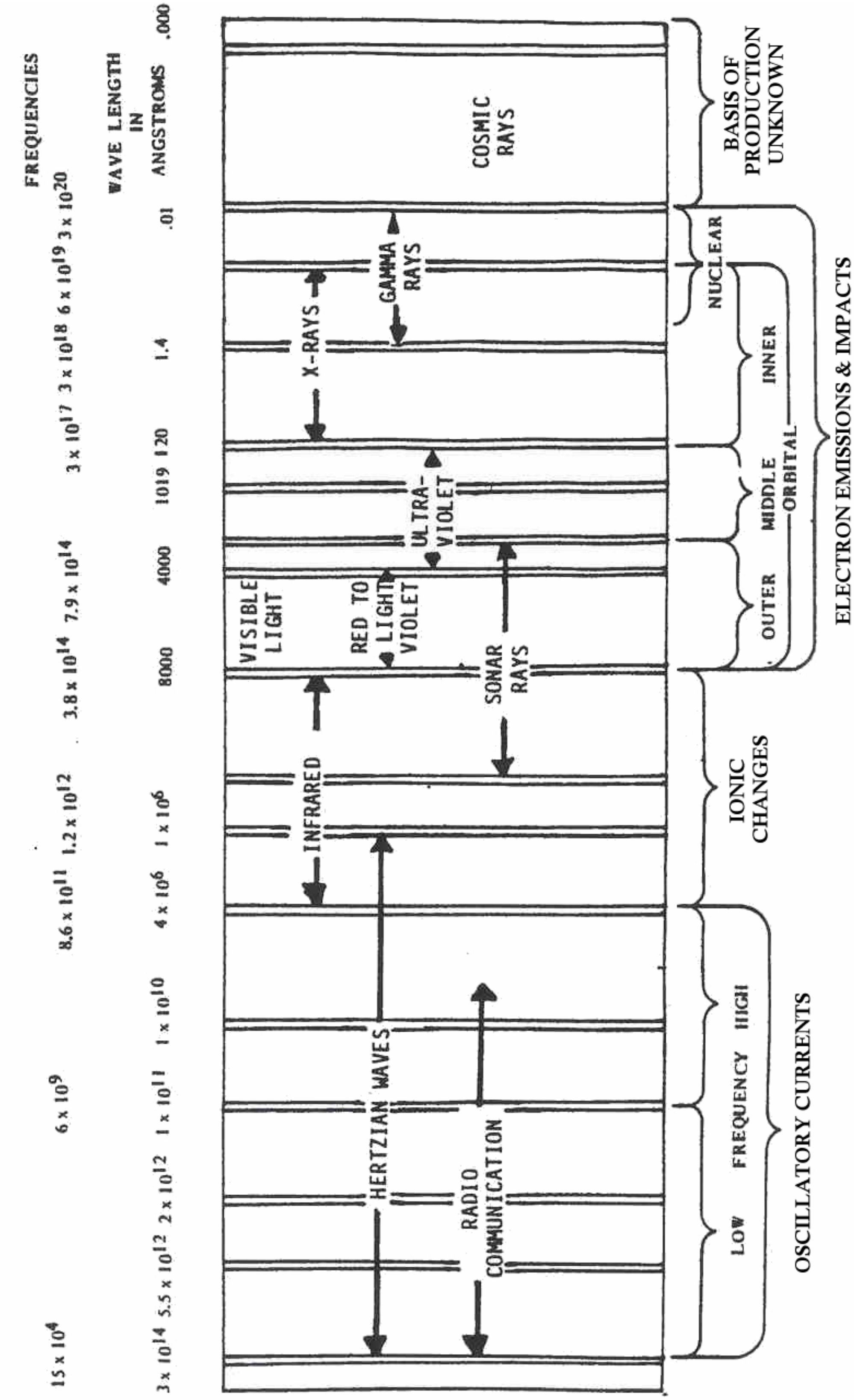


Figure 1-17. Electromagnetic spectrum.

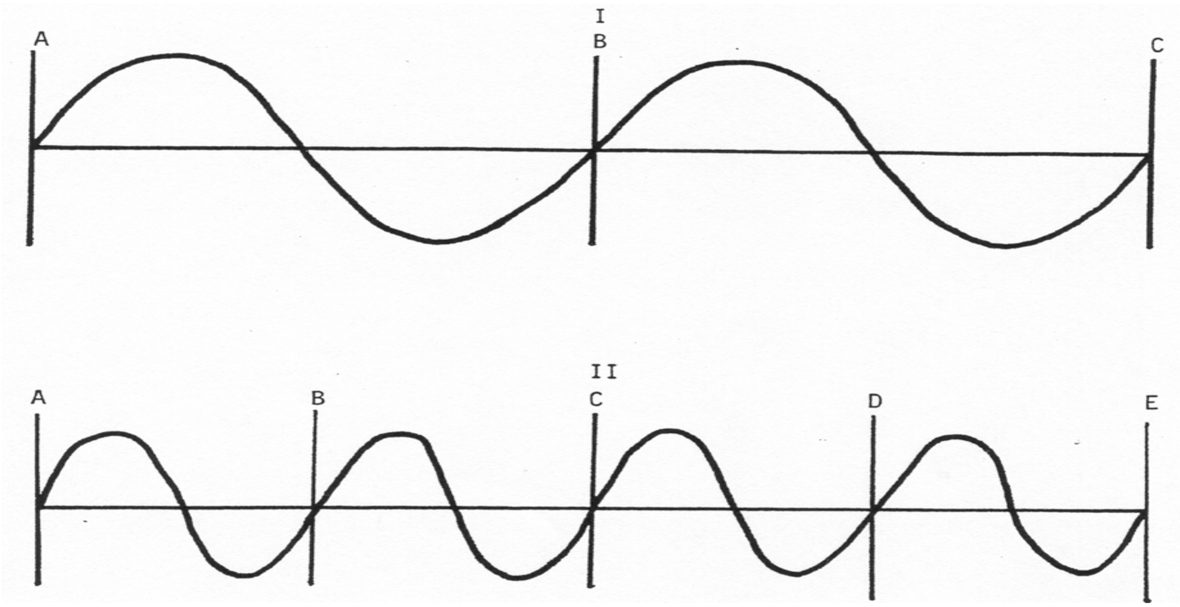


Figure 1-18. Two electromagnetic waves, differing in wave length and frequency. No. I has low frequency, low penetration and long wavelength. No. II has high frequency, high penetration and short wavelength.

Continue with Exercises

EXERCISES, LESSON 1

INSTRUCTIONS. The following exercises are to be answered by marking the lettered response that best answers the question, or by completing the incomplete statement, or by writing the answer in the space provided at the end of the question.

After you have completed all the exercises, turn to "Solutions to Exercises" at the end of the lesson and check your answers.

1. In the discovery of x-rays, what was the critical difference between Roentgen's observation and the observations of others who had previously produced x-rays unknowingly?

   a. Refracted rays unaffected by magnetic fields.

   b. Passage of the rays through black paper.

   c. Fluorescence of barium platinocyanide.

   d. Production of a photographic image.

2. That special branch of science having to do with radiant energy and radiant substances in both diagnosis and treatment is called:

   a. Roentgenism.

   b. Roentgenography.

   c. Radiography.

   d. Radiology.

3. Which of the following names best applies to the smallest particle of the element tungsten that has all of the properties of tungsten?

   a. Atom.

   b. Molecule.

   c. Compound.

   d. Nucleus.

4. The energy that a body has because of its motion is called:

   a. Kinetic.

   b. Potential.

   c. Mechanical.

   d. Atomic.

5. The function of the generator is to:

   a. Change AC voltage to DC voltage.

   b. Produce a strong magnetic field.

   c. Remove ions from electrons.

   d. Convert mechanical energy to electrical energy.

6. In physics, the tendency of a pencil resting on a desk to remain in that position and for a moving truck to continue moving is known as:

   a. Potential energy.

   b. Kinetic energy.

   c. Inertia.

   d. Force.

7. Work is expressed by which of the following equations?

   a. Work = inertia x resistance.

   b. Work = force x distance.

   c. Work = force x resistance.

   d. Work = resistance x distance.

8. Bohr's theory represents an atom as:

    a. Surrounded by waves of electrons.

    b. Surrounded by waves of protons

    c. A miniature solar system.

    d. A miniature planet.

9. Which of the following choices correctly lists the charged particles of an atom?

    a. Protons, neutrons, and electrons.

    b. Protons and electrons.

    c. Neutrons and electrons.

    d. Protons and neutrons.

10. The atomic nucleus contains positively charged particles called:

    a. Protons.

    b. Electrons.

    c. Photons.

    d. Neutrons.

11. Binding energy is stronger when electrons are:

    a. Farther from the nucleus.

    b. More in number.

    c. Larger.

    d. Closer to the nucleus.

12. The atom with higher potential energy is one which:

    a. Has a smaller nucleus.

    b. Has fewer neutrons.

    c. Has more electrons in its outer shells.

    d. Has fewer electrons in its outer shells.

13. Isotopes are atoms that:

    a. Have varying numbers of both neutrons and protons.

    b. Have the same number of protons, but varying numbers of neutrons.

    c. Have the same number of neutrons, but various numbers of protons

    d. Have the same number of both protons and neutrons.

14. Three kinds of bonds holding the atoms of molecules together are called ______________________________ bonds.

    a. Ionic, covalent, and hydrogen.

    b. Electron, ionic, and covalent.

    c. Ionic, covalent, and oxygen.

    d. Hydrogen, oxygen, and sodium.

15. An atom is said to be unstable when:

    a. Its inner shell is incomplete.

    b. Its inner shell is complete.

    c. Its nucleus is partly disintegrating.

    d. Its outer shell is complete.

16. X-rays, infrared rays, and gamma rays are classified as what kind of waves?

    a. Electromagnetic.

    b. Corpuscular.

    c. Sine.

    d. Cosmic.

17. Which of the following is a type of radiation that is identical to x-rays except for origin?

    a. Alpha.

    b. Beta.

    c. Gamma.

    d. Delta.

18. The length of time required for a particular radioactive substance to disintegrate so that its irradiation is cut in half is called its:

    a. Kinetic conversion rate.

    b. Dissipation rate.

    c. Half-life.

    d. FD.

19. Characteristic or line radiation is produced by:

    a. Photons being absorbed into tissue.

    b. Radium.

    c. Radioactive isotopes.

    d. Collision of electrons with matter.

20. In an x-ray tube, electrons strike a hard surface at high speed and produce:

    a. Dissipation.

    b. Photons.

    c. Binding energy.

    d. Atomic nuclei.

Check Your Answers on Next Page

SOLUTIONS TO EXERCISES, LESSON 1

1. b (para 1-3b)
2. d (para 1-4)
3. a (para 1-7b(1))
4. a (para 1-8b)
5. d (para 1-8e)
6. c (para 1-9)
7. b (para 1-9b)
8. c (para 1-11b)
9. b (para 1-11b)
10. a (para 1-11d(l))
11. d (para 1-11e(6); figure 1-4)
12. c (para 1-11e(7)(b))
13. b (para 1-12a)
14. a (para 1-14)
15. c (para 1-15)
16. a (paras 1-15c, 1-16c; figure 1-17)
17. c (para 1-15c(3))
18. c (para 1-15c(4))
19. d (para 1-16b)
20. b (para 1-16b(1))

End of Lesson 1

LESSON ASSIGNMENT

LESSON 2 Electricity, Magnets, and Circuits.

LESSON ASSIGNMENT Paragraphs 2-1 through 2-35.

LESSON OBJECTIVES After completing this lesson, you should be able to:

2-1. Explain the nature of static electricity.

2-2. Explain the production, measurement, functions and types of electrical current.

2-3. Explain conductors and nonconductors, Ohm's law.

2-4. Explain magnetism and its relationship to electricity, including the function of coils, choke-coils, electromagnets, and transformers.

SUGGESTION After studying the assignment, complete the exercises of this lesson. These exercises will help you to achieve the lesson objectives.

LESSON 2

ELECTRICITY, MAGNETS, AND CIRCUITS

Section I. INTRODUCTION

2-1. LAW OF ELECTROSTATICS

a. Like charges repel each other; unlike charges attract each other--this is the fundamental law of electricity. This attraction or repulsion is mutual and is easily demonstrated (figure 2-1). If two bodies are negatively (or positively) charged, they repel each other and remain separated. If one is negatively charged and the other is positively charged, they attract each other. The force of attraction (or repulsion) between two charged particles is directly proportional to the product of their charges and inversely proportional to the square of the distance between them.

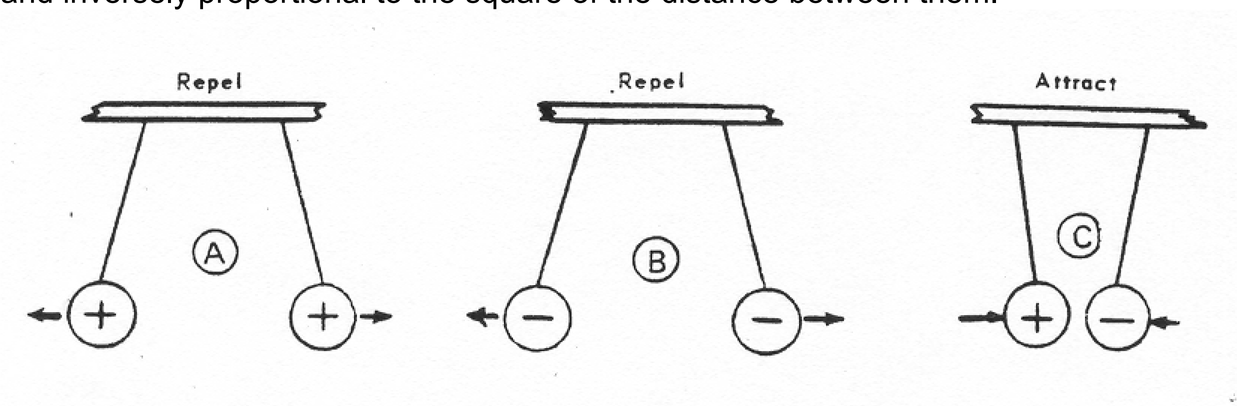


Figure 2-1. Like charges repel; unlike charges attract.

b. Since the positively charged ion is so much heavier and larger than the free electron, positive charges are less mobile than the lighter, negatively charged electrons. Usually only negative charges (electrons) move in a solid conductor; consequently, only negative charges move through wire. The electrons in the valence (outer) orbits, called "free" electrons, are not tightly bound to the atom; these are the ones that may move freely from atom to atom.

2-2. ELECTRIC CURRENT

a. Electric current indicates electric charges in motion. Dynamics deals with bodies in motion. The science of electricity in motion is known as electrodynamics.

b. In general, all materials may be divided into two major categories--conductors and nonconductors (insulators). A material's atomic structure determines its conductivity. Materials allowing electrons to flow with comparative freedom are conductors; those not allowing electrons to flow freely are nonconductors or insulators. Since materials have varying degrees of conductivity, there are no perfect conductors or perfect insulators.

c. In electricity, the word "ground" is used to refer to a connection made directly to the earth or to a conductor connected to the earth.

(1) Because of its atomic structure, the earth contains an almost limitless quantity of neutral atoms. This makes it possible for the earth to give up electrons without appreciably affecting the neutrality of the ground and, thus, to neutralize a large positive charge.

(2) Likewise, the earth can absorb excessive electrons to neutralize a large negative charge. If a body carrying a positive charge is connected to the ground, electrons flowing to it from the ground will neutralize it. If a negatively charged body is connected to the ground, electrons flowing from it into the ground will neutralize the body.

(3) Because of its ability to neutralize any possible charge the earth is considered to be at zero potential. Thus, <u>ground potential always equals zero potential</u>. This is an extremely important factor in the shock-proofing of x-ray machines and other electrical equipment.

Section II. ELECTRIC CURRENTS

2-3. NATURE Of AN ELECTRIC CURRENT

a. The term <u>electric current</u> refers to a flow of electrons through a conductor. An electric current, consisting of moving electrons, must have kinetic energy. The flow of electricity is based on the movement of electrons.

(1) To produce an electrical effect, some valence orbit electrons (called "free" electrons) must be removed from the atom and made to move from one atom to the next in a particular direction. In a material such as copper, there are many free electrons. This makes it an excellent conductor. The loosely bound valence orbit electrons of copper atoms can be put into motion and made to move progressively from one atom to the next atom through the wire. There is no continuous flow of electrons and a single electron will not go far--in effect, it may be considered as a series of jumps of an electron to the atom ahead.

(2) In order to have a flow of current, there must be a path, or conductor, in which electrons can move. This conductor must be in the form of a closed loop that provides a continuous path for the flow of current. This path, or closed loop, is a circuit. No significant electric current will flow in a nonconductor (such as glass, rubber, and mica) because the electrons in these substances are tightly bound to their respective atoms (there are few free electrons).

b. There are two general types of electric current--direct current (DC) and alternating current (AC).

(1) In DC, electrons flow in only one direction through a conductor. This current may be an even or uniform flow (continuous DC) or it may move in surges (pulsating DC).

(2) In AC, electrons surge first in one direction and then in the other through a conductor, causing a change in both amplitude (maximum level) and direction of the current.

2-4. SOURCES OF ELECTRIC CURRENT

Just as there must be pressure to cause a flow of water, there must be pressure to cause the flow of electrons. If we connect a wire between a point with an excessive number of electrons and another point with a deficiency of electrons, we will have a potential difference resulting in a flow of electrons. The greater the difference in the number of electrons, the greater the electrical pressure and the resulting electron flow. Therefore, if two bodies have unequal charges, a difference of potential exists between them. This difference of potential causes an electron current. The force needed to move the electrons is called <u>electromotive force</u> (EMF) or <u>voltage</u>. There are two commercially important sources of electrical pressure--chemical and mechanical.

a. **Chemical**. Chemical energy can be energy by a chemical reaction between two dissimilar substances. This principle is employed in batteries.

b. **Mechanical**. Dynamos and generators transform mechanical energy into electrical energy by electromagnetic induction. Generators are discussed in detail later in this lesson.

2-5. FUNDAMENTAL FACTORS PRESENT IN EVERY ELECTRIC CIRCUIT

In even the simplest direct current circuit, three fundamental factors are present--potential difference, current, and resistance.

a. **Potential Difference**. The terms potential difference, electromotive force (EMF), potential and voltage are used synonymously.

(1) Potential difference is the difference in electrical potential existing between two points in an electric circuit--one point has an excess of electrons (negative charge) and the other point has a deficiency of electrons (positive charge). Attraction between these two points supplies the force required for electrons to move between the two points.

(2) It is possible to pile up electrons at one point and remove them from the other point by means of a battery or generator. The greater the excess of electrons at one point and deficiency of electrons at another, the greater is the attraction or difference in potential between these points.

(3) The unit of measurement of this potential difference is the volt. A volt is the amount EMF needed to drive a current of one ampere through a resistance of one ohm.

b. **Current**.

(1) The intensity of electric current is determined by the number of electrons flowing past a point. in one second. The greater the number of electrons flowing per second, the greater the value of the current.

(2) The unit of measurement of current strength is the ampere, which is one coulomb of electricity flowing per second. The unit of quantity of electricity is a coulomb, which is 6.28×10^{18} electrons. The milliampere (mA) is 1/1000 as large as the ampere. Thus 6.28×10^{15} electrons (0.001 coulomb) flowing per second is equal to one mA.

NOTE: The mathematical shorthand used above is the explained as follows:

$10^1 = 10$	$10^5 = 100,000$
$10^2 = 100$	$10^6 = 1,000,000$
$10^3 = 1,000$	$10^{12} = 1,000,000,000,000$
$10^4 = 10,000$	$10^{15} = 1,000,000,000,000,000$

Thus, the power to which 10 is raised is equal to the number of zeroes in the fully written expression.

c. **Resistance**.

(1) In an electric circuit, resistance depends on the type and physical dimensions of the material making up the circuit. Every conductor resists the flow of electrons through it. Opposition or hindrance to the flow of electrons in an electric circuit is called resistance.

(2) The unit measure of resistance is the ohm; it is symbolized by the Greek letter omega (**Ω**)

(3) The ohmic resistance of a conductor depends upon four factors:

(a) Material. Most metals are conductors of electricity. Silver and copper have comparatively low resistance, allowing current to flow much more freely than do insulators or nonconductors such as rubber, glass, and plastics, which have high resistance. Copper is used almost exclusively in electric wiring as it offers less resistance to the flow of electric current than any other common material.

(b) Length. For a given material, the resistance of a conductor is directly proportional to its length. For example, 10 feet of wire has 10 times as much resistance as 1 foot of the same wire.

(c) Cross-section. The greater the cross-section of a conductor, the smaller will be its resistance per foot of length. For example, a wire 1 millimeter (mm) in diameter has four times as much resistance as a wire of the same length and material, but 2 mm in diameter, because the latter has four times as much cross-sectional area. The resistance of a conductor is inversely proportional to its cross-sectional area (or to the square of its radius).

(d) Temperature. For most conductors, the resistance increases with an increase in the conductor's temperature. The hotter the conductor becomes, the greater will be its resistance.

Section III. ELEMENTARY ELECTRIC CIRCUITS

2-6. INTRODUCTION

Every circuit has three essential requirements: (1) a source of potential difference (voltage), (2) a current-carrying wire (conductor), and (3) a resistive device to regulate the rate of current flow (resistance). Figure 2-2 shows some of the common diagrammatic symbols used in electrical drawings.

a. **Series**. A series circuit is one in which all the resistances are connected end to end so that the same current flows through each part of the circuit, using but one path. In the simple series circuit shown in figure 2-3, all of the current flowing from the battery must flow through the switch, the resistor, and the lamp, then back to the battery.

b. **Parallel**. Parallel circuits provide more than one path in which the current can flow. In figure 2-4, the current from the battery divides to follow two paths. Recombination of the current occurs when one portion of the current flows through the resistor and the other through the lamp. The amount of current flowing in each path (branch) depends on the resistance in that branch of the circuit.

c. **Closed**. A closed circuit results when a complete path is available through which the electrons can flow.

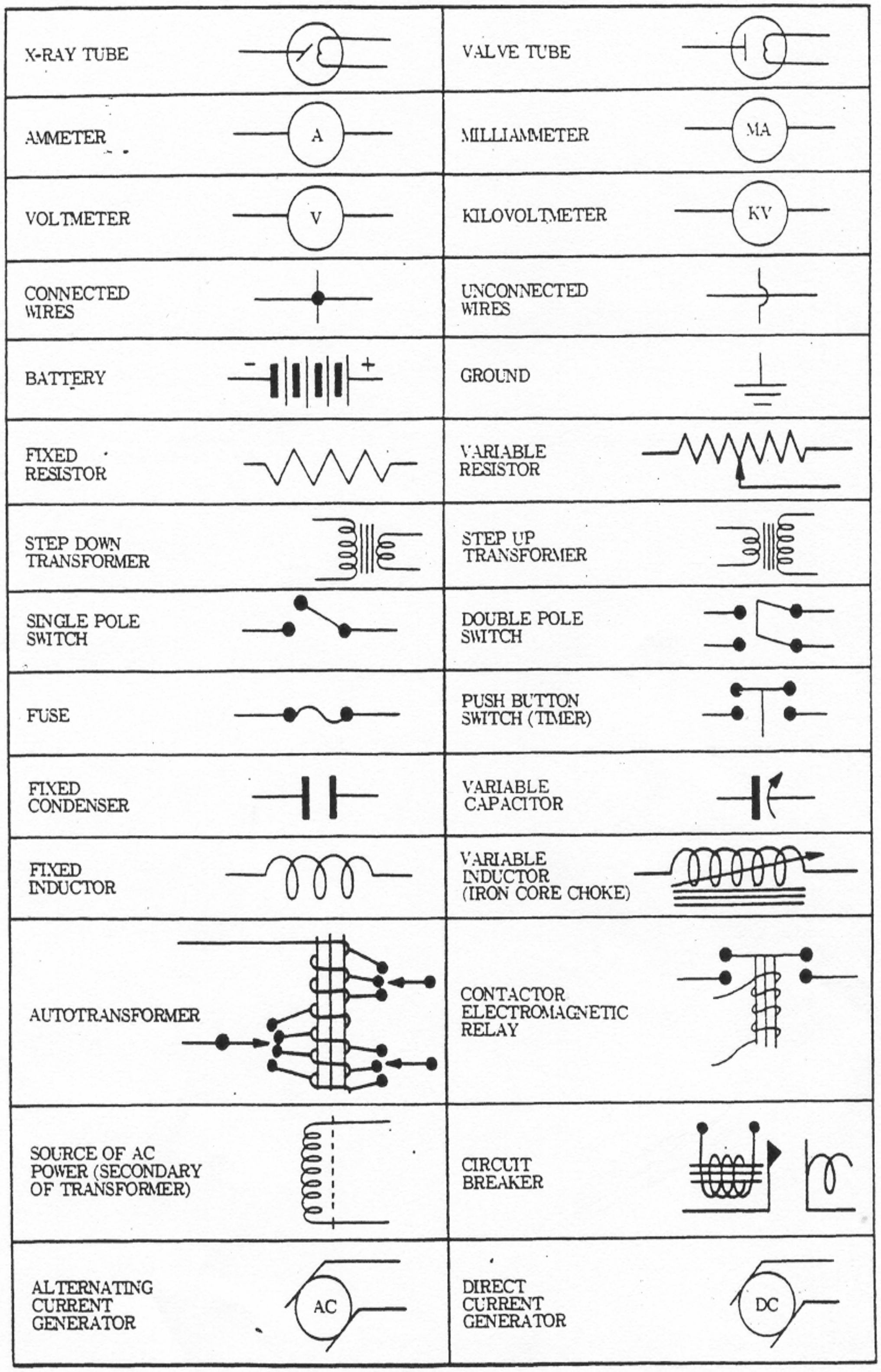


Figure 2-2. Common diagrammatic symbols used in electrical drawings.

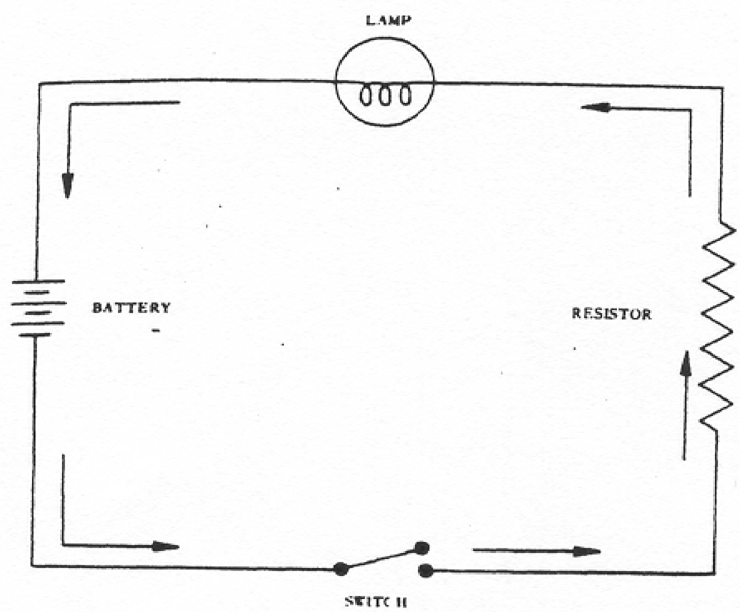


Figure 2-3. A simple series circuit.

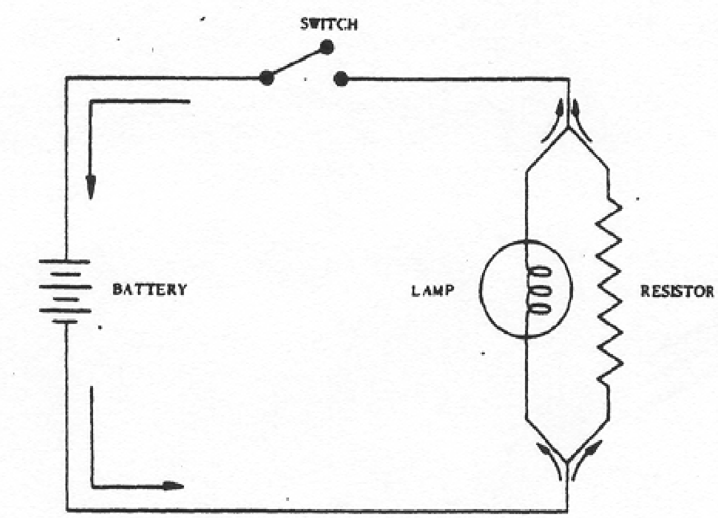


Figure 2-4. A simple parallel circuit.

2-7. OHM'S LAW

The basic principles of electricity are formulated in Ohm's law. The German physicist Ohm proved that when a direct current is flowing in an electric circuit, a definite relationship exists between the current (amperage), voltage and resistance.

a. Ohm's law states that the current flowing in a DC circuit is directly proportional to the EMF and inversely proportional to the resistance of the circuit. Ohm's law may be expressed by anyone of three equations. In common usage, I is current expressed in amperes, E is EMF expressed in volts, and R is resistance expressed in ohms.

$I = \frac{E}{R}$	$R = \frac{E}{I}$	$E = I \times R$

Thus, to find a resistance when E and I are known, use R = E/I (volts divided by amperes) to find the voltage. When I and R are known, use E = I X R. If any two of these values are known, it is possible to find the value of the unknown by using one of these formulas. A simple aid to memorizing Ohm's law formulas is to cover the unknown factor in the formula $\frac{E}{I \times R}$ and see what mathematical manipulations are required to find it. For example, if it is desired to find the resistance (R) when the applied voltage (E) is 12 volts and the current (I) is 3 amperes--cover R and note that E should be divided by I. Thus 12 volts ÷ 3 amperes = 4 ohms resistance.

2-8. WORK AND POWER IN AN ELECTRIC CIRCUIT

a. A given amount of electricity can do a definite amount of work. There is a simple relationship between the work produced and the voltage and amperage in a circuit.

(1) Power is the rate at which work is done per unit of time.

(2) The watt (W) is the unit of electrical power. It is equivalent to one ampere of current flowing at a pressure (EMF) of one volt.

(3) The power rule formula determines the power of continuous DC (the amount of work the current can do per second):

$P = I \times E$ power in watts = amperage times voltage

(4) The power of most electrical machinery is measured in terms of a unit called a horsepower: 746 watts are equal to one horsepower.

b. The most common loss of power in electrical work is due to the heat developed when current is flowing through a resistance. The greater the resistance of the circuit, the greater is the rate of heat production. A combination of the power formula and Ohm's law (E = I X R) gives the power loss due to heat production of a particular circuit. To find the power loss by this method, substitute the symbols I x R for the symbol E in the power formula. This combination gives the formula P = I x I x R. Thus, the power utilized in heat production is:

Power consumed = I^2R (in watts) (as heat)

where I is the current amperes and R is the resistance in ohms.

c. The portion of the circuit having the greatest resistance will produce the most heat, and the power loss is proportional to the square of the amperage. If the current is doubled, the power loss due to heat production is 2^2, or 4 times as great.

Section IV. MAGNETISM

2-9. CLASSIFICATION OF MAGNETS

A piece of metal that will attract bits of iron fillings is called a magnet. There are three classes of magnets.

a. **Natural Magnets**. The earth possesses a natural magnetic field. Magnetite, a natural magnet commonly referred to as lodestone, consists mainly of iron oxide and is assumed to have become magnetized because of lying in the earth's magnetic field. Natural magnets have very limited practical use because their magnetic force is very weak and irregular.

b. **Artificial Magnets**. Artificial magnets are man-made and are produced in a wide variety of shapes and sizes. They are constructed of hard steels or other special alloys that are artificially magnetized. Such magnets are used extensively in electrical equipment. They are classified as temporary or permanent. Their classification and strength are determined by the material from which they are manufactured.

c. **Electromagnets**. Electromagnets depend upon an electric current for their energy. They are usually temporary magnets that lose their magnetism when the electric current is turned off. One of their big advantages is the ability to control both the strength and duration of their magnetic force field.

2-10. PROPERTIES OF MAGNETS

a. **Poles of a Magnet**. Every magnet, regardless of shape, has two poles--the north-seeking pole and the south-seeking pole. If a freely suspended magnet is disturbed, it will return to north-south position and the north-seeking pole will always point north. This is the principle on which the compass works.

b. **Attraction and Repulsion of Magnetic Poles**. Like magnetic poles repel each other; unlike magnetic poles attract each other. When two magnets are brought close together so that the north pole of one magnet is directly opposite the north pole of the other magnet, a repelling force tends to keep the two magnets apart (figure 2-5A). If the magnets are positioned so that the north pole of one magnet faces the south pole of the other, a force of attraction pulls the two magnets together (figure 2-5B). The force (attraction or repulsion) between two magnetic poles is directly proportional to the product of the strength of the poles and inversely proportional to the square of the distance between them.

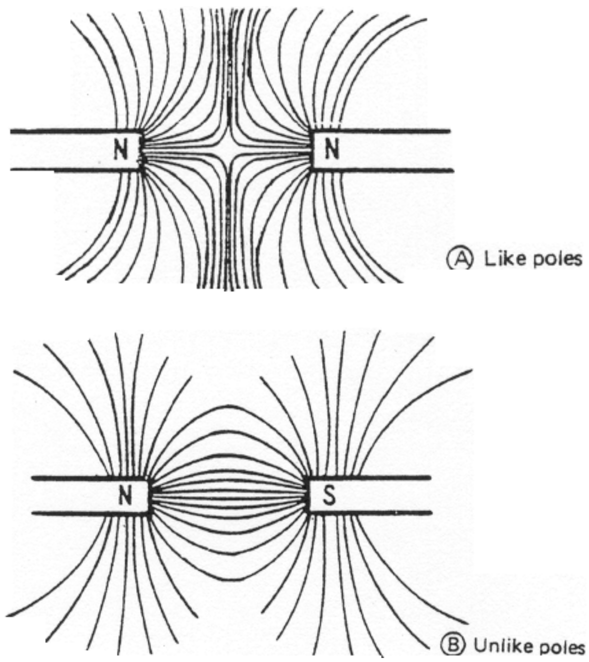


Figure 2-5. Attraction and repulsion of magnetic poles--
like poles repel; unlike poles attract.

2-11. MAGNETIC AND NONMAGNETIC SUBSTANCES

All matter is affected, to some extent, by a magnetic field. Substances that are strongly attracted by a magnet are called magnetic substances. Most materials, however, are not noticeably affected by magnets; they are classified as nonmagnetic materials.

a. **Magnetic Materials**. Iron and steel are strongly magnetic. Cobalt, nickel, and manganese are also magnetic, but to a lesser degree. These substances, or their alloys, are used to make permanent magnets.

b. **Nonmagnetic Materials**. Most common materials, such as wood, copper, glass, brass, lead, tin, silver, gold, rubber and plastics are nonmagnetic and, therefore, cannot be magnetized.

c. **Theory of Magnetism**. Magnetic materials consist of millions of tiny elementary magnets (magnetic dipoles) that are so small they cannot be seen by an optical microscope. They are probably molecular or atomic in size. The molecular magnets that make up a nonmagnetized bar of iron or steel are arranged at random; the magnetism of each molecule is neutralized by that of adjacent molecules and there is no external magnetic effect. When a magnetizing force is applied to this nonmagnetized iron bar, the molecules become aligned so that their north poles point in one direction and the south poles in the opposite direction (figure 2-6A). With the magnetic molecules aligned, their magnetic strengths combine and the bar is then said to be magnetized.

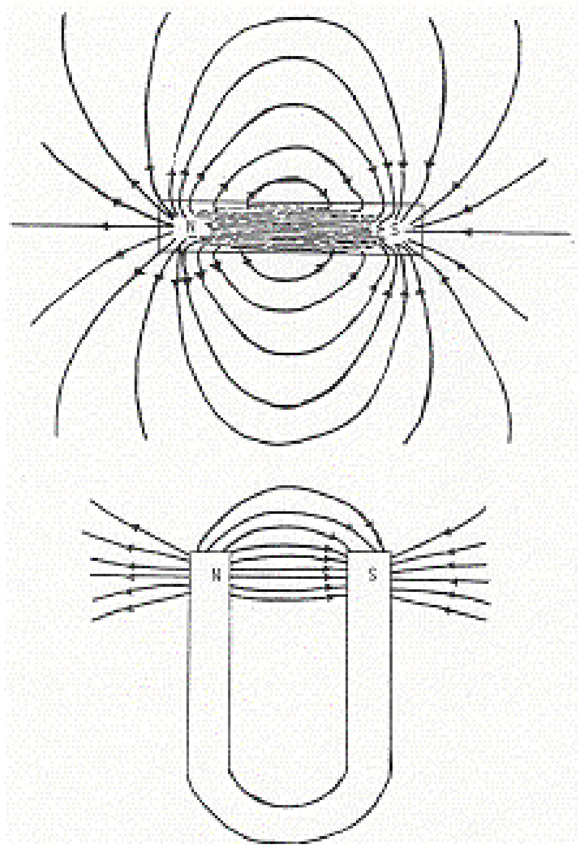


Figure 2-6. Magnetic fields -- bar magnet (top) and horseshoe magnet (bottom).

(The magnetic lines of force are represented by lines about the magnets. These lines of force are assumed to act from the north pole to the south pole of the magnet as indicated by the arrows.)

2-12. PROPERTIES OF MAGNETIC MATERIALS

The magnetic qualities of materials vary greatly. For instance, the magnetic molecules of some materials are more easily aligned under the influence of a magnetic field than the molecules of other materials. The ease with which a material can be magnetized is called its permeability. The ability of a material to retain its magnetism is called retentivity. Any metal that is easily magnetized loses its magnetism easily. Soft iron has high permeability but low retentivity; it is easily magnetized, but it loses magnetism easily. Hard steel has low permeability but high retentivity; it is more difficult to magnetize but retains magnetism for a long period.

2-13. MAGNETIC FIELDS

The region about a magnet in which its magnetic force is detectable is the magnetic field. A magnetic field can be demonstrated by putting a piece of paper over a bar magnet and sprinkling iron filings over the paper. If the paper is gently tapped, the filings arrange themselves in a pattern (figure 2-7) following the magnetic lines of force that make up the magnetic field. The concentration of lines of force determines the strength of the magnetic field at that point. The strength of a magnetic field is always greatest at the poles of the magnet.

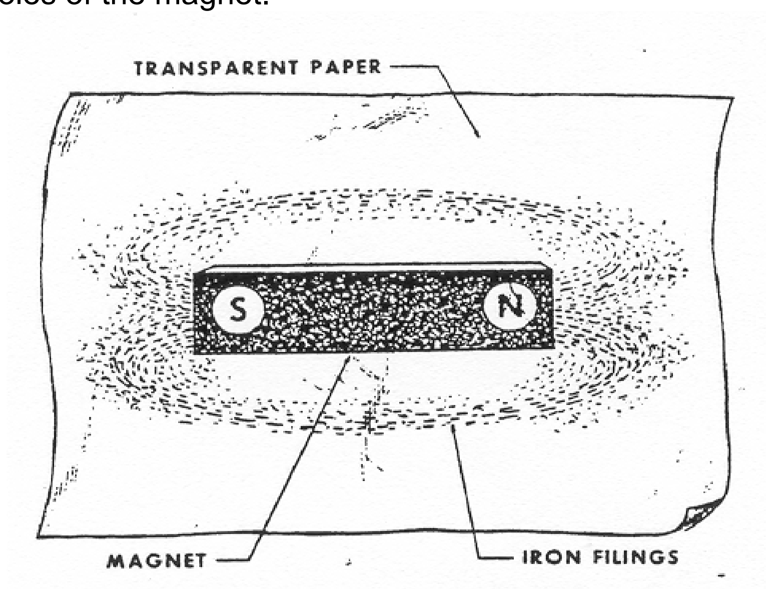


Figure 2-7. Iron filings on a transparent paper show the magnetic field around a magnet.

2-14. CHARACTERISTICS OF LINES OF FORCE

a. Lines of force are assumed to leave the north pole of a magnet and enter the south pole of a magnet (figure 2-6). Each line of force leaving the magnet at the North Pole returns to the magnet at the South Pole. Lines of force in a magnetic field repel each other; therefore, the lines tend to spread out and away from the surface of the magnet (figure 2-8A).

b. The tendency of magnetic materials to draw magnetic lines of force themselves explains magnetic permeability. The more permeable a substance, the more lines of force it will concentrate within itself (figure 2-8B) because it offers less resistance to magnetic lines of force than the surrounding air.

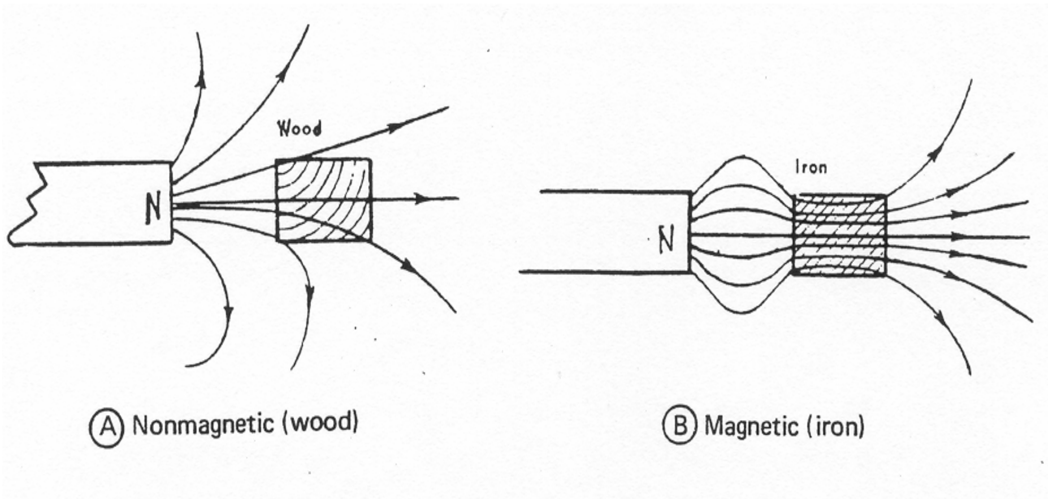


Figure 2-8. Magnetic permeability.

(Nonmagnetic materials have no effect on magnetic lines of force (A), but magnetic materials intensify the lines by drawing them from the air and concentrating them within themselves (B)).

2-15. ELECTROMAGNETISM

a. Magnetic and electrical phenomena are closely related--electricity always produces magnetism. Magnetism caused by an electric current flowing through a conductor is called electromagnetism. In 1820, the Danish scientist Oersted observed that a compass or suspended bar magnet was deflected when placed near a wire carrying an electric current and returned to its original position when the current ceased.

b. A wire carrying a current of electricity has around it a field of force that acts on iron filings placed on a cardboard in a manner similar to the field of force around a permanent magnet (figure 2-9).

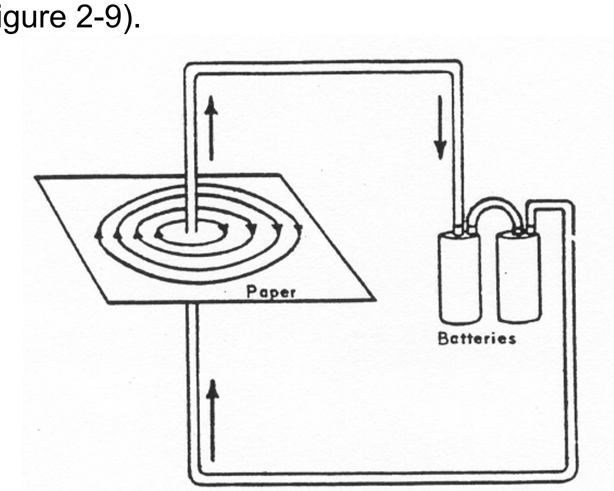


Figure 2-9. Electromagnetic lines of force around a current-carrying wire.

c. A magnetic field exists about a wire only during the time the current is flowing. When the current ceases to flow, the magnetic field around the wire collapses.

d. The strength or intensity of the magnetic field around a current-carrying conductor increases or decreases when the current increases or decreases. Reversing the direction of current in the conductor reverses the direction of the magnetic field.

2-16. PRODUCTION AND USE OF ELECTROMAGNETIC FORCE

a. If a conductor through which a current is flowing is bent in the form of a loop, the same circular lines of force (magnetic field) surrounds the conductor as when it is straight. Therefore, all the lines of force enter on one side (face) of the loop and leave on the other side, resulting in a north pole on one face and a south pole on the other. If several loops or turns of wire are so wound as to form a coil, it is called a helix or a solenoid (figure 2-10A). During current flow, the intensity of the magnetic lines of force around such a coil of wire are proportionately greater than those around a single loop of wire.

b. If a piece of magnetic material--usually soft iron--is placed within a solenoid through which current is flowing, the magnetic properties of the solenoid are tremendously increased. The inside of any coil is termed the core and, if the coil is wound on a core of magnetic material, it acts as an electromagnet (figure 2-10B).

c. Electromagnets are widely used in electrical equipment, for example, the electric bell, the telephone receiver, the motor, the generator, the transformer, the radio, and electrical measuring instruments. The principle of the electromagnet is utilized in many of the devices in an x-ray circuit such as relays, remote control switches, and circuit breakers.

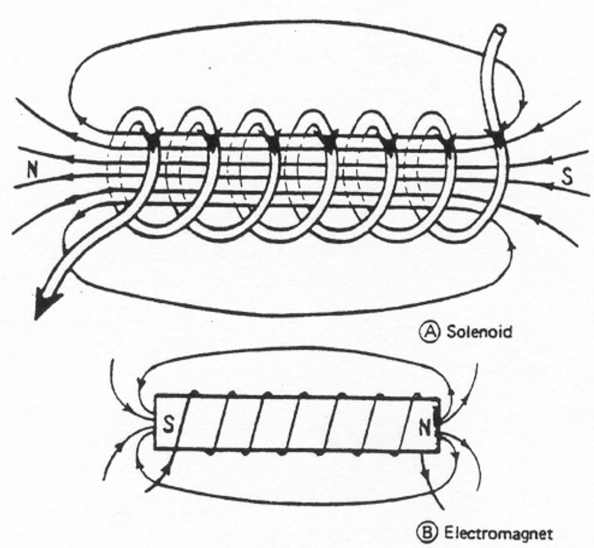


Figure 2-10. Relationship between solenoid and electromagnet (description in text).

2-17. ELECTROMAGNETIC INDUCTION

a. Current flowing through a conductor always produces a magnetic field around that conductor. Under certain conditions, a magnetic field can also produce current flow in a conductor. Technically, however, it is more acceptable to say that a magnetic field can produce an EMF and that this EMF (voltage) can cause current flow when there is a complete circuit. Whenever a conductor forming part of a closed circuit cuts across magnetic lines of force, an electric current is induced in the conductor. In 1831, Faraday demonstrated this principle by rapidly moving a wire through a magnetic field, causing an electric current to flow in the wire.

b. The magnitude of the induced voltage is dependent upon four factors:

(1) The speed or rate at which the wire moves. The more quickly the wire moves, the more lines of force it will cut.

(2) The strength of the magnetic field. When the lines of force are closely concentrated, the conductor cuts more lines per second.

(3) The angle between the motion of the conductor and the direction of the magnetic lines of force. As the angle approaches 90°, the voltage increases in magnitude because more lines of force are being cut per second (figure 2-11).

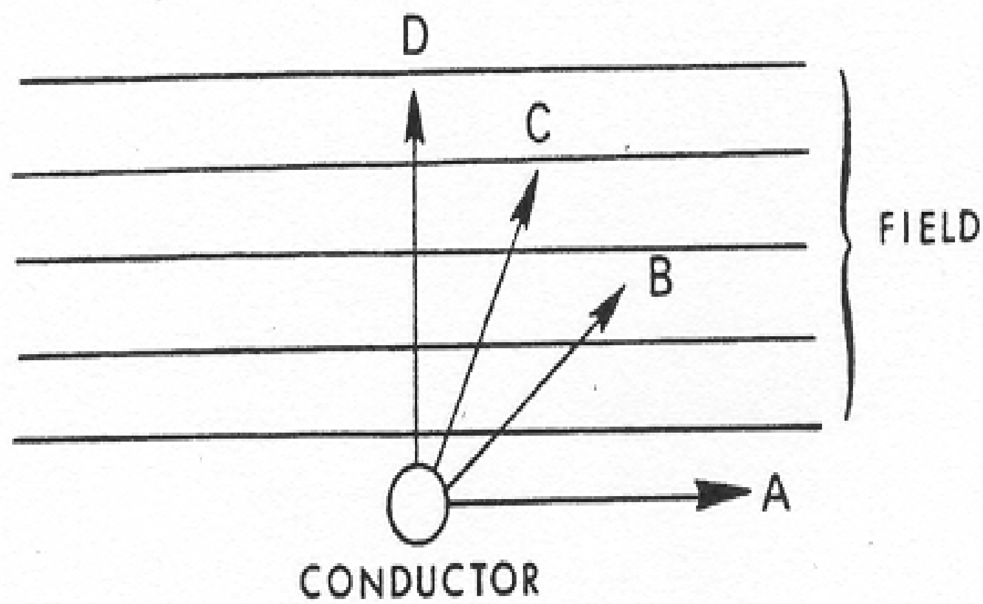


Figure 2-11. Various angles between the moving conductor and the lines of magnetic force.

(4) The number of turns in the conductor. Each turn of the wire cuts the lines of force; a 100-turn coil cuts the lines of force 100 times as often as a single wire moving at the same speed in the same magnetic field.

c. There are three ways in which an electric current can be induced in a conductor by electromagnetic induction:

(1) If a wire is moved across a stationary magnetic field.

(2) If a magnetic field moves across a stationary wire.

(3) If the magnetic field varies in strength or direction while a stationary conductor lies in it.

2-18. SELF-INDUCTION

a. Self-induction is defined as the process by which the magnetic field of a coil induces a counter EMF in the coil itself. This self-induced voltage will oppose the applied current.

(1) Consider a circuit consisting of a coil of wire in which uniform DC flows. The instant the switch is closed, a magnetic field builds up. This cuts across the coil, producing a voltage (counter EMF) which will always be opposite in polarity to the voltage causing the original current to flow. The field surrounds the conductor in concentric circles, increasing in intensity to a maximum, where it remains as long as current flows.

(2) The moment the switch is opened, the current stops, the field collapses, and the lines of force move across the coil in the opposite direction. This causes a short-lived induced voltage that tends to keep the current flowing in its original direction. When the switch is closed, a short-lived voltage tends to oppose the flow of current. When the switch is opened, the self-induced voltage reverses and tends to keep the current flowing in its original direction for a short time. In uniform DC, the self-induced voltage is present only when current flow is started or stopped; but with AC, this process goes on all the time because of the constantly reversing current.

b. The addition of a soft iron core inside a coil concentrates the magnetic field, thereby increasing the magnitude of the self-induced voltage (counter EMF) that opposes the original current. The magnitude of the induced voltage also depends on how far the iron core is pushed into the coil. The choke coil is designed on this principle. Changing the placement of the iron core may vary the current delivered through a choke coil.

2-19. MUTUAL INDUCTION

When the current flowing through a conductor is not uniform, there will be corresponding changes in the magnetic field. If a second (secondary) coil which is part of a closed circuit is placed near the first (primary) coil with its changing magnetic field, an alternating EMF will be induced in the second coil, producing alternating current in the second circuit. For mutual induction (inductance between two coils acting together) to occur, the magnetic field must change in strength or direction, such as with AC.

Section V. ELECTRIC GENERATORS AND MOTORS

2-20. INTRODUCTION

An electric generator or dynamo is a device that changes mechanical energy into electrical energy. Electric generators are based upon the principle that a voltage and current are induced in a coil when it cuts magnetic lines of force. A generator has a strong magnet to supply the necessary magnetic field and an armature, consisting of a coil of insulated wire wound around an iron core that is mounted so that it can rotate between the poles of the magnet. The mechanical energy required to rotate the armature may be obtained by such means as waterpower, steam, or gasoline engines. As the armature rotates, its coil cuts the magnetic lines of force and induces an EMF.

2-21. THE SIMPLE ALTERNATING CURRENT GENERATOR

a. The simplest form of an AC generator may be made by rotating a single loop of wire placed between the north and south poles of a magnet. It is possible to analyze what the characteristics of the induced current will be by studying the relation of the loop of wire in the rotating armature to the magnetic field. In figure 2-12, the two ends of the loop of wire (A and B) in the armature are separately connected to two metallic rings (slip rings X and Y), which are insulated from each other and mounted on the same shaft as the loop so that they rotate as the armature revolves on its axis. Two stationary metal or carbon strips, called brushes, rest lightly on the slip rings as they revolve with the loop. The ends of the wires of the external circuit (in this case, the meter) are connected to the brushes. As the brushes rub against the rotating slip rings, they take current from the armature and transmit it to the external circuit. The magnetic field passes from the North (N) Pole to the South (S) Pole. As wires A and B pass from left to right and right to left, respectively, through the magnetic field, currents induced flow in the direction shown by arrows (II, figure 2-12); current leaves wire A through slip ring Y, passes through the meter in the external circuit, and enters slip ring X, completing the circuit. As the armature rotates, A and B each move to the other's original position (III, figure 2-12); current leaves wire B through slip ring X, passes through the meter, and enters slip ring Y (IV, figure 2-12). The current reverses direction with every half-turn of the armature.

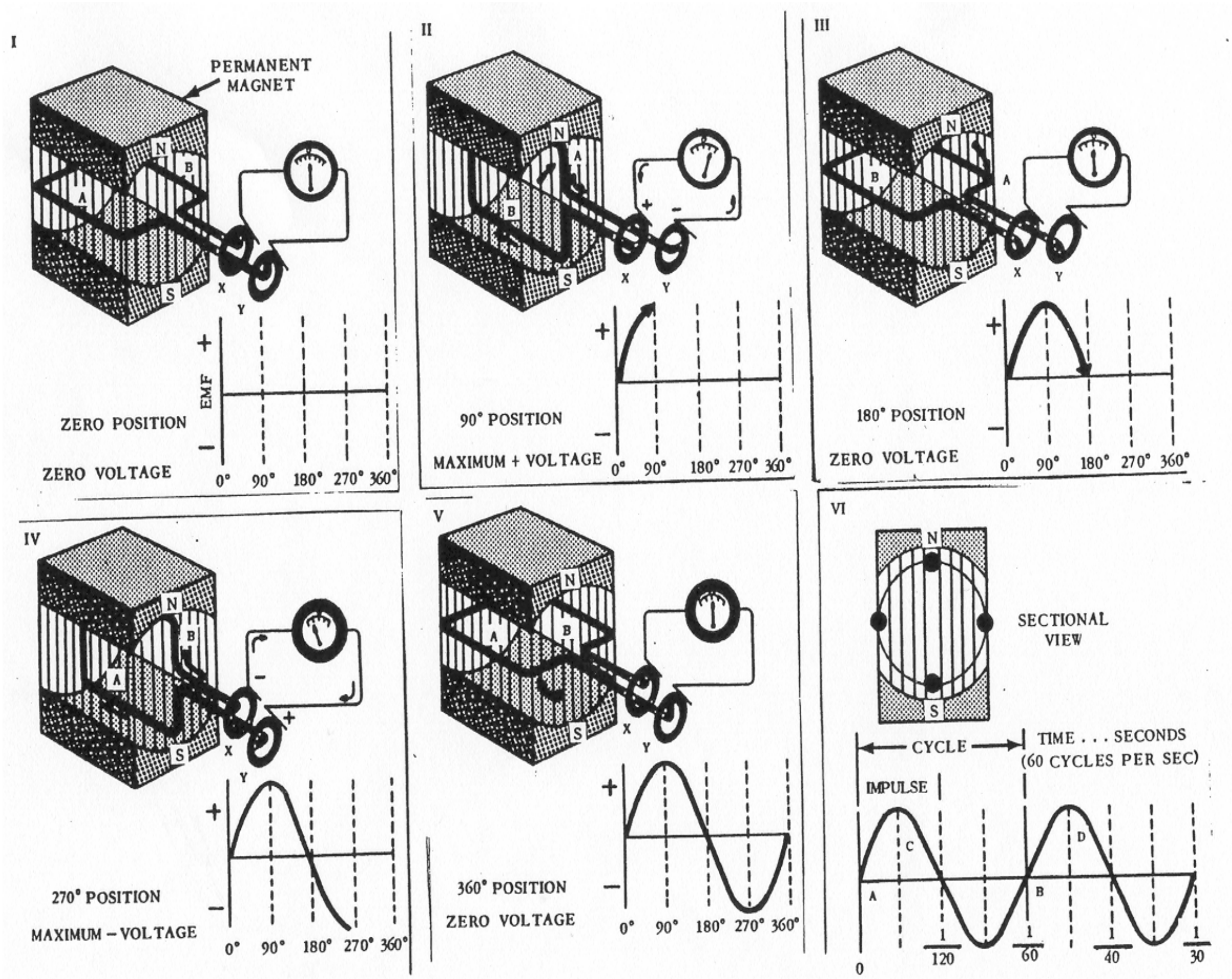


Figure 2-12. A simple alternating current generator.

b. The magnitude of the induced voltage as the coil rotates in the magnetic field may be plotted as a curve. As the armature moves parallel to the magnetic field, no lines of force are being cut and no EMF is being induced (I, figure 2-12). As the armature advances toward the 90º position (II, figure 2-12), it cuts more and more lines of force. When the conductor has moved through a 90º angle, the armature moves perpendicular to the magnetic lines of force and cuts the maximum number. At this point, a maximum voltage is induced in the positive direction. At the 180º position (III, figure 2-12), the armature has made one-half revolution; since it is again moving parallel to the magnetic field, there is no induced voltage. The armature again cuts the field at right angles (IV, figure 2-12); however, the lines of force being cut are in the opposite direction as before, reversing the induced voltage and giving a maximum negative voltage. The armature completes the cycle (V, figure 2-12), returns to its original zero position, and starts again the same series of changes.

c. The rotating coil or armature is represented in cross-section in VI, figure 2-12. The curve shown with the sectional view is a graphic representation of the AC produced. One complete revolution of the coil produces one cycle AC, mathematically termed a sine curve or sine wave. This curve demonstrates the instantaneous values of voltage or current as they vary with time, and is the normal waveform for AC. The curve between two successive corresponding points on the wave (A to B or C to D, VI, figure 2-12) represents one cycle of AC.

d. The AC most commonly used in the United States is 60-cycle (60 complete cycles occur per second). The number of cycles an AC completes per second is called its frequency. Each cycle consists of two impulses (alternations or pulsations) or changes in current direction; in 60-cycle AC, there are 120 impulses per second.

e. Since the current and voltage change from zero to maximum in each alternation, the measurements of an AC are not the same as those of a DC. However, AC is as effective in producing heat as a proportionately large DC. Thus, a simple relationship can be used to relate their effectiveness, providing a useful means of converting one value to the other. The values of AC are assumed to be effective values, unless otherwise specified. With pure sine wave AC, relationships between maximum and effective values of the current and maximum and effective voltage are:

maximum current = 1.414 x effective current
(maximum voltage) (effective voltage)

or

effective current = 0.707 x maximum current
(effective voltage) (maximum voltage)

2-22. DIRECT CURRENT GENERATOR

The fundamental difference between an AC and a DC generator is the method in which the current is collected. The distinguishing structural characteristic of the DC generator is the commutator. The terminals of the armature are not connected to slip rings, but to the segments of a commutator. The commutator changes alternating current into pulsating direct current before the current enters the external circuit. Although the voltage and current are at zero value once during each pulsation, the current flow is still only in one direction. The type of current produced by a simple DC generator has a waveform similar to that shown in figure 2-13A. Even the most complicated DC generator does not produce a truly uniform direct current (figure 2-13B).

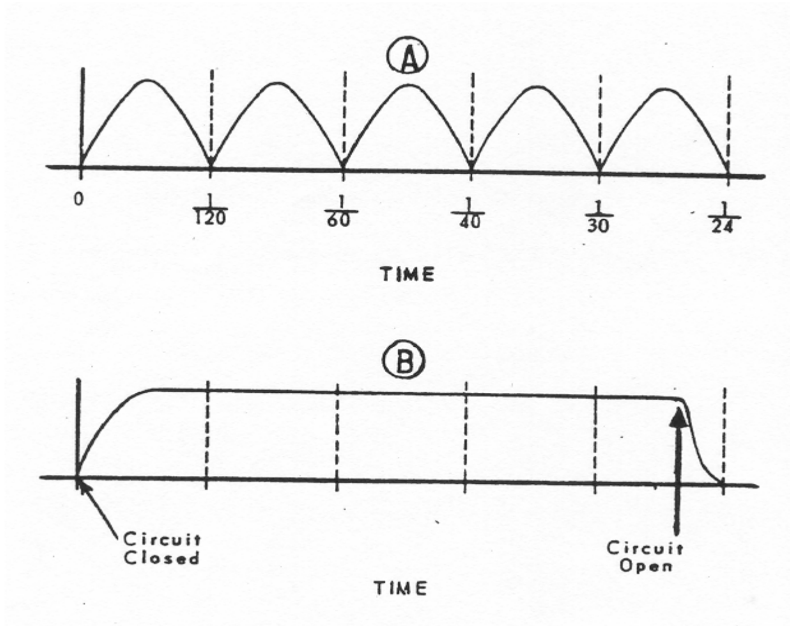


Figure 2-13. Direct current—(**A**) pulsating DC (full-wave); (**B**) uniform DC.

2-23. ADVANTAGES OF ALTERNATING CURRENT

a. Alternating current is a much more suitable and versatile source of power than direct current, which is limited in number and kind of applications to power machinery and electronic circuits

b. AC is required for the operation of high-voltage transformers used in industry, as well as in the production of x-rays. An AC voltage may be readily changed by transformers with little loss of energy.

c. Power generated at a power plant may be sent across great distances with relatively small loss if the current is kept low. When it reaches its destination, the high voltage (high-tension) AC is reduced in value, ordinarily to 110 or 220 volts. This reduction is accomplished by means of a transformer. A transformer cannot be used with DC, which is one of the chief reasons why AC is more widely used.

2-24. THE ELECTRIC MOTOR

a. Motors, like generators, are a means of transforming energy or power. The <u>electric motor</u> is a device that converts electrical energy into mechanical work. The simple electric motor does not differ essentially in construction from the generator or dynamo, but it operates exactly the reverse of an electric generator.

b. When an electric current flows through the armature of an electric motor, it sets up a magnetic field that is opposed by the field about the permanent magnet of the motor. The current is supplied to the armature in such a manner that when the rotating armature achieves a position (a half- turn) in which the magnetic fields are no longer opposed, the current is reversed in direction. The repulsion again exists between the two magnetic fields, causing the rotating armature to make another half-turn. In order to keep the armature turning steadily, this keeps occurring.

Section VI. ELECTRICAL DEVICES

2-25. CURRENT-MEASURING DEVICES

A magnetic field set up by current flowing in a conductor reacts against an external field. This is the basic principle utilized in the construction of current-measuring devices.

a. The d'Arsonval galvanometer (figure 2-14), the basic current- measuring device, consists of a pivoted coil of fine wire suspended between the poles of a permanent horseshoe magnet. Attached springs keep the coil in a zero or neutral position when no current flows.

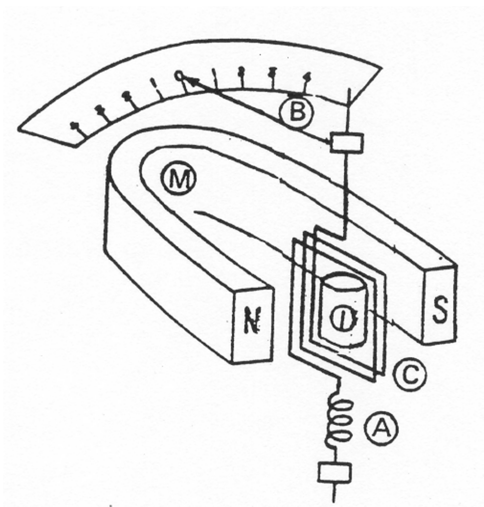


Figure 2-14. Galvanometer. A coil of wire *(C)* is suspended between the north and south poles of a magnet (M); the coil is attached to springs (A); a needle (B) indicates the magnitude of the current on a scale. An iron core (I) makes the magnetic field more uniform.

(1) When direct current passes through the coil, it becomes an electromagnet; its poles are repelled by the like poles of the permanent magnet, causing a twisting effect to be exerted on the coil against the resisting force of the supporting springs. When the circuit is opened, the coil returns to its original or zero position. The angle through which the coil turns is proportional to the strength of the current. Whenever the coil moves on its axis, a small pointer moves across a calibrated scale, indicating the current strength.

(2) The d'Arsonval galvanometer can be modified to measure either amperage or voltage in a circuit. When a low-resistance wire (a shunt) is connected in parallel with a galvanometer that has an appropriately calibrated scale, it serves as an ammeter; when a high-resistance wire is connected in series with the galvanometer, it serves as a voltmeter. To measure the voltage and current of AC, additional modifications are required, but the same principle is used in AC meters.

b. The voltmeter is a high-resistance galvanometer used to measure voltage. It measures the potential difference across any two points in an electric circuit and must always be connected in parallel (V, figure 2-15); that is, connected by means of a wire to either side of the device across which the voltage drop is to be measured.

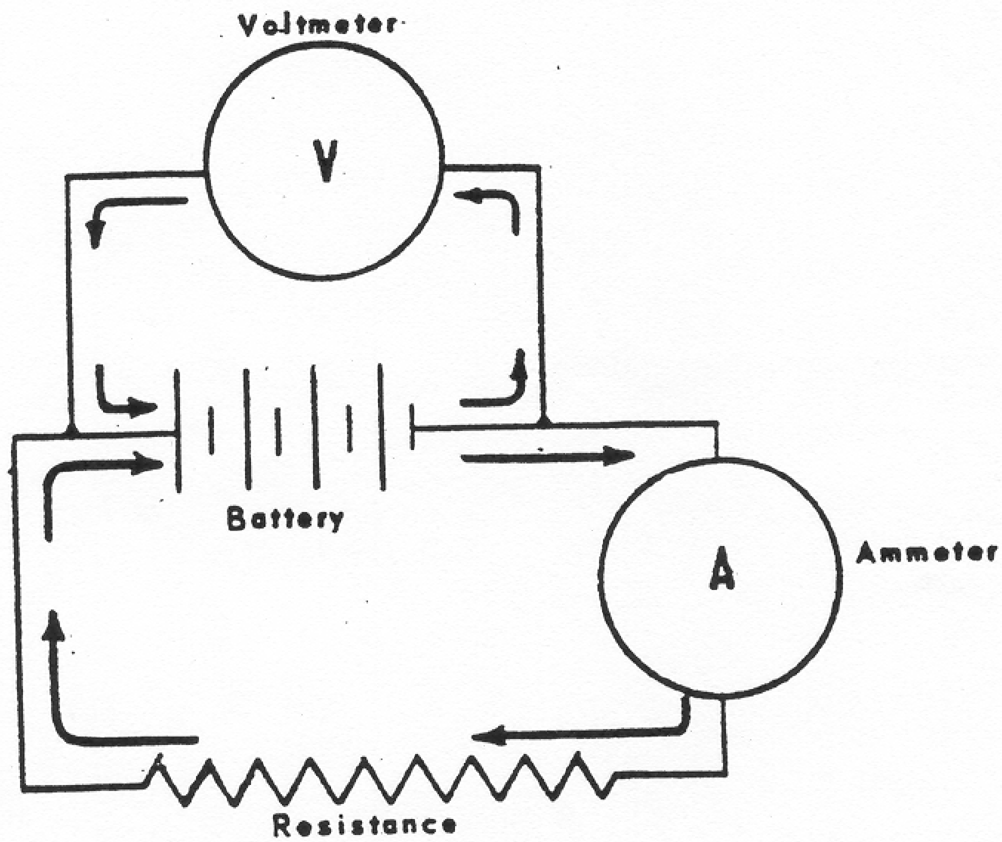


Figure 2-15. Placement of voltmeter and ammeter in circuit. The voltmeter (**V**) is connected in parallel with the device across which the voltage is to be measured (in this case the battery). The ammeter (**A**) is connected in series in the circuit so that all current passing through the circuit must pass through and be measured by the ammeter.

c. An ammeter measures in amperes the quantity of electricity (electrons) flowing per second in a circuit. In a simple series circuit, the current flowing through all points in the circuit is the same. Since the ammeter is used to measure all the current flowing in a circuit, it must be connected in series in that circuit--that is, directly into the circuit

d. In most equipment, the milliamperage meter can be converted to a ballistic or milliampere-second (mAs) meter. The conversion is accomplished by eddy current damping of the moving coil. By setting up eddy currents (counter EMF) in the moving coil, we can cause it to assume a high degree of inertia which causes the pointer or indicating needle to deflect slowly so that it registers a value equivalent to the milliampere-seconds (mAs). The ordinary moving-coil milliammeter does not have sufficient time to register the true mA at 1/2-second or less intervals. For very rapid exposures where high milliamperage is being used, the mAs meter gives a far more accurate reading than the milliammeter. At exposure times of greater than 1 second, the ordinary milliammeter will give an accurate reading.

2-26. TRANSFORMERS

a. For the production *of* x-rays, extremely high voltage is required. A transformer can be used to increase or decrease voltage with little loss *of* energy. Using the principle *of* mutual induction, the transformer transfers electrical energy from one circuit to another via an electromagnetic field.

b. In its simplest form, the transformer consists of a primary coil placed close to a secondary coil. The two coils are completely insulated from, and they lie parallel to, each other. This type of transformer is an air core transformer (figure 2-16). The primary coil (input side) is the one into which AC is introduced; the secondary coil (output side) is the one in which AC is developed by mutual induction. When AC flows in the primary winding (coil), it sets up an alternating magnetic field that expands about the coil and collapses each time the current changes direction. An alternating expanding and contracting magnetic field sweeps back and forth through the secondary winding inducing an EMF in the secondary coil.

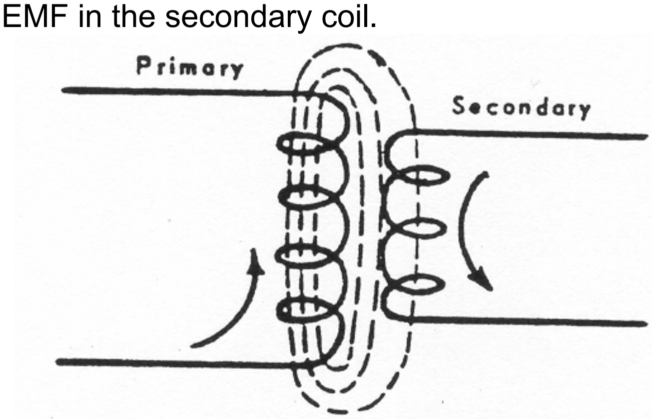


Figure 2-16. A simple air core transformer.

c. A step-up transformer has a greater number of turns in the secondary winding and increases the voltage, but decreases the current availability; a step-down transformer has more turns in the primary winding and decreases the voltage, but increases the current capability. In other words, the voltage in the primary winding is to the induced voltage in the secondary winding as the number of turns in the primary winding is to the number of turns in the secondary winding. The formula to express the relationship between the number of turns in the windings and the voltages is:

$$\frac{E_p}{E_p} = \frac{T_p}{T_s}$$

where E_P is the primary voltage, E_S is the secondary voltage, T_P is the number of turns in the primary coil, and T_s is the number of turns in the secondary coil.

(1) A transformer does not generate power; it transfers power from one circuit to another. The power output can be no greater than the power input, and the power input to the primary side (P_p) of the transformer must equal the power output of the secondary side (P_S), (The assumption that the transformer is 100 percent efficient simplifies the mathematics--actual1y, P_s is slightly less than P_p). In as much as the power in an electrical circuit equals voltage multiplied by amperage, $\beta = E_p$ x I_P and $P_s = E_S$ x I_S . Since $P_p = P_S$, E_P x $I_P = E_S$ x I_s where I_S is current in amperes in the secondary coil, I_P is current in the primary coil, E_S voltage in the secondary coil, and E_P is voltage in the primary coil. This relationship can be arranged to express the following equation:

$$\frac{E_p}{E_S} = \frac{I_S}{I_p}$$

(2) Step-up transformers are employed to obtain the high voltages needed in diagnostic x-ray equipment. A step-up transformer can take a low voltage source (50 to 220 volts) and increase this voltage to a value of 30,000 to 150,000 volts (30 to 150 kilovolts) or more, which supplies the high voltage required to force electrons across an x-ray tube at the high rate of speed (energy) that will produce x-radiation.

2-27. TRANSFORMER CORE TYPES

a. **Closed-Core**. The close-core transformer has heavily insulated coils wound around a square metal "doughnut" (figure 2-17A). The magnetic field is provided with a continuous path so that a relatively small amount of magnetic energy is lost. The transformer core is laminated (made up of thin strips of steel pressed together). Each strip or layer is insulated by paint or enamel. A laminated core offers a much higher resistance to the flow of eddy currents than a core of solid construction. The doughnut type of closed-core transformer is efficient and is commonly utilized in x-ray generating equipment. Usually, the high voltage transformer is submerged in a special type of oil to ensure maximum insulation and cooling.

b. **Shell-Type**. The shell-type transformer (figure 2-17B) is considered the most efficient. Such transformers are used in transmitting commercial power. The core of the shell-type transformer is made of laminated silicon steel sheets placed on top of one another. The coils are wound around the central section of the core. Since the primary and secondary coils are wound close together around the core, the windings must be highly insulated. A special insulating material is coated on the wires of both coils. For the high voltage used in x-ray, the entire transformer is immersed in a container filled with a special insulating oil or gas. The insulating oil also helps to cool the transformer during operation.

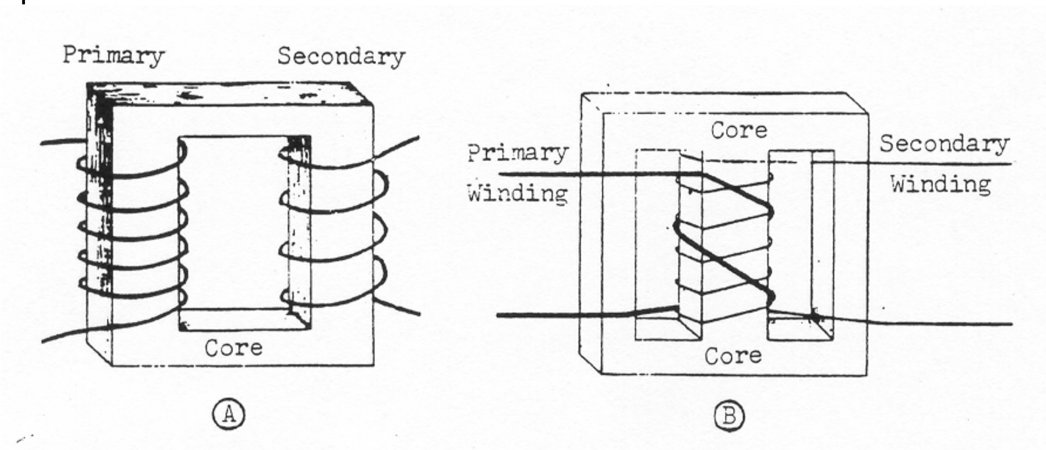


Figure 2-17. Transformers. (**A**) closed-core type. (**B**) shell-type.

2-28. TRANSFORMER LOSSES

a. **Resistance Losses**. These losses are due to the normal resistance of the wires that make up the primary and secondary windings of the transformer. This type of power loss can be cut down by using copper wire of sufficiently large cross-sectional area to reduce the resistance.

b. **Eddy Currents**. Eddy currents induced in the core cause the core to heat, resulting in power loss in the transformer. To reduce eddy currents to a minimum, the material making up the transformer core is laminated and each strip is sprayed with an insulating coating.

c. **Hysteresis**. Since the use of AC causes a rapidly changing magnetic field, there is a continuous reversal of the magnetic polarity in the core of the transformer. The tiny magnetic particles in the core are constantly shifted around, arranging themselves first in one direction and then in another, resulting in the development of friction between the molecules, which produces heat in the core. Since the electrical energy required to shift the molecules around must come from the primary current, some electrical energy is wasted. This loss, <u>hysteresis</u>, can be lessened by using a core material of high permeability.

2-29. VOLTAGE REGULATORS

a. By far, the most commonly used and most efficient method of varying the kilovoltage output of the high-tension transformer is the autotransformer control. If a transformer is made consisting of one continuous winding on a long laminated iron core and then voltage is applied across only one section of it, voltage will be induced in the turns that are not connected directly to the line in the same way as voltage is induced in the secondary of a conventional transformer. In fact, the section across which the line voltage is applied is called the primary, and the balance of the winding is called the secondary.

b. If the voltage is measured across various sections of a typical autotransformer, a situation like figure 2-18 might be present. By providing the autotransformer with a series of taps or connections to the different turns, there would be a convenient method present for getting a wide variety of voltages to apply to the primary of the high-tension transformer. In the circuit shown in figure 2-18, the following voltages could be obtained by setting the selector switch on the various taps: (This circuit has a constant number of volts per turn).

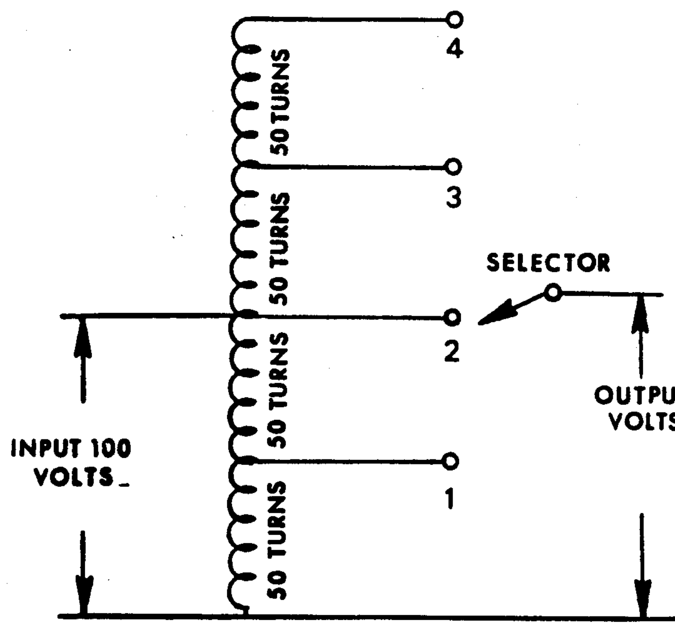


Figure 2-18. Autotransformer with output selector.

(1) Tap number 1--50 volts.

(2) Tap number 2--100 volts

(3) Tap number 3--150 volts

(4) Tap number 4--200 volts

c. The same results can be obtained by connecting the line to a number of selected taps and leaving the output connected to a given pair of taps, as in figure 2-19. In actual practice, autotransformers are usually provided with many taps in the primary as well as the secondary with the result that you have almost unlimited choice of voltage outputs. The autotransformer becomes, in this way, the basic source of all the supply voltages needed for operating the many components of a complete x-ray generator.

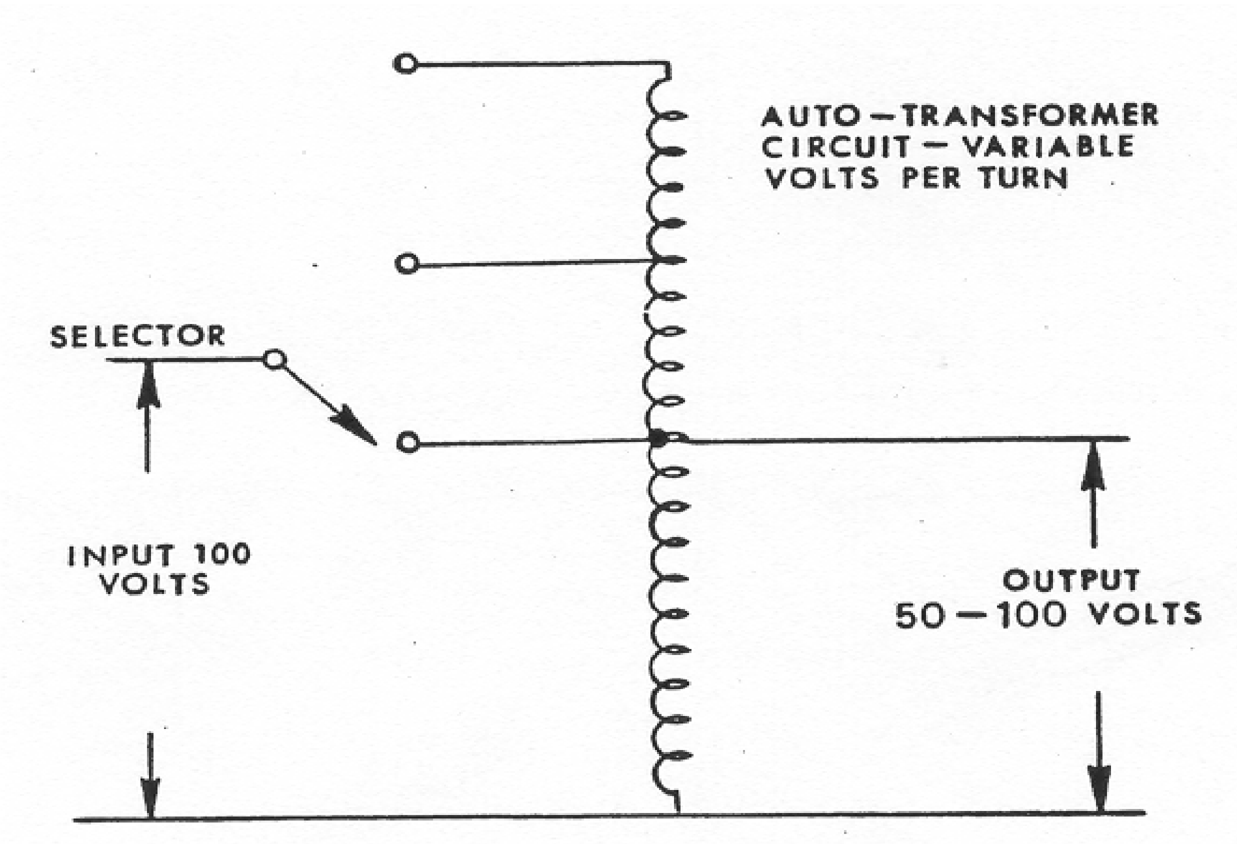


Figure 2-19. Autotransformer with input selector.

d. A common method of using the autotransformer to supply any of a wide selection of voltages to the primary of the high-tension transformer, and thus to vary the kilovoltage applied to the x-ray tube, is to use dual selectors in a circuit like the one shown in figure 2-20. In the figure, voltage is applied to fixed taps on the primary and "pick-off" voltages by adjustment of the selector switches that make connection with two sets of taps. The selector marked "Major" is connected to a series of taps between which there are relatively large differences in voltage. The selector marked "Minor" gives you small voltage changes. Usually, there are ten steps on the Minor selector that give you the same change in voltage as going from one step to the next on the Major selector. With a combination of 10 Minor and 10 Major steps, 100 different output voltages are available.

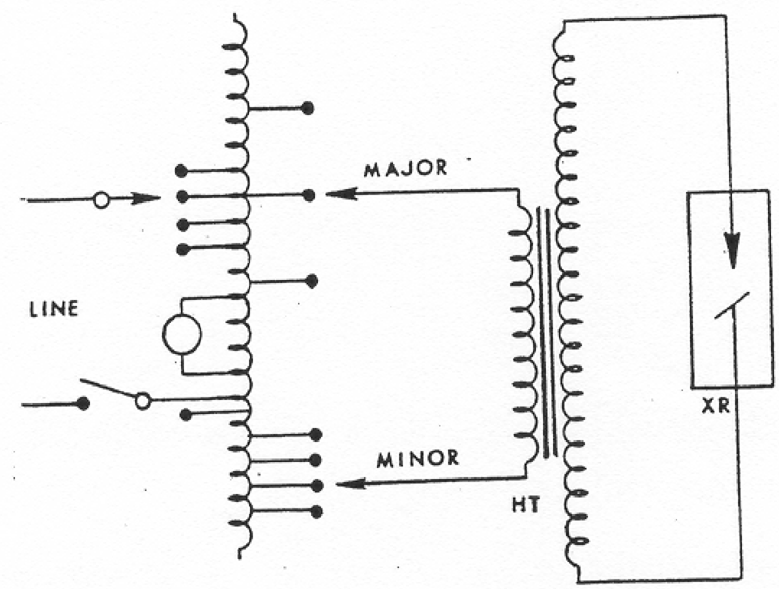


Figure 2-20. Autotransformer with dual selectors.

e. In systems like this, the voltage output across any given pair of taps will depend on the voltage of the supply line; the higher the input voltage, the higher the output. If the supply line voltage varies (as it often does), the same voltage will not always result from a given pair of output taps. This, however, is not too serious since a voltmeter can be placed across the selectors and the autotransformer can then simply be set on whatever combination of taps gives the desired voltage.

2-30. RECTIFICATION

For efficient operation, the x-ray tube should be supplied with DC. Commercial power sources supply AC, which is necessary for operation of the transformers of the x-ray machine. Because of the configuration and principles of operation of the x-ray tube, current can move in only one direction through it. Therefore, the alternating current must be changed to a form of direct current (rectification).

a. A simple way of changing AC to DC in the x-ray machine is to allow the x-ray tube to do the rectifying (self-rectification). Since the x-ray tube allows current to flow only from the filament of the cathode to the anode, any current attempting to flow in the opposite direction is blocked at the tube. This suppresses the current moving in the opposite direction during that half cycle and no current flows (half-wave rectification).

b. Self-rectification is detrimental to an x-ray tube because the tube must oppose the reverse flow of electrons 60 times during each second of operation. Moreover, if the anode becomes hot enough, it will liberate electrons by the process of thermionic emission and current will flow in the opposite direction, resulting in damage to the tube. Self-rectification is used only in small, portable x--ray machines and is the least efficient form of rectification.

2-31. VALVE TUBE RECTIFICATION

The type of rectifying device most commonly used in the past was the valve tube (figure 2-21). This vacuum tube works on the same general principles as x-ray tubes, but differs in certain details of construction.

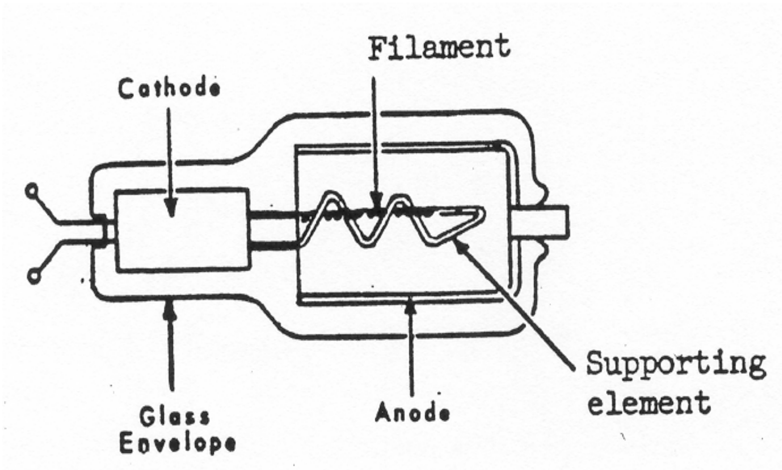


Figure 2-21. The valve tube.

a. **Cathode**. In a valve tube, the filament is a coil of tungsten wire that is both longer and larger in diameter than the filament of an x-ray tube. The filament is specially treated with thorium, making it possible for a greater number of electrons to be liberated with a lower voltage filament current. The filament is supported by a spiral-supporting element running into a hollow anode (figure 2-21). This arrangement makes use of the full 360^o of thermionic emission of electrons.

b. **Anode**. The anode has a large surface area and may be in the form of a cylinder surrounding the filament. In operation, the electrons emitted from the hot filament are attracted in all directions toward the entire surface of the anode.

c. **Principles of Operation**. The large thoriated filament, when heated to a high temperature by the filament current, liberates a large number of electrons, many more than are required to maintain current flow through the x-ray tube. Because of this excess of electrons, the voltage drop across a valve tube is very small. With this small voltage drop, the electrons cannot gain great speed and, therefore, do not have sufficient energy to produce x-rays in the valve tube. However, if, for some reason such as reduced electron emission from the filament, the forward resistance of the valve tube increases to the point where this voltage drop becomes 12 kV or higher, the electrons would be accelerated through the valve tube at a speed that would produce x-radiation when they strike the anode. Valve tubes can be used to produce either half-wave or full-wave rectification.

2-32. HALF-WAVE RECTIFICATION

In producing half-wave rectified current, two valve tubes may be used. If two valve tubes are used, (figure 2-22C), one is placed on the anode side of the x-ray tube and the other on the cathode side. The opposing voltage then is divided across the two valve tubes and the x-ray tube, thereby further increasing the capacity of the x-ray tube. Hence, the use of two valve tubes increases the efficiency of the rectification system over that of a self- rectified system. It should be noted that two-valve-tube rectifiers are not used for full-wave rectification in radiographic equipment.

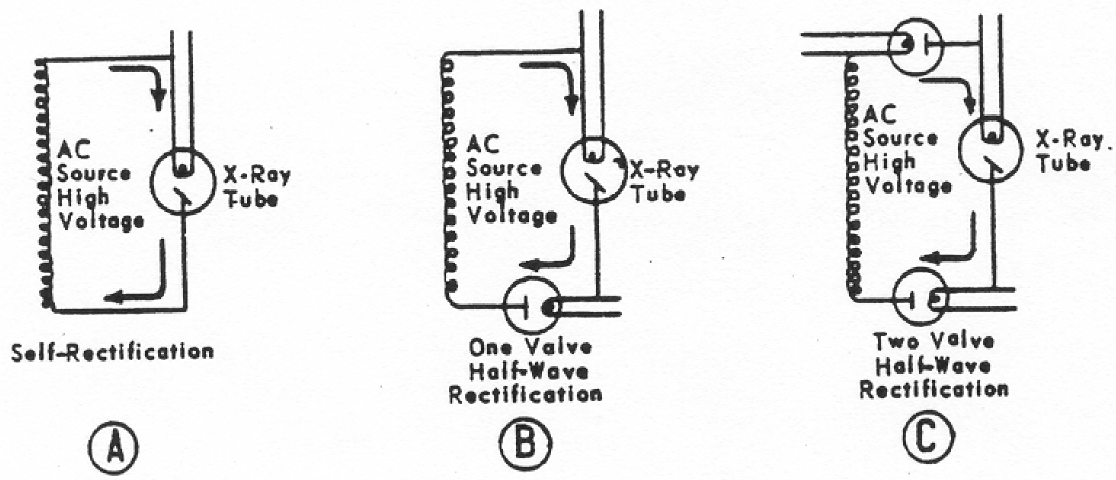


Figure 2-22. Systems of half-wave rectification.

2-33. FULL-WAVE RECTIFICATION

Full-wave rectification can be obtained by the use of a four-valve-tube rectifier system. The valve tubes are usually placed within the transformer tank or housing and are insulated by the oil contained in the latter. This arrangement affords protection from x-radiation in case of faulty tube operation, and provides protection against sparkover at the terminals of the valve tubes. The four valve tubes are connected so that the negative half of the alternating current cycle is redirected. The rectifying action of the four valve tubes considerably increases the capacity of an x-ray tube.

a. Figure 2-23 shows the arrangement of a four-valve-tube rectifying system called a bridge rectifier. For one given impulse, the current (indicated by the solid arrows) passes from the lower end of the secondary winding (negative polarity) of the transformer, through valve tube number one, through the x-ray tube, and finally through valve tube No.4 to the other end (positive polarity) of the transformer. When the transformer current is reversed during the next half-cycle, the current (indicated by broken arrows) passes from the upper end of the transformer, through valve tube number two, to the x-ray tube, and finally through valve tube number three to reach the opposite end of the transformer. In this way, both halves of each cycle of AC are applied to the x-ray tube for the production of x-rays.

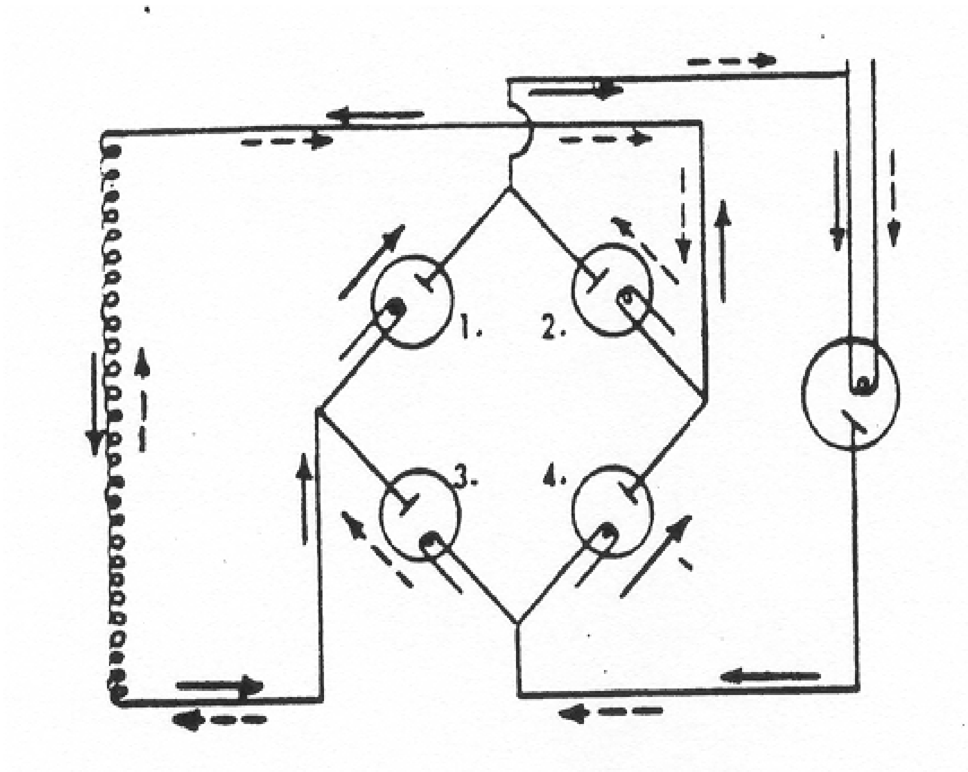


Figure 2-23. Full-wave rectification. Alternating current (solid and broken arrows pointing in opposite directions). Full-wave pulsating direct current (solid and broken arrows pointing in the same direction).

b. In essence, a full-wave rectification circuit is nothing more than a switching network that always keeps the cathode of the x-ray tube connected to the negative side of the transformer and the anode connected to the positive side.

(1) In recent years, valve tubes have been replaced by solid state and contact rectifiers in most of the new equipment. Silicon and other semiconductor materials, as well as stacked selenium rectifiers, are now available that will withstand the high voltages used in producing x-radiation. These devices have some distinct advantages over valve tubes.

(2) For example, they do not require filament supply transformers and operate much cooler without a heated filament. In addition, they have a lower forward resistance which results in a lower voltage drop across the rectifier. This means less power loss in the high voltage circuit. These rectifiers can be used to replace the valve tubes in older equipment; however, the high voltage circuit would have to be completely recalibrated.

2-34. METHOD OF TESTING RECTIFIERS AND TIMERS

If one of the rectifiers in a full-wave bridge rectifier circuit is not working, the mA will be below normal. The <u>spinning-top</u> test (figure 2-24) may be used to establish the operation of the rectifiers.

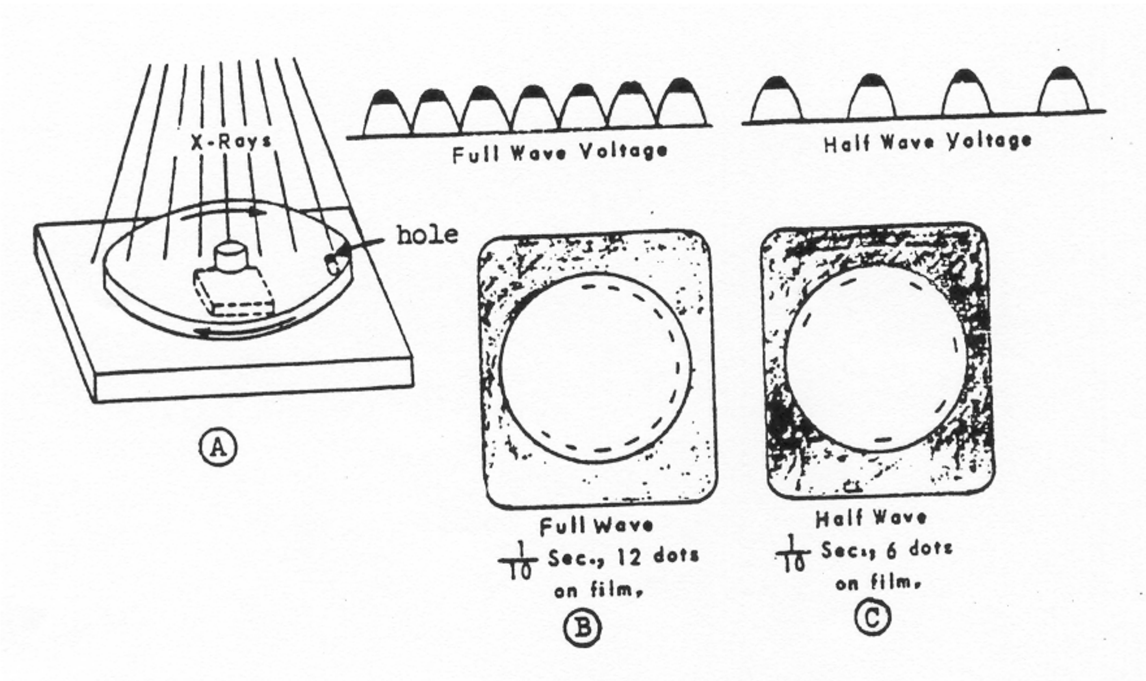


Figure 2-24. Spinning-top test.

a. The "top" is a flat metal disk with a small hole drilled near one edge (figure 2-24A); it is placed above an x-ray film or cassette and made to spin while a short exposure is made. In fully rectified current of 60 cycles, there are 120 pulsations a second (with a half-wave rectifier there are 60): x-rays are produced by each of these pulsations. The developed film will show a dot for each pulsation occurring during the given exposure time. If all four rectifiers are operating properly, there will be one dot for each 1/120 second of exposure used (60-cycle AC).

b. For example, for an exposure obtained in 1/10 second, 12 dark dots should show on the film (figure 2-24B); if only 6 dots show (figure 2-24C) there were only 6 pulsations in 1/10 second, indicating that only half of the transformer output is reaching the x-ray tube because one or more of the rectifiers requires replacement. The spinning-top method may also be used to establish the accuracy of the timer.

2-35. THREE-PHASE

One and two-pulse voltage patterns are produced by x-ray generators designed to operate on single-phase AC. Generators that operate on three- phase AC produce 6-pulse and 12-pulse tube voltage patterns. Figure 2-25 shows some characteristics of the four patterns as well as the alternating current form. Also shown is the voltage ripple, which is the difference between the peak and minimum voltage. Two-pulse tube voltage, for example, drops to zero value after each peak. Consequently, two-pulse ripple is 100 percent. On the other hand, 6-pulse and 12-pulse voltages do not drop to zero value. In 6-pulse systems, the voltage only drops a small amount before the next pulse has reached the same amplitude, so 6-pulse ripple is 13.5 percent. For 12-pulse, the voltage ripple is a mere 3.4 percent.

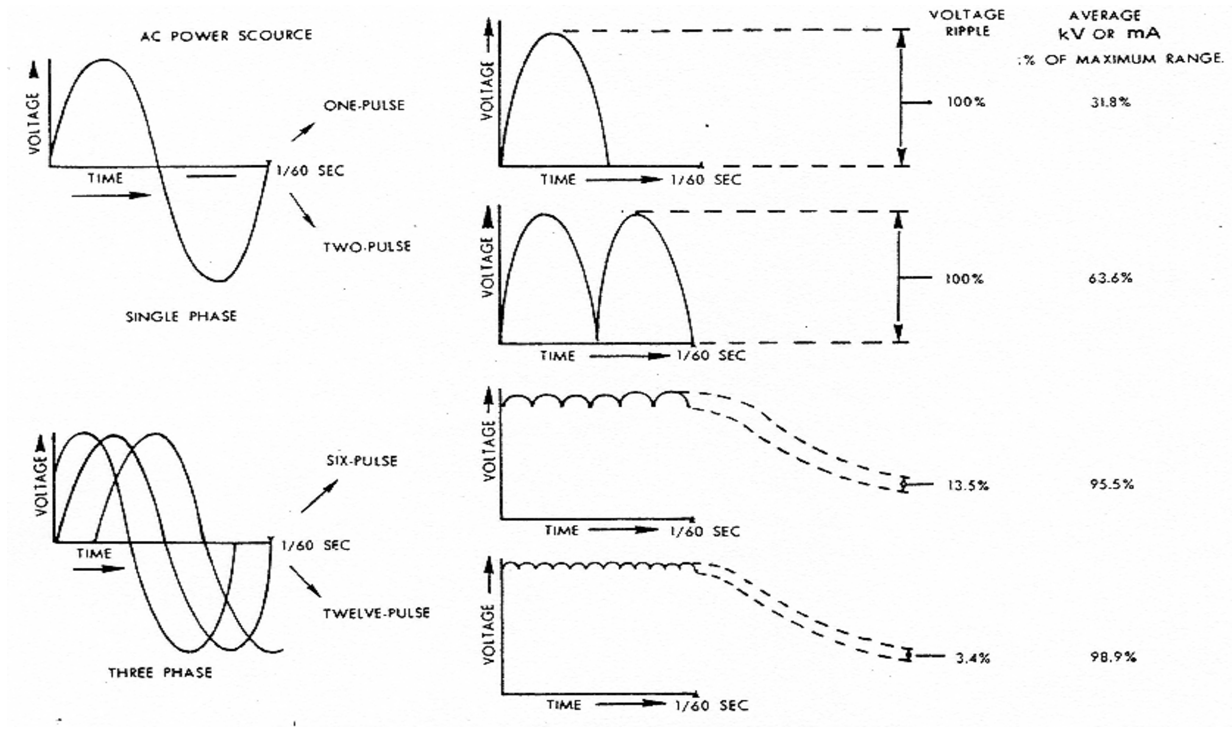


Figure 2-25. Patterns of voltage ripple.

a. Voltage ripple affects certain aspects of tube operation. One factor that it influences is the speed of the electrons across the x-ray tube.

(1) Consider figure 2-26, which shows a wave pattern produced in a single-phase generator and another produced in a three-phase, 12-pulse generator. With the 2-pulse wave, the voltage value rises to a peak and then falls to zero (100 percent ripple). This rise and fall of the voltage causes the kinetic energy of the electrons across the tube to vary accordingly. Consequently, if 100 kVp were applied to the x-ray tube, the kinetic energy of the electrons would theoretically range from zero, when the voltage value is at zero, to 100 keV, when the voltage value is at its peak.

(2) The 12-pulse wave from a three-phase generator does not drop to zero, as stated earlier. It only drops 3.4 percent below peak value. As a result, the kinetic energy of the electrons only drops 3.4 percent below peak kV value. In other words, the kinetic energy of electrons (at 100 kVp) in a 12- pulse system theoretically will range from 96.6 keV to 100 keV. This means that the average kinetic energy imparted to the electrons is much higher in the 12-pulse system than in the 2-pulse system.

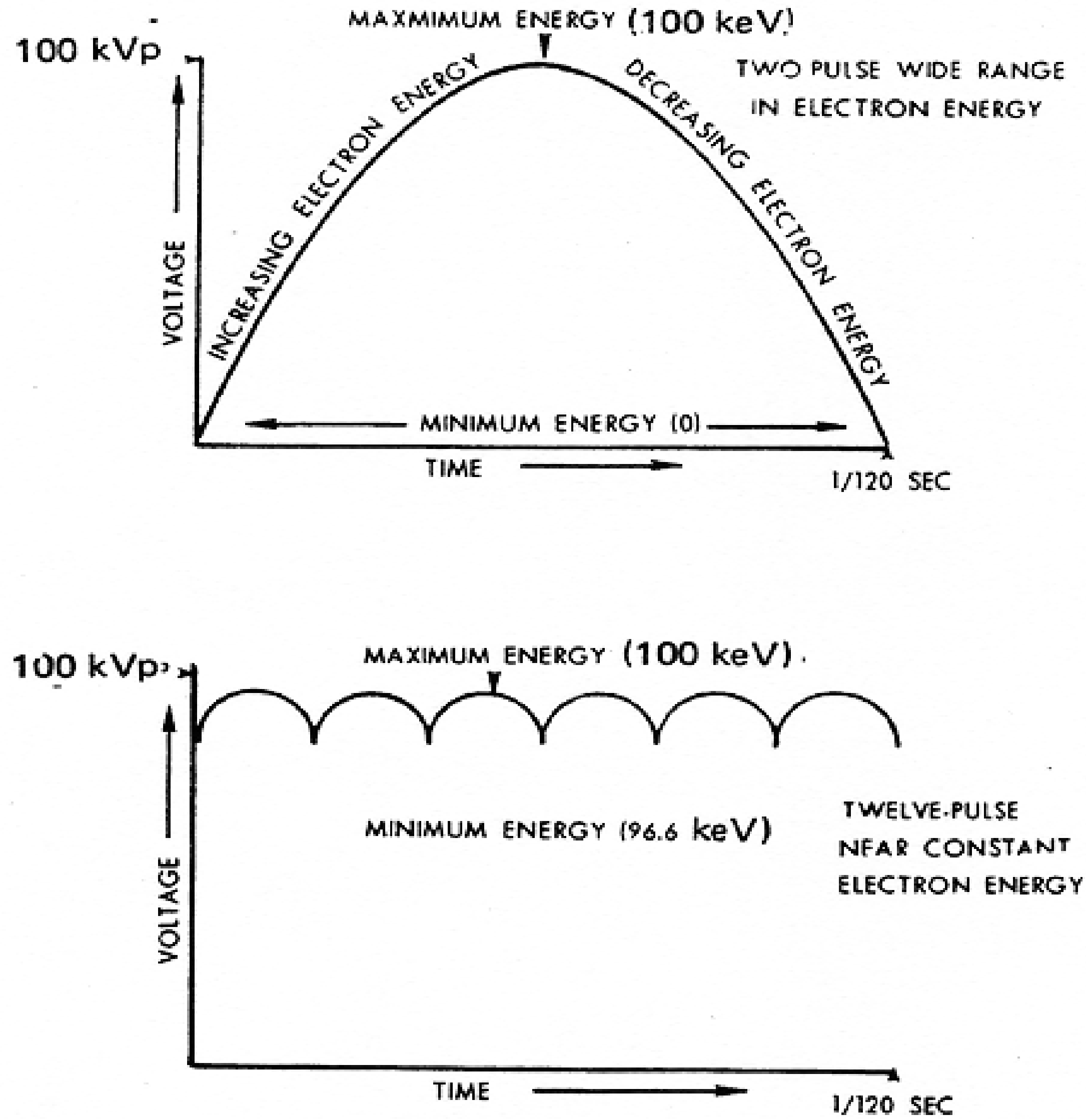


Figure 2-26. Comparison of two-pulse and 12-pulse patterns.

b. When low-speed electrons strike the target in an x-ray tube, their energy is converted into heat or into low-energy photons. Since a single-phase system produced comparatively more low-energy electrons, it also produces a greater proportion of heat and low-energy photons than a three- phase system.

(1) The average photon energy is less in a single-phase system. Low energy photons are absorbed by filtration or by the patient. In either case, they usually serve no useful purpose in diagnostic radiology since they do not reach the film to contribute to the exposure. (With certain examinations, such as mammography, some low energy photons are indeed useful since they contribute to this kind of exposure. However, in this type of examination, special techniques and equipment are used to form the low-energy radiation needed).

(2) The penetrating power or quality of a beam of x-rays is governed by photon energy; in the three-phase beam, the average photon energy is much greater. This, of course, is assuming that both systems are operated at equal peak kilovoltages. Notice that the qualitative difference in the two beams is in average photon energy. Both systems produce low-energy photons. The difference is in the proportion of low-energy photons, which, as stated before, is greater in single-phase systems.

c. The intensity of an x-ray beam is greater with a three-phase system than with a single-phase system for a given tube current. Therefore, the l2-pulse system will produce a given amount of radiation in a much shorter period than required for the 2-pulse system. Figure 2-26 shows 2-pulse and 12-pulse waveforms. Image-forming radiation is only produced at certain times with 2-pulse. At other times, either no radiation at all is produced (when the sine wave is at zero value) or radiation is produced that has insufficient energy to reach the film. The l2-pulse wave continuously produces image-forming radiation because of its near-constant voltage level.

d. The average energy level of the beam of radiation produced by a three-phase unit is higher than that produced by a single-phase unit when both are adjusted for the same peak kV. Therefore, to produce radiographs with the same general scale of contrast, it would be necessary to use a higher kVp with the single-phase unit. For a given mA station, it would require approximately twice as much exposure time for a single-phase unit as a three-phase (12-pulse). Therefore, it is probably more logical to make the technique compensation with kVp rather than mAs. If the (single-phase) kVp were increased by 15%, this would increase the average energy of the beam to a point where the single-phase unit would produce radiographs of approximately the same density and scale of contrast as those produced by the three-phase unit using the same mA and time (mAs) factors. In addition, the increase in kVp would tend to keep the absorbed dose of the patient to a minimum.

e. X-ray tube capacity is greater in a three-phase system for short exposures. One reason for the increased tube capacity is because the heat is spread over a larger area on the target. Figure 2-27 shows two rotating targets. Assume that each was subjected to exposures of 1/60 second. Target A was exposed by a single-phase, 2-pulse system, while target B was exposed by a three-phase, 12-pulse system. Target A shows two "hot spots" which would correspond to the peak of the two pulses produced at 1/60 second. Therefore, the point heat buildup at these "hot spots" would determine the maximum capacity of the tube on a short exposure. Target B, on the other hand, shows no "hot spots" due to point heat buildup, which results in a more even thermal load. In this matter, the anode disk is fully exploited for x-ray production. The thermal capacity for x-ray tubes operated on three-phase is increased only for exposures less than 1/2 second. From 1/2 to 1 second, the ratings are approximately the same as for single-phase. Above 1 second, the ratings can be greater for x-ray tubes operated on single phase.

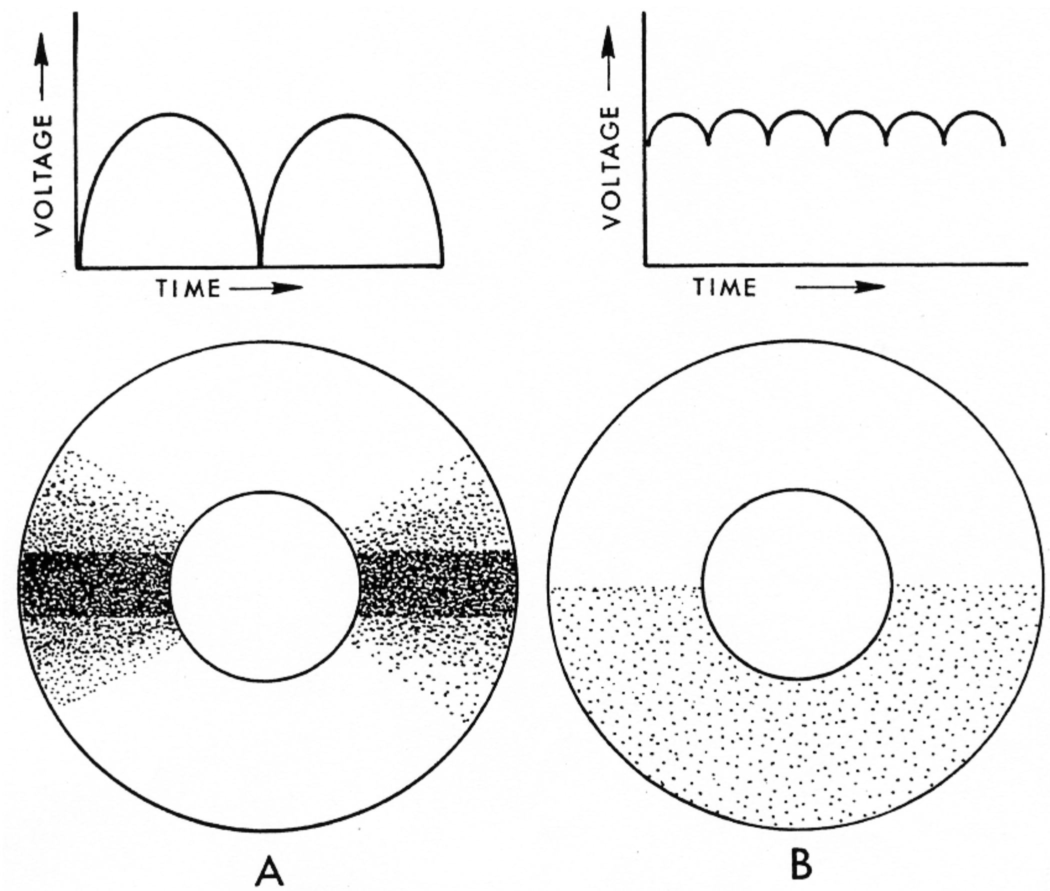


Figure 2-27. Comparison of anode heat patterns with single-phase and three-phase systems.

f. Special "spin-tops" have been devised to test the capabilities of three-phase equipment and capacitor discharge units. These special tops operate in a similar manner as those used for single-phase units. The major difference is that when the top is spinning at a specific number of revolutions per minute, a strobe disk synchronizes with the flicker in 60-cycle fluorescent lighting. With this type of spin-top, the time is determined by measuring the length of the strip exposed. Since the speed of the top is known, then time can be determined by how far it rotated during exposure. This top can be used to measure exposure times in the millisecond range.

Continue with Exercises

EXERCISES, LESSON 2

INSTRUCTIONS. The following exercises are to be answered by marking the lettered response that best answers the question, or by completing the incomplete statement, or by writing the answer in the space provided at the end of the question.

After you have completed all the exercises, turn to "Solutions to Exercises," at the end of the lesson and check your answers with the Academy solutions.

1. Suppose two bodies, one negatively charged and the other positively charged, are placed close together. How will they react to each other?

   a. Repel each other.

   b. Attract each other.

   c. Neutralize each other.

   d. Trade charges.

2. Voltage is a measurement of:

   a. Potential difference.

   b. Current flow.

   c. Resistance.

   d. Work.

3. Current is measured in:

   a. Volts

   b. Amperes.

   c. Ohms

   d. Watts.

4. In the current-carrying wire, the natural opposition to the flow of electrons is called:

    a. Polarity.

    b. Resistance.

    c. Gravity.

    d. High potential.

5. A conductor that allows current to flow freely is said to have _______ resistance.

    a. High.

    b. Low.

    c. Magnetic.

    d. Nonmagnetic.

6. A circuit in which all the current flows through the whole circuit is a ___________ circuit.

    a. Parallel.

    b. Series.

    c. High voltage.

    d. Solenoid.

7. The equation E = I x R relates to Ohm's law. If E = 115 volts and I = 15 amperes, what is R (resistance in ohms)?

    a. 7.67

    b. 10.40.

    c. 13.00.

    d. 16.25.

8. A metal is said to be magnetized when it has the ability to accomplish which of the following actions?

   a. Cause certain chemicals to fluoresce.

   b. Generate heat by chemical action.

   c. Ionize dust particles.

   d. Attract bits of iron.

9. Which of the following materials is an example of a nonmagnetic substance?

   a. Steel.

   b. Glass.

   c. Nickel.

   d. Cobalt.

10. A metal that can be magnetized more easily than another is said to have higher:

    a. Retentivity.

    b. Malleability.

    c. Permeability.

    d. Conductivity.

11. A coil of current-carrying wire wrapped around a soft iron core is a(n):

    a. Solenoid.

    b. Voltmeter.

    c. Electromagnet.

    d. Transformer.

12. What electric phenomenon causes counter EMF (electromotive force) in a coil of wire in which current has just started to flow?

    a. The magnetic field cutting across the coil induces an opposing voltage in the wire.

    b. The magnetic field surrounding the coil reverses the polarity of the wire.

    c. The wire leak voltage into the magnetic field.

    d. The expansion of the wire cuts across magnetic lines of force.

13. How is the magnetic field affected when a soft iron core is inserted in a choke coil?

    a. Intensifies the magnetic field.

    b. Causes the magnetic field to collapse.

    c. Causes the magnetic field to decrease the back electromotive force.

    d. Demagnetizes the magnetic field.

14. When variations of current in one circuit produce voltage (EMF) in another circuit nearby, the phenomenon is called:

    a. Counter electromotive force.

    b. Mutual induction.

    c. Opposite voltage flow.

    d. Direct current flowing in a coil.

15. In a 60-cycle alternating current, there are _____ impulses per second.

    a. 60.

    b. 90.

    c. 120.

    d. 180.

16. What device transfers electrical energy from one circuit to another by way of an electromagnetic field?

    a. Voltmeter.

    b. Ammeter.

    c. Rectifier.

    d. Transformer.

17. If a transformer is connected to 110 volts and has 10 windings on its primary side, how many windings would be needed on the secondary side to produce 1,100 volts?

    a. 1.

    b. 10.

    c. 100.

    d. 1,000.

18. In a closed-core transformer, the core is made of:

    a. Copper.

    b. Laminated steel.

    c. Glass.

    d. Air.

19. What kind of rectification is achieved when using a single-phase, self-rectifying x-ray machine system?

    a. Full-wave.

    b. Half-wave.

    c. Mechanical.

    d. Automatic.

20. If a spinning top is used to check a half-wave rectified, single-phase x-ray machine (60 cycles per second) and a 1/20-second exposure is used, how many dots should show on the film?

    a. 3.

    b. 6.

    c. 8.

    d. 12.

Check Your Answers on Next Page

SOLUTIONS TO EXERCISES. LESSON 2

1. b (para 2-1a)

2. a (para 2-5a(3))

3. b (para 2-5b(2))

4. b (para 2-5c(1))

5. b (para 2-5c(3)(a))

6. b (para 2-6a)

7. a (para 2-7)
   (E = IR
   115 = 15R
   R = 115/15 = 7 2/3 or 7.67)

8. d (para 2-9)

9. b (para 2-11b)

10. c (para 2-12)

11. c (para 2-16)

12. a (para 2-18a(1))

13. a (para 2-18b)

14. b (para 2-19)

15. c (para 2-21d)

16. d (para 2-26a)

17. c (para 2-26c) (110:10 as 1100: 100)

18. b (para 2-27a)

19. b (para 2-30a)

20. a (para 2-34a) (60 dots per set x 1/20 set = 3)

End of Lesson 2

LESSON ASSIGNMENT

LESSON 3 X-Ray Circuits and Tubes

LESSON ASSIGNMENT Paragraphs 3-1 through 3-14

LESSON OBJECTIVES After completing this lesson, you should be able to:

3-1. Describe the circuits and components of x-ray machines, including autotransformers, filament transformers, choke coils, prereading voltmeters, step-up transformers, milliammeters, timers, and x-ray tubes, and also discuss various methods of rectification.

3-2. Explain the production of x-rays, as well as the operation, purpose, materials, designs, and components of x-ray tubes.

3-3. Use charts and formulas designed to protect the x-ray tube from heat damage.

SUGGESTION After completing the assignment, complete the exercises of this lesson. These exercises will help you to achieve the lesson objectives.

LESSON 3

X-RAY CIRCUITS AND TUBES

Section I. MAJOR X-RAY MACHINE CIRCUITS

3-1. INTRODUCTION

The diagram of most medical x-ray units can be reduced to the following four basic circuits:

a. Line-to-autotransformer circuits, which provides adjustments to overcome variations of the normal incoming line voltage. It assists the operator to obtain specific voltages for the unit's operation.

b. X-ray tube filament circuit, primary and secondary, which provides the electrical power required to heat the x-ray tube filament, and means to vary the x-ray tube filament temperature as required to control the tube current (quantity of radiation).

c. High-tension circuit, primary and secondary, which permits development of the required high potential, its application across the x-ray tube, and adjustments which enable the operator to control kilovoltage peak (quality of radiation).

d. Control circuit (also called the timer circuit or operating circuit, which initiates, times, and terminates the x-ray production by controlling a switch that connects the primary circuit of the high-tension transformer to the power source.

e. Other circuits are found in an x-ray machine, but those described here are the ones essential for operation and control of both the quantity and quality of radiation produced.

3-2. LINE-TO-AUTOTRANSFORMER CIRCUIT

Since most practical x-ray units operate from standard service lines, the first circuit energized in any x-ray unit is the one that connects to the service lines. This is the circuit used to energize all other circuits in the x-ray unit. Before considering the circuit, consider the characteristics of the incoming power line.

a. The power source voltage will vary from day to day or even from hour to hour, depending on the demands placed upon it. At a time when the power drain is great, the source voltage will be lower than normal. At other times, when demands on the source are light, the voltage will be higher. The variation that follows the living cycle of the community is commonly called line variation.

(1) Some x-ray unit circuits must be supplied with a specific voltage for proper operation. Adjustments, therefore, are required to compensate for variations. If no attempt is made to correct for line variation, the penetrating ability of x-radiation produced would be variable due to the changing voltage applied to the circuit.

(2) Hence, the "line-to-autotransformer" circuit must have some adjustment to compensate for different line voltages. Later, in figure 3-3, you will notice a line voltage compensator, which is used to correct variations.

b. To supply the various circuits in the x-ray unit with the proper voltages, the volts-per-turn ratio of the autotransformer must be controlled. A voltmeter across a certain number of turns of the transformer is used to indicate when the volts-per-turn ratio is proper. When the voltmeter indicates a predetermined value, the volts-per-turn ratio of the autotransformer is proper for the unit's operation.

c. The prereading voltmeter (PRV) and the line voltage compensator permit adjustment of the volts-per-turn ratio of the autotransformer. There is a single line on the face of the meter. By manipulating the line compensator, the x-ray specialist adjusts the circuit until the pointer is aligned with this line, thus ensuring the proper volts-per-turn ratio of the autotransformer. In some equipment, this is accomplished automatically by regulating circuits.

d. The line strap is a major adjustment to be made by the medical equipment repairman at the time of installation. This adjustment is not available to the x-ray specialist.

e. A main switch is used to connect or disconnect the unit from the service line. The switch has two sections, one in each side of the incoming line. A ground wire connects to the frame of the unit. The ground wire will protect the operator from electrical shock should one of the wires of the incoming line become short-circuited to the chassis of the unit.

3-3. X-RAY TUBE FILAMENT CIRCUIT

The x-ray tube filament, as used in medical radiography, must be heated until incandescent. The hotter the filament, the larger the number of electrons liberated. A relatively high current is required to produce the desired temperature. The autotransformer (figure 3-1) is the power source used by a step-down transformer (filament transformer) to produce higher current (amperage) at a lower voltage. The filament transformer also isolates the high voltage, which appears across the x-ray tube, from the autotransformer.

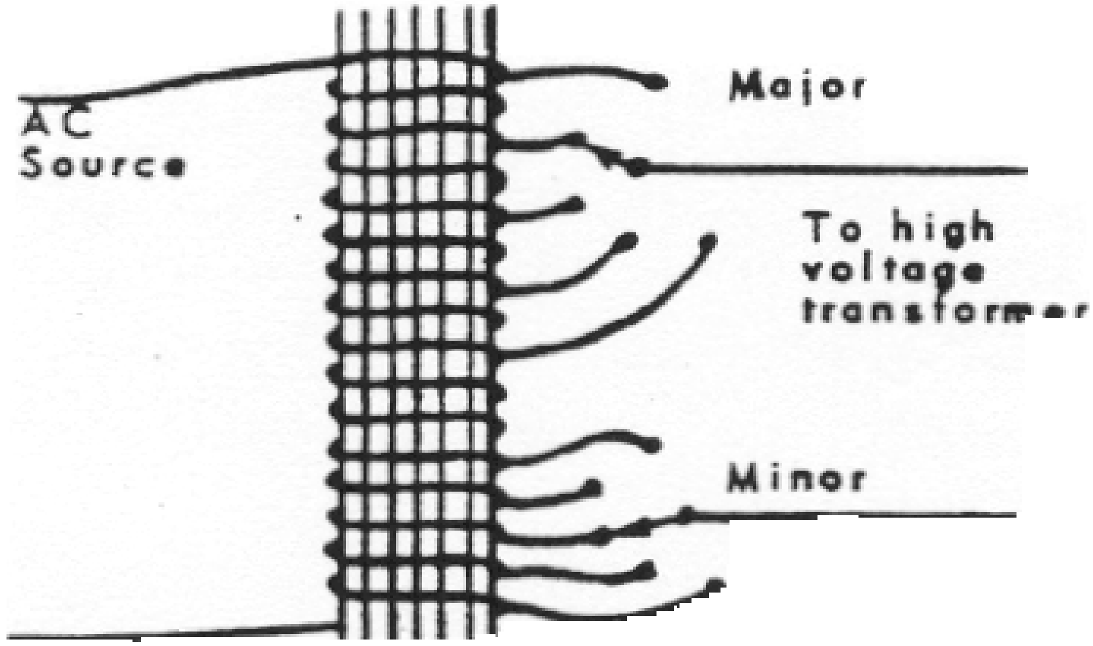


Figure 3-1. Autotransformer.

a. A basic x-ray tube filament circuit is seen in figure 3-2. The autotransformer serves as the power source. In series with the primary of the step-down transformer is an adjustment called the filament control or choke coil. To set the x-ray tube current, this adjustment permits variations in the x-ray tube filament temperature. The step-down, isolation-type transformer shown in figure 3-2 has the filament of the x-ray tube connected directly across its secondary winding.

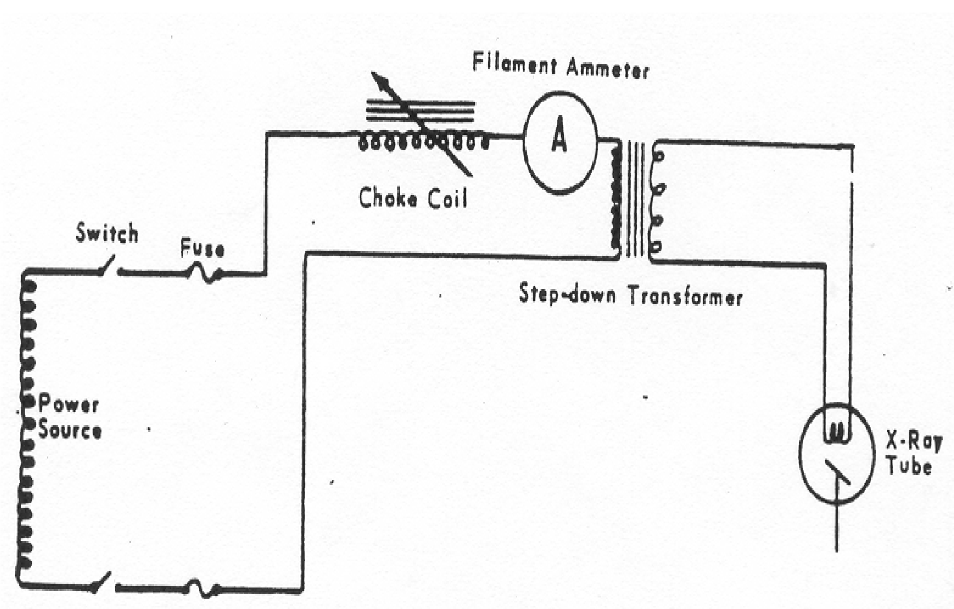


Figure 3-2. The mA or filament circuit.

b. Additional devices are found in most x-ray tube filament circuits. They include a filament limiter and a filament meter.

(1) Filament limiter. The filament limiter is an adjustable (strap-type) resistor, which is not available to the operator. By adjusting this resistor, the equipment repairman can limit the maximum tube current. This adjustment is needed to keep the x-ray tube within safe operating limits.

(2) Filament meter. A meter placed in the filament circuit can be used to good advantage. The x-ray tube filament temperature determines the x-ray tube current. This temperature is a function of the voltage and current of the primary of the x-ray tube filament circuit. Either a voltmeter or an ammeter on the primary circuit can be used to predict, with accuracy, the x-ray tube current before high voltage is applied to the tube. Normally, only one of these meters would be needed. Either meter, when used, requires preparation of a chart correlating the meter readings with the actual milliamperage obtained during exposure. The use of a fixed resistance selector method eliminates the need for a filament ammeter.

3-4. HIGH-TENSION CIRCUIT

The high-tension circuit (figure 3-3) uses a step-up transformer to develop the thousands of volts needed to produce x-radiation. It is easier to discuss the high-tension circuit, its installation and trouble-shooting, if the primary and secondary circuits are discussed separately.

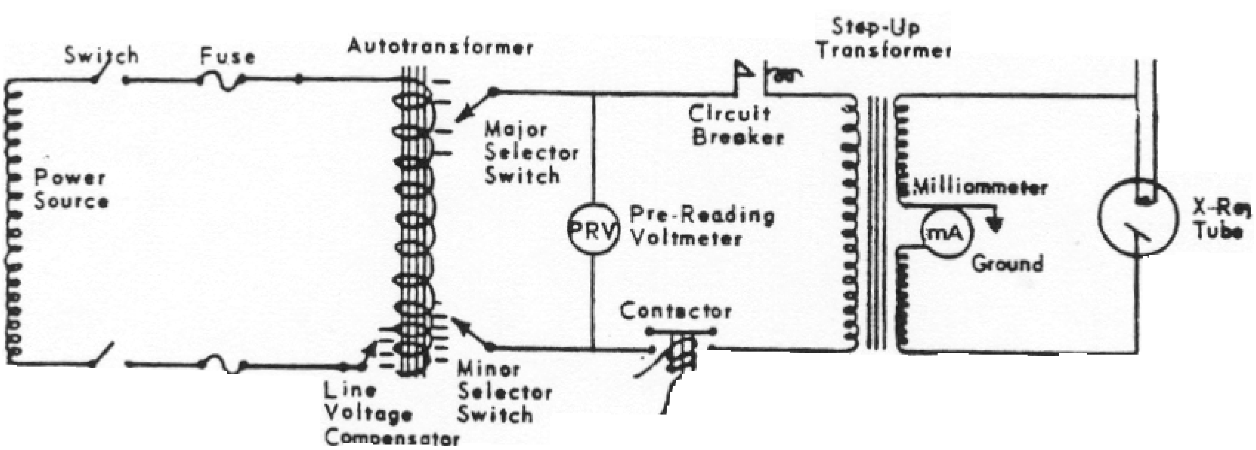


Figure 3-3. The kVp or high-tension circuit (self-rectified x-ray machine).

a. The primary high-tension (PHT) circuit includes electrical devices and conductors from the power source to the primary winding of the high-tension transformer and back to the power source. The power source is the autotransformer. The electrical devices incorporated within the basic PHT circuit of any x-ray unit include a means of adjusting the potential applied to the high-tension primary winding, thus varying the potential applied to the x-ray tube, a provision for closing and opening the PHT circuit, and some means of predicting the potential to be produced across the x-ray tube.

(1) In figure 3-3, the PHT circuit begins at the autotransformer (the major kilovoltage selector), through the primary winding to the contact points, then to the minor kilovoltage selector, and back to the autotransformer.

(2) The major and minor kilovoltage selectors are rotary tap switches. They provide a means of increasing or decreasing the peak kilovoltage across the x-ray tube by varying the potential across the primary winding of the high-tension transformer. The major kVp-selector usually adjusts in increments of 10 kVp, whereas the minor kVp-selector adjusts in increments of 1-2 kVp. Therefore, if the major kVp-selector were provided with eight steps and the minor with ten steps, it would yield a possibility of 80 different values.

(3) The contactor is used to close and open the primary high- tension circuit. As long as its points are open, there will be no high voltage impressed across the x-ray tube, and there will be no x-radiation by the tube. The contactor is normally an open relay, the coil of which is located in the operating circuit.

(4) The kilovoltage selectors must not be rotated when the PHT circuit is energized; if this precaution is ignored, severe arcing will damage the selectors.

(5) The prereading kVp meter is connected across the primary of the PHT. Although this meter is monitoring the low voltage input to the high-tension transformer, it is scaled to indicate the high voltage produced in the secondary of this transformer.

b. The secondary high-tension (SHT) circuit consists of the secondary winding of the step-up transformer, the x-ray tube, the milliammeter, and rectifiers.

(1) The step-up transformer multiplies the voltage so that the high EMF (voltage) needed to operate the x-ray tube is produced. This means that the secondary winding has a great many more turns than the primary winding.

(2) The milliammeter is necessary in this circuit as an indicator and has been discussed previously.

(3) Rectification is essential, since x-ray tubes require direct current for their operation. A complete discussion of various systems of rectification has been presented earlier in this subcourse. It is suggested that the student review this material. In brief, rectification is any method of changing AC to DC. In a self-rectifying x-ray machine (this would be a small, old-fashioned field unit), rectification is accomplished by

the x-ray tube itself. In other units, rectification may be done by valve-tubes or modern rectifiers. Some machines use two rectifiers, one placed on either side of the x-ray tube. This produces efficient "half-wave" rectification. For still greater efficiency, four rectifiers may be used in a bridge circuit (figure 2-23) to produce "full-wave" rectification.

(4) The x-ray tube is, of course, the primary component in the machine. All other devices and mechanisms in an x-ray machine are for bringing the proper currents to the tube at the proper times. The x-ray tube will be discussed at length later in this lesson.

3-5. THE TIMER OR CONTROL CIRCUIT

The timer circuit (figure 3-4) consists essentially of a timing device that can be varied. This timing device activates a contactor that allows high-tension voltage to be applied to the x-ray tube. The timer circuit draws its power from the main line, through the main line switch and fuses. The timer itself is a modification of a push-button switch, but has a timing mechanism that automatically cuts off the current after a preset time. Note that the contactor is closed (and x-rays are produced) only when current flows through the timer circuit. There are four main types of timers in general use at present. These are the hand or mechanical timer, the synchronous timer, the impulse timer, and the electronic timer. There is also another type, the photoelectric timer, which is not so widely used.

a. The hand or mechanical timer has a spring-wound motor that is allowed to run at constant speed, the timing dependent on how far the dial is initially set. The mechanical timer has a theoretical minimum time of l/8 second; however, it is usually not advisable to use such a timer for time intervals of less than 3/8 second because of its inaccuracy at these shorter time intervals. This type of timer is found almost exclusively on small portable machines, which do not require short accurate exposures.

b. The synchronous timer consists of a small synchronous motor, the revolutions of which are counted and used as the timing factor. The synchronous timer can usually be set for time intervals from as short as 1/20 second to as long as about 20 seconds (the exact range depending upon the particular manufacturer's design, as is true of all types of timers).

c. The impulse timer may operate at time intervals from as short as 1/120 second to as long as about 1/5 second. Because the maximum timing exposure of an impulse timer is usually about 1/5 second, a synchronous timer is generally installed along with it to provide for the longer exposures. The impulse timer is much more accurate than the synchronous since it starts and stops the current at the zero point (no-current interval) of the alternating current cycle.

d. Electronic timers use electronic circuitry to count the alternating current pulsations, and they cover the entire range of times from milliseconds to several seconds more accurately and reliable than impulse timers.

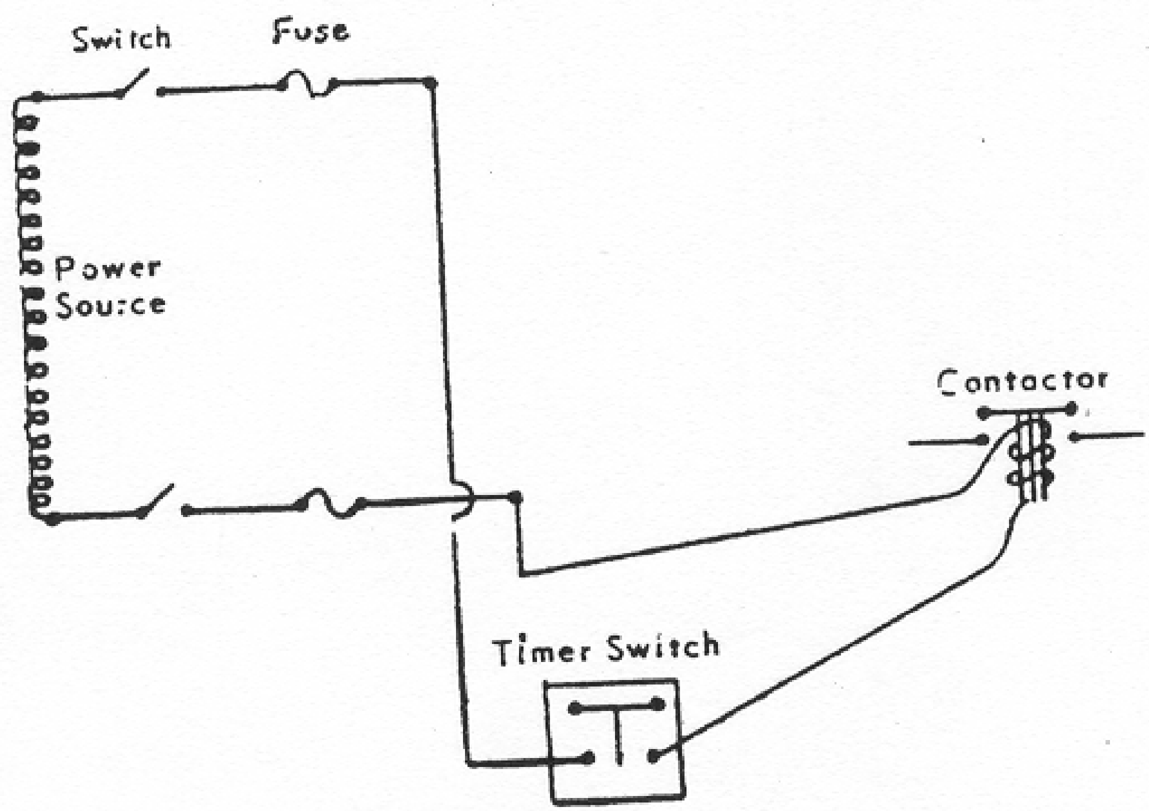


Figure 3-4. Timer (S) circuit.

e. The photoelectric timer requires the use of a photocell or photoelectric eye. A small fluorescent screen with a photocell is placed behind the cassette (a film holder, having a back through which x-rays may penetrate). When a predetermined quantity of radiation has struck the fluorescent screen, causing it to give off light that the phototube measures, a mechanism is activated which automatically stops the exposure at the correct time. This automatic timing device produces radiographs of exactly the same density. Photoelectric timers are used extensively in photofluorography, and have been found to be very useful in connection with spot film exposures in gastrointestinal work. However, they are not yet widely used in making conventional diagnostic radiographs.

3-6. CIRCUITRY IN A TYPICAL X-RAY MACHINE

Following is a discussion of figure 3-5 which shows the entire circuit layout for a full-wave rectified x-ray machine.

a. Device number one marks the on-off switch. When this is closed, a complete circuit is formed with the incoming line. The incoming line-voltage passes through the double line fuses (device number two) and then on to both the internal and external line-voltage compensators (devices number four and number five). The line-voltage compensator meter (device number three) indicates the number of volts per turn on the autotransformer. Now the voltage is impressed over all the turns of the autotransformer (device number six). From here, it is channeled into three different circuits.

b. The first of the three is the primary circuit. The kV selectors (devices number seven and number eight) select the voltage to be impressed on the primary circuit and, in turn, the high-voltage circuit. After the kV has been selected, the kV meter (prereading voltmeter) (device number nine) indicates what the resulting kV will be. The timer circuit (device number ten) is also located in the primary circuit along with the circuit breaker (device number 11). The voltage is then fed into the primary of the step-up transformer (device number 12).

c. There are taps (points a and b) that connect the rectifier transformers with the autotransformer. The lines from the autotransformer lead to the valve-tube (step-down) transformers (device number 15). These transformers supply the increased amperage needed by the tubes within the vacuum-tube rectification circuit (device number 14).

d. Taps c and d channel the voltage, taken off a certain number of turns of the autotransformer, to the filament transformer (device number 17), which is used to supply milliamperage in the filament circuit. This circuit is controlled by one of three arrangements: a tap-selector resistor (device number 18A), an adjustable resistor (device number 18B), or a choke coil (device number 18C). There is sometimes a filament ammeter in this circuit, although it is not shown in figure 3-5.

e. On the secondary side of the high-voltage transformer (device number 12), we find the high-voltage circuit. Within this circuit, we find the mA meter (device number 13), the bridge-type rectifier (device number 14), and the x-ray tube itself (device number 16). All these are activated when the step-up transformer is activated, and the exposure is actually being made.

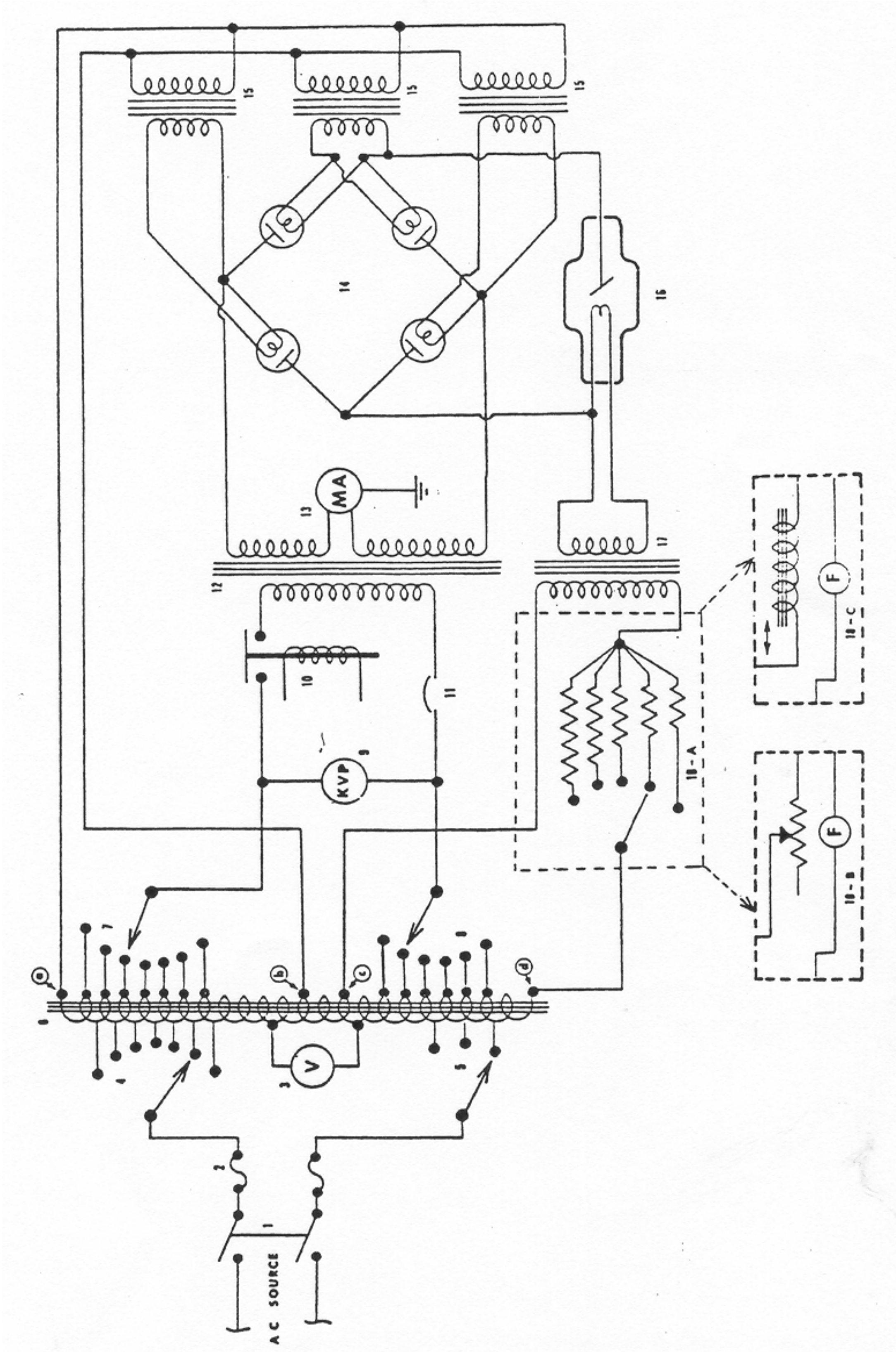


Figure 3-5. A typical X-ray machine electrical circuitry.

Section II. X-RAY TUBES

3-7. INTRODUCTION

X-rays are produced when high-speed electrons undergo a loss of energy in matter. The loss of energy and subsequent generation of x-rays occurs in one of the following ways: either the electrons are decelerated, or they collide with atomic nuclei and orbital electrons. Three conditions are necessary for the production of x-rays:

a. A source of electrons.

b. A means of accelerating the electrons.

c. A hard, dense target in which the kinetic energy of the electrons is converted into x-rays.

3-8. THE PRODUCTION OF X-RADIATION

For the purpose of simplification, the production of x-rays can be divided into three steps: (1) the filament in the cathode end is heated by an electric current causing it to emit electrons (figure 3-6A); (2) high voltage is applied across the x-ray tube to accelerate the electrons toward the target (figure 3-6B); and (3) the high-speed electrons are rapidly decelerated by the target, producing x-radiation (figure 3-6C).

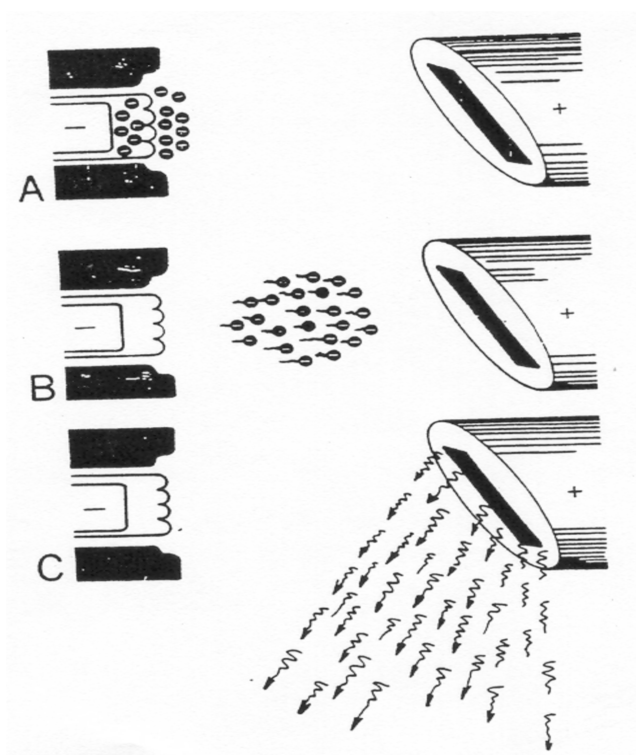


Figure 3-6. Production of x-rays.

a. The first step provides a means of controlling the quantity of x- radiation by control of filament temperature. As a higher mA station is selected on the x-ray generator, the filament temperature of the x-ray tube is raised, which in turn increases electron emission. (Because the filament reaches extreme temperatures, it is usually made of tungsten, which has a melting point of 3,370ºC.) If a lower mA station is selected, the filament temperature and the rate of emission will decrease. Consequently, by varying the mA station, the quantity of x-radiation can be varied. The last statement applies only to a set period. Naturally, the elapsed time of x-ray production will also affect quantity.

b. The second step (acceleration of the electrons) controls the quality of the x-rays. When high voltage is applied across the tube, the anode becomes positively charged with respect to the cathode and the electrons are repelled by the cathode and attracted by the anode, which causes higher voltage and greater speed of the electrons. The higher speed increases the energy range of the photons. In other words, by varying the kilovoltage (kVp), we can vary the quality of the x-rays.

c. The process by which x-radiation is produced when electrons strike the target (step 3) is described earlier in the subcourse and will not be repeated here. However, the target plays an important role in other areas as will be explained later in this lesson.

3-9. DEVELOPMENT OF X-RAY TUBES

a. The Hittorf-Crookes tube, used by Roentgen in his discovery, had no target as such. The x-radiation was produced in the glass wall of the tube when it was bombarded by the cathode rays (accelerated electrons), as seen in figure 3-7. The glass wall was not practical as an x-ray source because it could not withstand the heat generated by the electron bombardment and because it was too large to produce detailed radiographs. Consequently, one major step in the development of x-ray tubes was to place a metallic target inside the tube and direct the electrons to it instead of allowing them to interact with the glass wall. Not only did the metallic target better withstand the heat, but it also reduced the size of the x-ray source and enhanced radiographic detail.

b. Although the addition of the metallic target was a significant improvement, the early tubes still presented some serious problems. One of the problems stemmed from the method by which the electrons were obtained. Rarefied gas in the tube was partially ionized, and the positive ions in the gas were attracted by the negatively charged cathode, striking it with sufficient energy to release electrons from its surface, attracted the positive ions in the gas. The electrons thus released were accelerated by the electric field between the cathode and the anode. A major problem with these tubes was lack of control over both the quantity and quality of the x-radiation because of variations in gas pressure as the tube warmed up.

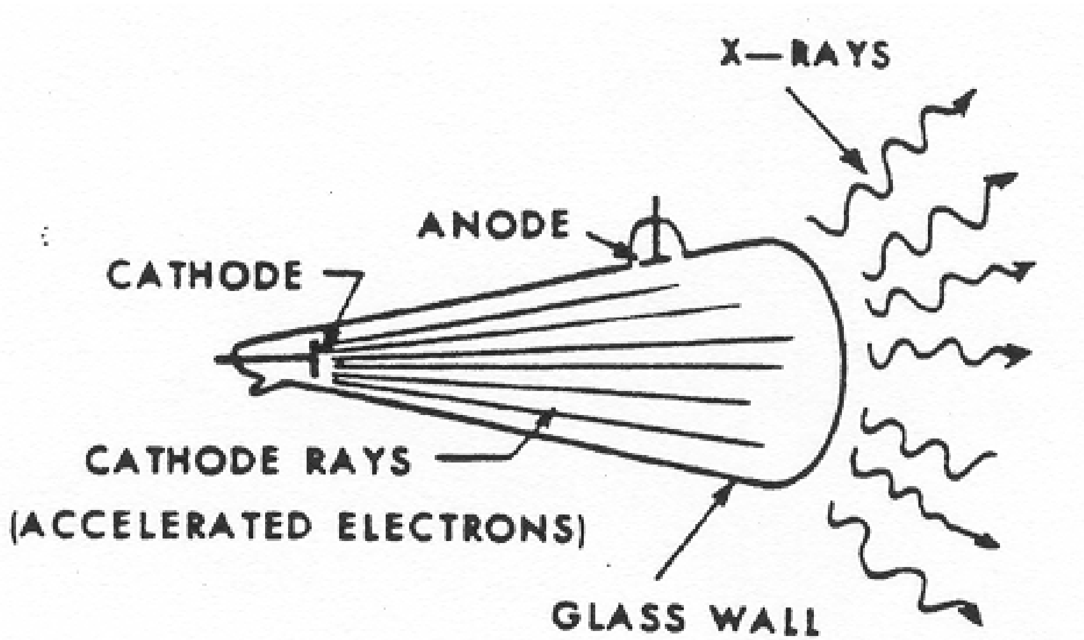


Figure 3-7. Production of x-rays by electrons striking the glass wall of the tube.

c. Gas tubes were used until 1913 when W. D. Coolidge introduced the "hot cathode" tube. With the Coolidge tube, electrons are obtained by heating a wire filament to incandescence by a low voltage current. At incandescent temperatures, the filament emits electrons by a process known as thermionic emission. Gas is undesirable; consequently, the best possible vacuum is used. In the hot cathode tube, the number of electrons (and consequently the quantity of x-rays) is easily regulated by adjusting the temperature of the filament. In addition, electron speed (and consequently the quality of x-rays) is easily regulated by adjusting the strength of the electric field between the cathode and anode.

d. Other major advances in the development of x-ray tubes are the rotating anode and the grid-controlled tube. Both are described later in this lesson.

3-10. TARGET MATERIAL AND ANODE CONSTRUCTION

a. Since early in the development of x-ray tubes, tungsten has been used as the material for target construction. One reason for this is its high atomic number (74). As the atomic number of the target increases, so does the energy of its characteristic radiation. As described previously, the energy of characteristic radiation produced in tungsten reaches 69.5 keV, a value that is considered useful in conventional radiography. A target with a higher atomic number would produce more energetic characteristic radiation and, therefore, would seem better suited for x-ray production. However, target material must meet other requirements in addition to the high atomic number.

b. One such requirement is a high melting point. The production of x-rays is a very inefficient process as less than 1% of the energy supplied to the x-ray tube is converted into x-rays. The remaining 99% is converted into thermal energy (heat). Consequently, the target temperature frequently reaches high proportions. Tungsten's 3,370°C melting point makes it suitable to withstand high temperatures. The target must also be able to conduct the heat away as it is generated in order to keep temperatures below the melting point. Tungsten's heat conductivity, while not extremely high, is considered acceptable in view of its other excellent characteristics.

c. Some x-ray targets are constructed with a rhenium-tungsten alloy. The addition of rhenium makes the target surface more resistant to surface etching at high temperatures.

d. Molybdenum is used for the target material in some x-ray tubes made especially for mammography. The characteristic radiation produced in molybdenum is somewhat lower than that produced in tungsten, which makes the x-ray beam more suitable for x-rays of thick, soft tissue.

e. Even with tungsten1s high melting point, overheating of the target to the point of melting, cracking, pitting, etc. is a continuing problem. One way to provide better heat dissipation is to embed the tungsten in copper, as illustrated in the stationary anode in figure 3-8. Copper has higher heat conductivity than tungsten and, therefore, carries the heat away more quickly. Another way to reduce point heat buildup is to rotate the anode, as seen in figure 3-9. By continuous spinning of the target, the focal spot presented to the electron stream is always changing. This spreads the electrons and, consequently, the heat over a larger area. Most modern x-ray tubes have a rotating anode. In some special-purpose tubes, the anode can be rotated at speeds up to 10,000 rpm.

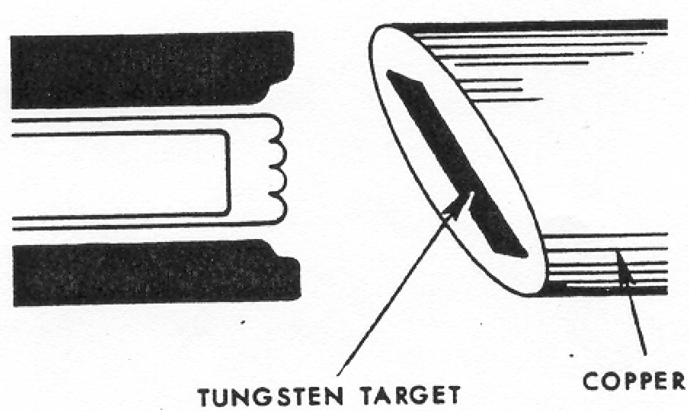


Figure 3-8. Copper anode used to help dissipate heat.

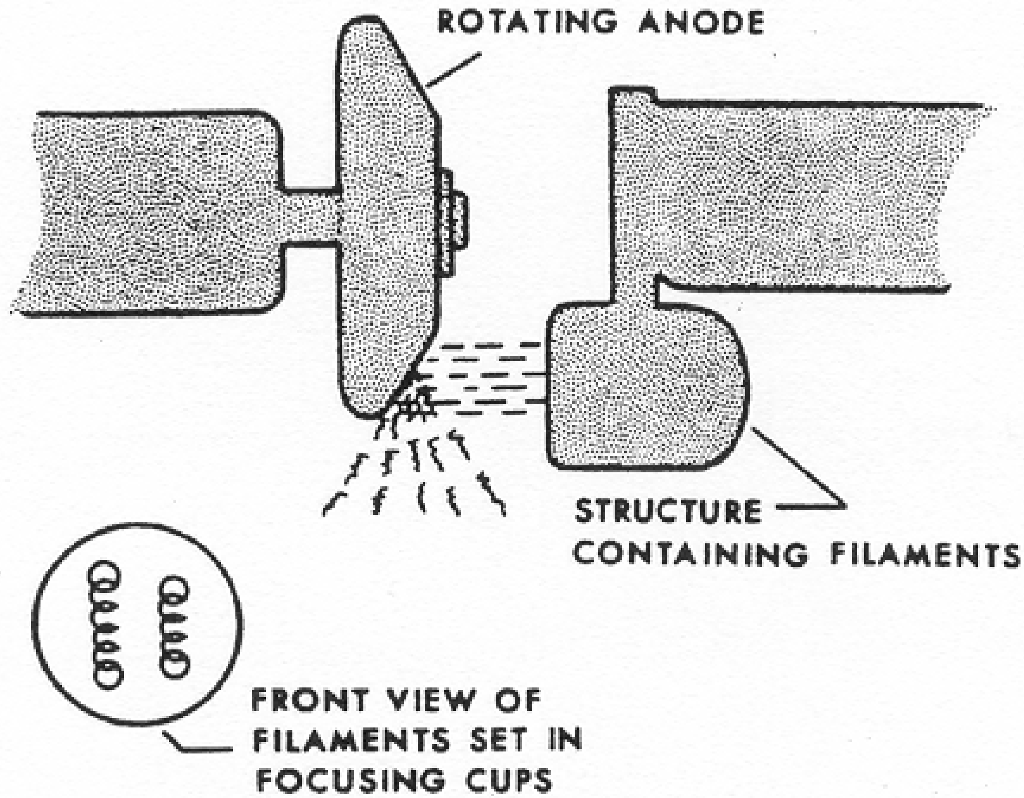


Figure 3-9. Rotating anode used to dissipate heat.

3-11. FOCAL SPOT

a. **Actual Focal Spot**. Electrons are focused to a specific area on the target by means of a focusing cup. The focusing cup is merely a depression in the cathode structure that partially surrounds the filament. That area of the target bombarded by the electrons is known as the actual focal spot. The actual focal spot and the focusing cup are illustrated in figure 3-10. The size of the actual focal spot significantly affects the heat loading capacity of the tube. With larger focal spots, greater heat loading is possible. The size of the focal spot is determined by a combination of three factors: (a) the size and shape of the filament, (b) the size and shape of the focusing cup, and (c) the angle of the target surface.

b. **Effective Focal Spot**. The focal spot, as it appears from directly beneath the tube at right angles to the electron stream, is called the effective focal spot and is also shown in figure 3-10. The size of the effective focal spot is a very important factor in a diagnostic x-ray tube because it affects the detail on a radiograph; the smaller it is, the better the detail. The size of the effective focal spot is determined by the size of the actual focal spot and the angle of the target.

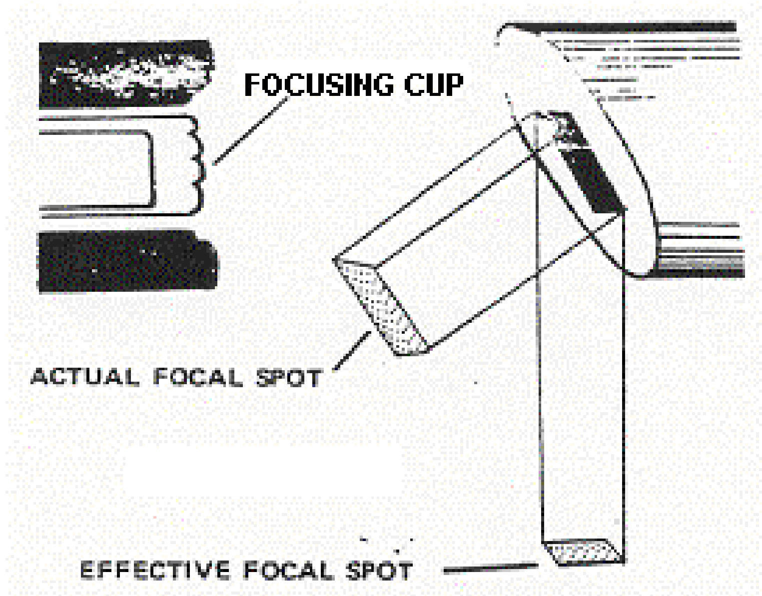
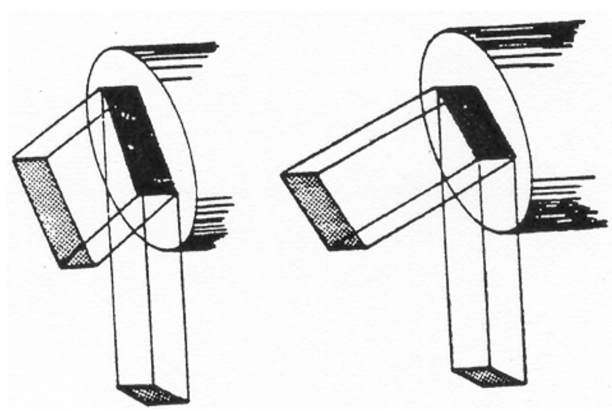


Figure 3-10. Actual focal spot and effective focal spot.

c. **Line Focus**. For maximum effectiveness, a diagnostic x-ray tube should provide an actual focal spot large enough to permit the necessary heatloading and an effective focal spot small enough to produce optimum detail. This is accomplished in part by the application of the line focus principle. For the purpose of line focus, the x-ray tube is designed so that the electrons bombard a rectangular area on the target surface. A specific target angle will then produce an effective focal spot that will be approximately square and much smaller than the actual focal spot. Figure 3-11 shows two different targets with angles of 20º and 40º. As you can see, both targets produce effective focal spots of equal size, but the actual focal spot at 20º is considerably larger. Consequently, the 20º tube produces a relatively large actual and a relatively small effective focus.



20° **40°**

Figure 3-11. Angle and actual focal spot size in relations to effective focal spot size.

3-12. ANODE HEEL EFFECT

Because .the anode is angled, the intensity of the x-ray beam along the longitudinal axis of the tube varies. This variation in intensity results from absorption of some photons by the target itself. Consider figure 3-12 where several photons are given off at a point within the target. Those photons which make up the anode side of the x-ray beam stand a greater chance of being absorbed because they have to travel through more target material than those which make up the cathode side of the beam. (Notice the different distances from the point where the photons are given off to the edge of the target.) Consequently, the intensity of the x-ray beam is greater on the cathode side than on the anode side. This nonuniformity is known as <u>anode heel effect</u>.

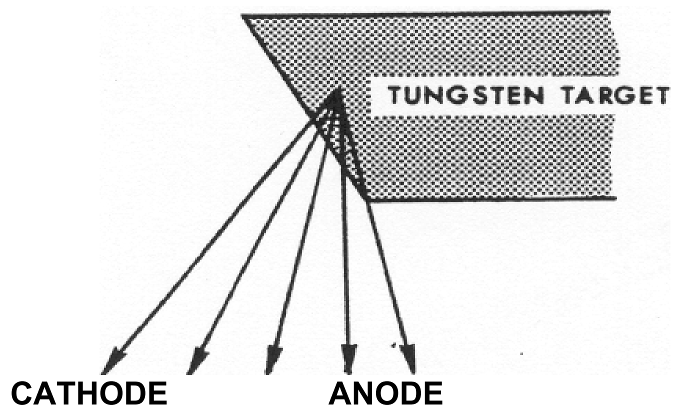


Figure 3-12. Anode heel effect.

a. The anode heel effect can be used to advantage when x-raying parts of uneven thickness and/or density, such as the lower leg. By placing the proximal end of the leg under the cathode side of the tube, the finished radiograph would have balanced density. On the other hand, a disadvantage of the heel effect can be experienced when parts of even density and thickness are x-rayed.

(1) Figure 3-13 shows intensity percentages caused by the heel effect with a 20^{o} target at various emission angles. Note how focus-film distance affects the percentage variations. If a radiograph were made of part number one using film number one a, the intensity spread over the film would be 95 percent to 104 percent, a difference of 9 percent, which would be negligible. If a radiograph were made of part number two, using film number two a, the intensity spread would be 31percent to 95 percent, a difference of 64 percent, which is not tolerable for interpretation.

(2) From the above information, one can see that the focus-film distance and, therefore, the area of the x-ray beam to be used, must be considered in connection with the heel effect. In other words, the anode heel effect can cause an exposure problem at short focus-film distances while at long focus-film distances, the problem is less likely to exist.

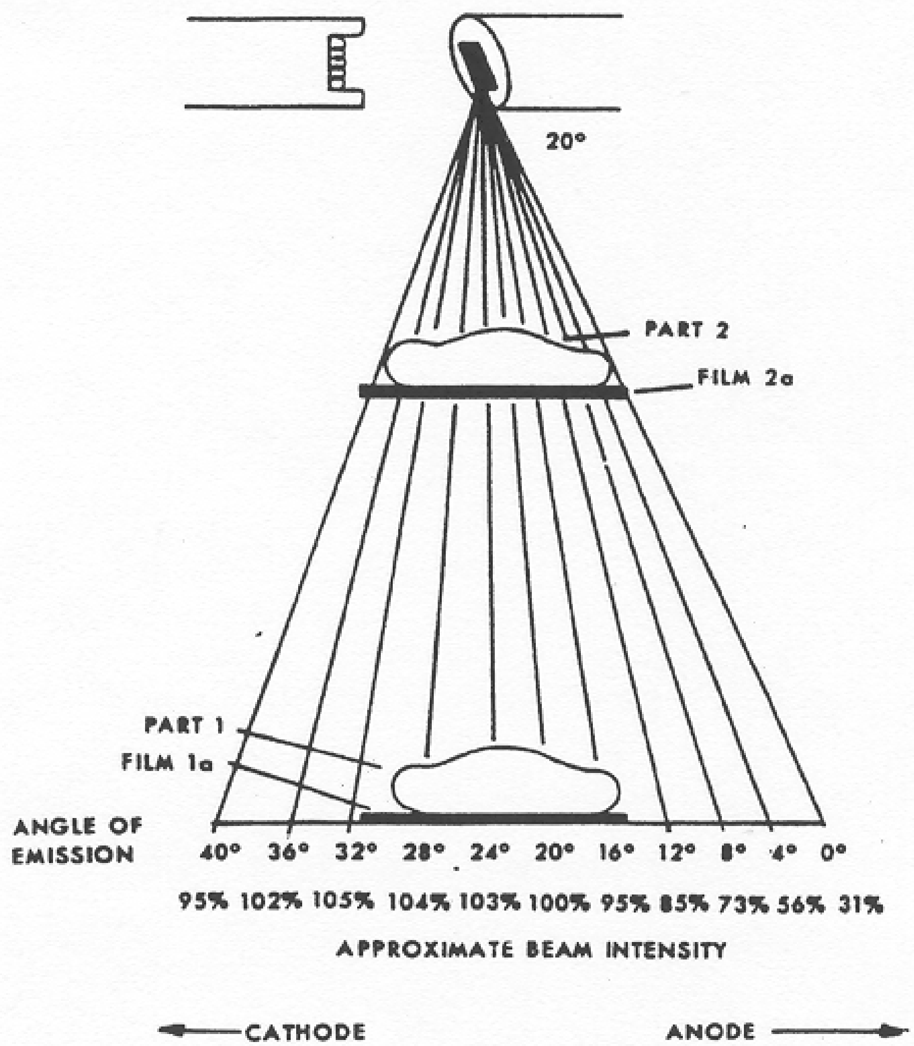


Figure 3-13. Anode heel effect and focus-film distance.

b. The intensity percentages given in figure 3-13 are specifically for a 20° target. As the target angle becomes smaller, the difference in the intensity percentages becomes greater, which in effect is further non-uniformity of the x-ray beam. Hence, when using tubes with small target angles, extra care should be taken to avoid the unbalanced density that the anode heel effect can cause on radiographs.

c. The target angle also affects the total area of x-ray coverage. As the angle is reduced, so is x-ray coverage, as seen in figure 3-14. The 10º target has less coverage than the 20º target at an equal distance from the tube. X-ray coverage usually is of no consequence, but with small target angles it may interfere with certain examinations. For instance, a 12º target at a 40-inch focus-film distance (FFD) will only cover an area with an a 8 ½ inch radius and a 10° target at a 40-inch FFD will only cover area with a 7-inch radius. Clearly, these two targets will not cover a 14 x 17 film at 40 inches since an 11-inch radius is needed to cover the 14 x 17 area. To determine x-ray coverage, use the following formula: the tangent of the target angle (tan) times the focus-film distance (FFD) equals the radius of the area covered (RC) or tan X FFD = RC. Example: If the target angle is 20° and the FFD is 40 inches, the radius of the covered area would be 14 ½ inches, since the tangent of 20º is 0.364.

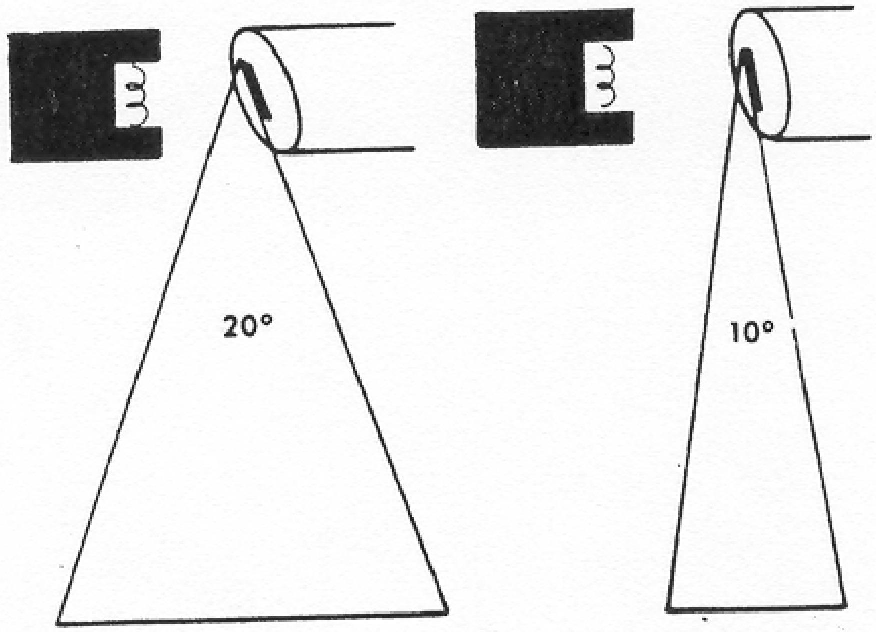


Figure 3-14. Target angle and x-ray coverage.

3-13. GRID-CONTROLLED TUBE

a. To prevent relay damage due to arcing, an x-ray exposure is normally synchronized to the line voltage so that it begins and ends when the sine wave is at zero value. With this system, in a single-phase generator the shortest exposure possible is 1/120 second since the sine wave reaches zero value every 1/120-second. With a grid-controlled tube, the exposure is also synchronized with the line voltage, but it does not necessarily begin and end at zero value. It can be synchronized to a particular portion of the sine wave.

(1) Figure 3-15 shows two waveforms with exposures of 1/120 second on a conventional times tube and 1/360 second on a grid-controlled tube. Since the conventional exposure should begin and end at zero value, it must encompass one complete pulse. On the other hand, the grid-controlled exposure indicated here includes only the middle third of the pulse. Even shorter exposures are possible with grid-controlled tubes, and this makes them desirable for examinations requiring very short exposures.

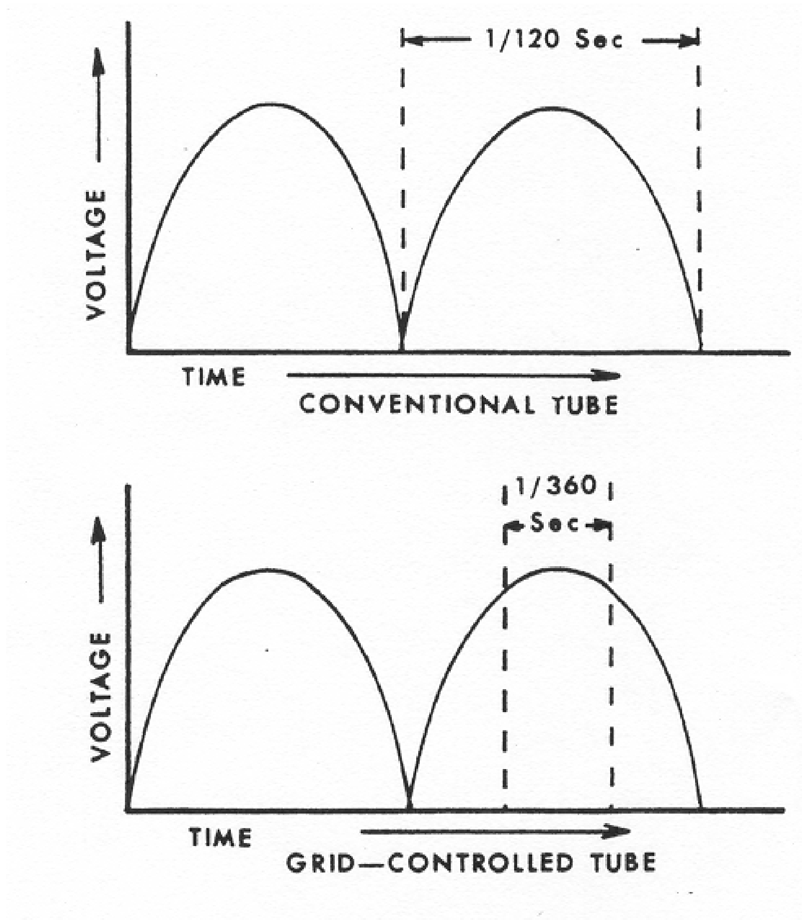


Figure 3-15. Effect of conventional and grid-controlled tubes.

(2) When a grid-controlled, short exposure is used, such as is demonstrated in figure 3-15, the radiation dose to the patient is reduced. The reduction occurs because the exposure does not encompass the portions of the wave that produce only lower energy photons. The patient dose is also reduced when grid-controlled tubes are used with cinefluorography (cine = motion picture) because x-ray production can be synchronized with the cinecamera. The synchronization reduces the radiation dose to the patient because x-rays are produced only when the shutter is open.

b. In addition to the two conventional elements, the cathode and anode, the grid-controlled tube has a third element or grid. The grid, which is actually the focusing cup, is electrically isolated from the filament. In operation, negative (bias) voltage is applied to the grid, which makes the grid negative with respect to the filament. A "negative electrostatic field" is set up which acts as a gate to stop electron flow by repelling the negatively charged electrons. Therefore, when the bias voltage is applied, no electrons reach the anode and x-rays are not produced. When the bias is removed, electrons flow to the anode and x-rays are produced. Because the grid is closer to the filament, a comparatively small change in the voltage to the grid will override a much larger positive charge of the anode.

3-14. RATING CHARTS

a. **Tube Rating Charts**. X-ray tubes must be operated within the limitations set by the manufacturer. If not, they can be permanently damaged by excessive heat that results when improper exposure factors are used. To prevent damage to tubes, radiologic specialists must be aware of tube rating charts and how to apply them in the daily operation of the x-ray unit. With each tube, the manufacturer supplies a series of rating charts to be used only with that particular tube.

(1) The amount of heat generated within a tube depends upon the electrical energy expended in the tube and is measured in heat units. Heat units (HU) are the product of kVp X mA X exposure time in single-phase, full-wave equipment. The formula is written HU = kVp X mA X sec. For example, how many heat units would be generated in a tube by the following exposure factors?

75 kVp   100 mA   1/2 second

Solution: HU = kVp X mA X set
HU = 75 X 100 X 1/2
HU = 7,500 X 1/2
HU = 3,750   Answer: 3,750 HU

(2) Heat units are an arbitrary measure and are the product of kVp X mA X second only in single-phase, full-wave equipment. The product of these factors in a three-phase, full-wave generator does not accurately reflect the heat units. To determine heat units in three-phase equipment, multiply the product of the exposure factors by 1.35 for 6-pulse and by 1.41 for 12-pu1se. In other words, HU in three-phase equipment are determined by the following formulas:

Six-pulse generator
HU = kVp X mA X second X 1.35

Twelve-pulse generator
HU = kVp X mA X second X 1.41

For example, how many Hu would be generated in a three-phase, 6-pulse unit using the following exposure factors?

70 kVp   100 mA   1/2 second

Solution: HU = kVp X mA X second X 1.35
HU = 70 X 100 X 1/2 X 1.35
HU = 3,500 X 1.35
HU = 4,725   Answer: 4,725 HU

b. **Rating Chart Selection**. It is important when applying tube-rating charts to use the proper one. For example, if the x-ray machine has full-wave rectification, then the chart for full-wave rectification must be used since tube capacity varies with the type of rectification and charts may be available for both. Tube capacity also varies with single or three- phase generators. So, again, the appropriate chart must be used. Factors such as those mentioned above need to be determined only once and will remain constant, unless there is a major modification in the machine or in the x-ray tube itself. One factor, however, that can vary from exposure to exposure, and has a very definite effect on tube capacity, is <u>focal spot size</u>. Consequently, the x-ray specialist must be aware of the size of the focal spot he is using so he can apply the appropriate tube-rating chart.

(1) <u>Radiographic (tube) rating chart</u>. This chart shows the maximum exposure factors allowable for a single radiographic exposure. Figure 3-16 shows two such charts for the same tube. One is for a 2-mm (large) focus and the other is for a 1-mm (small) focus. The factors to be considered on these charts are mA, kVp, and exposure time; when any two of them are known, the third can be easily found.

(a) For example, with the large focus, using 150 mA and 90 kVp, the maximum exposure time allowable could be found as follows: Find 150 mA on the left margin of the chart, and follow the line across the chart until it intersects with the 90-kVp line. From that point, follow an imaginary line straight down to the exposure time scale. The maximum exposure time in this case would be 4 1/2 seconds. Anything above that would exceed the tube's capacity and could damage the tube.

(b) By following the same procedure on the small focus chart, you can see that the same mA and kVp would allow a maximum exposure time of only 3/4 second. This comparison shows that the load capacity of a tube using the small focus is considerably less than with the large focus.

(2) <u>Angiographic rating chart</u>. In calculating the maximum number of exposures in angiography before the tube is allowed to cool, you will need to consult an angiographic rating chart for that tube. First, find the heat units (HU) for each exposure as discussed above. Then find the line for that HU on the chart and coordinate this with the number of exposures per second you are to make. This will show the number of exposures you can make before cooling the tube.

(3) <u>Cineradiographic rating charts</u>. Cineradiographic rating charts are arranged in various ways. It is very important to make your calculations carefully using a chart correct for the tube you have in use.

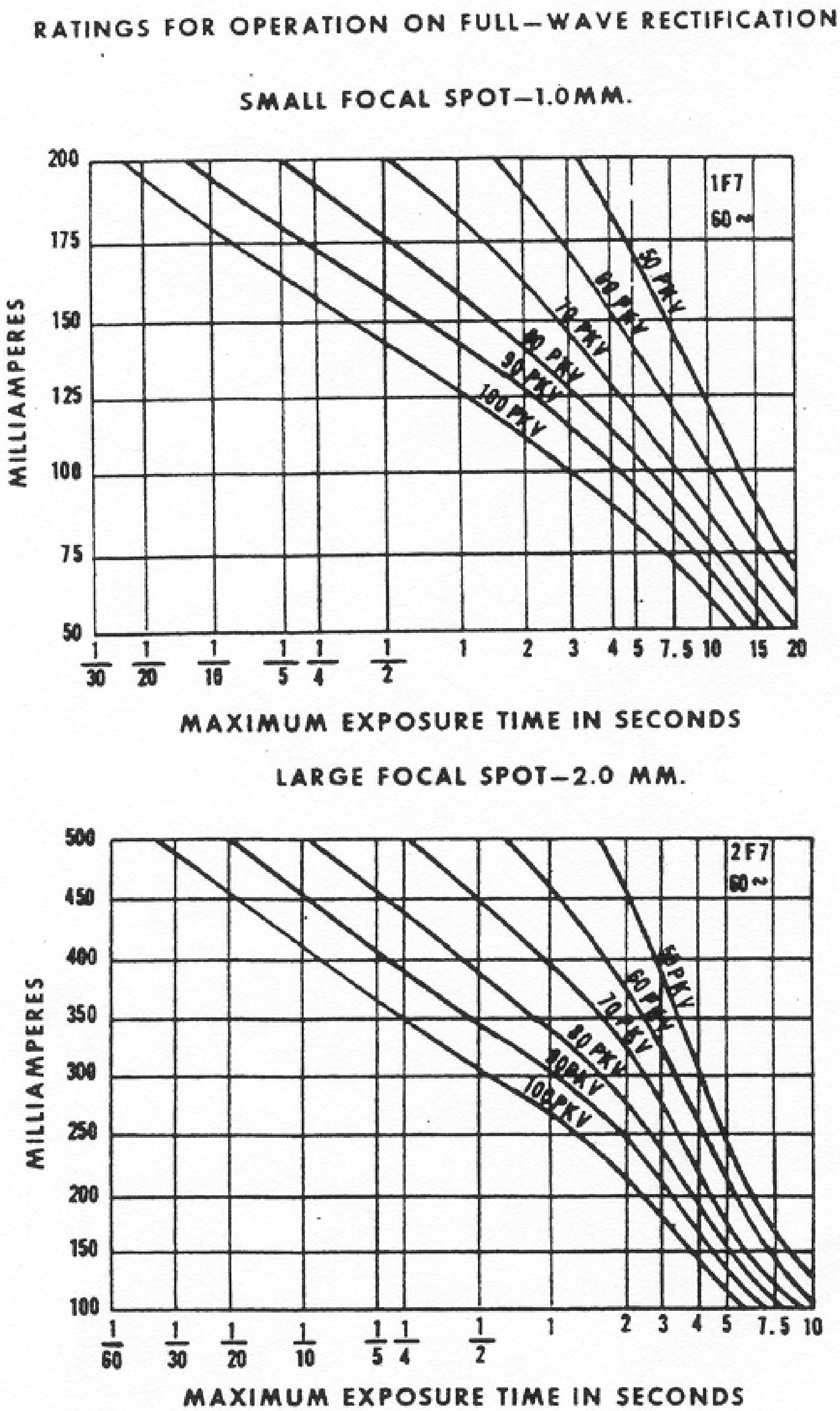


Figure 3-16. Two tube rating charts for the same tube, using large and small focal spots.

(4) Anode-cooling chart. Figure 3-17 illustrates a typical anode-cooling chart. From the curve on this chart, you will note that the maximum HU permissible is 72,000. When this maximum has been reached, you must wait 6 minutes before this same quantity of heat may be applied to the anode again. Exposures may be made before the six-minute period has elapsed, but the total HU must not exceed 72,000. For example, if four series of exposures are needed and each series generates 24,000 HU, you would have to wait after the third series until the tube had cooled. To find the shortest possible cooling time, consult the chart. You will see that cooling from 72,000 HU to 48,000 HU will require about 1 1/4 minutes.

NOTE: To find how many exposures per minute are possible with a tube already heated to capacity, divide the cooling rate per minute as the chart by the heat units per exposure:

Cooling rate in HU per minute/HU per exposure = Exposures per minute

The cooling rate (CR) as shown for a full-wave rectified machine on the chart (figure 3-17) is 6 minutes divided into 72,000 HU. Thus, the CR is 12,000 HU per minute. If exposures producing 1,000 HU per exposure are to be made with an already heated tube, divided 12,000 HU (cooling rate, or CR) by 1,000 HU (HU per exposure) to find how many evenly divided exposures can be made per minute. Cooling rate (CR) here, as you will note on the chart, means average CR since the rate of cooling is not the same at every temperature.

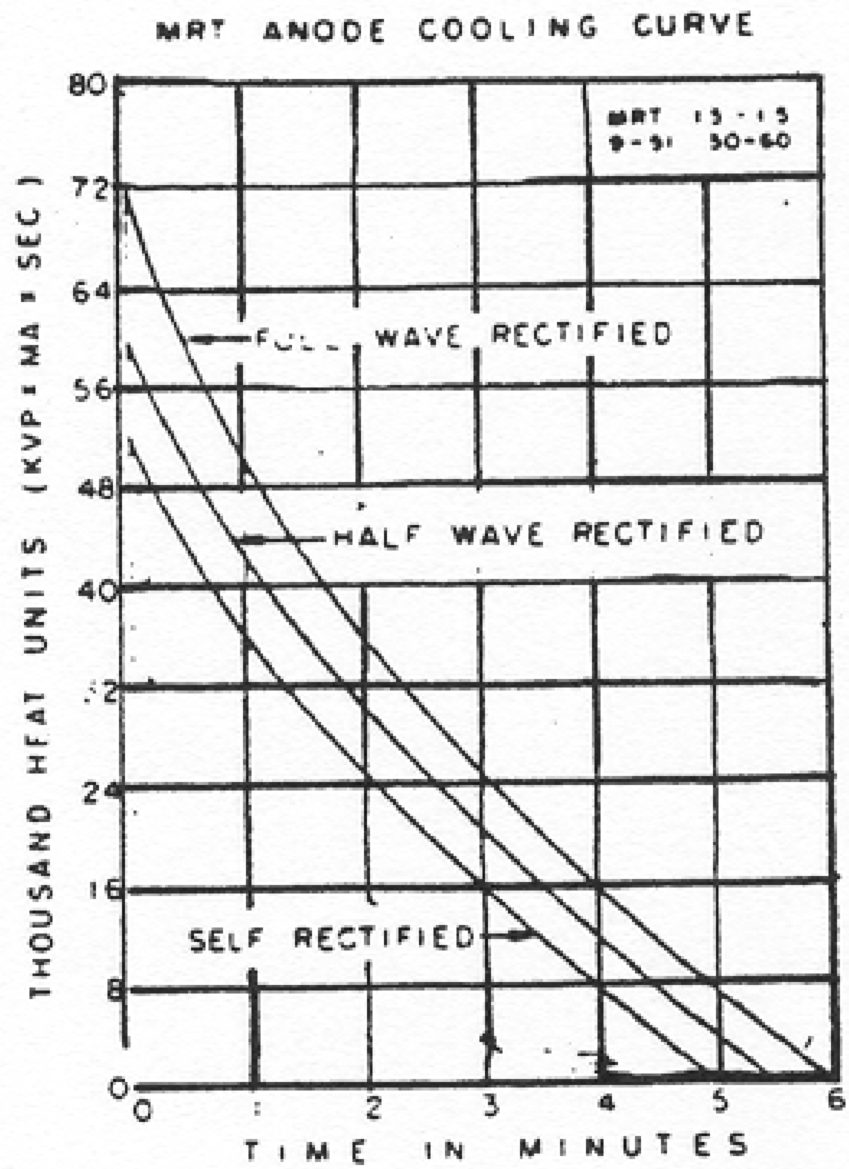


Figure 3-17. Typical anode cooling chart.

Continue with Exercises

EXERCISES, LESSON 3

INSTRUCTIONS. The following exercises are to be answered by marking the lettered response that best answers the Question, or by completing the incomplete statement, or by writing the answer in the space provided at the end 'of the Question.

After you have completed all the exercises, turn to "Solutions to Exercises," at the end of the lesson and check your answers with the Academy solutions.

1. The function of the autotransformer is to:

    a. Stabilize the fixed voltage of the step-down transformer.

    b. Act as a voltage regulator to the filament.

    c. Select the primary voltage for x-ray machine circuits.

    d. Help reduce power loss in the transformer due to eddy currents.

2. The filament transformer isolates the high voltage from auto- transfers and:

    a. Raises the voltage in the filament circuit.

    b. Reduces the amperage in the filament circuit.

    c. Cools the filament.

    d. Produces a relatively high amperage.

3. What electrical device selects the mA to be used in the filament circuit?

    a. Step-down transformer.

    b. Choke coil.

    c. Main line switch.

    d. Thermionic valve tube.

4. The prereading voltmeter indicates the desired voltage for an exposure. In what part of the kVp circuit is this located?

   a. Between the line voltage compensator and autotransformer.

   b. Across the filament circuit.

   c. Across the primary side of the autotransformer.

   d. Across the primary side of the step-up transformer.

5. The function of the step-up transformer in x-ray equipment is to:

   a. Change AC voltage to DC.

   b. Produce high voltage.

   c. Increase milliamperes to amperes.

   d. Reduce the power loss in the x-ray tube.

6. Three of the meters listed below are activated when the main switch is turned on. Which meter becomes the fourth to show a reading when an exposure is made?

   a. Line voltage compensator meter.

   b. Prereading voltmeter.

   c. Filament ammeter.

   d. Milliammeter.

7. Of the following, which type of rectification is considered most efficient for the production of x-rays?

   a. Self.

   b. Half-wave.

   c. Full-wave.

   d. Inverse suppressor.

8. When a two-valve rectification system is used, the current flows from the power source through which of the following sequences of tubes?

   a. First valve tube, the x-ray tube, the other valve tube, and back to the source.

   b. Two valve tubes in a series, the x-ray tube, and back to the source.

   c. X-ray tube, the two valve tubes in series, then back to the source.

   d. X-ray tube, the two valve tubes in parallel, then back to the source.

9. At what point in the circuit of the self-rectifying x-ray machine does rectification occur?

   a. Between the power source and the prereading voltmeter.

   b. Between the prereading voltmeter and the contactor.

   c. Between the timer and the step-down transformer.

   d. Within the x-ray tube.

10. What kind of timer always produces radiographs of exactly the same density?

   a. Synchronous timer.

   b. Impulse timer.

   c. Photoelectric timer.

   d. Electronic timer.

11. Which of the following phenomena is necessary before electrical x-rays can be produced?

   a. Electrons of any speed using a high voltage.

   b. Wavelengths with low frequency.

   c. Electrons striking any target of porous material.

   d. High-speed electrons stopped by a hard, dense target.

12. Which part of the X-ray tube controls the rate at which electrons are released?

    a. Anode.

    b. Glass envelope.

    c. Target.

    d. Filament.

13. What are the two basic requirements of the target in an x-ray tube?

    a. Low electrical resistance and strong magnetic fields.

    b. High melting point and high atomic number.

    c. Electrical neutrality and good heat conduction.

    d. Low electron emission and high potential to ground.

14. In order to increase resistance to surface etching, ____________________________ is sometimes used as a target material.

    a. Rhenium-tungsten alloy.

    b. Steel.

    c. Molybdenum.

    d. Copper.

15. What main characteristic of a rotating anode tube permits it to be used for a number of exposures with less waiting than is necessary with a stationary tube?

    a. Changing target face.

    b. Larger anode stem.

    c. Increased size of the tube portal.

    d. Choice of two focal spots.

16. The size of the actual focal spot affects:

    a. Line focus.

    b. Picture size.

    c. Heat loading capacity.

    d. Rotation of the anode.

17. A device for shortening exposure times by cutting out part of the sine wave is a:

    a. Photon activator.

    b. Tungsten target.

    c. Copper anode.

    d. Grid-controlled tube.

18. The maximum single-exposure factors for an x-ray tube are obtained from

    a. A universal tube chart.

    b. A tube rating chart pertaining to that tube.

    c. A housing cooling chart.

    d. A heat unit chart.

19. How many HU (heat units) would be generated by one exposure using 95 kVp, 100 mA, and 1/2 second on a single phase, full-wave machine?

    a. 950 HU.

    b. 1,500 HU.

    c. 3,000 HU.

    d. 4,750 HU.

20. How many exposures per minute can be made with safety when the cooling rate is 27,000 heat units per minute, the tube is at maximum heat, and the following technique is used: 90 kVp; 150 mA; 3/10 second, on a single phase full-wave machine?

    a. 4.

    b. 5.

    c. 6.

    d. 66.

Check Your Answers on Next Page

SOLUTIONS TO EXERCISES, LESSON 3

1. c (para 3-2b)
2. d (para 3-3)
3. b (para 3-3a)
4. d (para 3-4a(5))
5. b (para 3-4b(1))
6. d (para 3-6)
7. c (para 3-4b(3))
8. a (para 3-4b(3))
9. d (para 3-4b(3))
10. c (para 3-5e)
11. d (para 3-7)
12. d (para 3-8a)
13. b (paras 3-10a, b)
14. a (para 3-10c)
15. a (para 3-10e)
16. c (para 3-11a)
17. d (para 3-13a)
18. b (para 3-14a)
19. d (para 3-14a(1)) (HU = kVp x mA x sec
    = 95 x 100 x .5
    = 4,150)
20. c (paras 3-14a(1), b(4)) (HU = kVp x mA x sec
    = 90 x 150 x .3 = 4050
    CR/HU = Exposures per minute
    27.000/4050 = 6.7 exposures per minute)

End of Lesson 3

LESSON ASSIGNMENT

LESSON 4 X-Ray Safety.

LESSON ASSIGNMENT Paragraphs 4-1 through 4-36.

LESSON OBJECTIVES After completing this lesson, you should be able to:

4-1. Identify means of protecting both yourself and the patient from electrical shock and unnecessary radiation.

4-2. Be able to discuss fuses, circuit breakers, grounding, resistance, rescue and resuscitation of shock victims.

4-3. Be able to discuss ionization, photoelectric effect, bremsstrahlung effect, factors influencing radiation damage, radiation measurement, maximum permissible dose.

4-4. Describe kinds and effects of radiation damage.

SUGGESTION After completing the assignment, complete the exercises of this lesson. These exercises will help you to achieve the lesson objectives.

LESSON 4

X-RAY SAFETY

Section I. AVOIDING ELECTRICAL HAZARDS

4-1. INTRODUCTION

Electrical shocks do not just happen--they are caused. Generally, they are the result of carelessness or ignorance. The radiology specialist operates elaborate electronic equipment. The maintenance of this equipment is not his responsibility. However, he must understand the basic principles of electrical protection so he can recognize potential hazards and take actions to have them eliminated before an accident does occur.

4-2. FUSES--MACHINE PROTECTION ONLY

Fuses and circuit breakers are protective devices that open the circuit when current flow becomes excessive. However, a fuse does not offer any protection for the x-ray specialist or the patient. It protects only the equipment. This point must be remembered so you will not have a false sense of security when you work around fused electrical circuits. The circuit shown in figure 4-1 has a 15-ampere fuse. If the currents through resistors 1, 2, and 3 are added, they total 14.5 amperes. This is close to the maximum current carrying ability of the 15-ampere fuse. Figure 4-2 shows the same circuit with an additional parallel branch--a human body. Let us assume that the electrical resistance of the body is 11,000 ohms. The current through the body as determined by Ohm's law is

$$I = \frac{E}{R} \text{ or } \frac{100}{11000} \text{ equals 0.01 amperes.}$$

Therefore, connecting the human body has increased the total current through the fuse from 14.5 to 14.51 amperes. Obviously, not enough to burn out the fuse and open the current--but enough to kill.

a. **Fuse Ratings**. The rating of a fuse for a particular circuit is based on the amount of current that the circuit is designed to carry under normal operating conditions. If a fuse burns out, it should be replaced with a fuse of the same rating. Under no conditions should the fuse be replaced with one that has a higher rating. Furthermore, if the replaced fuse burns out again, turn off the equipment and initiate actions to have the equipment repaired. The same holds if a circuit breaker repeatedly opens the circuit.

b. **Fuse Overloads**. Electrical fires are frequently caused by circuit overloads. For instance, **if** someone replaces a 15-ampere fuse with one rated at 30 amperes, the current in the circuit would have to double before the fuse would burn out. Besides damaging the equipment, the increased current could generate enough heat to cause a fire.

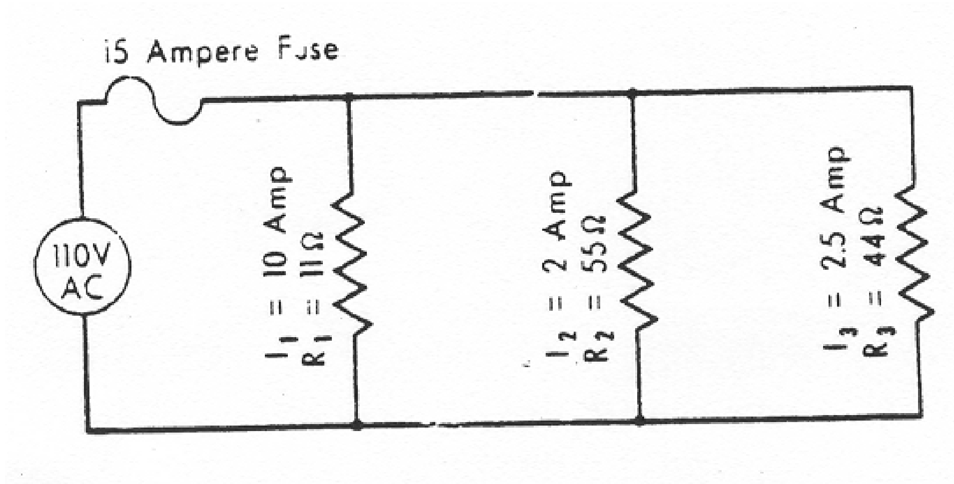


Figure 4-1. Representative parallel circuit.

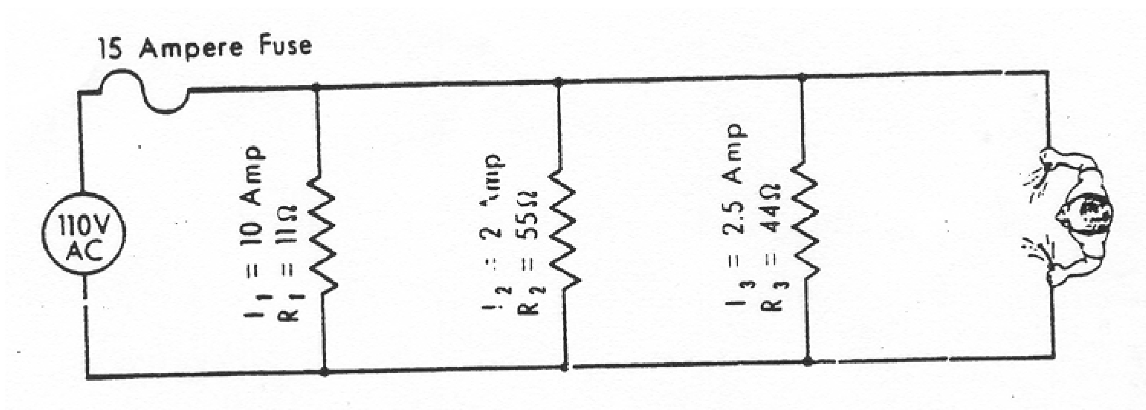


Figure 4-2. Representative parallel circuit with human body added as one element.

4-3. SEVERITY OF ELECTRICAL SHOCK

The severity of an electrical shock is primarily determined by the amount of current and the area of the body that is involved.

a. **Effects of Amperage**. No medical authority will state the minimum amount of current required to kill because there are many factors involved.

(1) However, some approximate values of electrical current and their associated physiological effects are:

(a) <u>0.001 amperes</u>. Threshold of perception. Sensation of tingling.

(b) <u>0.016 amperes</u>. "Can't-let-go" current. Level of current where subject is unable to release grip on the electrical conductor.

(c) <u>0.050 amperes</u>. Pain, possible fainting, exhaustion, mechanical injury. Heart and respiratory function may continue.

(d) <u>0.100-3.0 amperes</u>. Ventricular fibrillation.

(2) Some important factors that determine whether or not an electrical shock is fatal are the person involved and his state of health, the area of the body involved, and the length of time the shock is received.

(a) Electrical shock can have both psychological and physiological effects. In the case of elderly people or those in poor health, an electrical shock that would otherwise be minor could trigger a fatal heart attack. It is generally recognized that a current of 0.001 amperes through the body will give a tingling sensation. Although not sufficient to kill, it is sufficient to bring about a psychological reaction that could result in death. Consequently, to be safe--it is best to prevent any type of electrical shock.

(b) The area of the body involved in an electrical shock is very important. If a current of 0.05 amperes flows from the hand to the elbow, the effects would probably be minor. On the other hand, if the same amount of current would flow from hand-to-hand through the heart, it could be fatal.

(c) The length of time the shock is received is a very important factor. If the shock is of short duration, the chances of survival are much better.

b. **Effects of Resistance**. Because current determines the severity of an electrical shock, the goal of electrical protection must be to reduce electrical currents through the body to an absolute minimum. The voltage in an electrical circuit does not change simply because a person decides to be careless and touch it. According to Ohm's law, the only current-limiting factor over which you have control is the resistance. Electrical protection, therefore, is based on the premise of reducing electrical currents through the body by offering a very high resistance to current flow.

(1) Let's assume that an individual touching the 110-volt line has dry hands and represents a resistance of 22,000 ohms. According to Ohm's law, the current would be 0.005 amperes. This would probably cause an unpleasant tingle, and the individual would quickly withdraw his hands from the circuit.

(2) In the same situation, if the individual had wet hands, the body resistance would decrease to 5,500 ohms. As a result, the current would increase to 0.02 amperes, which would probably be enough to make it difficult for the victim to free himself from the circuit.

(3) If, however, the individual touches one side of the circuit with rubber gloves, the high resistance of the rubber increases the total body resistance and, as a result, the body current is too low to be detected by the individual.

(4) The resistive values of the preceding examples were approximate. Their exact value would depend on many other factors such as area of contact, callous formation, moisture of the hands, etc. The point you should remember is that a given voltage may be harmless under certain conditions and kill under slightly different conditions.

(5) It has been determined that the amount of current determines the severity of an electrical shock, and that for a given voltage, the current can be decreased by increasing the resistance. Therefore, the voltage required to produce a given amount of current depends on the resistance of the conducting pathway. For example, a patient undergoing heart catheterization could be accidentally electrocuted by 10 volts or less because catheters and wires bypass the skin resistance.

4-4. GROUNDING

Proper grounding of equipment is the most effective way of reducing electrical hazards. Proper grounding of portable electrical equipment can be achieved with polarized three-prong plugs. Otherwise, portable equipment must be grounded in some other way. Permanently installed equipment, such as the x-ray table, tube stand, fluoroscopic apparatus, etc., are all connected to a common ground. The purpose of the common ground is to ensure that there is no difference in potential between the chassis of the various pieces of equipment.

a. Polarized plugs ensure proper grounding by the use of three prongs. The third prong connects the casing of the equipment to ground, thus preventing the possibility of a potential difference between the equipment and ground. Unfortunately, removing the ground connector to fit the three-prong plug to a two-prong outlet too often voids the safety features of the three-prong plug.

b. Another common blunder is to use an adapter to connect the three-prong plug to a two-prong outlet without using the ground wire. If, for some reason, a three-prong plug must be connected to a two-prong outlet, the ground wire of the adapter should be connected to the center screw of the cover plate.

4-5. COMMON DANGER AREA

In order to function safely, the x-ray specialist must know some common danger areas within an x-ray department and how he can contribute to preventing electrical shock to himself, the patient, and to fellow workers.

a. Equipment should be inspected daily for frayed wires and loose connections. If discrepancies are found, they are reported to the department supervisor immediately so that he can initiate actions to have the equipment repaired.

b. Always make sure that any accessory equipment used is grounded to the same ground point as the fixed equipment. Dangerous voltage differences can exist between different equipment unless each item uses a common ground. In the special procedure room, this becomes extremely important since a number of electrical devices may be connected directly to the patient. Without the skin resistance, electrocution can result from very low voltages.

c. The darkroom is always a danger spot. Wet floors and water pipes provide good connections to ground. Be careful not to connect yourself into the circuit by touching ground with one hand and an electrical voltage with the other at the same time (one-hand rule). Again, if the casings of all electrical items are properly grounded, the potential differences between the equipment and ground are eliminated.

d. Portable radiographic units should never be used unless they are properly grounded. If a three-prong plug is not available, the casing of the portable can be grounded to a radiator or water pipe. Before using radiators or water pipes as a ground connection, let the medical maintenance specialist check them out to make sure that they constitute a ground. At times, a plastic pipe or connector may insulate them from ground.

e. A radiologic specialist is not an equipment repairman. Except for minor maintenance, qualified maintenance personnel should do repairs.

4-6. RESCUE OF ELECTRICAL SHOCK VICTIMS

Although necessary precautions have been taken, electrical shock can still occur. When and if it occurs, the x-ray specialist must be familiar with the procedure for rescuing the victim.

a. First, you should check to see that whatever shocked the victim does not pose any danger to you, too. If the victim is still in contact with the source of electricity, you must separate him from the source, or the next person to come along will have two people to rescue.

b. If you can remove the danger by turning the power off, do it! If that seems to be impossible or impractical, use a stick or any other object made of a nonconductive material to separate the victim from the source of shock.

c. If you cannot remove the source of shock, then remove the victim. Touching only his clothes or using some other type of nonconductor, drag the patient to safety. Whatever you do, do it fast! The sooner resuscitation procedures are started, the better the victim's chances of survival. Artificial respiration and closed-chest massage may be needed.

d. The best weapon against electrical shock is knowledge of electricity and common sense. Ignorance when handling electricity can be a passport to death

Section II. RADIATION--INTERACTION OF PHOTONS WITH MATTER

4-7. INTRODUCTION

The definition of the term interaction is quite simple: it is one force or body having a measurable effect on another force or body. One can see daily evidence of interaction: in a bowling alley, at the lake watching a sailboat, or on the job in the many uses of electrical transformers. The interaction that the radiologic specialist must fully understand is that which takes place when a beam of x-ray photons passes through anything having mass and occupying space, or more simply, matter. An x-ray beam, consisting of photons of pure energy, transfers its energy to the matter through which it is passing, whether it be air, an x-ray film, or the living tissues of the radiologic specialist or the patient. This transfer of energy is not as simple as that seen in bowling, sailing, or electric transformers: it involves the x-ray photons, which cannot be seen, heard, felt, or detected with the normal senses; and, in many cases. the interaction itself is not immediately evident without complicated devices to detect these events. Some, if not all, of the x-ray energy seems to disappear in certain materials. The term which best describes this phenomenon is absorption. Absorption is the process by which an x-ray photon transfers its inherent energy to the medium through which it is passing. Some results of this absorption are: (1) chemical changes in film emulsion, (2) electrical changes in a radiation detection instrument, and (3) biological changes in living tissue.

4-8. IONIZATION

The changes mentioned above are all brought about by a process known as ionization. Ionization can be defined as any process that results in the removal or addition of an orbital electron from or to an atom or molecule, thereby leaving the atom or molecule with an overall positive or negative charge.

a. Ionization can occur when an electron is struck by a photon, at which time an energy transfer will take place. Although it is technically possible for this energy transfer to take place in the nucleus, the chances of a photon reaching that vicinity are extremely remote. After an ionizing event occurs, the remaining particles are called a pair of ions (in the case of electron removal). The parent atom (minus an electron) has an overall positive charge and is known as a positive ion. The ejected electron has a negative charge and is known as a negative ion. This process of ionization is illustrated in figure 4-3.

b. Radiation is measured by the number of ion pairs it causes. The amount of radiation that causes approximately two billion pairs of ions to be formed in one cubic centimeter of air (at normal pressure/temperature) is known as one roentgen (R).

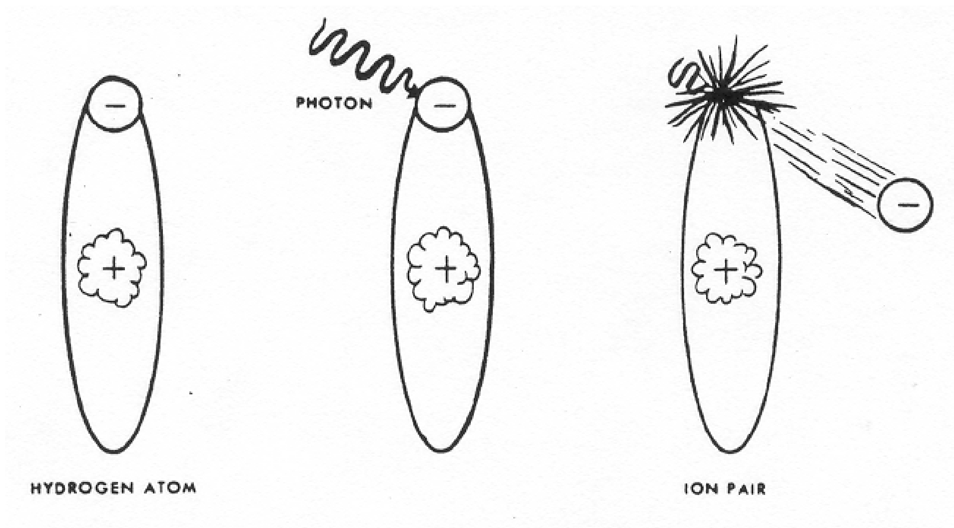


Figure 4-3. Ionization of an atom.

c. The two types of ionization that generally occur in the diagnostic radiation energy range are the photoelectric effect and the Compton effect.

(1) Photoelectric effect. The photoelectric effect, illustrated in figure 4-4, is an all-or-none energy exchange in that the photon strikes an electron, imparts all of its energy to it, and simply vanishes. The electron ejected in this way is called a photoelectron. It departs with all the inherent energy of the photon and can cause secondary ionization due to its increased kinetic energy. In the meantime, as the excited atom returns to the normal state, it quickly attracts another electron to fill the vacant "hole," and radiation is emitted. The energy of the radiation (and the sequence of events that causes the radiation) is much the same as the replenishment of an electron shell vacancy created by the ejection of an electron by electron collision as explained earlier in this subcourse. The photoelectric effect normally occurs with photon energies up to 100 keV.

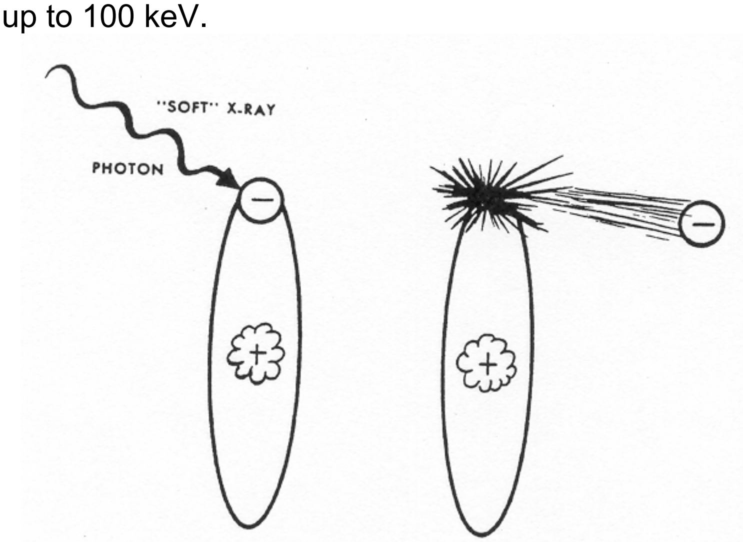


Figure 4-4. Photoelectric effect.

(2) Compton effect. The Compton effect, also referred to as modified or incoherent scattering, is the result of a partial transfer of energy from an x-ray photon to an orbital electron, as seen in figure 4-5. In this case the photon strikes a glancing blow to the electron and ejects it from orbit. Although considerably weakened in energy (longer wavelength), the photon will continue on. While the now "soft" photon will eventually disappear via a final photoelectric effect, the ejected electron can, as in the previous case, continue on to cause another, or secondary, ionization of a nearby atom. In contrast to the photoelectric effect, the Compton effect increases with increasingly higher keV levels, becoming the dominant type at levels above 70 keV.

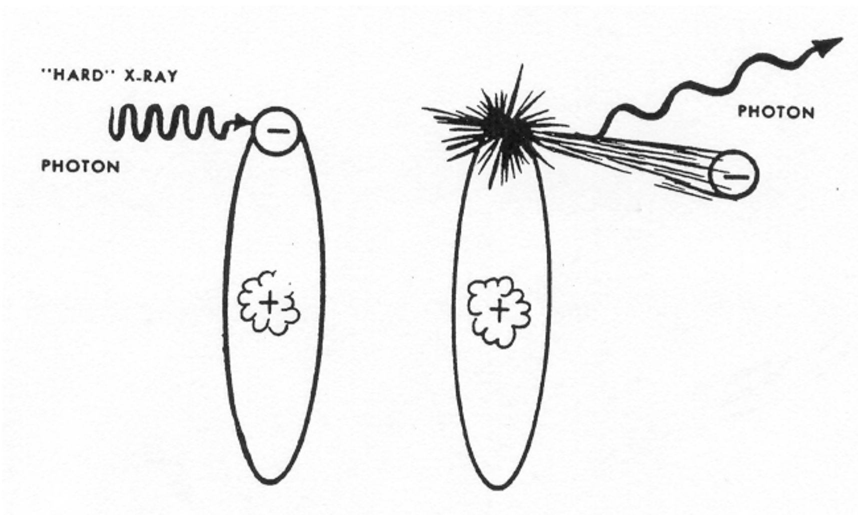


Figure 4-5. Comptom effect.

4-9. OTHER INTERACTIONS

X-ray photons also undergo other interactions in matter. Two of them are described briefly here, although they do not occur with photons in the diagnostic energy range.

a. **Thomson Effect**. The Thomson effect, also known as unmodified, classical, and coherent scattering, is the result of a photon interacting with a whole atom as shown in figure 4-6. This interaction results in the deflection or scattering of the photon from its original direction without a loss of energy to the atom. The Thomson effect occurs with photons of only a few kiloelectron volts of energy.

b. **Pair Production**. With gamma and x-radiation photons of energies greater than 1.02 MeV, pair production occurs. At such energy levels, it is possible that all three interactions can take place in a matter of microseconds. But pair production is predominant among photons with energy in the 5- to 12-MeV range.

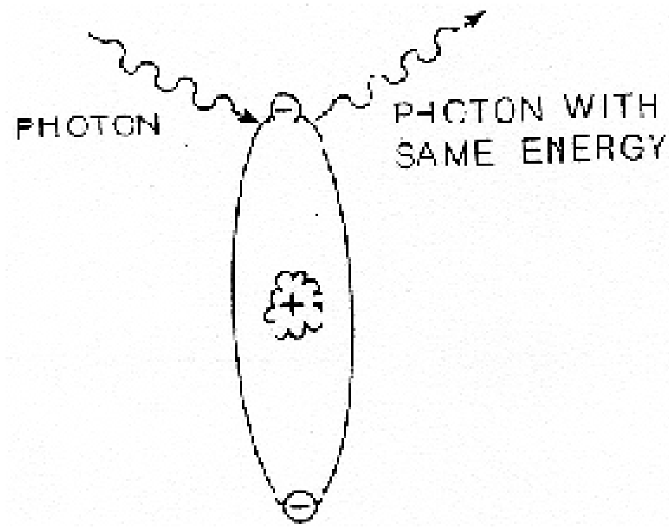


Figure 4-6. Thomson effect.

(1) Only when a high-energy photon passes very close to the nucleus of a heavy atom can it interact with the electric and magnetic fields in such a way that the photon or part of its energy is converted at the same instant into two particles--an electron and a positron of equal mass and equal but opposite electrical charge. This conversion requires photon energy of 1.02 MeV.

(2) The electron can cause ionization in its path and may end up as a free electron.

(3) The positron can also cause ionization in its path. However, the positron, once formed, has a very short life. After losing its speed (energy) by colliding with and ionizing atoms of matter, the positron undergoes a unique and final interaction with an electron. They unite and annihilate each other, giving off two (gamma ray) 0.511-MeV photons. These new photons may produce further ionization by photoelectric effect or by Compton effect.

Section III. RADIATION--DETECTION AND MEASUREMENT

4-10. INTRODUCTION

Since none of the five senses can detect the presence of x-radiation indirect methods must be employed. Although the ionizing capability is harmful and in some cases deadly to living tissue, it is this same ability which is used to provide detection through two means: (1) chemical changes. and (2) electrical changes.

a. **Chemical Change**. Radiologic specialists are familiar with one of the benefits of chemical change. The ionization of silver bromide crystals in a film emulsion causes a chemical change such that those crystals will reduce to black metallic silver when exposed to developing chemicals. The un-ionized crystals remain chemically inert to the developer and are removed during the fixing and clearing' process. Thus, the degree of darkening on a film badge, when processed under controlled conditions, is used to determine the quantity or total dose of radiation received by the wearer.

b. **Electrical Change**. The electrical changes brought about by the ionization process are also useful in detecting the presence of x-radiation. It is possible to detect and measure radiation from the number of freed electrons since and x-ray beam will provide a large number of such electrons where there was essentially none before.

4-11. TOTAL DOSE AND DOSE RATE

<u>Total dose</u> and <u>dose rate</u> are two terms that must be clearly understood before further discussion of the detection and measurement of x-radiation. Total dose is the total amount of radiation received, such as 50 rem, with no indication of the time during which it was received. It may have been 1 minute or 1 year. As the dose gets larger, this time element becomes extremely critical, and in the case of a careless x-ray specialist, perhaps even deadly. Therefore, it is necessary to be able to discuss radiation doses in terms of the rate at which they are being received. Dose rate is the amount of radiation received per unit time such as 50 rem per hour (50 rem/hr). A dose rate of 100 rem/min for 4 minutes would result in a total dose of 400 rem. Additional discussion of dosage and dose rates will be found in Section VI.

4-12. ION CHAMBER

An ion chamber (figure 4-7) is an example of an instrument that measures radiation dose or exposure rates. A difference in potential across the chamber causes movement of the free electrons. The rate of current flow then reflects the amount of radiation striking the chamber. The instrument can be calibrated by using a known quantity of radiation. Figure 4-7A shows no reading on the meter because there is no ionization (no electrons are being freed); consequently, there is no electron flow. In figure 4-7B, ionization is taking place (electrons are being freed) and the application of a potential difference is causing electron flow that results in a reading on the meter. The meter, of course, would be calibrated in roentgens, or some other units. Two examples of instruments used to measure radiation in this manner are the Geiger-Mueller Counter and the Jordan Ion Chamber.

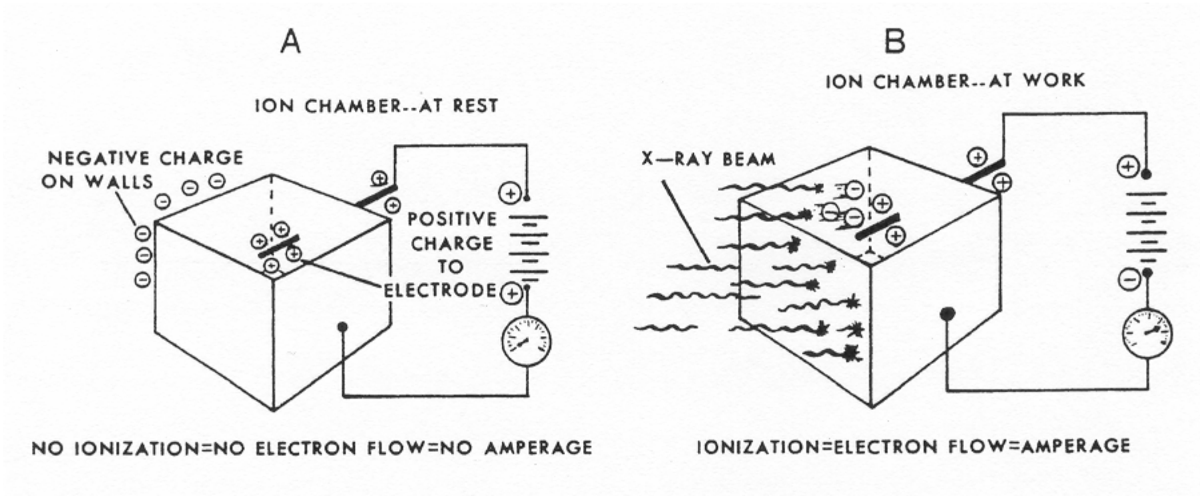


Figure 4-7. Ion chamber.

4-13. FILM BADGE

The film badge is an example of a total dose detector. It is the device most commonly used to detect and measure occupational radiation exposures. Precise procedures concerning wearing and maintenance of film badges can be found in the appropriate directives.

a. A film badge consists of a film packet in a film holder usually constructed of plastic or metal. In the film packet are two pieces of photographic film. One has a double emulsion, and one has emulsion on one side only. The single emulsion is of prime importance when loading the film holder. The film may contain only an x-ray sensitive emulsion, or it may be sensitive to x-rays, gamma rays, and beta particles. Special films are available to detect and measure neutrons.

b. The film responds to radiation exactly as does radiographic film; ionization occurs within the emulsion layer, bringing about a chemical sensitivity to developer solution in those silver bromide crystals so ionized. Then the radiation dosage is determined by the film density. Processing is carried out under extremely controlled conditions by a central agency to ensure accurate and constant results.

c. The film badge should be worn according to the previously mentioned directives, so refer to them for guidance. Generally it is worn on an area of the body expected to receive the highest exposure, such as the chest. (Occasionally, it may be advisable to wear an additional film badge to determine local exposure. An example would be a wrist badge worn by a radiologist during fluoroscopy to check exposure to that area.) The film badge should not be carried in a pocket or behind any obstruction such as coins, combs, or cigarette packages as they tend to absorb radiation and reduce the ultimate density reading of the film. Wearing of the film badge in conjunction with a protective apron is described in the appropriate directive. X-ray specialists should avoid receiving a direct exposure of x-rays while wearing the film badge, such as when undergoing diagnostic or therapeutic x-ray exposure themselves. This is because x-ray exposure in those instances is not to be included in the maximum permissible dose. Film badges should also be protected against direct sunlight to prevent thermal sensitization and possible light leaks in the wrapping paper.

d. When not in use, film badges should be stored in a radiation-free area along with a control film badge. The purpose of the control film badge is to permit the laboratory responsible for processing and evaluating the film badge to take into account such factors as background radiation, temperature variations, etc., that would otherwise be recorded as an occupational exposure.

e When an overexposure is indicated on a film, an investigation is conducted to see if the exposure was indeed accidental or if it was the result of a deliberate act or carelessness. Some of the most common causes of overexposure are:

(1) Deliberate exposure of the film badge.

(2) Improper storage of the film badge.

(3) Failure of the individual to utilize protective shielding.

(4) Improper working techniques.

(5) Inadequate or defective radiation shielding.

(6) Unintentional wear of the film badge while receiving diagnostic or therapeutic x-rays.

(7) Failure on the part of the submitting installation to identify the questionable film packet as having been used for nonroutine recording of radiation exposure.

f. Improper use of film badges results in misleading reports and waste of time and money in unnecessary investigations. Film badge programs are designed to provide radiation workers with a means for detecting accidental exposure to radiation in order that they can be provided with medical treatment if necessary. It behooves specialists to wear the film badge when appropriate to do so and to take required measures to ensure the success of the film badge dosimetry program.

Section IV. RADIATION--PROTECTION

4-14. INTRODUCTION

Radiation protection can be provided in several ways. The factors that determine the level of protection provided are time, distance, and shielding. Generally speaking, the time of exposures should be limited to the absolute minimum required for diagnosis and/or therapy. In other words, ensure that exposure times are kept as short as possible. Distance from the source of radiation also has an effect on the level of protection provided. And shielding, which is the intentional use of materials of varying densities to limit, control, or modify the electromagnetic energy output of an x-ray tube, is a very useful way of providing protection. To understand the effects of shielding and, therefore, be able to take advantage of it as a radiation protection tool, it is necessary to review certain facts about x-ray photon interaction with matter. Photon energy is lost by many different methods, with photoelectric and Compton effects being the two predominant in the wavelengths associated with medical x-rays. As x-ray photons travel through an absorber (the shielding), the amount of reduction, or attenuation, is determined by three important factors: (1) the energy of the photons, (2) the atomic mass of the absorbing material, and (3) the thickness of the absorbing material.

4-15. INVERSE SQUARE LAW

Distance from the x-ray source is a highly effective method of reducing the intensity of an x-ray beam. This can be expressed in terms of the inverse square law, which states that the x- or gamma-radiation intensity from a point source varies inversely with the square of the distance from the source. Expressed mathematically, the inverse square law is:

$$\frac{I_1}{I_2} = \frac{(D_2)^2}{(D_1)^2}$$

where

I_1 = intensity at original distance.

I_2 = intensity at new distance.

D_1 = original distance.

D_2 = new distance.

Suppose the intensity of an x-ray beam was 100 R/min at a distance of 2 feet from the x-ray tube; what would the new intensity be at a distance of 4 feet? By substituting the data from the above problem into the formula, the new intensity can be found as follows:

$$\frac{100}{I_2} = \frac{(4)^2}{(2)^2}$$

$$\frac{100}{I_2} = \frac{16}{4}$$

$$\frac{100}{I_2} = \frac{4}{1}$$

$$4(I_2) = 100$$

$$I_2 = 25 \text{ R/min}$$

By doubling the distance from the x-ray tube, the intensity of the beam can be reduced to one-fourth its original value--100 R/min to 25 R/min. This is an impressive reduction in intensity that can be used to advantage by the x-ray specialist in keeping his exposure to radiation to the barest minimum. As stated in the definition of the inverse square law, the formula is applicable only to radiation from a very small source such as the target in an x-ray tube.

4-16. PHOTON ENERGY FACTOR

A factor that influences photon absorption or beam attenuation is the energy level of the photons. The higher the photon energy, the more penetrating is the x-ray beam, regardless of the material used for shielding. As kVp is increased, photon energy is increased, causing more penetration. Figure 4-8 shows three blocks of absorbing material. As can be seen, more of the high-energy photons penetrate the absorber than do the low-energy photons.

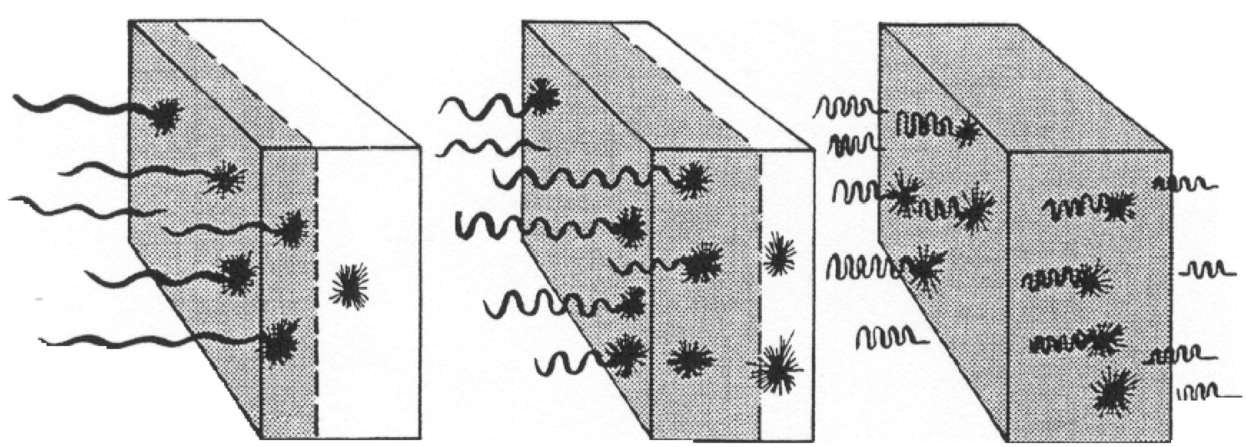
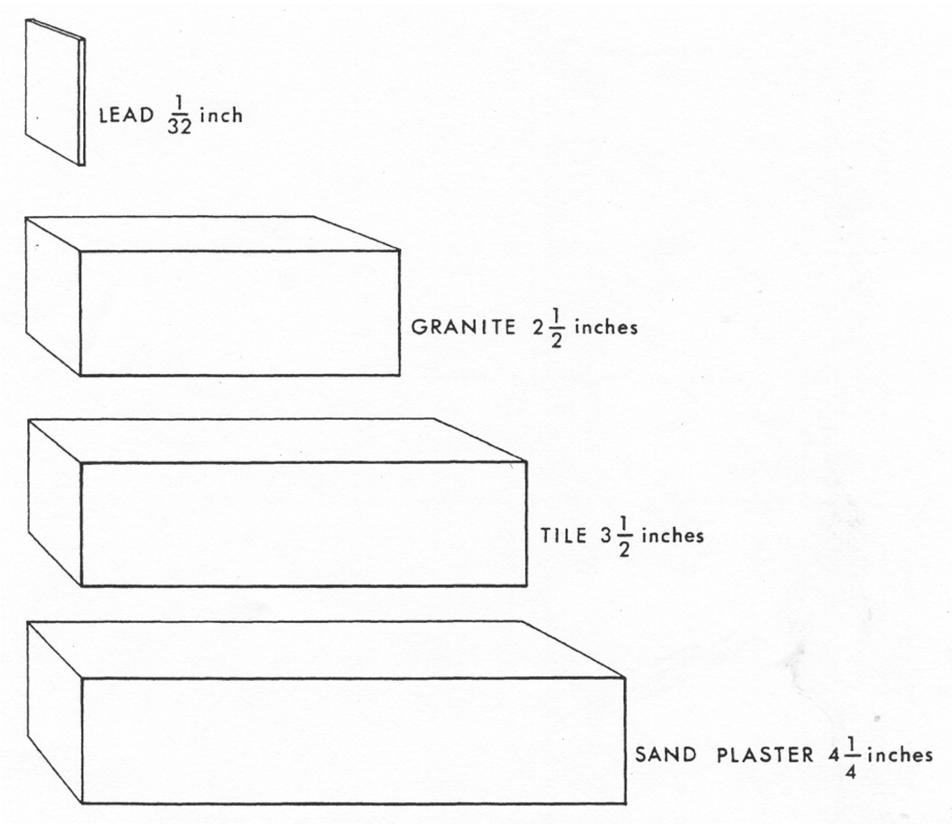


Figure 4-8. Penetration power of photons of various energy levers.

4-17. ABSORBER DENSITY

A characteristic of an absorber, which determines its ability to absorb radiation is atomic density. The more closely packed the atoms, the greater is the probability for photon/electron interaction to take place. Consider two pieces of absorbing material -- wood and lead. Both are of equal thickness, but the lead will cause greater attenuation because of its higher density. Due to its density, lead is an excellent shielding material and is widely used in and around radiology departments. The shielding abilities of some common shielding materials as compared to lead are shown in figure 4-9.



4-9. Various shielding materials and their relative effectiveness.

4-18. ABSORBER THICKNESS

Another factor that influences attenuation is the thickness of the absorbing material. If photon energy and absorber density remain constant, then further attenuation can be accomplished by simply adding more absorber material. In other words, if 6 inches of concrete is good, then 12 inches is better. Figure 4-10 shows three blocks of concrete of different thickness with each being subjected to x-ray beams having the same photon energy. Attenuation is greatest with the thickest block of concrete.

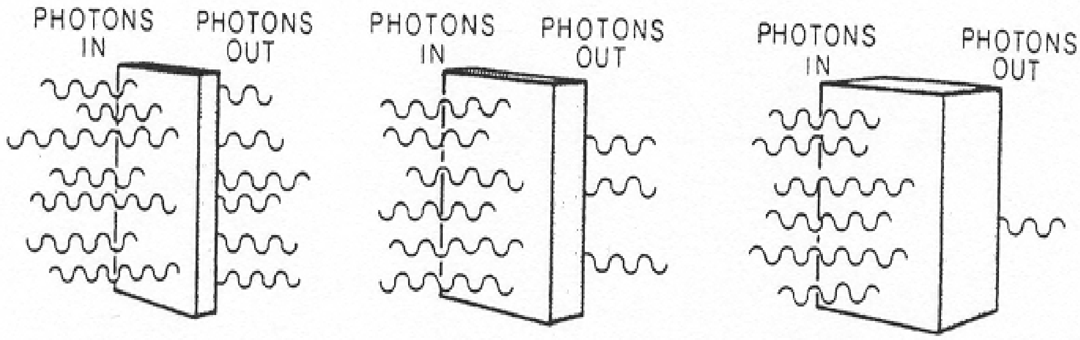


Figure 4-10. Relative shielding effectiveness of various thicknesses of concrete.

Section V. RADIATION--CELLULAR CONCEPTS

4-19. INTRODUCTION

The careless use of x-radiation can incapacitate, disfigure, or even produce death. Since the x-ray specialist plays such a vital role in reducing radiation exposure to himself as well as to his patients, it is necessary for him to be knowledgeable of the concepts involved. This section describes cell structure and activity, how radiation can affect the cell, and the variation in radiosensitivity of different cells.

4-20. LIFE CYCLE OF A CELL

Reproduction, maturation, and death are the three phases in the life cycle of a cell. Reproduction is the process in which a cell divides into two cells. In this process, the genetic operating instructions of the original cell are given to the daughter cells. Certain highly specialized cells do not reproduce themselves and cannot be replaced if destroyed. These include nerve cells and, to a large extent, adult muscle tissue. The blood cells released into the blood stream do not divide, but simply mature and die. However, those retained in the bone marrow reproduce continually and continue to liberate blood cells for use in the body. Cellular reproduction and maturation provide constant tissue repair and growth for the body. If radiation alters cellular processes, the cell may not reproduce or function correctly.

4-21. CLASSIFICATION OF CELLS

Cells are classified as somatic or gonadal. Differentiation between these varieties is essential to any discussion of radiation biology, since irradiation produces distinct effects dependent upon the type of cell involved.

a. **Somatic Cells**. Somatic cells are those of a specific individual tissue such as heart, lung, or liver. Their functions provide life for an individual. Somatic cells give their daughter cells operating instructions to act like they themselves acted.

b. **Gonadal Cells**. Gonadal cells ensure a species' continuance. When creating a new member of the species, the operating or genetic instructions of two cells interweave, add, subtract, and modify. If either cell has been previously modified, it cannot pass on the genetic instructions it should.

4-22. DEOXYRIBONUCLEIC ACID AND RIBONUCLEIC ACID

All cells have one common and extremely vital characteristic: they pass on to their daughter cells operating instructions which are extremely detailed, highly complex, and an exact duplicate of the instructions they received from their parent cells. Deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) are substances found in all cells and serve as blueprints for cell reproduction.

a. **Deoxyribonuclei Acid Molecule**. The DNA molecule is a double helix that has two important functions--replication and control of cellular activities. The fundamental unit of DNA is the nucleotide, which consists of a phosphate group, a 5-carbon sugar, and a nitrogen base. There are four nitrogen bases found in DNA--guanine, cytosine, adenine, and thymine. They are shown in figure 4-11 with different shapes for illustrative purposes. One end of each nitrogen base is identical to the others. It fits the 5-carbon sugar perfectly, but it will not fit the phosphate group. The nitrogen bases fit each other only in specific combinations: guanine with cytosine and adenine with thymine.

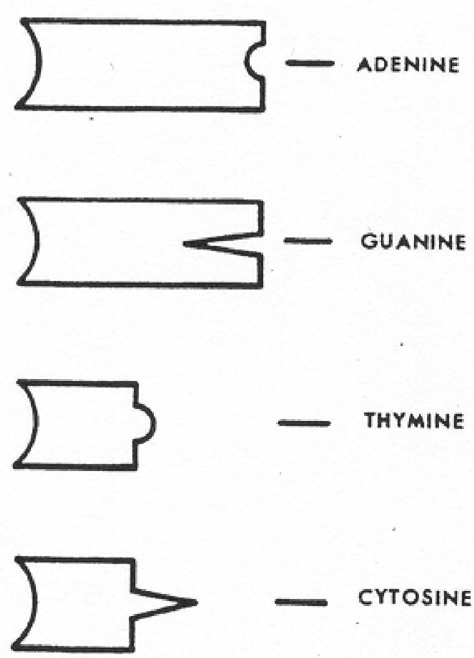


Figure 4-11. The 5 nitrogen bases found in DNA.

(1) The four nitrogen bases constitute the genetic alphabet. They form the blueprints for cell reproduction and are the building blocks of life. Figure 4-12 is an example of an unwound DNA molecule. Notice that the sugar phosphate chain forms the sides of the ladder and various combinations of the nitrogen bases are the rungs. The weakest link in this complex chain is the point where the nitrogen bases join together. This is a hydrogen bond, one of the weakest chemical bonds known. Also note the sequence of the nitrogen bases in figure 4-12. Each variety of cell will have a certain sequence. This sequence is the critical factor when the DNA molecule performs its two functions--replication and control of cellular activity.

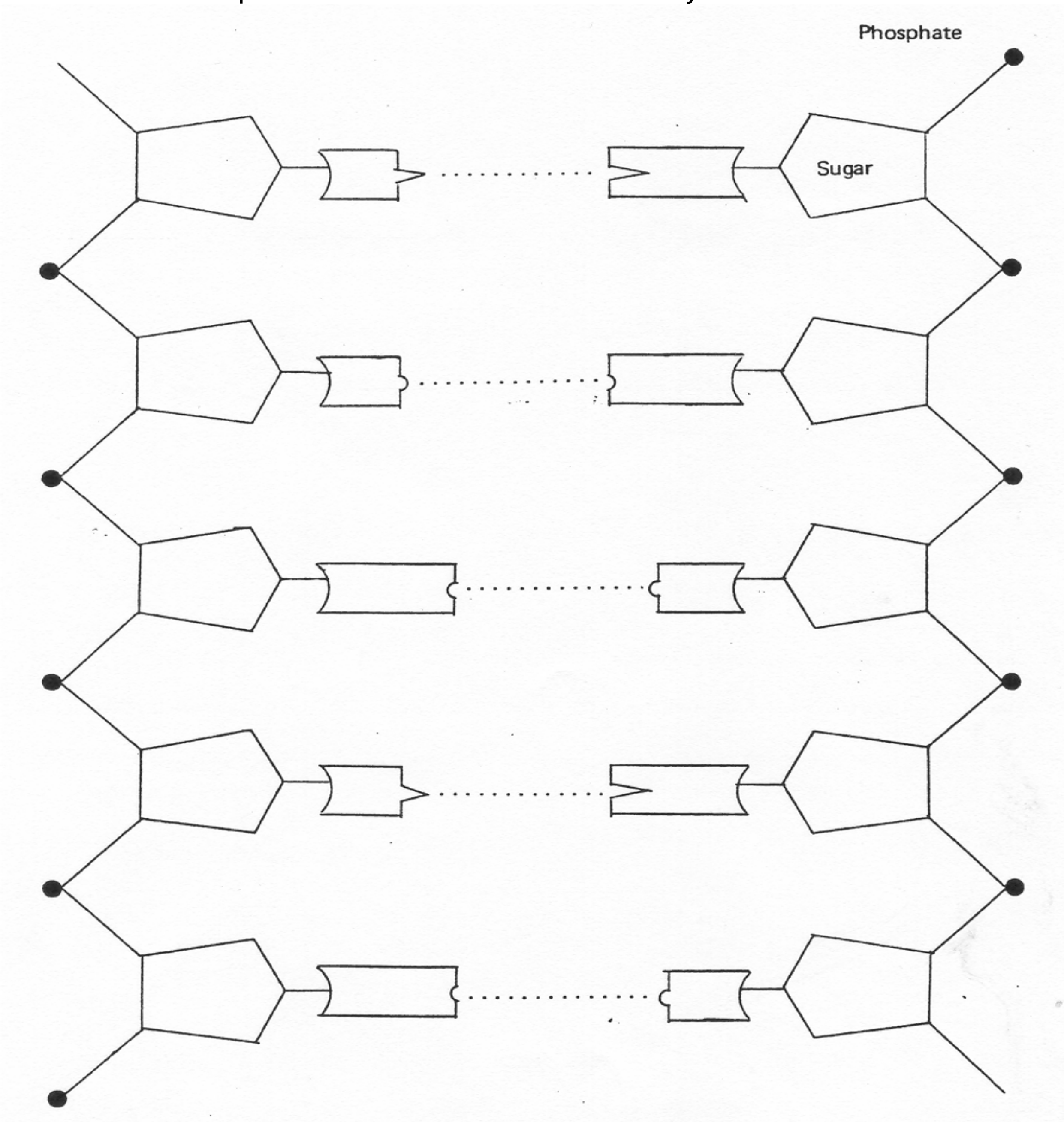


Figure 4-12. Segment of DNA molecule unwound.

(2) Replication must not be confused with duplication. In duplication, a copy of the original is made and the original remains intact. In replication, the original divides and forms two new molecules that resemble the original. Figure 4-13 shows a DNA molecule in replication, before or during mitosis, cell division. The weak hydrogen bond between the nitrogen bases <u>is released</u> and the DNA molecule starts to split. Each separation leaves an exposed nitrogen base that will recombine with nitrogen bases found in the cytoplasm of the cell. When they recombine, the second molecule will be identical to the original molecule, as seen in figure 4-14.

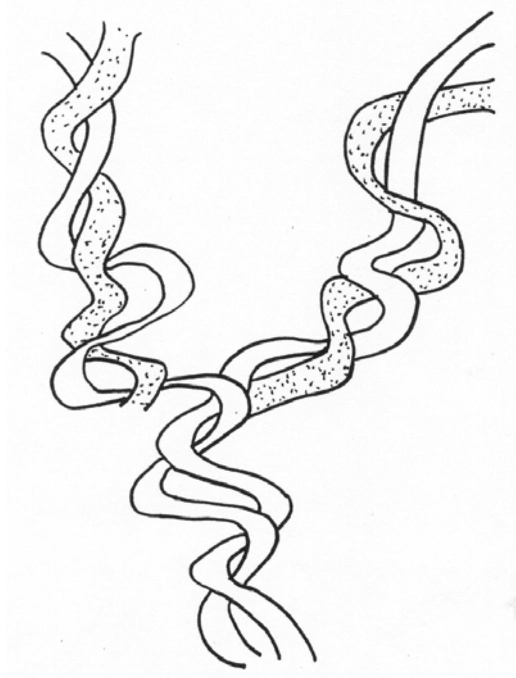


Figure 4-13. Deoxyribonuciel molecule in replication.

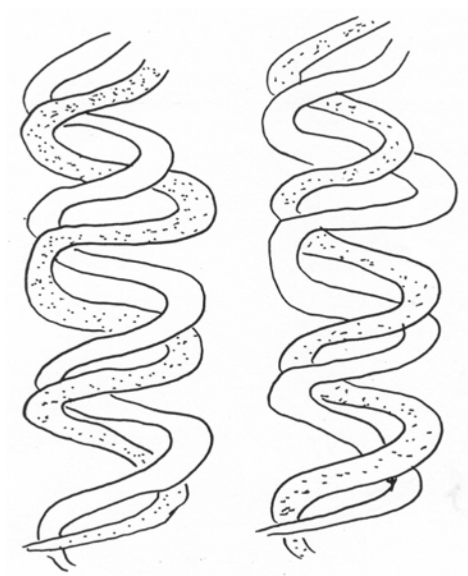


Figure 4-14. Two DNA molecules resulting from replication.

b. **Ribonucleic Molecule**. After replication, there are two identical cells. RNA, which is the messenger system for DNA, enables the cells to function as specific cells. RNA is a single-stranded molecule produced by DNA. In a single cell, the DNA molecule partially splits and produces an RNA molecule. This molecule is given a set of coded instructions that it takes to the ribosome of the cell. The ribosome of a cell is the protein-producing part of a cell, which manufactures the necessary nutrients for a cell by combining certain amino acids that are found within the cell. The RNA molecule instructs the ribosome how to combine these amino acids. When this has occurred, the cell will function properly.

c. **Disturbing the Functions of Deoxyribonuciel**. The above explanation of DNA and RNA is by no means comprehensive. Cell division is a complex process. Fortunately, DNA performs its functions without error as long as its structure is not disturbed. Although other conditions will affect DNA, the one of interest to the x-ray specialist is ionizing radiation.

4-23. HOW IONIZING RADIATION AFFECTS DEOXYRIBONUCIEL

Ionization, you will recall, is the removal of an orbital electron. If this electron is forming the bond between the nitrogen bases, then the ability to replicate exactly is lost. This means that one of the rungs in a DNA molecule may be incomplete or perhaps reincorporated in the wrong order.

a. Any modification in the sequence of nitrogen bases will result in a change of instructions passed from DNA to RNA. When this happens, mutations occur. Mutations are generally considered to be harmful, but, fortunately, they are often recessive and are usually overcome by the dominant characteristics of the normal cells.

b. Sickle cell anemia is a mutation not necessarily caused by radiation. It is an inherited defect in man in which the red blood cells become distorted in the shape of sickles. They tend to form clumps that block the smaller blood vessels, and their tendency to burst brings about anemia, usually resulting in early death. This serious hereditary defect in man is brought about by the substitution of only one nitrogen base in the DNA molecule--a single change in the sequence of the rungs.

4-24. MECHANISMS OF RADIATION INJURY

Two explanations of radiation damage are known as the <u>target theory</u> and the <u>indirect damage theory</u>.

a. **Target Theory**. The <u>target theory</u> is concerned with <u>direct effects</u>. These effects can be produced at cell level or in the whole animal. In either case, they alter cell structure.

(1) At cell level, the changes are produced when energy imparted by radiation acts in contact with the biological structure causing adverse effects. In the whole animal, direct effects can be produced in given tissue by virtue of its life span and function. For example, bone marrow continuously produces blood cells. These immature cells are highly susceptible to radiation injury. A high enough dose of radiation received by bone could result in bone marrow depression with a subsequent drop in the blood count of an individual.

(2) One of the possibilities of direct effects is a chromosome break. Such a break would require 20 ion pairs and could occur as the result of secondary ionization. Gene mutations, on the other hand, can be produced by as little as one ion pair. Chromosome breaks do not necessarily cause immediate cell death. One result of a chromosome break is the possibility of an abnormal recombination. Despite this, the whole cell may still be "operating" normally for the present. There is a definite delay before the injurious effects of radiation are observed. Cell death may occur during attempts at cell division (mitotic-linked death). The sooner the division following radiation, the greater the chances for cell death. Cell death may also occur during subsequent divisions due to loss of chromosome material.

(3) First and second generations may appear perfectly normal and be able to function normally. It should be noted that chromosome damage generally does not bring about cell death unless and until the cell enters division after irradiation.

b. **Indirect Damage Theory**. The indirect damage theory covers all other effects, which are generally produced in the fluid environment and in neighboring cells. These effects may be found in one part of the body due to irradiation of another part. Indirect effects may be the result of circulating toxic substances, histamine imbalance, or autointoxication by tissue breakdown products. The resulting mechanical/chemical injury to cells leads to cell death. It occurs in both man and animal, but animals have provided most of the experimental data. Keep in mind that a given amount of radiation will not produce the same biological effects in a man as it does in a rat. In fact, it will not produce the same injury in different cells in the same man. It appears likely that both direct and indirect actions contribute to the chemical changes that lead to radiation injury in a biological system.

4-25. RADIOSENSITIVITY OF CELLS

Two important factors influencing the varying responses to radiation or radiosensitivity are cell variety and species variety.

a. These factors are explained by the Bergonie-Tribondeau law, which states, "the more undifferentiated physiologically and morphologically, and active mitotically, the longer the cell requires to undergo active mitosis; and the more division it has yet to go through, then the more radiosensitive is the cell." Stated generally, this means immature and rapidly dividing cells are more radiosensitive than mature ones and/or those of stable tissues. A cell in mitosis is much more radiosensitive than the same cell at rest. Blood-forming cells and immature gonadal cells are examples of types of cells that are particularly sensitive to radiation.

b. Nerve, brain, and muscle cells are least sensitive. The reduced sensitivity of nerve, brain, and muscle is due to the fact that a person is born with all the nerve, brain, and muscle cells he will have. Therefore, according to the Bergonie-Tribondeau law, these cells are neither immature nor rapidly dividing and should have a greater resistance to radiation.

4-26. RADIOSENSITIVITY OF SPECIES

Species show an even greater variation in radiosensitivity, as shown in the following examples. The LD (lethal dose) 50/30 varies for humans, sheep, poultry, and bacteria. $^{LD}50/30$ is the amount of radiation required to produce death in 50 percent of the exposed animals or humans within 30 days.

SPECIES	$^{LD}50/30$
Human	400 R
Sheep	525 R
Poultry	900 R
Bacteria	3,000 to 5,000 R

Section VI. RADIATION--RESIDUAL DOSAGE

4-27. INTRODUCTION

a. It is often said that "x-rays accumulate in the body." This statement is not technically accurate; it is more accurate to say that the <u>damaging effects</u> of radiation are cumulative. The basis for this statement is the fact that damage caused by radiation has two components: one component is irreparable or permanent and is often referred to as residual dose; the other component is reparable in that it is possible to recover from its effects. It is believed that about 90 percent of the damage caused by any exposure to radiation can be repaired, leaving about a 10 percent residual component that will not be repaired. It follows, then, that multiple exposures can result in an accumulation of radiation injury.

b. Although the word "safe" is commonly used in referring to radiation exposure, it should be clearly understood that no amount of radiation, regardless of the amount, can be considered 100 percent safe. "Biologically acceptable" is more descriptive in that no individual receiving up to that amount would be expected to develop manifestations of radiation injury.

c. Organizations responsible for defining safe radiation limits provide recommendations that cover all types of ionizing radiation, whether applied internally or externally. Our major concern is exposure to x-radiation from an external source, the x-ray tube. Among the organizations responsible for defining safe radiation limits are:

(1) National Committee on Radiation Protection and Measurement.

(2) International Commission of Radiological Protection.

(3) Nuclear Regulatory Agency.

(4) Environmental Protection Agency.

(5) Energy Research and Development Administration.

d. The safe limits known as Radiation Protection Guides (RPGs) as recommended by some of the organizations previously mentioned are divided into two categories: those governing radiation workers and those governing all others (meaning the general population). A further breakdown specifies the limits for whole-body and partial-body radiation exposure.

4-28. UNITS OF RADIATION DOSAGE

Fundamentally, the harmful consequences of ionizing radiation to a living organism are due to the energy absorbed by the cells and tissues that form the organisms. This absorbed energy (or dose) produces chemical decomposition of the molecules present in the living cells. The mechanism of the decomposition appears to be related to ionization and excitation interactions between the radiation and atoms within the tissue. The amount of ionization or number of ion pairs produced by ionizing radiation in the cells or tissues provides some measure of the amount of physiological damage that might be expected from a given quantity or dose. The ideal basis for radiation-dose measurement, therefore, would be the number of ion pairs produced within the medium of interest. However, for certain practical reasons, the medium used in establishing a unit of measurement was air.

a. **Roentgen**. A roentgen (R) is a unit of exposure. One roentgen is the exposure of x- or gamma radiation such that the associated corpuscular emission per kilogram of air produces in air, ions carrying 2.58×10^{-4} coulomb of electrical charge of either sign (IR = 2.58×10^{-4} coulomb/Kg = 7.7410^{2} electrostatic units per gram of air.).

b. **Absorbed Dose (rad)**. Absorbed dose is the energy imparted to matter in a suitably small element of volume by ionizing radiation, divided by the mass of that element of volume. The rad is the unit of absorbed dose; one rad equals 0.01 joule per kilogram, which equals 100 ergs per gram.

c. **Radiation Equivalent Man (rem)**. The rem is the absorbed dose in rads multiplied by various quality factors. Fortunately, in the energy range used for medical radiography, 1 R = 1 rad = 1 rem. In other words for all practical purposes the rad and rem will be the same as the R.

4-29. MAXIMUM PERMISSIBLE DOSE

Maximum permissible dose (MPD) is affected both by the size of each dose and the rate at which these doses are received. For radiation workers or those individuals whose occupation requires exposure to ionizing radiation on a regular basis (such as the x-ray specialist), radiation protection guides recommend the following maximum accumulated dose. For external exposure, from x- or gamma rays, to the whole body, the maximum average dose rate should not exceed 5 rems per year. The same dose rate applies to the head and trunk, active blood-forming organs, the gonads, and the lens of the eye. When only a single portion of the body is exposed, as compared to the whole body, the maximum permissible dose is sometimes higher. For example, it is recommended that the average dose rate to the hands, forearms, feet, and ankles should not exceed 75 rems per year.

a. No occupational dose is allowed persons under 18 years of age. Individuals who are over 18 years of age, but who have not yet reached their 19th birthday, may be occupationally exposed to ionizing radiation, provided they do not exceed 1.25 rems dose equivalent to the whole-body in any calendar quarter, nor 3 rems in the 12 consecutive months prior to their 19th birthday. The accumulated dose at any subsequent age should not exceed 5(N-18), where 5 is the maximum dose rate per year, N is the age of the worker in years, and 18 is the age prior to which no occupational dose is allowed. Following are two examples of calculating the maximum permissible (accumulated) dose.

Age 20.
5(N-18) = 5(20-18) = 5(2) = 10 rems.

Age 31.
5(N-1B} = 5(31-1B} = 5(13} = 65 rems.

b. AR 40-14, Control and Recording Procedures for Occupational Exposure to Ionizing Radiation, further delineates maximum exposure levels by stating that the accumulated dose equivalent of radiation to the whole-body, head, and trunk, active blood-forming organs, gonads, and lenses of the eye will not exceed 1.25 rem in any calendar quarter nor 5 rems in anyone calendar year.

c. The maximum permissible dose for an individual in the general population group (excluding radiation workers) is significantly lower than that of radiation workers. Currently, it is recommended that the yearly radiation exposure to individuals in the general population should be held to one-tenth that of the occupational limits. This does not include exposure to natural radiation or medical and dental x-ray. Thus, for whole body exposure the radiation dose should not exceed 0.5 rems per year, and partial-body radiation dose should not exceed 7.5 rems per year. The reason that medical and dental x-rays are not included in these totals is that for medical procedures the risk of the exam itself is outweighed by the medical significance of the exam results. (Without the exam, an undiagnosed illness, disease, or injury could be life-threatening.).

d. Study groups that have spent many years in researching the safe amount of radiation that a radiation worker may receive have taken into account the environmental and other man-made radiation to which he is exposed. This includes everything from cosmic rays to watch dials and TV screen emissions. Man's use of radiation in various forms grows day by day. Consequently, the daily nonprofessional exposure can be expected to rise. Three broad factors contribute to critical decisions concerning how much radiation we can or should tolerate. They are:

(1) Changing levels of environmental radiation.

(2) Rapid progressions in technology.

(3) Increasing knowledge of the biological effects of radiation, particularly those that may affect or modify the species.

The radiation protection guides discussed here are subject to constant modification and revision. It is the professional responsibility of every radiologic specialist to remain alert to these changing factors.

Section VII. RADIATION--BIOLOGICAL EFFECTS

4-30. INTRODUCTION

Biological effects, also known as radiation injuries, are described as either chronic or acute. Chronic injuries are those that appear after a large number of repeated exposures to radiation. These injuries appear in 1, 5, or 30 years or perhaps in succeeding generations. Acute injuries are those appearing relatively soon after intense exposure (with 60 days or less). Such intense exposures, if survived, can lead to chronic effects later. The acute effects of whole-body irradiation will probably never be seen in an x-ray specialist, even with the most careless individual imaginable. Therefore, the discussion of these effects will be brief and of academic interest only. Chronic effects are, however, of vital concern to the x-ray specialist not only for his personal interest, but also because of his responsibility to the patient in assuring an absolute minimum of needless exposure. CHRONIC EFFECTS CAN BE BROUGHT ABOUT BY THE CARELESS SPECIALIST through small overexposures that occur too frequently.

4-31. ACUTE RADIATION SYNDROME

The acute radiation syndrome (ARS), due to whole-body x- or gamma radiation, may reflect a variety of illnesses that are dose-dependent. Three major biological systems emerge as the centers of concern, depending upon the amount of radiation received at the time of exposure. They are the hematopoietic (marrow) system, gastrointestinal (GI) system, and the central nervous (brain) system.

a. The marrow ARS is evident between doses of 100 rad and 600 rad. Extreme depression of the blood cells results in severe anemia and overwhelming infection. Deaths average from 20 percent at the lower end of the range to 100 percent at the upper extreme. Medical treatment is extremely complicated and of long duration, but biological salvage is possible.

b. The GI ARS is evident in dose ranges of 300 rad to 1,000 rad. The classic picture is bloody diarrhea and dynamic ileuse, resulting in severe fluid and electrolyte loss. Deaths are 100 percent as there is no effective medical treatment.

c. The brain ARS, following somewhat higher exposures, is also 100 percent fatal. Incapacitation is produced in less than 10 minutes. The classical symptoms are convulsions progressing to coma and death. Cause of death is a sudden and overwhelming cerebral edema. Obviously, there is no effective treatment.

4-32. CHRONIC EFFECTS

It should be noted that chronic effects are not qualified by the whole or partial-body exposure theories. Chronic effects can and do result from intermediate dose ranges, and even from very low dose ranges if exposure is repeated often enough.

a. Radiation exposures increase the incidence of certain types of cancer in man. While the exact mechanism of this damage is not known, repeated radiation damage and repair seems *to* account *for some* cases; whereas in others, the occurrence of somatic cell mutations seems an attractive hypothesis. Earliest evidence was the occurrence of skin cancers at the site of repeated x-ray burns among the early x-ray workers. Bone tumors were markedly increased among the radium watch dial painters.

b. Increases of leukemia incidence have been documented, particularly among early radiologists. Since 1911, when four cases were described, the incidence of leukemia among radiologists has increased. The rate in 1952 was some eight times greater than among the general population. This reflects the fact that the early radiologists were reaching the age at which the delayed effects become more obvious. Since that time, however, the use of protective devices and procedures has caused the incidence of leukemia among radiological workers to become more nearly comparable to that of the general population.

c. Extensive animal data has established that radiation exposure produces an acceleration of the aging process. This effect is quite apart from any specific disease manifestation. The animal simply ages faster and dies sooner from causes indistinguishable from those of nonirradiated animals. As with carcinogenesis, no threshold is apparent.

d. As early as 1927, it was reported that radiation increases the rate of mutations in the fruit fly. This work has since been confirmed in other species. As further evidence of the difference in species' resistance to radiation, it has been shown that the mutagenic effect is ten times greater in the mouse than in the fruit fly for a given radiation dose. Obviously, there is very little human data regarding radiation-induced mutations. However, the following biological facts provide sufficient evidence to warrant concern:

(1) Mutations are transmitted to succeeding generations.

(2) Mutations may be dominant or recessive.

(3) Mutations may eventually result in a genetic line dying out.

(4) There is no threshold dose for the genetic effects of radiation

(5) Any exposure may be accompanied by the production of some.

(6) The number of mutations is proportional to the dose.

e. Direct exposure of the gamete or zygote may occur during x-ray examination of the parent. Indeed, any exposure during the first trimester (first 3 months) of pregnancy MAY carry the penalty of an abnormal child. Chromosome activity is at its maximum in early pregnancy. It has been determined on numerous occasions that therapeutic doses of radiation to the pregnant woman can even produce fetal death. The degree of abnormality varies roughly in proportion to dose rates and exposure time, but there is as yet insufficient evidence to establish a minimum threshold dose for humans.

f. Fertility effects are a grossly overrated radiation effect. True, radiation is capable of reducing fertility--the amount of reduction being dependent upon the dose. However, except for direct, intentional exposure to the gonads, no radiation environment in peacetime is expected to be high enough to cause sterility, either temporary or permanent.

g. Irradiation of the eye has been shown to result in cataract formation (lenticular opacity), which appears some time after exposure by x- or gamma rays.

Section VIII. PRACTICING RADIATION PROTECTION

4-33. INTRODUCTION

The previous discussion shows how adverse biological effects can occur as a result of exposure to ionizing radiation. The discussion also shows that the effects can occur well within the dose levels used in medical x-ray diagnosis and treatment. Consequently, radiation protection must be the concern of every x-ray specialist. In addition to having some knowledge of the biological effects of ionizing radiation, you must practice positive, protective measures in the exposure room. Furthermore, it is not enough to limit the protection to yourself, the x-ray specialist; the patient deserves, and should be given, equal consideration to keep his exposure also at a minimum. The final responsibility for protecting both yourself and the patient from needless exposure to radiation rests with you. Granted, health physicists, radiologists, supervisors, and other personnel establish and maintain protective programs in the radiology department. But without the constant efforts of the x-ray specialist who makes the radiographs, effective protection against ionizing radiation will not exist. This section will present some procedures to be used by the x-ray specialist to reduce exposure to himself, to patients, and to others who must be present in the exposure room.

4-34. PROTECTION FOR THE SPECIALIST

Good working habits, common sense, and proper respect for ionizing radiation are very important in radiation protection. With present day knowledge and the vast amount of protective resources at your disposal, there is absolutely no reason for you to even closely approach the maximum permissible dose. If proper precautionary measures are practiced daily, the risk involved in being an x-ray specialist is very small when compared to other risks such as driving a car or crossing the street. The steps necessary to keep your exposure at a minimum can be divided into two categories: (1) those that protect you from the primary beam, and (2) those that protect you from secondary and scattered radiation (SR).

a. **Protection from the Primary Beam**. Protecting yourself from primary radiation is very simple: do not expose any part of your body to the primary beam. This means that during exposure you should never hold a patient or cassette, or in any other way subject yourself to primary radiation. In addition, you should not allow another x-ray specialist to perform these tasks. If assistance is needed to obtain a radiograph on uncooperative patients, use someone who is not occupationally exposed to ionizing radiation and be sure that he wears protective clothing such as lead gloves and apron.

b. **Protection from Secondary and Scatter Radiation**. Although the intensity of SR is less than primary radiation (for a given technique), the radiation hazard to the x-ray specialist is perhaps greater with SR. The reason for this is because SR can reach virtually all parts of the exposure room while the primary beam is restricted to an area which is much smaller by comparison. Therefore, while it is a simple matter to remain clear of the primary beam, it is somewhat more difficult to elude SR. Following are some general rules.

(1) Standing behind a protective barrier. Always remain behind a protective barrier when making an exposure. Control booths are designed so that the specialist will not be exposed to any radiation that has scattered only once. In other words, the radiation must scatter at least twice before it reaches you. Use the lead impregnated glass window to observe the patient. Do not defeat the purpose of the control booth by leaning out from behind the barrier to make the exposure.

(2) Using distance for protection. Distance is an effective means to reduce exposure. Since radiation intensity decreases as the distance from the source increases, exposure can be reduced by staying as far from the source as possible. This rule is particularly important to remember when taking portable radiographs where protective barriers are usually not available.

(3) Protection during fluoroscopy. During fluoroscopy, be sure to wear a protective apron. When you are not needed to assist the radiologist, remain in the control booth.

4-35. PROTECTION FOR THE PATIENT

As previously mentioned, any radiation protection program must include patients. There are several ways to reduce radiation exposure to the patient.

a. **Avoid Repeat Films**. A common cause of additional patient exposure is to repeat films. When a film is repeated because of improper processing, positioning, technique selection, or other technical reasons, the patient and you are both subjected to twice the original exposure. Therefore, getting a diagnostic radiograph on the first attempt helps considerably in avoiding damage.

b. **Collimation**. A major cause of excessive patient exposure is failure to adequately restrict the primary beam. Always limit the primary beam to the- smallest size necessary to include the part or parts being x-rayed. Primary radiation should not cover any areas beyond the borders of the film. In other words, if you are using a 14" X 17" film, the beam should never be greater than 14" X 17." There are times when it is advisable to restrict the primary beam to a size smaller than the size of the film. Some examples are sinuses, spot films, and other examinations where a restricted beam will not interfere with the diagnostic information. (An added "bonus" of restricting the primary beam to the smallest practical size is the reduction of SR, and consequently less fogging of the film).

c. **Filtration**. In most instances, soft or low energy x-rays that exit from the tube serve no useful purpose in diagnostic radiology. They have little or no penetrating power and consequently are absorbed by the patient1s skin. To protect the patient from this type of radiation, filters must be added to the useful beam. According to U.S. Army TB MED 521, total filtration in the useful beam shall not be less than 2.5 mm of aluminum or its equivalent for voltages greater than 70 kVp. For voltages between 50 and 70 kVp, a minimum of 1.5 mm of aluminum or its equivalent is required. Below 50 kVp, total filtration should be 0.5 mm of aluminum or its equivalent. This requirement (0.5 mm) may be assumed to have been met if a conventional diagnostic tube is employed since inherent filtration in conventional tubes is at least equivalent to 0.5 mm of aluminum. If a beryllium window tube is employed, added filtration will be required.

d. **High-kVp Technique**. The absorbed radiation dose, and the biologically significant dose to the patient, can be reduced by using the high-kVp technique. Intelligent use of high-kVp technique produces excellent results, but the x-ray specialist must be aware of its limitations. Obviously, when the maximum contrast is required, as in mammography, high kVp cannot be used. In terms of radiation protection, high kVp does not necessarily mean 100 to 150 kVp, but it should be interpreted to mean the highest kVp that will produce a good quality radiograph of a particular part.

e. **Films and Screens**. High-speed screens and films are available and their use will certainly reduce the radiation exposure of the patient. Again, they must be intelligently used. When the speed of a screen or film is increased, there is some loss of detail. If the radiologist is willing to sacrifice some radiographic detail in order to reduce exposure to the patient, by all means use high-speed screens and films. The radiologist must make the decision, since he is the one who interprets the films.

f. **Shielding**. Appropriate and effective gonadal shielding should be utilized on patients who have a reasonable reproductive potential when the gonads will be within the useful beam or within 2 inches (5 cm) of the beam edge of an adjacent useful beam despite proper beam limitation, unless such devices interfere with the conditions or clinical objectives of the examination. Specific area gonad shielding should provide attenuation of x-rays at least equivalent to that afforded by 0.25 mm of lead. In the case of male patients, it is recommended that specific area testicular shielding be employed for those examinations in which the pubic symphysis can be visualized on the film and the clinical objectives will not be compromised by the use of specific area testicular shielding. Specific area testicular shielding should always be used during those examinations in which the testes usually are in the useful (primary) beam, such as projections of the pelvis, hip, and upper femur. Specific area testicular shielding is also warranted in projections of the abdomen, lumbar spine, and lumbosacral spine; intravenous pylograms; and abdominal scout films for barium enemas and upper GI series. In addition to the aforementioned instances in which shielding is indicated, when children are being examined by x-ray, a special effort should be made to protect the sternum, femurs, and the humeri, since most of the red blood cells are produced in the marrow of these bones.

g. **Pregnant Patients**. The dangers of exposing pregnant women to ionizing radiation, particularly during early pregnancy, have already been discussed. The decision as to whether the diagnostic information to be gained outweighs the potential radiation danger rests entirely with the patient's physician. In some cases such as "prenatal" chest films and pelvimetry, diagnostic information may be considered necessary. In other cases, it may be appropriate to delay the examination until later in the pregnancy or after delivery. As mentioned before, these decisions rest entirely with the patient's physician because he is more familiar with her particular case than anyone else. The problem arises when the physician does not know that his patient is pregnant. In this case, you should inform the patient's physician or the radiologist so a decision can be made regarding her x-rays. How do you know the patient's pregnancy status? Ask her! There are some general rules to observe when asking a patient if she is pregnant. Keep in mind that you should use common sense and good judgment to avoid embarrassing questions.

(1) Do not ask her in the presence of others. Choose a private place such as the exposure room.

(2) Choose words that are in good taste.

(3) Explain why you want to know but do not alarm her with the information that radiation will absolutely result in damage to the fetus.

(4) Ask only those that are procreative. For example, do not ask a 65-year-old patient if she is pregnant.

4-36. PROTECTION FOR OTHERS

Anyone who is not needed to assist should not be allowed in the exposure room during the examination. At times, it will be necessary for others to remain in the room. Persons who may be needed for assistance and some steps to take to protect them from radiation are discussed below.

a. Parents will sometimes be required to remain in the room with a child. They should not remain in the exposure room during the examination unless they are needed. They may be needed to hold the film, to hold the child, or merely to be present to assist the x-ray specialist in getting the child's cooperation. If possible, they should remain in the control booth during exposure. If needed to hold the film or child, be sure to have them wear protective aprons and gloves. (Pregnant women should not be allowed to hold a film or child during exposure).

b. At times, it will be necessary to use other hospital personnel to assist you by holding film, patients, and so forth. Use only personnel not occupationally exposed to ionizing radiation, and do not use the same person for extended periods of time. Again, be sure they are properly protected with lead aprons and gloves.

Continue with Exercises

EXERCISES, LESSON 4

INTRUCTIONS. The following exercises are to be answered by marking the lettered response that best answers the Question, or by completing the incomplete statement, or by writing the answer in the space provided at the end of the Question.

After you have completed all the exercises, turn to "Solutions to Exercises," at the end of the lesson and check your answers with the Academy solutions.

1. Fuses in an x-ray machine will provide protection primarily for:

   a. The specialist.

   b. The patient.

   c. Bystanders.

   d. The machine.

2. Which of the following best describes the manner in which a circuit breaker works?

   a. Opens circuit to prevent excessive overloads.

   b. Keeps the anode from revolving too fast.

   c. Controls heat loss in the step-up transformer.

   d. Closes the contact switch automagnetically.

3. Wet hands increase the danger of:

   a. Radioactivity.

   b. Ionization.

   c. Electric shock.

   d. DNA disturbance.

4. You are going on a ward to make an x-ray, and discover that no three-prong socket is available there. You should:

   a. Put a rubber sheet under the patient.

   b. Remove the extra prong from the plug.

   c. Wear rubber gloves.

   d. Be sure to ground the machine before making the exposure.

5. If a shock victim is still in contact with the current, the first thing to do is to:

   a. Call a doctor.

   b. Give closed chest massage.

   c. Turn off the current, if possible.

   d. Give mouth-to-mouth resuscitation.

6. X-rays eject electrons from some of the atoms of tissue they strike. These atoms are then said to be:

   a. Moribund.

   b. Ionized.

   c. Mutated.

   d. Infertile.

7. One of the most common ways to check for excess irradiation of x-ray personnel is the use of:

   a. A film badge.

   b. Canaries in the control booth.

   c. A geiger counter.

   d. The target plan.

8. Ionizing irradiation of cells may cause damage of the DNA, possibly resulting in:

   a. Sickle cell anemia.

   b. Mutations.

   c. Toxic substances.

   d. Breakdown of H_2O.

9. The length of time required for chromosome damage to manifest itself is:

   a. Dependent upon the rate of cell division.

   b. Very short

   c. Shorter for x-ray specialists.

   d. Easy to determine with x-ray examination.

10. The effect of irradiation on fluid in and around the cells of the body is:

    a. Deoxyribonuciel disturbance.

    b. Dehydration.

    c. Insignificant.

    d. The formation of a poison (toxin).

11. Radiosensitivity of cells is affected most strongly by:

    a. The rate of cell division.

    b. The amount of water in the tissue.

    c. The genetic strength of the individual.

    d. Ohm's law.

12. The organs most vulnerable to x-ray damage are:

    a. Brain, gonads, and blood-forming organs.

    b. Stomach, eye lenses, and gonads.

    c. Blood-forming organs and the gonads.

    d. Hands, feet, and ears.

13. Tissue from x-ray exposure is usually 90 percent reparable. However, about _____________ of the damage can never be repaired.

    a. One percent.

    b. Five percent.

    c. Ten percent.

    d. 20 percent.

14. In the energy range employed in medical radiography, the relationship among RE (roentgen), rad (absorbed dose), and rem (rad equivalent man) can be expressed as follows:

    a. R x rad = rem.

    b. R - rad = rem.

    c. 1 R = 1 rad = 1 rem.

    d. R/rad = rem.

15. There is no truly safe dose of irradiation. However, the subcourse speaks of a ________________________ dose.

    a. Protected.

    b. Maximum permissible.

    c. Sensible.

    d. Target.

16. Normally, an x-ray worker should not receive more than _______ rems of exposure per year to the whole body and ________ rems of exposure per year to hands and feet.

    a. 2, 10.

    b. 5, 75.

    c. 10, 50.

    d. 35, 100.

17. There are some adverse effects of x-ray exposure for which safe exposure rates are not established. One of these is:

    a. Acute marrow damage.

    b. Acute brain damage.

    c. Acute gastrointestinal damage.

    d. Leukemia.

18. Which of the following can help reduce radiation exposure for the x-ray specialist?

    a. Choices b, c, and d below.

    b. Using the operator's booth.

    c. Keeping your distance.

    d. Never holding a patient who is being x-rayed.

    e. None of the above.

19. Which of the following can help reduce radiation exposure of the patient?

    a. Choices b, c, and d, below.

    b. High speed film.

    c. Filtration.

    d. Shielding.

    e. None of the above.

20. Special care against radiation should be exercised if a(n) ______________ patient must be x-rayed.

    a. Arthritic.

    b. Pregnant.

    c. Elderly.

    d. Cancer.

Check Your Answers on Next Page

SOLUTIONS TO EXERCISES, LESSON 4

1. d (para 4-2)

2. a (para 4-2)

3. c (paras 4-3b(1), (2})

4. d (para 4-4)

5. c (paras 4-6a, b)

6. b (para 4-8)

7. a (para 4-13)

8. b (para 4-23)

9. a (para 4-24a(2))

10. d (para 4-24b)

11. a (para 4-25a)

12. c (para 4-25a)

13. c (para 4-27a)

14. c (para 4-28c)

15. b (para 4-29)

16. b (para 4-29)

17. d (paras 4-31, 4-32b)

18. a (paras 4-34a, b(1), (2))

19. a (paras 4-35c, e, and f)

20. b (para 4-35g)

End of Lesson 4

APPENDIX

RADIATION THERAPY GUIDELINES

1. X-RAY THERAPY GUIDELINES

The following guidelines for the use of x-ray therapy equipment should assist you in using such equipment safely:

a. An x-ray therapy machine must be calibrated by a qualified expert before its use in the treatment of patients.

b. X-ray therapy equipment should not be operated routinely until the radiation safety of the installation has been established by a radiation protection survey. All x-ray therapy equipment should be operated in conformance with the recommendations of the survey.

c. Both the control panel and the patient should be kept under observation during exposure.

d. When a patient must be held in position for radiation therapy, mechanical supporting or restraining devices should be used. If an individual must hold the patient, that individual should be adequately protected. He/she must be positioned so that the useful beam will not strike any part of his/her body. The exposure of any individual used for this purpose should be monitored.

e. If the x-ray tube of a contact therapy machine is hand-held during irradiation, the operator should wear protective gloves and apron. When practical, a cap of at least 0.5 mm lead or its equivalent should cover the aperture window of the tube housing of such apparatus when it is not being used.

f. The x-ray control circuit should be so designed that it is not possible to energize the x-ray tube to produce x-rays without resetting the "ON" switch at the control panel. If this safety precaution has not been built into the circuit, the "ON-OFF" switch at the control should always be turned off first, then the primary switch (or wall plug disconnected). This sequence should never be reversed.

g. Lead, lead rubber, or lead foil used for limiting the field should not transmit more than 5 percent of the useful beam.

2. GAMMA-BEAM THERAPY GUIDELINES

Some guidelines for the use of gamma-beam therapy equipment follow:

a. Both the control panel and the patient should be kept under observation during exposure.

b. The gamma-beam apparatus must be calibrated by a qualified expert before use for the treatment of patients.

c. The gamma-beam therapy installation should not be operated routinely until the radiation safety has been established by a radiation protection survey. The apparatus should be operated only in conformance with recommendations of the survey. A resurvey should be performed each time the apparatus is loaded with a new source.

d. Emergency procedures to be followed in the event of failure of the beam control mechanism should be established and posted at the control panel.

e. When a patient must be held in position for radiation therapy, mechanical supporting or restraining devices should be used. If an individual must hold the patient, that individual should be adequately protected and he should be positioned so that the useful beam will not strike any part of his body. The exposure of any individual used for this purpose should be monitored.

f. With the possible exception cited above, no person other than the patient should be in the treatment room while the source is in the "ON" position.

g. Records required by Federal and other applicable authorities as well as records consistent with the competent practice of radiation therapy must be maintained.

h. Leak test results should be kept on a consecutive entry log and the removable activity should be recorded in microcuries.

i. Lead, lead ruber, or lead foil used for limiting the field should not transmit more than 5 percent of the useful beam.

3. EXAMPLE OF EMERGENCY PROCEDURES FOR FAILURE OF GAMMA-BEAM CONTROL MECHANISM

If the light signals indicate that the beam control mechanism has failed to terminate the exposure at the end of the preset time (for example, if the red light stays on and/or the green signal does not light up), the source may still be in the "ON" position. The following steps are to be carried out in a calm manner.

a. For the radiation therapy technician:

(1) Open the door to the treatment room.

(2) If the patient is ambulatory, direct him to get off the table and leave the room.

(3) If the patient is not ambulatory:

(a) Enter the treatment room, but avoid exposure to the useful beam.

(b) Pull the treatment table as far away from the useful beam as possible.

(c) Transfer the patient to a stretcher and remove him from the room.

(4) Close the door.

(5) Turn off the main switch at the control panel.

(6) Notify the radiation therapist and radiation protection officer.

b. For the radiation protection officer:

(1) Secure a portable survey meter. Check to see that the meter is functioning properly.

(2) Turn the power on and open the door a few inches.

(3) Stand behind the door and insert the survey meter into the door opening to test whether, in fact, the source is still in the "ON" position.

(4) If the source is still "ON," enter the room and manually turn the source "OFF" as indicated by the manufacturer's instructions. Avoid intercepting the useful beam with any part of your body.

(5) Adjust the limiting diaphragms to the smallest field size.

(6) Close the door to the treatment room. Turn off the power. Lock the control panel. Post a sign warning people not to enter.

(7) Notify the equipment manufacturer's representative.

NOTE: The emergency procedure above is based on "Medical X-Ray and Gamma-Ray Protection for Energies up to 10 MeV," (NCRP Report Number. 33, pp 46-47).

End of Appendix