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MILITARY HANDBOOK

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RADIOLOGIC TESTING

DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

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STANDARDS, MILITARY
    MIL-STD-453 - Radiographic Inspection

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REGULATIONS, DEFENSE LOGISTICS AGENCY
    DLAR 8220.4, DLAR 1000.28

NON-GOVERNMENT PUBLICATIONS
    ASTM Annual Book of Standards 03.03 - Nondestructive Testing

5. SAFETY NOTICE

Radiographic testing requires the use of radiation beams with energies sufficient to penetrate material objects.

It is the potential exposure to these penetrating radiations that makes radiographic testing the greatest safety concern of all the nondestructive testing methods covered in this handbook. Normally, these radiating beams can not be detected by any of our five senses. When radioactive sources are present, they are always "on." Therefore, strict compliance with safety regulations is required. Modern x-ray machines use high voltages and therefore safety procedures for electrical hazards must also be employed. Section 5.8 presents a more thorough coverage of the safety precautions and rules associated with this test method.

5.1 INTRODUCTION AND SCOPE

Radiologic examination provides a nondestructive method of inspecting the internal continuity of a specimen. It is one of the earliest nondestructive practices, particularly in the various radiographic methods of testing and inspection. Recent advances in radioscopic and computed tomographic techniques have opened many more application areas to now make radiology one of the most modern nondestructive methods. Even though it is often expensive and involves extensive safety considerations, its uniqueness and applicability find it in wide use in manufacturing, research, and in medical diagnostics and therapy.

Although a study of radiologic testing might include only x-rays and their uses, this handbook includes both natural and artificial radiation sources with coverage of x-ray, gamma-ray (γ-ray) and neutron-ray(N-ray) radiology.

As defined in ASTM Annual Book of Standards 03.03 on Nondestructive Testing, radiology is the science and application of all penetrating radiation, radiography incorporates direct converstion to a recording medium, and radioscopy is the electronic production of a radiological image that follows very closely the changes with time of the object being imaged.

This handbook provides the fundamental principles and guides associated with radiologic testing. It includes the theory of operation, the type of equipment, the advantages and disadvantages of the method, various applications and standards, and guides for specific disciplines. The information contained in Handbook 728/1 should be included with this handbook for general guidelines to the employment of all NDT methods and for a more complete understanding of radiologic testing as it compares with other basic methods.

Two DLA regulations which may be of interest to the reader are DLAR 8220.4 and DLAR 1000.28.

5.2 BASIC PRINCIPLES

Radiographic testing involves three basic concepts. First, there must be a beam of radiating energy that can penetrate a specimen. Second, the beam must be selectively attenuated by the variables of the specimen as penetration occurs. Last, the results of this selective attenuation must be detected and/or displayed. Therefore, we will study penetrating radiation beams, their attenuations due to the absorption characteristics of materials, and present-day detection and display systems.

5.2.1 Penetrating radiation Radiographic testing normally involves two types of penetrating radiation: electromagnetic radiation of high-energy photons or a collimated beam of neutrons. Some of the principles presented in the following subsections are applicable to both types of penetrating beams, but the discussions in this and some of the following subsections are specifically directed to x-rays and γ-rays, the radiation of high-energy photons.

Figure 5.2(1) shows the electromagnetic spectrum. Gamma rays and x-rays comprise the high energy, short wavelength portion of the spectrum. The boundaries shown in figure 5.2(1) between the areas listed are fairly arbitrary. There are no sharp, natural boundaries or exact, or fixed, limits. The visible range might provide the greatest exceptions to these statements, but even here the exact limits of the boundaries are often debated.

The low energy, low frequency, long wavelength x-rays are called "soft" x-rays, and the high energy, high frequency, short wavelength x-rays are called "hard" x-rays.

It has been found that an electromagnetic radiation field can always be divided into fixed-sized energy bundles called photons. The energies of these single units, or bundles, are fixed by their wavelengths, or frequencies. The characteristics of an ultraviolet, x-ray or a gamma ray photon, can be identical if they have the same wavelength. In other words, all photons are essentially the same except for their wavelengths, or equivalent frequencies or energies. The proper differentiation between x-ray and γ-ray photons is their source of origin. An x-ray photon is produced from a man-made device (an x-ray tube), while a γ-ray photon is produced by a radiation from a naturally radioactive isotope.

The total energy in an electromagnetic beam is dependent upon both the energy of the individual photons and the total number of photons that are present. It is the energy of the individual photons in the ray that determines the penetration capabilities of the rays. The total number of photons, however, determines if the amount of penetration is sufficient for detection. Two beams can have the same total amount of energy, but one will penetrate a specimen and the other will not because of differences in energies of their individual photons. Therefore, to properly work with radiography, one must know both the frequency or wavelength spectrum of a beam and its total energy. When a chart or table shows the energy of a beam, it must be determined if the Chart is showing the energies of the individual photons, or the total energy of the beam. These differences are not always clearly indicated and yet both are important.

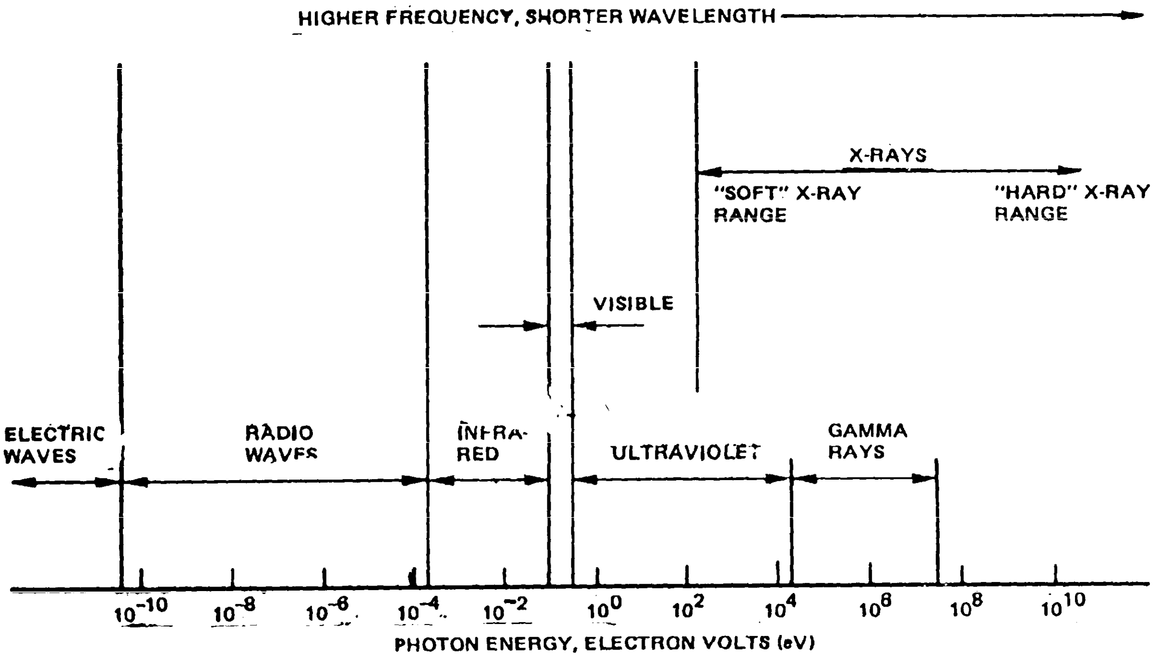


FIGURE 5.2(1). The electromagnetic spectrum.

The spectrum of an x-ray beam differs greatly from that of a radioactive source. A radioactive source can have a single frequency, single energy photon emission. (In most cases, there is more than one radioactive process involved, and so more than one frequency of radiation is present, but those that are present are each of one fixed photon energy level.) The spectrum of an x-ray beam, however, includes a continuous spectrum, along with fixed frequency characteristic rays, as shown in figure 5.2(2).

Table 5.2(1) lists some common radioactive gamma ray energy levels (10^6eV = 1 MeV).

For gamma ray sources, the individual photon energies can be high or low, depending on the specific isotope, but the total energy of the beam will depend on the amount of the isotope present and its overall activity.

The maximum energy level of a photon in an x-ray spectrum is limited by the voltage applied to the x-ray tube (the voltage used to accelerate the electron beam). (See Paragraph 5.3 for an x-ray tube description.) The total amount of energy in the beam, however, is dependent upon the current of the electron beam. Therefore, both current values and voltage values are important when x-rays are involved.

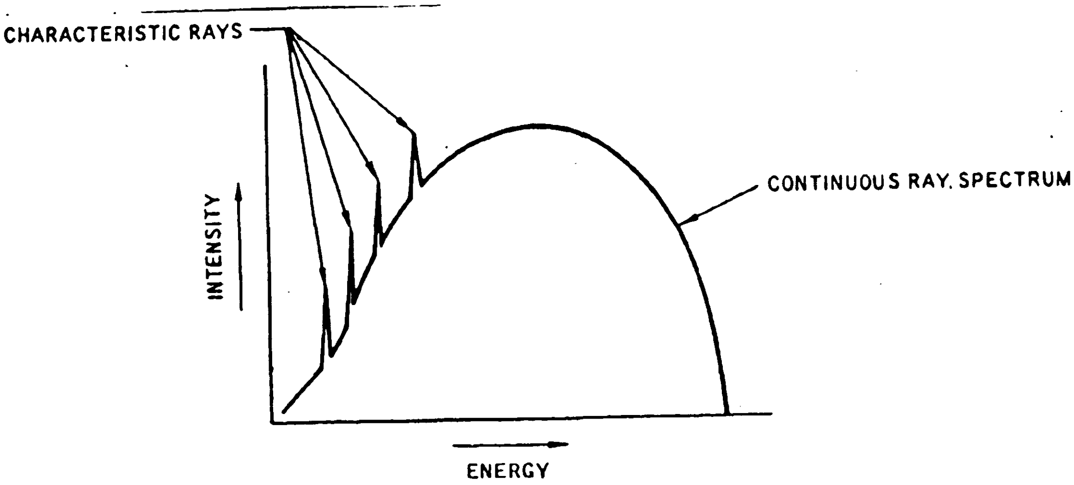


FIGURE 5.2(2). X-ray spectrum.

TABLE 5.2(1). Gamma ray energy (energy of the individual photons).

ISOTOPE	GAMMA RAY ENERGY MeV
COBALT 60	1.33, 1.17
IRIDIUM 192	0.31, 0.47, 0.60, ETC.
THULIUM 170	0.84, 0.062
CESIUM 137	0.66

The characteristic rays of an x-ray tube (see figure 5.2(2)) are determined by the atoms that make up the x-ray tube's anode and are the excitation levels of these atoms. Tungsten is a common anode material and tungsten characteristic rays do not begin until an energy of about 70 KeV is reached. Since these characteristic rays are narrow, single frequency spectrums, they contain very little of the total energy of the ray and are not of direct use in most x-ray work.

Figure 5.2(3) shows how the spectrum can be varied by changing the current and voltage applied to the tube. With the same applied voltage, an increase in x-ray tube current produces more total energy even though the individual photons have the same energy limits and distributions. When the current remains the same but the tube voltage is increased, both the total amount of energy and the energy limits of the photons increase. When the voltage is increased, a new energy range of photons appears. All those above point a of figure 5.2(3) have higher energies than those that were present at the lower voltage. It can be noted that the photon energy levels of the characteristic rays remain fixed and do not shift (on the horizontal axis) with changes in either the voltage or the current.

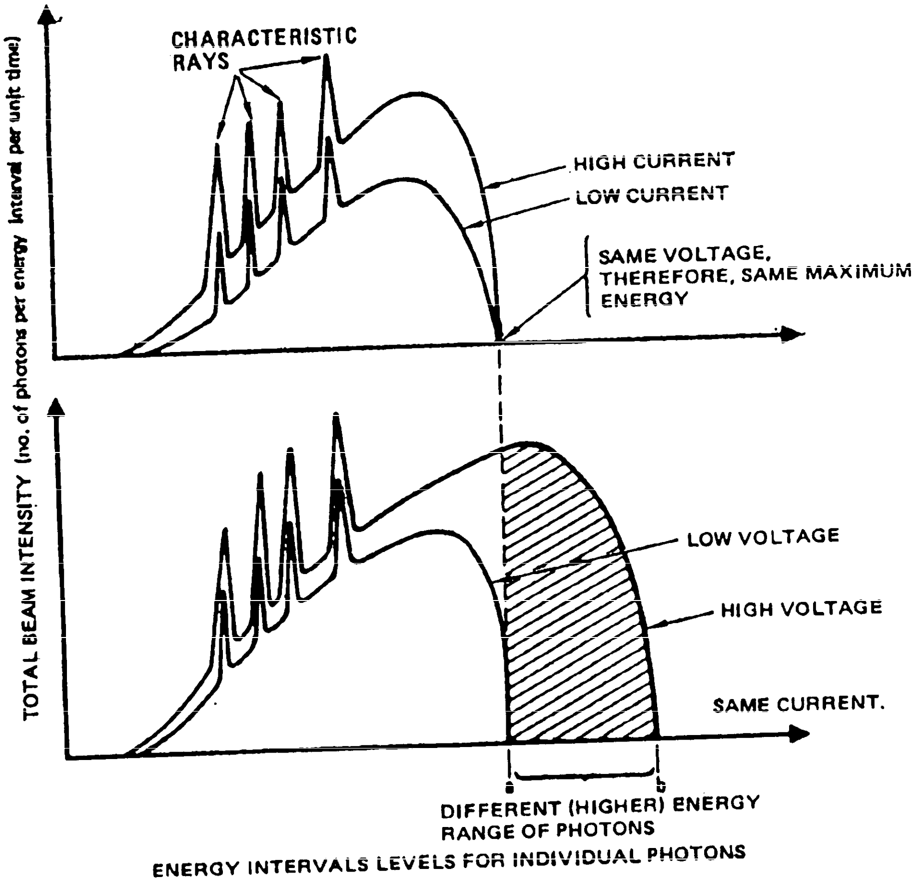


FIGURE 5.2(3). Varying energy spectrums.

Mathematical relationships useful for some of these variables are:
For photons,

$$E = hf = hc/\lambda, \tag{1}$$

where

E = energy of photon (ergs)

h = Planck's constant (6.626×10^{-27} erg-sec)

f = frequency of radiation energy (Hz or cycles/sec)

c = speed of light (2.998×10^{10} cm/sec)

λ = wavelength of radiation energy (cm).

or

$$E \quad \frac{12{,}400}{\lambda} \tag{2}$$

where E = energy in electron volts (eV) (same magnitude as the volts, V, applied to the x-ray tube) and = wavelength in angstroms (10^{-8} cm).

The maximum energy photon from an x-ray tube is eV, and thus the minimum wavelength and maximum frequency from an x-ray tube, will be:

$$\lambda_{min} = \frac{12{,}400}{V}, \tag{3}$$

and

$$f_{max} = 2.42 \times 10^{14} V, \tag{4}$$

where

λ = wavelength in angstroms

f = frequency in hertz

V = Volts applied to x-ray tube.

(e = electronic charge carried by an electron, 1.6×10^{-19} coulombs or 1.6×10^{-12} ergs/volt)

The total power of an x-ray beam (P):

$$P = K_1 AZV^{K_2} \tag{5}$$

where

P = Energy per unit time

K_1 = Constant which varies with tube design, etc.

A = Tube current

Z = Atomic number of tube's anode material

K_2 = Constant, almost always greater than 2, often around 2.5.

The constant K_1 is very small, so small that only a small percent of the total energy applied to the tube is ever seen as x-ray energy. The vast majority of the energy appears as heat. An analyses of Equation 5 will show that the efficiency of an x-ray tube increases with increased voltage, being at least proportional to the voltage raised to the first power or more.

5.2.2 Beam attenuation and material absorption characteristics. Several factors affect the attenuation of a beam. Any beam that radiates from a localized source will exhibit an intensity loss because of the geometric increase in the area of the distribution as radiation proceeds from the source. Theoretically, for a point source, this geometric factor will be proportional to d^{-2}, where d is the distance from the source. For electromagnetic beams, there are other losses in intensity due to interaction with matter that may be located in the path of the beam. There are several kinds of interactions between photons and matter: simple scattering, photoelectric absorption, Compton scattering, pair production, and x-ray generation. These interactions are described as follows:

a. Scattering (includes Rayleigh scattering). When photons approach close to charged particles (normally the "orbital" electrons around a nucleus) the directions of some of the photons can be changed with no measurable loss in their energies. The amount and degree of direction changes made depends on the number of particles present and their relative size as functions of wavelengths. The interaction involves what could be termed reflection and/or refraction.

b. Photoelectric Absorption. When a photon passes through matter, its entire energy can be transferred to an orbital electron. The photon thus ceases to exist. Part of the photon energy is expended in ejecting the electron from its orbit and the remainder imparts velocity to the electron. This phenomena is known as photoelectric effect or absorption (see Figure 5.2(4)). Radiography is most often dependent upon this absorption process which is usually the most predominant relationship for photons with energies of 0.5 MeV or less. Photoelectric absorption is an ionization effect that can result in the release of negligibly small-energy photons when the atom returns to its normal state.

c. Compton Scattering. A photon can interact with an orbital electron and transfer only a portion of its energy to the electron. This effect is called Compton scattering (see Figure 5.2(4)) and often occurs when the photon energy ranges from about 0.1 to 3.0 MeV. Part of the photon energy is expended in dislodging the orbital electron and imparting velocity to it. The remainder of the photon energy continues on as a lower energy photon at an angle to the original photon path. This process can be repeated, progressively weakening "the photon" until a photoelectric effect completely absorbs the final photon.

d. Pair Production. (Figure 5.2(4)) Pair production occurs only with very high energy photons of 1.02 MeV or more. At these energy levels, usually when the photon approaches the nucleus of an atom, the photon can be changed to an electron-positron pair. Positrons carry a positive charge, have the same mass as electrons, and are extremely short lived. They combine at the end of their path with electrons to emit two 0.51 MeV or greater photons which can then again be subject to Compton scattering and photoelectric effect.

e. Secondary X-ray Generation. The last three processes, photoelectric absorption, Compton scattering, and pair production, all liberate free electrons that move with different velocities in various directions. Since x-rays are generated whenever free electrons collide with matter, it follows that x-rays in passing through matter can cause the generation of secondary x-rays. These secondary x-rays, or photons, can then repeat any of the first four processes, depending upon their respective energies, etc.

Most of these interactions result in losses in the x-ray intensity. The last interaction, e, results in a regaining of some of these losses. This "gain" is normally a minor part of the whole, and because there is a large amount of randomness in its directions, it is usually of no value and can actually cause a blurring of the x-ray image along with the rest of the scattering that occurs. It is possible, however, to use this process, along with others, to some advantage when it occurs in the immediate vicinity of the film, and can at that point result in an enhanced intensity of the image with negligible blurring.

In general, all these effects of attenuation, alone or combined together, follow an exponential relationship such that:

$$I_x = I_o e^{-\mu x} \tag{6}$$

where

I_x = beam intensity after penetrating a distance x

I_o = original beam intensity (at x = 0)

μ = attenuation coefficient (cm^{-1})
(a function of photon energy and material)

x = distance of penetration travel (cm)

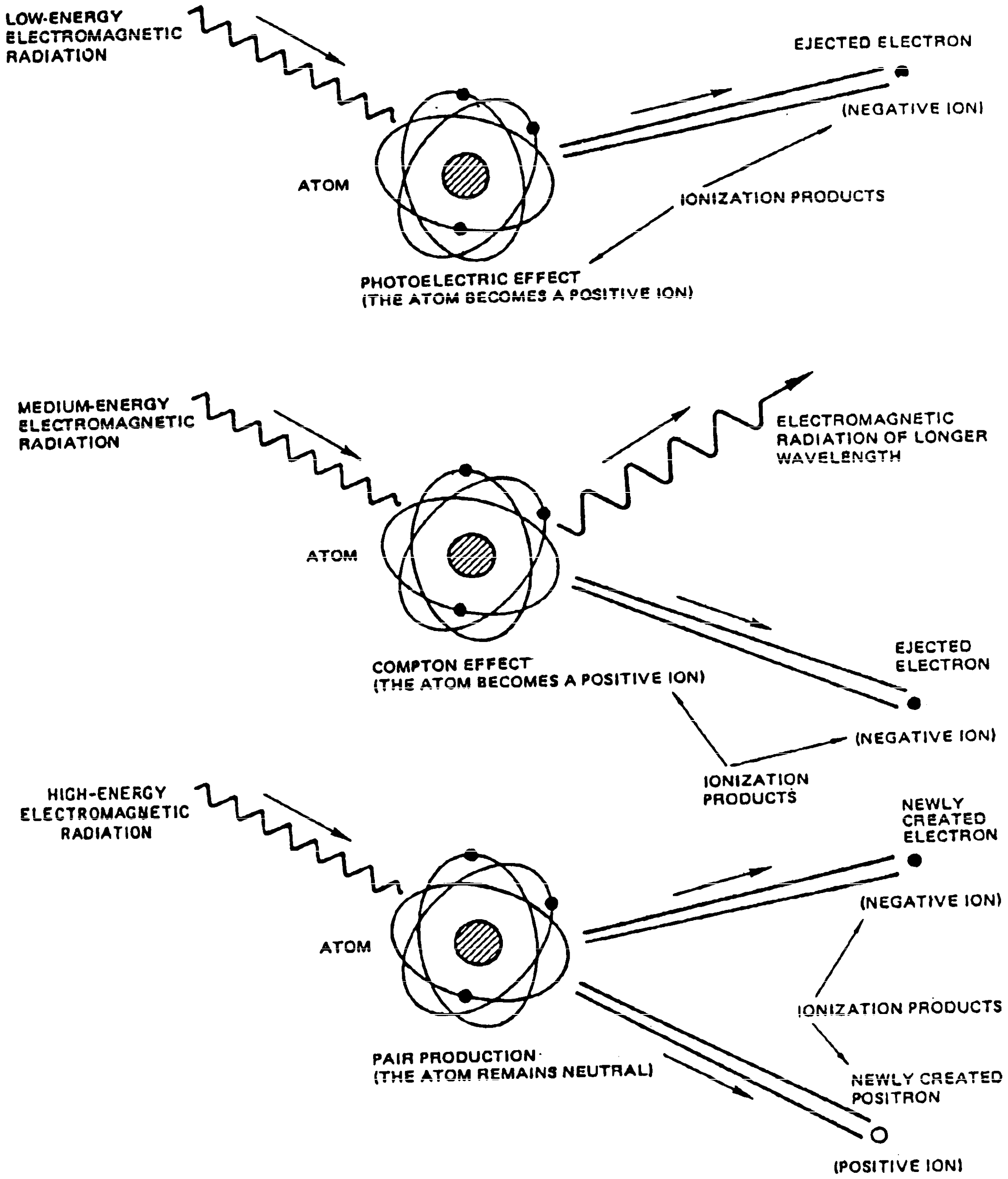


FIGURE 5.2(4). Ionization interactions of photons with matter.

This law is seldom exactly applicable. It is theoretically correct only when the beam is a narrow, parallel beam, with only one wavelength or photon energy present, with no selective absorption or scattering, and the material is of uniform density, etc. It basically is the law, however, upon which x-ray images are established. It shows the changes in the energy or the intensity of the beam that accounts for the contrast seen in recorded images.

In place of the attenuation coefficient, the absorption coefficient is often used. The absorption coefficient relates to actual photons lost and does not include those photons which leave the beam due to scattering. Therefore, the attenuation coefficient is always slightly more than the absorption coefficient.

The amount (thickness) of material that reduces the intensity of a beam to one-half of its original value is called the half-value layer. This thickness can be related to the absorption coefficient :

$$t_{HVL} = \frac{0.693}{\mu} \qquad (7)$$

where

t_{HVL} = thickness of the half-value layer (cm),
μ = absorption coefficient (cm^{-1})

It must be kept in mind that the attenuation or absorption varies greatly with the energy levels (or wavelength spectrum) of the photons and the type material, and they are exact for only idealized conditions. These "coefficients" are statistical relationships, and short term deviations are "expected" even when conditions are perfect.

These coefficients are often expressed as a mass absorption or mass attenuation coefficient, $_m$, derived by dividing by , the density of the material. This allows these equations to be used where variances in material densities are expected. Also, separate elements combined either chemically or physically into material compounds can be considered.

These relationships are:

$$I_x = I_o e^{-\mu_m \rho x} \qquad (8)$$

or

$$I_x = I_o e^{-(\mu_{m1} \rho_1 + \mu_{m2} \rho_2 + \ldots.)x} \qquad (9)$$

where

μ_{m1} = mass attenuation coefficient for element 1
ρ_1 = mass density of 1, as part of the total density of the compound, etc.

In almost all practical situations, the amount of radiation that comes through a material is greater than that amount represented by Equations 6, 8 or 9, and this increase in penetration over that theoretically estimated is called "buildup." It is due to the gain obtained from photons being scattered into (or back into) the beam path, re-radiation from ionized atoms, energy from combining electrons-positrons, or new radiations from the energetic electrons that were ejected in the original absorption process. It must be noted that, because the absorption or attenuation is an exponential function, no amount of shielding can ever stop all the radiation even from a weak source. Therefore, while a safe level of radiation can usually be achieved or maintained, it is never totally eliminated. Table 5.2(2) shows typical half-value layers for different energy levels for different materials.

TABLE 5.2(2). Approximate half-value layers for certain x-ray tube potentials and gamma-ray sources.

SHIELDING MATERIAL IN INCHES	HALF-VALUE LAYER FOR TUBE POTENTIAL IN KILO-VOLTS PEAK (KVP)							
	50 KVP	70 KVP	100 KVP	125 KVP	150 KVP	200 KVP	250 KVP	300 KVP
LEAD (IN.)	0.002	0.007	0.01	0.011	0.012	0.02	0.03	0.06
CONCRETE (IN.)	0.2	0.5	0.7	0.8	0.9	1.0	1.1	1.2

SHIELDING MATERIAL IN INCHES	HALF-VALUE LAYER FOR RADIOISOTOPE SOURCE		
	IRIDIUM-192	CESIUM-137	COBALT-60
LEAD (IN.)	0.19	0.25	0.49
STEEL (IN.)	0.61	0.68	0.87
CONCRETE OR ALUMINUM (IN.)	1.9	2.1	2.6

If two half-value layers are penetrated, the exiting intensity is 1/4 of the initial intensity since one-half of the intensity is lost through the first layer, then one-half of the remaining half is lost in the second layer.

If three half-value layers are traversed, then only 1/2 x 1/2 x 1/2 = $(1/2)^3$ = 1/8 of the original intensity is able to penetrate. To repeat, some radiation will always be able to penetrate no matter how many layers are present.

5.2.3 Detection systems. The most common detection system is the "exposure" of a film negative to the radiating beam as it exits the specimen. The negative becomes "sensitized" by the degree of radiation exposure so that when it is "developed," a particular chemical rate of reaction will be faster for the more exposed areas than for the less exposed areas. The differences in these chemical rates of reactions can be used to produce an image of the original beam intensity gradient. This image is basically a two-dimensional image, resulting in a shadow-graph of the specimen.

The usefulness of a radiograph is usually measured by the response it can produce on the human eye. When the radiographer interprets a radiograph, he is seeing the details of the specimen image in terms of the amount of light passing through the processed film. Areas of high density (areas exposed to relatively large amounts of radiation) will appear dark gray; areas of light density (areas exposed to less radiation) will appear light gray. The density difference between any two film areas is known as contrast. The sharpness of the film image is known as definition. Successful interpretation of any radiograph relies upon contrast and definition detectable by the eye.

The ability of film to record different radiation exposures as differences in density is called film contrast. Radiographic film is fabricated with a variety of emulsions which give different film contrasts and other properties such as speed and graininess.

The film contrast for any particular film is usually determined from a plotted relationship between the film exposure and the resulting film density. This relationship is expressed in the form of film characteristic curves, often called H & D curves. Figure 5.2(5) is an example of one of these curves. It shows film density on a linear, vertical scale and the relative exposure as a horizontal, log scale. Each type and make of film has a different curve. The film contrast is proportional to the slope of the curve.

These H & D curves cannot give exact exposure factors for every particular setup or equipment, but once a point is established on a curve with a particular setup, the change in the exposure required to reach another point on the curve can be determined. For x-rays, the "exposure" variable is proportional to tube current times the time of exposure, usually measured in milliampere-minutes. For γ-rays, the "exposure" is proportional to source strength times the time of exposure, usually measured in millicuries-hours.

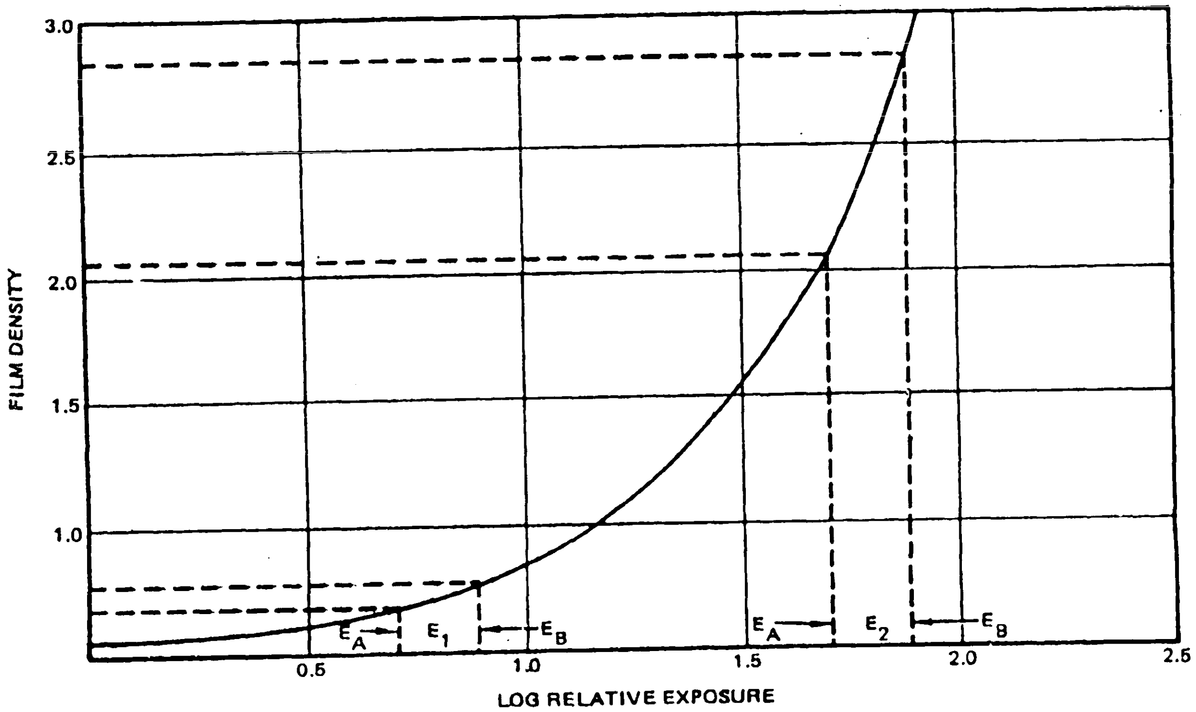


FIGURE 5.2(5). Film characteristic (H & D) curve.

The "density" variable is the common logarithm of the ratio of visible light incident upon one side of a radiograph to the visible light transmitted through the radiograph. Expressed mathematically,

$$D = \log_{10} \frac{I_o}{I} , \qquad (10)$$

where D is the film density, I_o the intensity of the incident light, and I the intensity of the transmitted light.

It is difficult for the eye to distinguish between small density differences, and there is a lower limit of contrast that the eye cannot detect. The H & D curves for most films make it readily apparent that as exposure increases,
overall film density increases and, more importantly, film contrast (the slope of the curve) increases. Referring to Figure 5.2(5) it is obvious that film exposure E_A is less than E_B and that it is the difference between the two that the radiographer must be able to observe. For a low exposure E_1, the difference in density between E_A and E_B due to the low slope of the curve, is relatively small, and will probably not be discernible by the eye. By increasing the exposure to the value represented by E_2, not only is the overall density of the radiograph increased, but the density difference (radiographic contrast) between E_A and E_B is greatly increased. The resulting contrast is easily detectable by the eye. Selection of a correct exposure can use the film's contrast characteristics to amplify the subject contrast, resulting in a useful radiograph. In industrial radiography, films

should always be exposed for a density of at least 1.5. The highest desirable density is limited only by the light intensity available for reading the radiograph, usually no greater than 4.

Film speed is measured by the exposure required to obtain a desired film density. High-speed film needs only low exposure while slow-speed film requires more exposure to attain the same film density. Figure 5.2(6) illustrates H & D curves for three different speed films. The shape of each curve and its position on the log relative exposure axis is determined by the design of the film. Film speed is a consideration of importance since time is a cost factor in any industrial operation. Whenever other considerations permits, such as being able to accept increased graininess, fast film may be used.

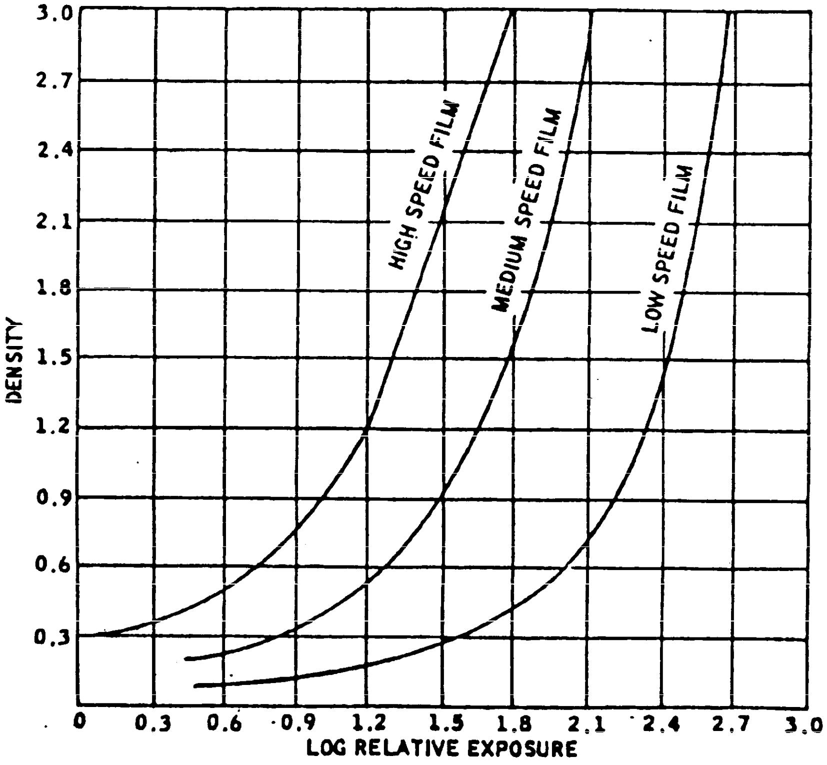


FIGURE 5.2(6). Relative film speed.

Graininess is the visible evidence of the grouping into clumps of the minute silver particles (grains) that form the image on radiographic film. Graininess affects film contrast and image definition, and all film is subject to it (see Figure 5.2(7)). The degree of graininess of any film is dependent upon:

a. The fine or coarse grain structure of the original film emulsion.

b. The quality of the radiation to which the film is exposed (an increase in the penetrating quality of the radiation will cause an increase in graininess).

c. Film processing. (Graininess can be directly affected by the development process. Under normal conditions of development, any increase in development time is accompanied by an increase in film graininess.)

d. The use of fluorescent screens. (Fluorescent screens also amplify the increased graininess with increase in radiation energy.)

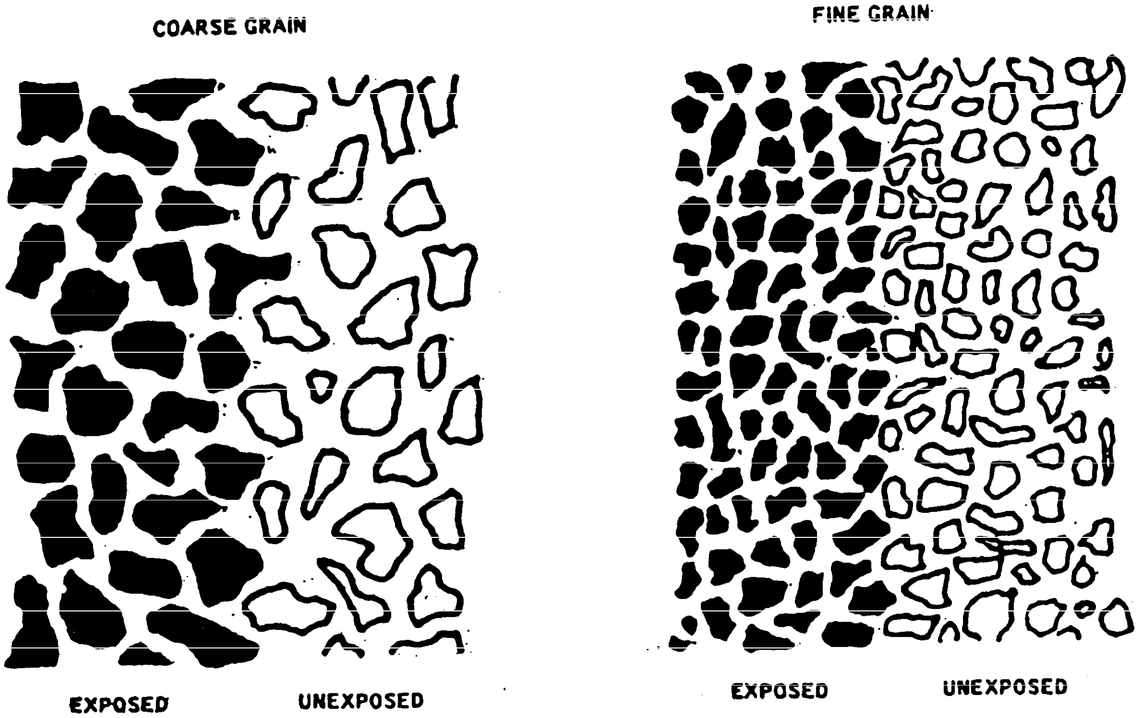


FIGURE 5.2(7). Film grain (greatly magnified).

The selection of film by the radiographer is based on the need for radiographs of a certain contrast and definition quality. Film contrast, speed, and graininess are interrelated and fast films usually have large grains and poor resolution, whereas slow films have fine grain and good resolution. Therefore, though it is economically advantageous to make exposures as short as possible, the use of fast film is limited by the graininess that can be tolerated in the radiograph. Film manufacturers have created films of various characteristics, each designed for a specific purpose. Their recommendations as to film usage should be considered.

Other detection systems are used. They are:

(1) Fluoroscopy uses a screen that becomes proportionally fluorescent when exposed to different intensities of x-rays to produce a direct image on the screen. In this detection method the screen must be viewed indirectly; e.g., by a mirror, to prevent direct exposure of the viewer to the x-rays. Image amplifiers can be used to increase the intensity of the fluorescent image.

(2) A special television camera can be used that is x-ray sensitive rather than photo-sensitive.

Other special detection methods (ionization detectors, photolithographic processes, and others) are also in use. In all these cases, simple two-dimensional images can at most be recorded, all obtained from straight line (ray) data. Through mathematical analysis and/or multiple exposures, three-dimensional information can be constructed (as is done in tomography), but the direct imaging is at best two dimensional.

5.2.4 Gamma rays. Since gamma rays are high-energy photons, then all previous comments about photons, their interaction with matter, their absorption and scattering, etc., are applicable to gamma rays. There are several concepts and definitions, however, that are applicable just to gamma ray sources.

Gamma rays are produced by the nuclei of isotopes which are undergoing natural disintegration. Isotopes are varieties of the same chemical element having different atomic weights. A parent element and its isotopes all have an identical number of protons in their nuclei but a different number of neutrons. Among the known elements, there are more than 800 isotopes of which more than 500 are radioactive.

There are natural radioactive isotopes and man-made radioactive isotopes. Radium is one of the best known and most used natural radioactive sources. Man-made radioactive sources include Cesium 137, Cobalt 60, Thulium 170, and Iridium 192. The first of these is obtained as a fission by-product; the others are obtained by neutron bombardment. Both natural and artificially produced isotopes produce gamma rays, alpha particles and/or beta particles.

In radiography, the more penetrating gamma rays are, except for safety, the only radiations of direct interest. The intensity of an isotope source is measured in roentgens per hour at a distance of one meter (rhm) or at a distance of one foot (rhf). This is a measure of radiation emission over a given period of time at a fixed distance. The activity (amount of radioactive material) of a gamma ray source determines the intensity of its radiation. The activity of artificial radioisotope sources is determined by the effectiveness of the neutron bombardment that created the isotopes. The measure of activity is the curie (3.7×10^{10} disintegrations per second).

Specific activity is defined as the degree of concentration of radioactive material within a gamma ray source. It is usually expressed in terms of curies per gram or curies per cubic centimeter. Two isotope sources of the same material with the same activity (curies) but different specific activities will have different dimensions. The source with the greater specific activity will be the smaller of the two. For radiographic purposes, specific activity is an important measure of radioisotopes, since the smaller the radioactive source the greater the sharpness of the resultant film image (see figure 5.4(2)).

The length of time required for the activity of a radioisotope to decay (disintegrate) to one-half of its initial strength is termed "half-life." The half-life of a radioisotope is a basic characteristic and is dependent upon the particular isotope of a given element. In radiography, the half-life of a gamma ray source is used as a measure of activity in relation to time, and dated decay curves, similar to that shown in figure 5.2(8), are supplied with radioisotopes upon procurement.

Radioactive decay follows an exponential relationship, and therefore a straight line plot occurs on a semi-log graph, as shown in figure 5.2(8).

5.2.5 Neutron rays Figure 5.2(9) indicates one reason why N-rays are used and why they are important. The mass absorption of x-rays follow fairly uniformly the atomic number of the elements, being largely affected by the number of orbital electrons that are present with which the x-ray photons can interact. The absorption of neutrons, however, is much different. As figure 5.2(9) shows, some of the lowest atomic number elements, where x-rays are the least absorbed, have great absorptivity for neutrons. It is this great difference in relative absorption capabilities that can make N-rays useful when x-rays cannot do the job. For one example, when explosives (explosives usually contain a large number of hydrogen atoms) must be viewed within a steel case, x-rays are fairly useless since the x-rays are almost entirely absorbed by the steel and are relatively unaffected by the explosive. Neutron rays, however, will normally give good results, going easily through the steel, but absorbed by the least amount of explosive that might be present. The degree of usefulness of N-rays depends upon these differential absorptivities. Therefore, the proper choice of an N-ray method requires knowledge of the atomic numbers of the elements that are present and their relative absorption as shown in figure 5.2(9).

It should be noted that both x-rays and N-rays are often used on the same task. They each show different variables, and it is not always a choice of which is best. The choice of whether x-rays alone, or N-rays alone, or both are to be used depends upon each individual problem and the differences in absorptivities that may be required.

* 5.2.6 Radioscopy. Radioscopy consists of real-time and near real-time-non-film detection, display, and recording of radiological images. These images are produced by penetrating radiation passing through the test object and impinging on a detecting medium. Imaging devices are subsystems that transform the transmitted x-rays (or other penetrating radiation) into a "prompt response" optical or electronic signal. Parameters of the imaging devices that are of critical interest are the field of view, the resolution, and the dynamic inspection capability (of which speed of inspection is inherent in the system). These parameters are related to each other, and improvements in one usually result in lower capability for one or more of the others. Brightness and magnification can be determined, and these quantities are critical for the subsystem capability and usefulness. For example, as the image is magnified, detail contrast is reduced and outlines are less distinct.

Three-dimensional information can be obtained in both static and dynamic radioscopic systems. As determined by radiological density differences, relative location of internal parts of test objects, their sizes, and potential performance capability can be analyzed. Product integrity can be quickly assessed, and acceptance standards can be used to accept or reject parts. Speed of operation for testing is useful for radioscopic systems compared to radiographic ones, although extra care must always be used when motion is involved.

* 5.2.7 Computed tomography. As defined in ASTM E1316, computed tomography is a nondestructive technique in which penetrating radiation measurements of the x-ray [or other] opacity of an object along many paths are used to compute a cross-sectional CT-density map called a tomogram. CT-density is an all-encompassing term that refers to any of a number of physical features of the object (mass, density, electron density, optical density, image density, etc.) that are of significance for the purposes of the experimental work. Several more limited definitions for CT are also used, with the expression always referring to planes that include source(s), object, and detector(s), and the resultant total output is the superposition of results for these planes.

Industrial radiology utilizes geometries which do not necessarily require the speed used in medical applications, but there is some overlap in the relative motion of source and detector subsystems. One way of describing the scan geometries employed in CT is by the "generation" of CT systems, as defined in ASTM E1441. First-generation CT systems are characterized by a single x-ray source and a single detector that undero both translational (linear) and rotational motions. Second-generation CT systems use the same scan geometry as the first-generation systems for translational and rotational progression; however, the source provides a fan beam of radiation and mulitple detectors are used. A series of views is acquired for each translational step, and the scan times are thus shorter for second-generation systems than for first-generation ones.

Third-generation CT systems depend on a rotate-only geometry, with a complete set of data available for the detector array for each translational position. Detector arrays are critical for achieving successful results. More sensors are needed than with first and second-generation systems. Rotate-only scanners impose much more stringent requirements on detector performance.

Fourth-generation CT systems also employ a rotate-only scan motion. They differ from third-generation systems in that they use a stationary circular array of detectors and only the source moves. They are resistant to artifacts as are second-generation units and they have the speed of third-generation units. They can be more complex and costly than the other ones, and they require that the object fit within the fan of x-rays.

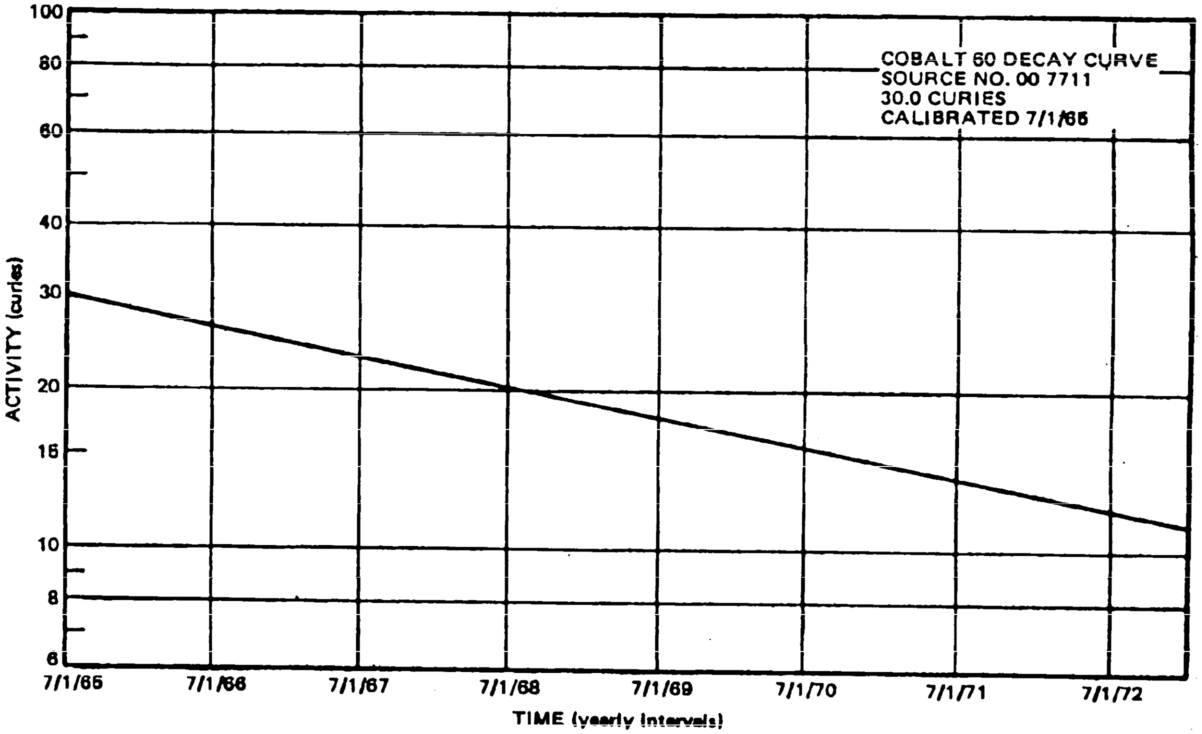
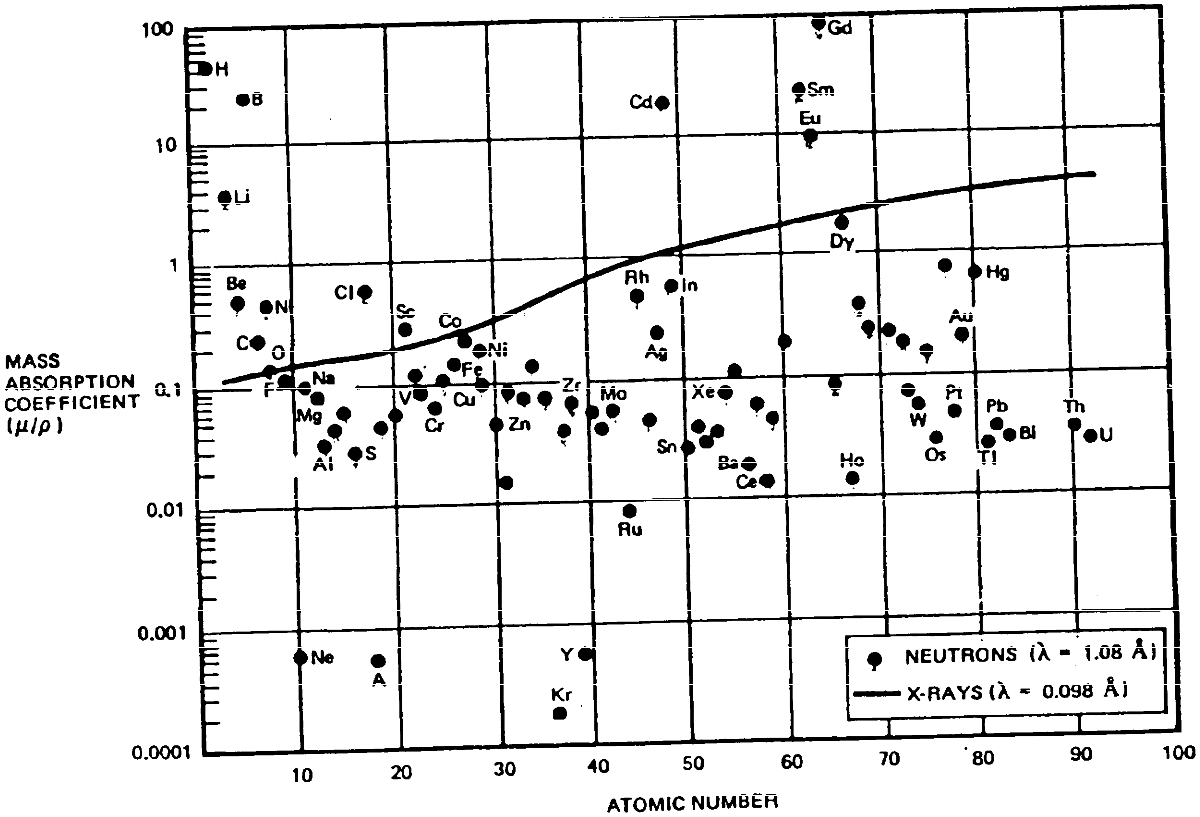


FIGURE 5.2(8). Dated decay curve.

FIGURE 5.2(9). Absorption comparisons between X-rays and N-rays.



5.3 EQUIPMENT AND MATERIALS

5.3.1 X-ray equipment. Radiographic equipment includes portable or mobile systems, laboratory systems, and large, fixed installations. There are electronic controls that can provide automatic exposures. Automatic film development is common. The selection of equipment, materials, and facilities available is extensive.

In selecting x-ray equipment, one of the most important factors to be considered is the maximum thickness and type of material to be examined. The material and its thickness will essentially dictate the necessary peak voltage rating of the equipment. x-ray equipment must be especially designed to operate at the low kilovolt range. Usually a Beryllium window is included to allow the long wavelengths to exit the x-ray tube and expose the specimen. When equipment is designed to operate at the high voltage range, it is difficult to provide adequate heat sinks and radiation protection is usually massive and expensive. Because of these factors, the same equipment is not normally used for all voltage ranges.

Table 5.3(1) shows relationships between voltage ratings and thicknesses of steel that can be inspected. Table 5.3(2) shows different applications for different voltage ratings. Each application or material to be inspected could require a different rating, or range in rating, of peak voltage.

Other important choices might be the size of the specimen to be examined, safety aspects, mobility requirements, and the ability of the floor and foundations to support the weight of the equipment. Other equipment characteristics that can be mentioned are radiation quality, radiation output, and source size. A description of these three items follows.

(1) Radiation Quality. One must normally make a compromise between high energies resulting in short exposure times, and the greater radiation absorption at lower energies which results in better contrast and improved radiographic quality. When selecting x-ray equipment, it is best to obtain a unit which will emit a radiation spectrum containing a large portion of the short wavelengths indicative of the maximum or peak voltage. With such a unit, it is usually possible to operate, if and when necessary, over a limited range of lower energies to get the longer wavelength x-rays which improve radiographic contrast. However, if the unit does not deliver a good quantity of the more penetrating x-rays indicated by the peak potential rating, the exposure time can be less than that of other equipment of similar peak voltages. To assess the quality of an x-ray source, we must know the characteristic half-value layer which it produces. When comparing two x-ray machines at the same current and voltage, the machine which produces the larger half-value thickness in a given material has the highest quality beam.

TABLE 5.3(1). Relationship between voltage ratings and steel thickness.

VOLTAGE RATINGS	THICKNESS FOR PRODUCTION PARTS STEEL (INCHES)
175 KV	1/8 - 1
250 KV	1/4 - 2
1000 KV	1/2 - 4
2000 KV	3/4 - 8
15 MeV	3/4 - 14

TABLE 5.3(2). Relationship between voltage ratings and application.

VOLTAGE RATING	GENERAL APPLICATION
50 KV	RADIOGRAPHY OF WOOD, PLASTICS, NONMETALIC COMPONENTS, TEXTILES, LEATHER; DIFFRACTION AND MICRORADIOGRAPHY.
100 KV	RADIOGRAPHY OF LIGHT METALS AND ALLOYS. FLUOROSCOPY OF FOOD STUFFS, PLASTIC PARTS AND ASSEMBLIES, AND SMALL LIGHT ALLOY CASTINGS.
150 KV	RADIOGRAPHY OF HEAVY SECTIONS OF LIGHT METALS AND ALLOYS, AND OF THIN SECTIONS OF STEEL OR COPPER ALLOYS. FLUOROSCOPY OF LIGHT METALS.
250 KV	RADIOGRAPHY OF HEAVIER SECTIONS OF STEEL OR COPPER. FLUOROSCOPY IS NOT GENERALLY USED AT THIS VOLTAGE.
1000-2000 KV-RADIOACTIVE ISOTOPES	RADIOGRAPHY OF VERY HEAVY FERROUS AND NON-FERROUS SECTIONS. (3 IN. STEEL OR GREATER)

(2) Radiation Output. The conversion of electrons into x-rays is an inefficient process. Over 90 percent of the power consumed by an x-ray machine is wasted in the production and dissipation of heat. This heat problem is a most significant economic factor in the design and construction of x-ray equipment and is directly related to the x-ray output. To reduce heat, the x-ray output is often curtailed. A second factor which influences the x-ray output is the effective potential applied in accelerating the electrons. This is the same characteristic mentioned in connection with the quality of radiation, but it is a different influence of this characteristic. The quantity of x-rays generated increases with the 2.5 power of the applied potential; i.e., conversion of the electron energy to x-rays becomes more efficient as the applied potential increases. Therefore, the larger percentage of electrons which are accelerated at the higher or near to peak potential, the greater the output of the x-ray machine. A third factor which affects the output is the quantity of x-rays absorbed in the material of which the machine is constructed. This is termed inherent absorption. To assess the radiation output or productivity from an x-ray machine, we must know the roentgen output. The roentgen output is a measure of the number of

x-ray photons developed, based upon the ionization effect produced when these photons are absorbed in air. When comparing two x-ray machines which are generally equal in design, the machine with the highest output in roentgens is the more suitable. For comparison purposes, all factors concerned with the roentgen measurement must be equivalent. Roentgen output can be expressed in terms of roentgens per hour at a distance of one meter (rhm).

(3) Source Size. The sharpness of a radiographic film image is partly determined by the size of the radiation source (focal spot). The electron beam in most x-ray tubes is focused so that a small area of the target is bombarded by the beam. Usually the target (anode) is set at an angle (figure 5.3(1)) and the projected size of the bombarded area, as viewed from the specimen, is smaller than the actual focal spot. This projected area of the electron beam is the effective focal spot. In theory, the optimum tube would contain a pinpoint focal spot. In practice, the size to which the focal spot can be reduced is limited by the heat generated in target bombardment. If the actual focal spot is reduced beyond certain limits the heat at the point of impact destroys the target.

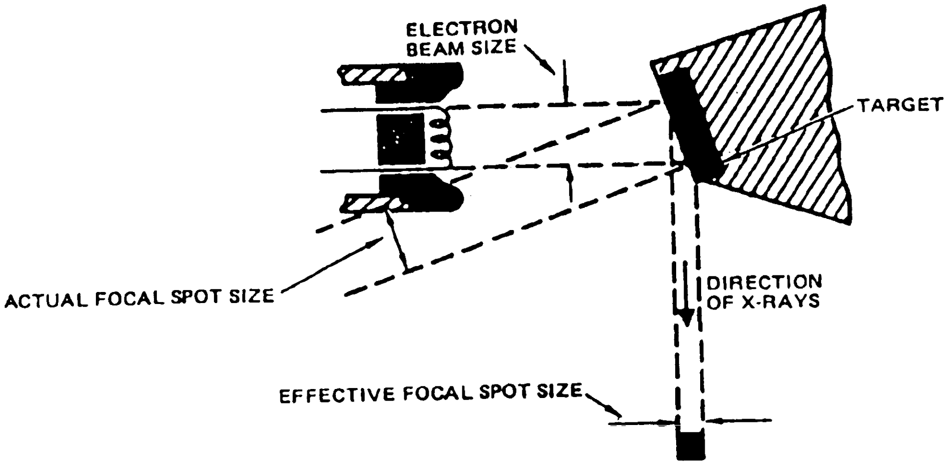


FIGURE 5.3(1). Effective versus actual focal spot size.

Many accessories are necessary for x-ray work. They are:

a. Diaphragms, Collimators, and Cones. Diaphragms, collimators, and cones are thicknesses of lead, fitted to the tubehead of x-ray equipment, or built to limit the area of radiation (see figure 5.3(2)). They decrease the amount of scatter radiation by limiting the beam to the desired test area. Many x-ray machines have built-in adjustable diaphragms designed so that the beam at a fixed distance covers a standard film size area.

b. Filters. Filters are sheets of high atomic number metal, usually brass, copper, steel, or lead, placed in the x-ray beam at the tubehead (see Figure 5.3(3)). By absorbing the "soft" radiation of the beam, filters accomplish two purposes: they reduce subject contrast permitting a wider range of test item thicknesses to be recorded with one exposure; and they eliminate scatter caused by soft radiation. Filters are particularly useful in

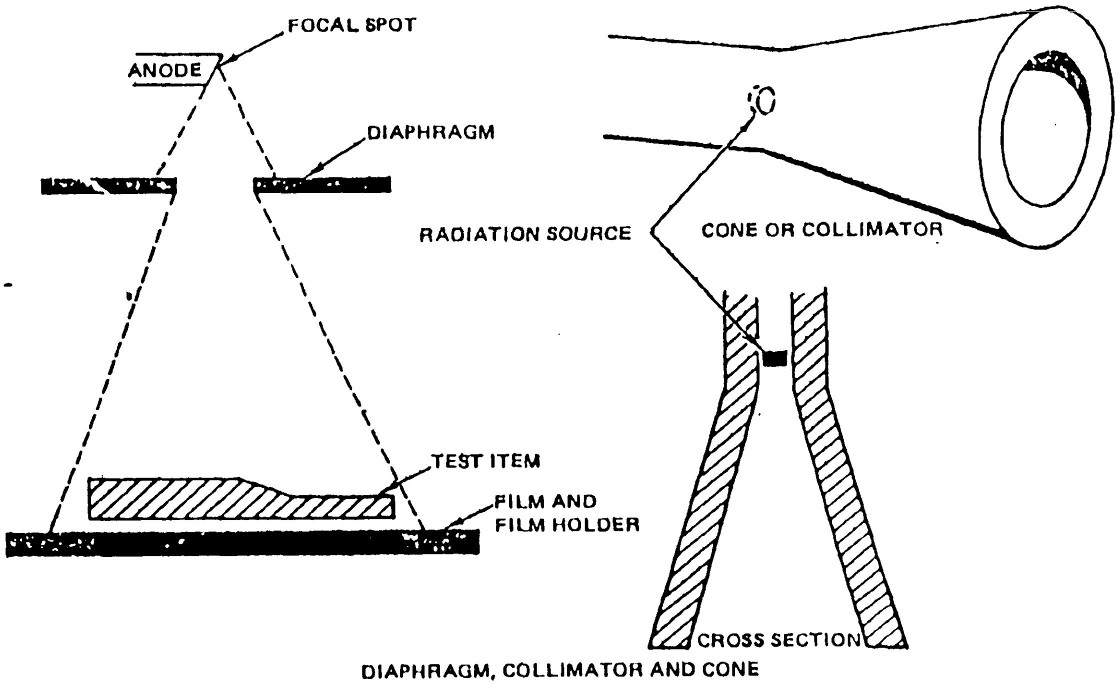


FIGURE 5.3(2). Accessories for radiographic testing.

radiology of items with adjacent thick and thin sections. The material and thickness of the test item and its range of thicknesses determine the filter action required. In radiographing steel, good results are usually obtained by using: lead filters 3 percent of the maximum test item thickness; or copper filters 20 percent of the maximum test item thickness.

c. Screens. When an x- or gamma-ray beam comes in contact with film, less than one percent of the radiation energy available is absorbed by the film in producing an image through photographic effect. To convert the unused energy into a form that can be absorbed by film, fluorescent or lead radiographic screens may be used on the front and/or the back of the film. The intensification factor of lead screens is much lower than that of fluorescent screens. When exposed to low energy photons, it is possible for the front screen absorption effect to be of such magnitude that required exposure is greater than that without screens. However, because of their capability for reducing the effects of scattered radiation and the resultant better contrast and definition of the radiographic image, lead screens can still be practical. They are used in almost all gamma ray applications and for most x-ray work above 100 KVP. Back screens also filter out low-level scatter arising from materials behind the film.

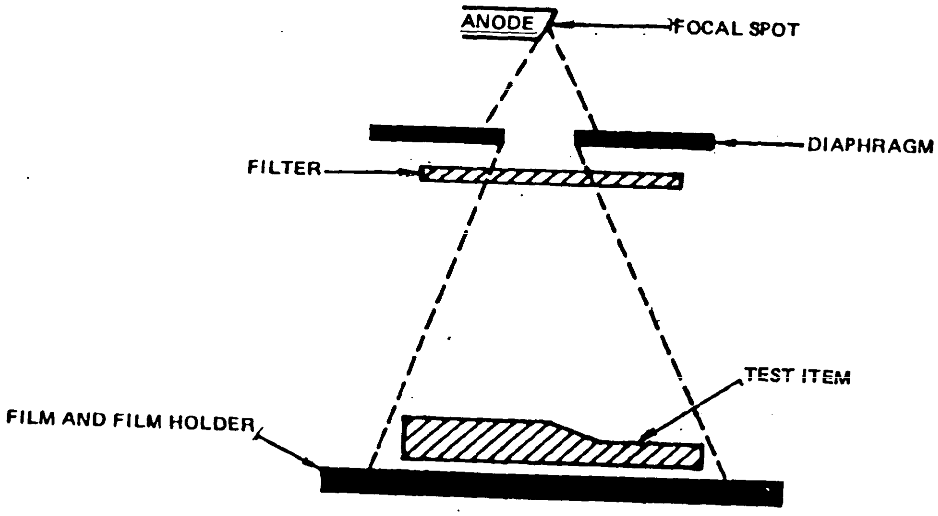


FIGURE 5.3(3). Filters.

To ensure the intensification action of lead screens, they must be kept free from dirt, grease, and lint since these materials have high electron absorption qualities and can absorb the "intensifying" electrons emitted by the screens. The screens may be cleaned with commercial cleaners that are nontoxic and nonflammable. If a more thorough cleaning is desired, fine steel wool can sometimes be used. The fine abrasion marks caused by gently rubbing with steel wool leave no harmful effects. Scratches can be a problem in very fine detailed radiography. Deep scratches, gouges, wrinkles, or depressions that affect the flatness of the screen surface will cause poor radiographic results. It is important that intimate contact be maintained between the lead screens and film surfaces. Small air gaps can cause a fuzzy image. This is due to scatter of the photo electrons by the air. The photo electrons are knocked off the surface of the lead by the x-ray photons.

d. Masking Material. Masking is the practice of covering, or surrounding, portions of the test item with highly absorbent material during exposure. Masking reduces the test item exposure in the masked areas, eliminating much scatter. Commonly used masking materials are lead, barium clay, and metallic shot (see figure 5.3(4)). When barium clay is used as a mask material, it should be thick enough so that radiation absorption of the clay is appreciably greater than that of the test item. Otherwise, the clay will generate noticeable scatter. In any circumstance, the sole purpose of masking is to limit scattered radiation by reducing the area of the test item exposed to the primary beam.

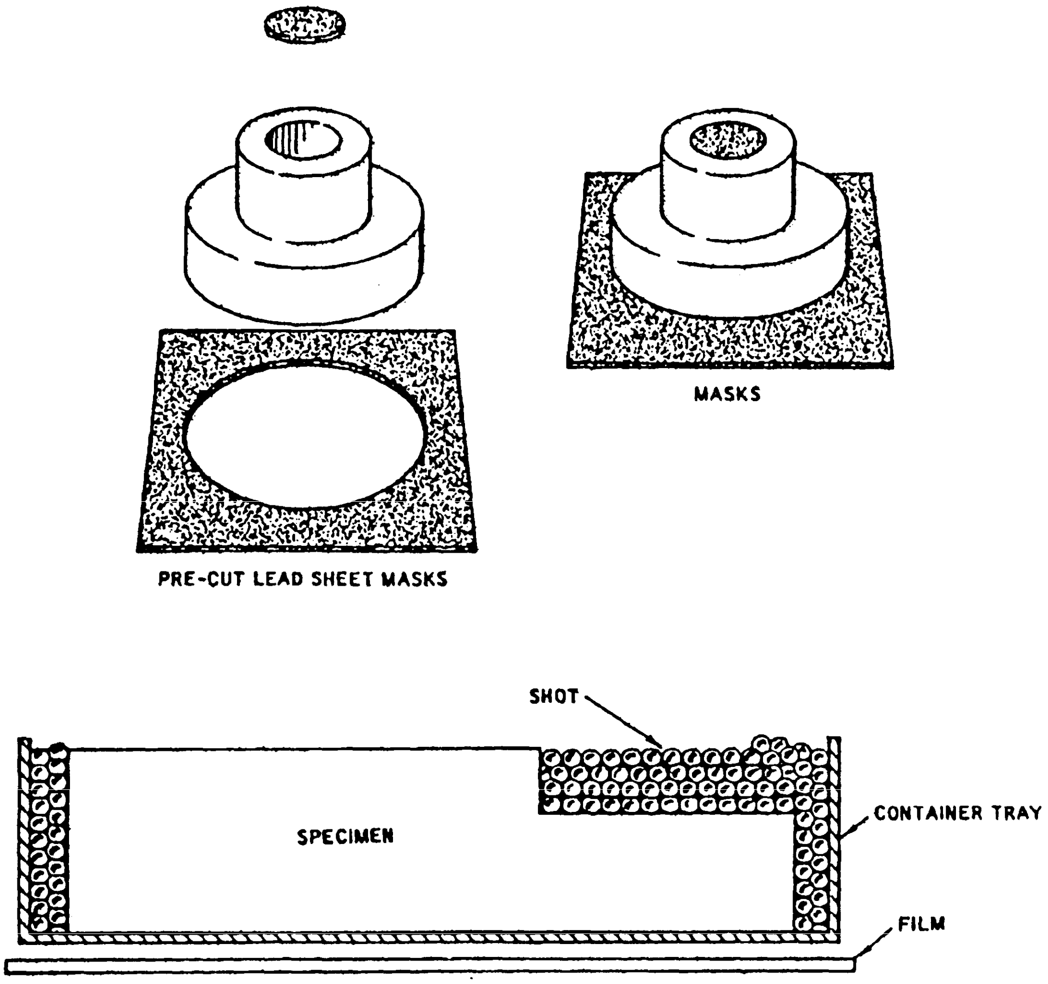


FIGURE 5.3(4). Masking techniques for radiography.

e. Penetrameters. The penetrameter, for indicating image quality, is composed of material identical, or radiographically similar, to the specimen being radiographed and whose thickness is a percentage of the specimen thickness. It may also contain steps, holes or slots. When placed in the path of radiation, its image provides a check on the radiographic technique used. (Figure 5.3(5) shows a penetrameter for one-inch material.)

Penetrameters are used to indicate the contrast and definition which exist in a given radiograph. The type generally used in the U.S. is a small rectangular plate of the same material as the object being x-rayed. The

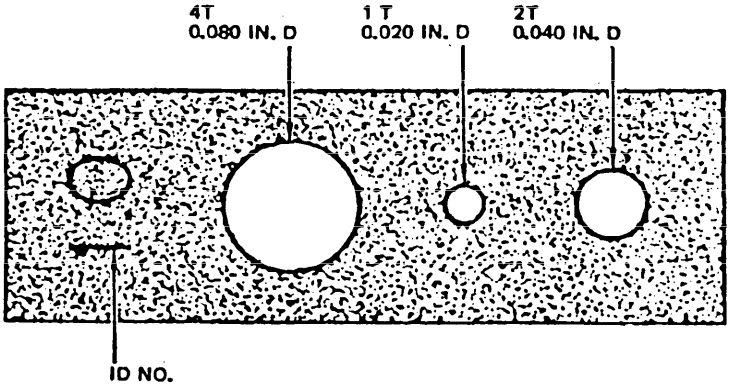


FIGURE 5.3(5). Standard penetrameter for one-inch material.

construction of film holders and cassettes should be of such design as to insure intimate contact between films and screens. It is of uniform thickness (usually two percent of the object thickness) and has holes drilled though it. Hole diameters of one, two, and four times the thickness of the penetrameter are specified by ASTM. In addition to the type of penetrameter just described; step, wire, and bead penetrameters are also used. These are described in the literature and in ASTM Specification E-94. When a set-up is vertical, the heavy lead screens tend to slump or bulge. The common penetrameters (also called Image Quality Indicators) are made of aluminum, steel, magnesium, copper, and titanium.

The degree of sharpness evidenced by the detail of the outline of the penetrameter is referred to as the contrast sensitivity. If the outline is clearly defined, the contrast sensitivity is referred to as two percent or better. Detail is defined as the degree of sharpness of outline of the image. If the radiograph does not show a clear definition of the test item or a flaw in the test item, it is of little value, although it may have adequate contrast and density. Penetrameters of different types have been devised for special uses; e.g., special small wire penetrameters are used in the radiography of small electronic components.

f. Shim Stock. Shim stock for radiographic testing may be defined as thin pieces of material identical to test item material. They are used in radiography of welds, etc., where the area of radiographic interest is thicker than the test item thickness. Shims are selected so that the thickness of the shim equals the thickness added to the test item (by the weld) in the area of interest (see figure 5.3(6)).

The shim is placed underneath the penetrameter (between the penetrameter and the test item). In this way, the image of a penetrameter is projected through a thickness of material equal to the thickness in the area of interest. In use, the length and width of the shim should always be greater than the similar dimensions of a penetrameter as indicated in Figure 5.3(6).

g. Film Holders and Cassettes. Film holders are designed to shield film from light and to protect it from damage. Film holders are made from a variety of materials including rubber and plastic. The holders are flexible

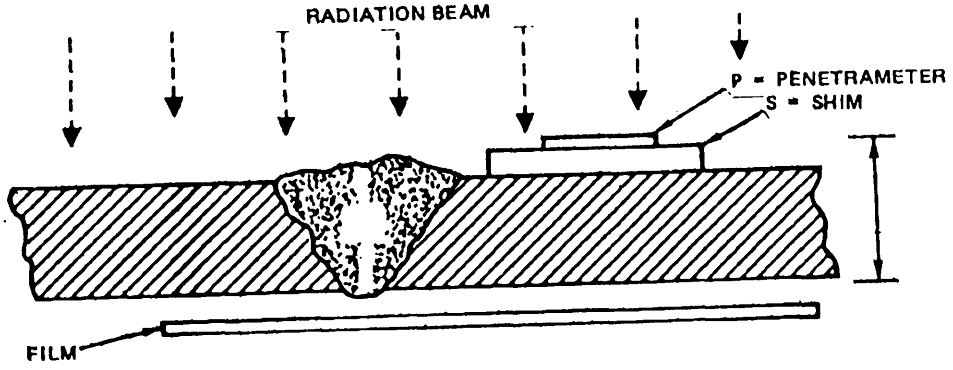


FIGURE 5.3(6). Use of shim stock.

and permit molding the film to the contours of the test item, thereby holding item-to-film distance at a minimum. Cassettes are specially designed, rigid, usually two-piece hinged, film holders that spring-clamp tightly together. Cassettes are of use when flexibility is not required since their clamping action holds screens and film together, and firmly in place.

h. Linear and Angular Measuring Devices. Correct source-to-film distance and knowledge of test item thicknesses are required for any radiographic setup. For these measurements, a six-inch machinist's scale and a tape measure are often tools of the radiographer. When a task requires radiography at an angle other than that normal to the plane of the test item, a plumb bob and protractor may be used to determine the correct angular setup.

i. Positioning Devices. For quality radiography, the position of the source, the test item, and the film should remain fixed during exposure. For both x- and gamma-ray equipment, the floor, a table, or any stable surface may suffice to support the test item. Specifically designed holders (usually tripods) are used to position the cable containing the source. Any positioning arrangement complying with safety considerations and not causing excess scatter radiation is generally acceptable.

j. Identification and Orientation Markers. To permit correct interpretation of the finished radiograph, the test item and the radiograph must be marked so that the test item and its orientation can be identified with the radiograph. This may be accomplished by affixing lead numbers or letters to (or adjacent to) the test item during exposure, and marking the test item in identical fashion with a marking pen, or by scribing. The lead numbers or letters, which are attached with masking tape, appear on the radiograph. Comparison of the radiograph with the marked test item eliminates any possibility of wrong identification.

k. Area Shielding Equipment. The control of scatter radiation can be accomplished by proper use of shielding. Areas in which radiography takes place must be adequately protected against both side and back scatter. In permanent installations, this is accomplished by use of lead shielded rooms or compartments. When permanent installations are not available, lead screens may be placed so that areas reached by the primary radiation are shielded. The area immediately beneath (or behind) the film should always be covered with lead.

l. X-ray Film. Basically there are three grades of film for industrial radiography: coarse grain, fine grain, and extra-fine grain film. The extra-fine grain film gives the highest contrast or quality, but requires relatively long exposure times. The coarser grain films do not quite give the good quality results that the finer grain films do, but they need only relatively short exposure times. Since there is a wide variety of films to choose from, one is able to select the optimum film for a given job. (See Section 5.2(3) for basic film considerations.) Note that the grading of industrial x-ray film is rather arbitrary and is mainly determined by the film manufacturers. Therefore, any candidate x-ray film should be tested and evaluated before applying it to a particular inspection job.

Commercial radiographic film is normally sold in sheet film of various standard dimensions (which may be coated with the photosensitive emulsion on only one side or on both sides of the film) or in rolls of various widths and practically unlimited length. The roll form is especially useful for radiographing circumferential areas. Most radiographic films are relatively insensitive to red or yellow light. For this reason, films may be handled in a dark room which is properly illuminated with red or yellow safelights of low intensity. Several types of such lights are commercially available with special filters for use in the processing of radiographic film.

m. X-Ray Exposure Charts. x-ray exposure charts show the relationship between material thickness, kilovoltage, and exposure. Each chart applies only to a specific set of conditions: a certain x-ray machine; a certain target-to-film distance; a certain type of film; certain processing conditions; and the density upon which the chart is based. Exposure charts are adequate to determine exposures of test items of uniform thickness, but should be used only as a guide when radiographing a test item of wide thickness variations. Charts furnished by manufacturers are accurate only within ±10 percent (since no two x-ray machines are identical). For quality radiography, x-ray exposure charts should be based on: (1) the material most often radiographed; (2) the film most commonly used; and (3) a reasonably chosen target-to-film distance. These should be prepared for each x-ray machine in use.

Exposure charts can also be prepared to show film latitude (which is defined as the variation in material thickness which can be radiographed with one exposure) while maintaining film density within acceptable limits. These limits are fixed by the lowest and highest densities that are acceptable in the finished radiograph.

n. Gamma Ray Exposure Charts. The variables in gamma radiography are the source strength and the source-to-film distance. These are related on the chart to each of different speed films. By selecting a given film type, the radiographer can determine exposure time for desired image density. Gamma ray exposure charts are similar to x-ray exposure charts, and are adequate to determine exposures of test items of uniform thickness. However, they should be used only as a guide when radiographing a test item of wide thickness variation. Charts are available from film manufacturers and are generally accurate when used with film processed in compliance with the manufacturer's recommendations. These exposure charts must be used in conjunction with dated decay curves (see next item).

o. Dated Decay Curves. Dated decay curves are supplied with radioisotopes. By use of the curve, the source strength may be determined at any time. Since the source strength must be known before exposure calculations can be made, the decay curve eliminates the necessity of source strength measurement, or calculation, prior to source use. When source strength is known, decay curves are readily prepared by using half-life values and plotting the resultant curve on semi-logarithmic paper.

p. Densitometer. The densitometer is an instrument used to measure photographic film density. Radiographic film density is defined as the degree of blackening of the film. Visual and electronic densitometers are commercially available. Accuracy is desirable in a densitometer but consistency is more important. A good densitometer, under similar conditions of use, will give similar readings each time.

5.3.2 Gamma ray equipment. Radiation from radioactive material producing gamma rays cannot be shut off. Gamma ray equipment is therefore designed to provide radiation-safe storage and remote handling of a radioisotope source. The United States Nuclear Regulatory Commission (USNRC) and various state agencies prescribe safety standards for the storage and handling of radioisotopes under their control. Similar safety procedures are required for the storage and use of radium which is not under USNRC control.

The effective focal spot in x-radiology is the x-ray generating portion of the target as viewed from the specimen. In gamma-radiology, since all of the radioactive material is producing gamma rays, the focal spot includes all the surface area of the material as viewed from the specimen. For this reason it is desirable that the dimensions of a gamma ray source be as small as possible. Most isotope sources used in radiography are right cylinders whose diameter and length are approximately equal. This source shape permits the use of any surface as the focal spot, since all surfaces, as viewed from the specimen, are approximately equal in area. To assure maximum sharpness of the film image when using isotope sources that are not right cylinders, it is necessary to place the smallest surface area of the source parallel to the plane of the specimen.

Some specific radioactive sources are:

a. Radium. Radium is a natural radioactive substance having a half-life of approximately 1600 years. In practical applications, radium, because of its slow disintegration, is considered to have a constant rate of gamma ray emission. Radium itself does not produce useful gamma rays, but through decomposition produces radon and other daughter products, that cause the emission of useful gamma rays. By placing radium in a gas-tight capsule, preventing the escape of radon, a state of equilibrium is reached whereby the amount of radon lost through disintegration is equal to the amount produced by decomposition of the radium. For practical purposes, this state of balance causes a constant rate of gamma ray emission from a radium source. Pure radium is not used in radiography and most sources consist of radium sulfate packaged in either spherical or cylindrical capsules. Because of its low specific activity, radium is little used in industrial radiography.

b. Cobalt 60. Cobalt 60 is an artificial isotope created by neutron bombardment of cobalt, having a half-life of 5.3 years. Cobalt 60 primary gamma ray emission consists of 1.33- and 1.17-MeV rays similar in energy content to the output of a 2-MeV x-ray machine. The radioisotope is supplied in the form of a capsuled pellet and may be obtained in different sizes. It is used for radiography of steel, copper, brass, and other medium weight metals of thicknesses ranging from 1 to 8 inches. Because of its penetrating radiation, its use requires thick shielding, with resultant weight and handling difficulty.

c. Iridium 192. Iridium 192, another artificial isotope produced by neutron bombardment, has a half-life of approximately 75 days. It has high specific activity and emits gamma rays of 0.31, 0.47, and 0.60 MeV, comparable in penetrating power to those of a 600-KVP x-ray machine. Industrially, it is used for radiography of steel and similar metals of thicknesses between 0.25 and 3.0 inches. Its relatively low energy radiation and its high specific activity combine to make it an easily shielded, strong radiation source of small physical size (focal spot). The radioisotope is obtainable in the form of a capsuled pellet.

d. Thulium 170. Thulium 170, obtained by neutron bombardment of thulium, has a half-life of approximately 130 days. The disintegration of the isotope produces 84-KeV and 52-KeV gamma rays, soft rays similar to the radiation of x-ray equipment operating in the 50- to 100-KVP range. It is the best isotope known for radiography of thin metals since it is capable of producing good radiographs of steel specimens less than one-half inch thick. One of the major advantages of the use of thulium 170 is its soft wave radiation, which permits its containment in small equipment units of extreme portability since only a small amount of shielding is required. Because the pure metal is difficult to obtain, the isotope is usually supplied in capsules containing the oxide TM_2O_3 in powder form.

e. Cesium 137. Cesium 137, a by-product of the fission process, has a half-life of 30 years. It emits gamma rays of 0.66 MeV, equivalent in energy to the radiation of a one-MeV x-ray machine. It is used in the radiography of steel of thicknesses between one and two-and-one-half inches. It is superior to other isotopes of similar capability only in its slow rate of decay. Cesium 137 is usually handled in the form of the chloride CsCl, a soluble powder requiring special safety precautions. The USNRC recommends double encapsulation in containers constructed of silver-brazed stainless steel.

f. Other Radioisotopes. Many other radioisotopes that are radiographically useful are not considered here because in practical applications one or another of the four discussed is superior. Table 5.3(3) is a summary of the characteristics of the four most-used isotopes.

Because of the ever-present radiation hazard, isotope sources must be handled with extreme care, and stored and locked in adequately shielded containers when not in use. Equipment to accomplish safe handling and storage of isotope sources, together with a source, is called a camera. Figure 5.3(7) shows a typical camera consisting of:

a. Shield Case Assembly. A shield case assembly is a heavy gage steel case containing a block of lead or Uranium 238 (storage pig) which shields the source when not in use. Microswitches within the case energize the stored and open lights which indicate source positions. One end of the case has a connector for the control cable-to-crank extension and the other a connector for the extended source position cable.

b. Reel Assembly. The reel assembly is comprised of a storage reel for the flexible armored steel cables, a crank to extend and draw back the source, and a light panel housing three lights that indicate positions of the source: "STORED" (safely shielded within the pig), "OPEN" (partially extended), and "ON" (fully extended).

c. Source Switch Assembly. Located at the extreme end of the extended source position cable, the source switch assembly houses the source capsule when it is in the fully extended position. The assembly contains a switch which functions to energize the "ON" indicating light when the source is in the fully extended position.

d. Source Capsule Assembly. The Source capsule assembly is a short length of cable with the source, in a stainless steel container, attached to one end and a connector for attachment to the control cable on the other. figure 5.3(8) shows operation of a typical camera. Cameras that use a direct reading of the length of cable extended to indicate source position, and cameras that replace the manual crank with pneumatic or electrical drive units, are only modifications of the basic design. There are, however, other types of cameras (figure 5.3(9)) that do not require removal of the source from the storage pig. These cameras permit exposure by removing or rotating a part of the source shielding. The required physical movement to expose the source is initiated from remote positions, either manually with long poles, or by electric drive units.

* 5.3.3 Radioscopic equipment. In addition to standard radiographic film imaging systems, fluoroscopic and television imaging systems are also used. Direct viewing systems substitute a fluorescent screen for the film used in conventional (film) radiography. The x-ray image is produced directly on the fluorescent screen, and is viewed indirectly through an optical system to prevent direct eye exposure to hazardous radiation. It is a relatively low-cost, high-speed process and is easily adapted to production line requirements. It is widely used in applications where rapid scanning of articles for gross internal flaws or abnormal conditions is desired. By use of fluoroscopy, a large number of articles can be screened prior to radiographic test. Those with gross defects are immediately rejected, with resultant cost savings. Fluoroscopy cannot be used with test items that are thick or of dense material since the intensity of the radiation passing through the test item would be too low to brighten the screen sufficiently for viewing. In using fluoroscopy, an image amplifier is employed to enhance the

TABLE 5.3(3). Isotope characteristics.

ISOTOPE	COBALT-60	IRIDIUM-192	THULIUM-170	CESIUM-137
HALF-LIFE	5.3 YR	75 DAYS	130 DAYS	30 YR
CHEMICAL FORM	Co	Ir	Tm_2O_3	$CsCl$
GAMMAS MeV	1.33, 1.17	0.31, 0.47, 0.60	0.084, 0.052	0.66
RADIATION LEVEL RHF/CURIE	14.4	5.9	0.032*	4.2
PRACTICAL SOURCES				
CURIES	20	50	50	75
RHM	27	27	0.1	30
APPROX DIAMETER	3 mm	3 mm	3 mm	10 mm

*VARIES WIDELY BECAUSE OF HIGH SELF-ABSORPTION

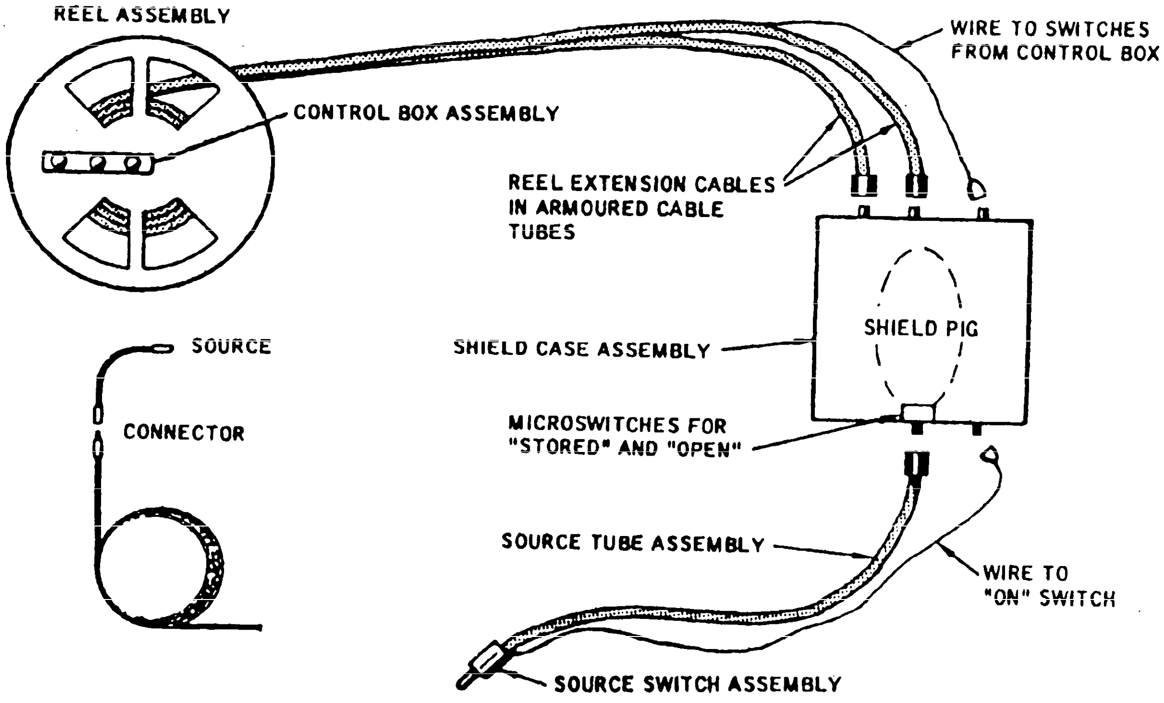


FIGURE 5.3(7). Diagram of typical isotope camera.

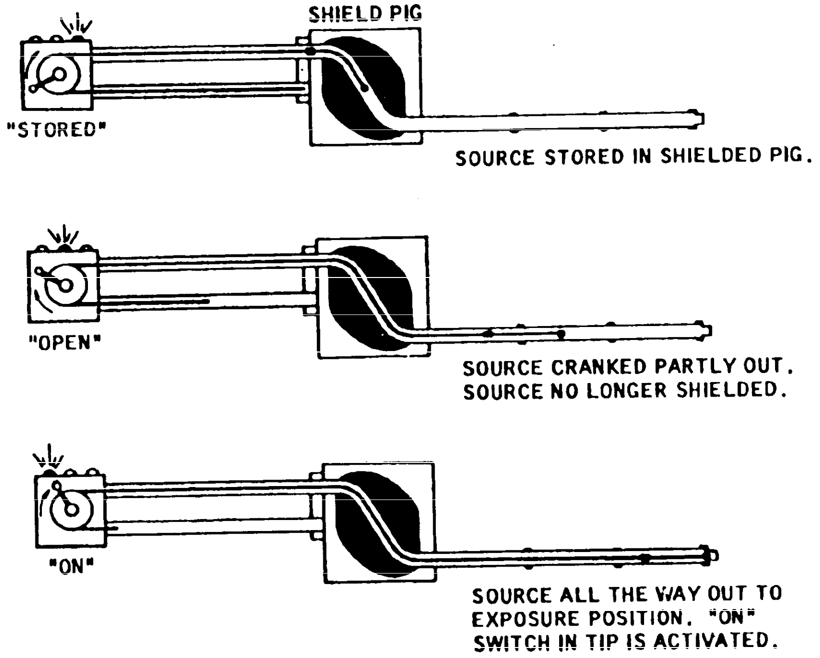


FIGURE 5.3(8). Operation of typical isotope camera.

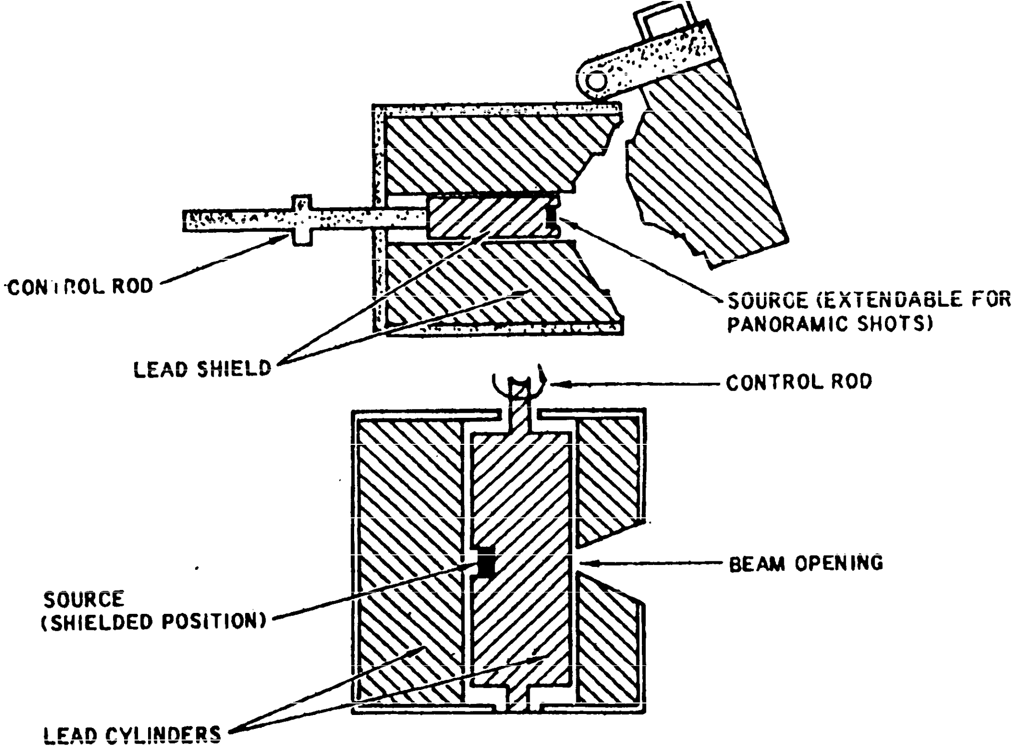


FIGURE 5.3(9). Isotope cameras.

brightness of the image. This image amplifier also serves to protect the operator from radiation. It consists of an image tube and an optical system. The image tube converts the x-ray image on the fluorescent screen to electrons, and it accelerates and electrostatically focuses the electrons to reproduce the image on the smaller fluorescent screen. The optical system magnifies the image.

For television imaging or remote viewing systems, advanced electronic techniques are available which allow viewing radiologic images as television pictures. A special vidicon television pickup tube is used in the place of the film in conventional (film) radiography; associated circuitry and controls allow the x-ray image to be displayed directly on a television monitor screen. The tube differs from normal vidicon tubes in that it is x-ray sensitive rather than photo- sensitive. It is widely used to permit instant image reproduction, combined with observer protection from exposure. The system is designed for radiologic inspection of small items such as electronic components and assemblies, and system components. It is highly suitable for in-motion x-ray inspection. Permanent records may be obtained by photographing the monitor screen of the readout system.

Recently digital electronic radiography has been introduced which is growing in importance. Various methods are used to generate electronic images, which are digitized and processed by computers. Enhanced images are then presented to the inspector, or the computer may analyze the image automatically.

Advantages for both of the above systems include:

a. There is no delay in obtaining the image.
b. They can be used for in-motion imaging of test objects.
c. Television-type systems are applicable to remote monitoring, thus enabling the observer to be out of range of hazardous radiation.
d. Cost of film processing and identification of areas of test objects being radiographed are eliminated by fluoroscopic and electronic imaging systems.
e. Electronic x-ray imaging is applicable to continuous x-ray inspection to observe process operations and details.

Television imaging systems do have certain disadvantages:

a. Require additional expensive equipment.
b. Less sensitive than film radiography.
c. Radiation shielding might be a problem for certain applications.
d. A complete exposure and imaging system is required for one inspector; i.e., inspection cannot be "multiplexed" for productivity as with film.
e. Systems tend to be more specialized, being less flexible than film radiography.
f. Permanent records usually suffer loss of detail since they are secondary recording media (video tape, photographs, etc.) and they are not as "transportable" as x-ray film in that they often require special equipment for viewing.

x-ray sources are the most commonly used sources for radioscopy. Detection of the x-rays depends on two basic processes: x-ray to light conversion and x-ray to electron conversion. A complete discussion of this subject is given in ASTM E1000.

In x-ray to light conversion, x-rays are converted to visible light by fluorescence and scintillation. Phosphors and scintillators are materisls used to effect the converstion.

In x-ray to electron conversion, semiconductor materials are usually used, with the mechanism enabling this brought about by the energizing of semiconductor junctions or the x-rays affecting the resistance of the semiconductors. The most common example of the latter is the x-ray sensitive vidicon camera tube.

Recent developments include the use of microchannel plates, which consist of an array or bundle of very tiny, short tubes, each of which can emit a large number of electrons from one end when x-rays strike the other end.

The usual display for radioscopic systems is graphic, and the display must have sufficient size, color, brightness, contrast, and resolution to meet the minimum image-quality-indicator sensitivity levels established by specification. Advances in electronics and digital techniques are revolutionizing graphic displays, and the available equipment is extensive.

Static photographs may be made of either directly viewed or remote television monitor presentations, with the photographic factors adjusted for the light level.

* 5.3.4 Computed tomography equipment. Computed tomography (CT) is a very specialized form of radioscopy that utilizes similar equipment to that used in radioscopic testing. However, it also includes complex computer equipment as well as fine mechanical control and detector capability. Basically, CT provides an image with quantitative information on both density and geometry for thin cross sections through an object. In its restricted definition these cross sections are planes including source, object, and image (detector). A variation, in which information can be obtained for planes perpendicular to these (laminography) is not included here, although its applications have also become important.

As described in ASTM E1441, Guide for CT Imaging, CT images are useful for visualizing objects. The work is done by the complex computer operations that are required. For standard radioscopy, more interpretation of results is usually necessary. Also, CT images are digital, and readily enhanced, analyzed, compressed, and the data is readily available for performance calculations and comparison with digital data from other NDE methods.

The basic CT system is made up of (1) a source of penetrating radiation, (2) a detector subsystem that usually consists of an array of detectors, (3) a scanning assembly that is mechanically operated, with possible degrees of freedom for translational and rotational motions, (4) computer control, (5) display subsystem, and (6) data storage for maintaining information for display in a single and flexible format.

* 5.3.4.1 Penetrating radiation sources for CT. The radiation sources for CT are similar to other sources used in radiology. X-ray sources include

tubes and machines. Machines that are usually used are linear accelerators. Gamma-ray sources are the various radioactive isotopes discussed in detail in the paragraphs for radiography/x-ray equipment.

* 5.3.4.2 Detectors for CT. Useful detector arrays contain hundreds of sensors. To achieve the performance levels needed for CT, small sensors with excellent resolution capability are required. Detectors for CT are ionization detectors and scintillation detectors. Ionization detectors contain noble gases under high pressure. x-rays ionize the gas, producing electrons. The electrons are next accelerated to produce a charge directly proportional to the intensity of incident x-rays. Different methods are used for measuring the electric charge. Scintillation detectors convert the incoming x-rays to visible light. The light is then converted to an electrical signal by a photodiode or photomultiplier tube. Both ionization and scintillation detectors are capable of withstanding mechanical abuse and are useful in a number of configurations.

* 5.3.4.3 Mechanical scanning hardware. Developments in relative motion of the test object and the source-detector subsystem have been a result of various requirements and tradeoffs of (1) required resolution, (2) available time for scanning, and (3) cost. Various configurations for relative motion are used, as discussed earlier, classified as first - to fourth-generation scan geometries. Rotate only geometries are fastest in covering the test object completely, and useful for medical applications. For industrial use, flexibility is more important, with scan time secondary except in situations in which inspection utilizing high throughput is called for. Details of these scan geometries can be found in ASTM E1441, Standard Guide for Computed Tomography (CT) Imaging, and numerous references given there.

* 5.3.4.4 Computer control systems. The computer is the "brain" for CT scanning, for data acquisition and processing, and for display and storage. Selection of appropriate micro processors and other computer equipment is directly dependent on the use for the CT system.

* 5.3.4.5 Display subsystem. Various enhancement capabilities can be incorporated into the visual presentation, as brought about by the computer and the display hardware. Many of the same techniques are used for CT as for radioscopic display. The digital nature of data acquisition and processing is neded to achieve the latitude and/or contrast required for CT, and the amount of data that is needed is much greater than for most radiographic work.

* 5.3.4.6 Data storage: Reconstruction of images for CT is complicated. An advantage of the computerized data storage is the flexibility permitted in uilizing the stored digital information at future times if newer algorithms are developed or if emphasis or utilizing information is changed. The storage medium may be a magnetic tape, a floppy disk, or an optical disk.

5.4 PROCEDURES AND TECHNIQUES

5.4.1 Basic procedures and techniques. To produce an acceptable radiograph, there are several specific determinations that must be established.

Somewhat in order, they are:

a. The specimen: the exact point and/or area of the specimen to be examined, the specimen variable being sought, the expected or preferred orientation(s), the number of desired shots and/or views, the material composing the specimen, the total thicknesses, the percent density variance expected, etc.

b. Geometric limitations: distance available between a source and the specimen, relative placement of film, etc.

c. Type of film (or recording device).

d. Desired densities and/or standards.

Once these first four items are established, a choice of equipment, if choices are available, must be made. (See section 5.3 for information on basic differences in equipment.) With selection of the equipment, initial settings must then be determined (these initial settings are expected to be changed when test results indicate a need for a change).

e. The exact geometries (distance from beam source to specimen, distance to film, etc.).

f. Initial voltage settings and initial amperage settings for x-rays.

g. Isotope selections for γ-rays.

h. Exposure times.

Throughout this process, safety must always be considered. Also, most of the above decisions will be affected by factors relating to the quality, or perfection, of the radiograph required or desired versus the allowable time or cost. There will sometimes be special problems, often relating to the accessibility or mobility of the specimen or the equipment.

Some of the last items that need to be considered are:

i. Identifications and markers to appear on each radiograph, for each view, etc.

j. Special filters, shields, screens, etc.

Not all specimens and specimen variables can be effectively examined by radiography. Since radiographs are shadowgraphs, specimens that have complicated geometries might consist of superimposed images that will preclude proper examination of the area of interest. This is especially true if internal scattering is present. In some cases, the geometry of the specimens prevents proper orientations between the beam rays, the expected defects, and/or the film.

The information depicted in a radiograph is obtained by virtue of density differences brought about by differential absorption of the radiation. These density differences, unless gross in nature, must be oriented parallel to the direction in which the radiation is traveling. Discontinuities of small volume, such as laminar flaws, will often be undetected because they do not present a sufficient density differential to the radiation. The very nature of a delamination precludes their ready detection, and radiographic inspection is seldom used to locate this type of flaw. A specimen can be too thick to penetrate. As material thickness is increased, the time required to obtain sufficient information on the film also increases. For a given energy (penetrating power) of x- or gamma radiation, there exists an economic maximum thickness beyond which radiography is not feasible. If the cost is warranted, radiographic equipment of higher energy potential could be obtained. Such costs increase markedly because of the barriers required to protect personnel from the harmful effects of the radiation as well as the basic cost of larger equipment.

Thus, it is vital for a radiographer to know and understand the limits of radiography. The determination of the feasibility of any particular assignment and its success will depend upon knowledge of the specimen; the type, nature, and extent of the expected defects or variables; and the choices in orientations or views available to the radiographer.

The geometric relationships are important for four reasons: 1) the area of exposure is normally a function of the distance from the source to the specimen, 2) the intensity of the beam and the exposure time required is a function of the distance from the source to the film, 3) the magnification factor between the image on the film and the specimen is the ratio of the distance between the film and source (d_f) to the distance between the specimen and source (d_s), and 4) the sharpness of the image will be a function of the difference between the above two distances (d_s-d_f) times the effective diameter of the source.

Figures 5.4(1) and (2) illustrate some of these concepts.

Optimum geometrical sharpness of the image is obtained when the radiation source is small, the distance from the source to the test item is relatively large, and the distance from the test item to the film is relatively small. The magnification factor approaches one under these optimum conditions, and normally radiographs are seldom taken with magnifications much different than one unless an extremely small focal spot was purposely designed into the x-ray apparatus.

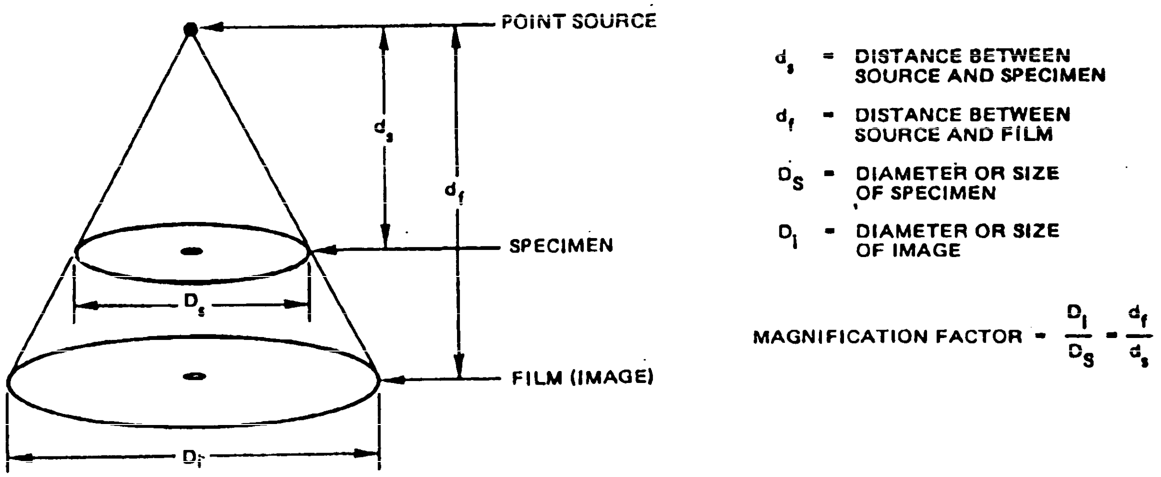


FIGURE 5.4(1). Magnification factor.

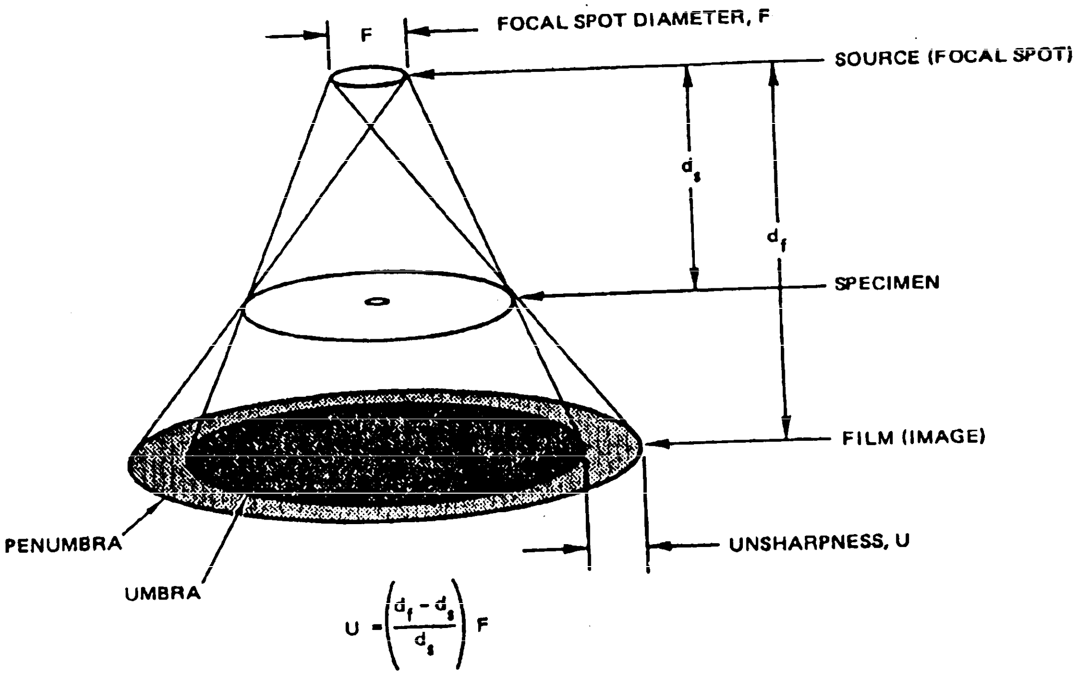


FIGURE 5.4(2). Geometric sharpness factor.

When x-ray films are read by eye, an unsharpness, U, as defined in Figure 5.4 (2), of 0.02 inches or less is often found to be acceptable. Assuming that the film is located directly behind the specimen, this degree of unsharpness will require a minimum source-to-specimen distance for any particular apparatus and thickness of material tested. This limit should be known by the radiographer for his equipment.

FIGURE 5.4(3) and(4) illustrates other geometric variables.

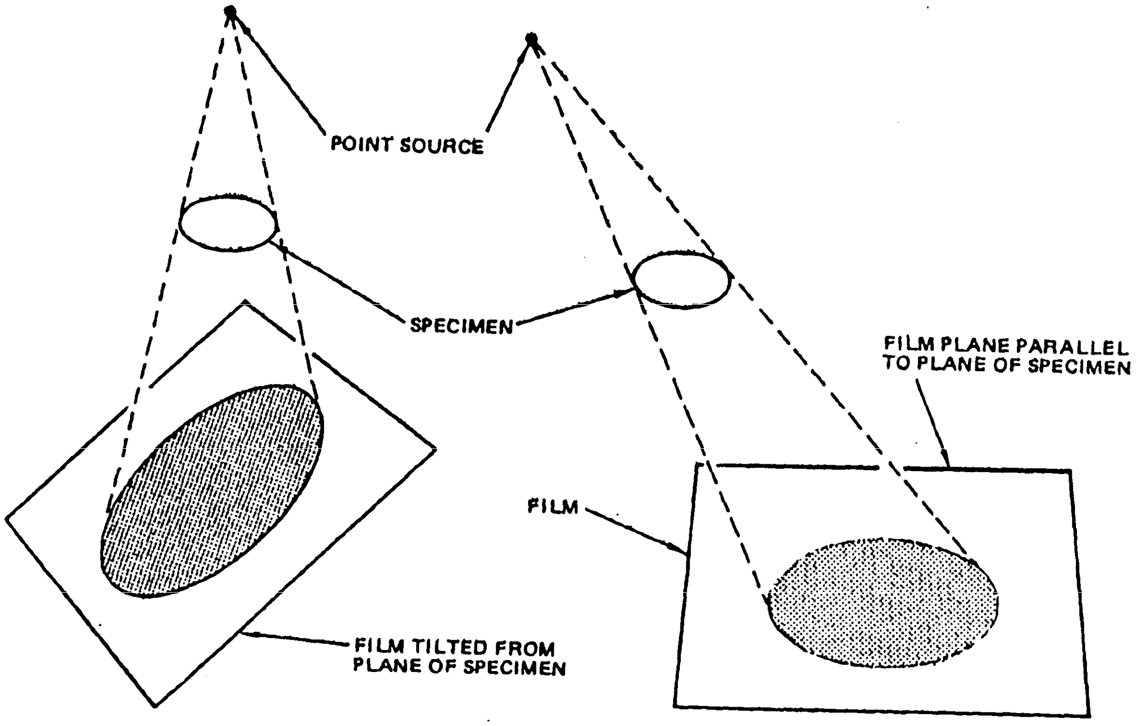
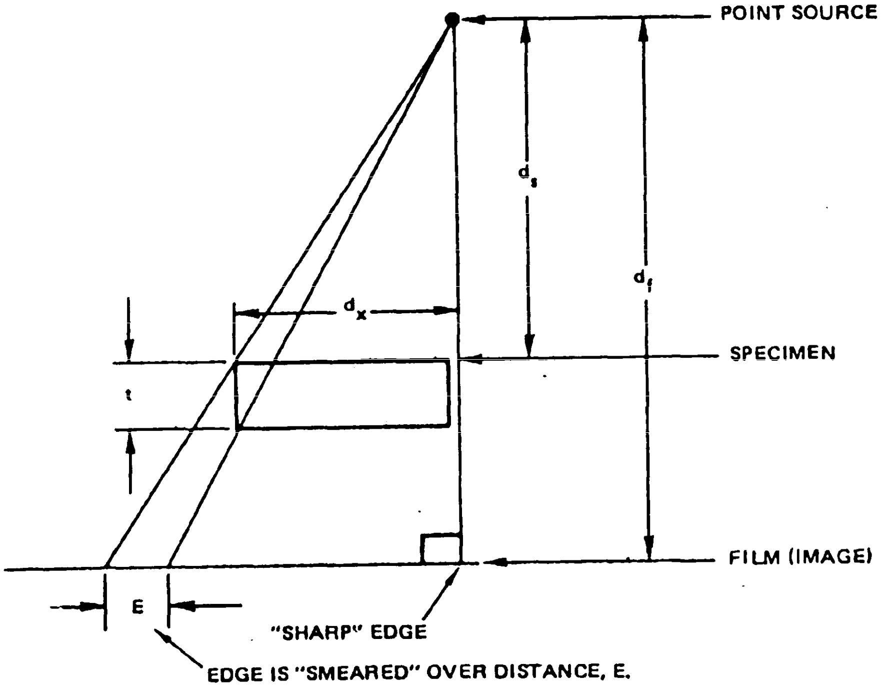


FIGURE 5.4(3). <u>Angular image distortions</u>.

If the plane of the test item and the plane of the film are not parallel, image distortion results. The same is true if the radiation beam is not directly perpendicular to the film plane. Whenever film distortion is unavoidable (as a result of physical limitations of a test), it should be remembered that <u>all</u> parts of the image, defects as well as geometry, are distorted; otherwise, an incorrect interpretation could result.

Very small source-to-specimen distances may be required when extremely low voltages (15 KVP or less) are being used when not in a vacuum. Air will greatly attenuate these beams, and must therefore be considered in these low-voltage setups.



t = DEPTH OR THICKNESS OF EDGE.

d_x = DISTANCE FROM BEAM RAY THAT IS PERPENDICULAR TO FILM AND SPECIMEN.

$$E \approx (t)\frac{d_x d_f}{(d_s)^2} \approx t\frac{d_x}{d_s} \text{ WHEN MAGNIFICATION} \rightarrow 1.0$$

FIGURE 5.4(4). Edge or depth distortion factor.

Thus, the distance between source and specimen might need to be small to increase magnification (if desired), to increase beam intensity, and to shorten exposure times. This source-to-specimen distance might, however, need to be large to improve sharpness, to cover a larger area, or to improve angle or depth distortions. The proper choices often require compromises in these variables.

In choosing the voltage, current, and time settings, several considerations are important. The higher the voltage, the greater the penetration. Higher voltages allow thicker specimens to be examined and/or exposure times to be shortened. However, differentiations in thickness generally become less. If very small changes in thickness must be observed, then the lower kilovolt peak settings are often necessary.

The density of the film is dependent upon the beam intensity multiplied by the time of exposure. Generally speaking, the more dense the film, the greater will be the sensitivity of the information recorded. However, the ability to see this information will depend upon the brightness of the light that is used to read the film. Therefore, there is always a maximum, or optimum, density dependent upon the type of film reader available to the viewer. Normally a density of 2 to 4 is specified. Each film has an exposure characteristic curve that can be used to indicate the "amount of information" and establish the range of latitude that can be recorded. Normally the lower the density of the film, the greater the latitude.

Thus, if very small changes in variables must be detected, low voltages with extra long exposure times (for high film densities) must be expected. If large latitudes are required (exposing several different thicknesses at the same time), then high voltages and short exposure times will be needed. Again, compromises are often necessary.

All basic procedures and techniques cannot be covered in one handbook. Basic procedures used in x-raying various specimen geometries, choosing films, reducing scatter, using charts, etc., do exist. The most important guide, however, even when procedures are being used, is to observe the results. Only by making changes based on the results can optimum conditions be established.

5.4.2 Newest procedures and techniques. Advancements are being made in radiography, to include better films, more sensitive detectors, smaller focal spot sizes, and more efficient x-ray generators. Several "liquids" are now used, such as 1,4-Diiodobutane ($I(CH_2)_4I$), which can wick into surface cracks and delaminations, and because of their high x-ray densities, can be easily observed by x-rays. Using this method, many flaws can be observed that otherwise would not appear on a radiograph. These liquids are used on low density materials, such as organic matrix composites, to improve the detectability of surface-connected defects.

Because of computers, tomography is a useful modern method. Tomography uses multiple x-ray sources and receivers (or a single source and receiver that can move to multiple positions and orientations). The x-ray signals received are correlated by a computer routine to reconstruct a three-dimensional image of the specimen, and allows establishment of views that could not be done by a simple two-dimensional exposure.

A new x-ray method exists which allows x-ray analysis to be made on the same side as the x-ray source. Use is made of Compton scattering. A high power, narrow beam of x-rays, penetrating on a line through a material with detectors focused at specific points on this line, will "image" the part by detecting the amount of Compton scattering occurring at each point. The amount of scattering will be a function of the amount of mass present at each point. This method should find rapid employment in all areas where complicated geometries exist or where there is limited access.

* 5.4.3 Basic procedures and techniques for radioscopy.

* 5.4.3.1 Direct viewing systems. Systems in which an observer view the image from a fluoroscopic unit directly, after a mirror and radiation barrier window have been placed between the fluorescent screen and the observer, are the early versions used for x-ray "real-time" nondestructive inspection and evaluation. Although less frequently encountered than remote viewing systems,

they still have occasional historic significance. The radiation source, object, and screen are oriented in the same way as in (film) radiography. The advantages of direct viewing (fluoroscopic) systems are their low cost and fast inspection, as well as utilization of simple equipment and procedures. Relative to (film) radiography, fluorescent systems do not give a useful record and have relatively low sensitivity as well as poor resolution.

* Visual acuity is important for determining the optimum techniques to use for direct viewing. Several characteristics of the system that produce the limiting values for observation are dark adaptations of the eye at low brightness, the contrast sensitivity, and the ultimate resolutions as determined from overall unsharpness (geometrical, screen, and overall system) as determined from the various dimensions and system scatter. Good collimation is especially helpful in reducing unsharpness.

* 5.4.3.2 Remote viewing systems. Improvements for radioscopic viewing are achieved by using a television pickup of the x-ray image. As discussed in the equipment sector, expenses are greater because of the image intensifier and TV camera introduced between the fluorescent screen and monitor or videotape. However, greater flexibility in operation and the potential for high contrast and resolution become available for these systems.

* Image intensifier tubes convert x-rays to electrons (for which multiplication and/or accelerations are effected), resulting in greater brightness and definition. Other useful systems make use of light amplification (so-called image converters). Microchannel arrays have been used more recently, as well as solid-state cameras.

* Techniques for obtaining better resolution are achieved by increasing the time for obtaining the image, thus increasing the time for performing inspection.

* Details on geometric sharpness are given in the ASNT Handbook on Radiography and Radiation Testing and in Standard ASTM E1000. Overall technique is improved by utilizing a small focal spot for the source and by placing the pick-up tubes close to the test object. Dynamic requirements usually reduce both contrast and resolution capability, thus leading to the use of compromise and slower scanning for the system than initial recommendations.

* Unsharpness is related to geometric unsharpness, screen unsharpness, and motion unsharpness. This affects mostly the spatial resolution capability.

* Various image enhancement techniques are needed to improve image quality and resolution. Digital processing is necessary for the various enhancement methods in use today.

* Use of an image quality indicator (IQI) or penetrameter, is useful for radioscopic systems. It is important to use a system IQI, since image production is more dependent on the overall system (for which greater variations can be produced) than for the film systems. One or two locations for IQI's in a film system are usually sufficient to give contrast and resolution information. For many remote viewing radioscopic systems, an IQI that is tailored to the geometry that is present must be selected and used.

For scanning systems for which variable speeds are utilized, a different IQI or calibration at different speeds should be available. Interpretation then also becomes important.

* Typical image quality indicators are used for contrast sensitivity determination. Spatial resolution can be specified in terms of total unsharpness and can be measured by special standards that lead to knowledge of line pairs per mm or the modulation transfer function for the system. Contrast sensitivity and spatial resolution are somewhat related, but system capability is defined by specifying both.

* 5.4.4 Newest procedures and techniques for radioscopy.

* 5.4.4.1 Enhancement of images. Image enhancement techniques are used to improve contrast at edges or other locations which are critical, while leaving non-critical areas in the image as originaly produced or averaging over these or subtracting out. Methods that are used involve summation, continuous image averaging, and various filtering techniques. One of the most widely developed image detail enhancement procedures incorporates the subtraction of low frequency components of a signal, leaving the high spatial frequencies, which are then amplified to give an image that emphisizes edge effects. These procedures essentially enhance brightness changes at edges or other areas where detail is present. The only major requirement is that a memory is present in the system to store one image, from which the next image can be subtracted (the image produced with the low pass filter).

* Other filtering methods are being developed. Emphasis is now put on reducing the time required to effect the subtraction (or differentiation), so that the "real-time image" is achieved as quickly as possible, permitting scanning to be effective.

* 5.4.4.2 Handling systems. Manipulation of test objects is critical for inspection in certain radioscopic applications. Rotation of a test object (as well as high speed translation) introduces blurring. Care must be taken to obtain snapshot images in a predetermined manner. It is often useful to introduce standards, such as calibration blocks with simulated defects, placed into the system in the same position as the test objects and manipulated through the same range of motions as the test objects undergo.

* The advanced handling systems utilize complete automated control of the object. They use a microprocessor to coordinate the controls for the imaging system, the source power supply, and the handling system. Interaction with the microprocessor is also available to the individual running the system. Appropriate software is needed according to the system design and the output requirements set by the inspection process.

* There are static and dynamic inspection systems available. In the static work, the object is translated and/or rotated to the inspection positions. For each position an image is produced, to be analyzed in conjunction with the software. Dynamic systems require very good alignment of source, object, and detector subsystems in order to achieve relatively low unsharpness. The images are produced more quickly and efficiently, and the requirements for handling systems are greater but result in greater throughput and flexibility.

* 5.4.5 Newest procedures and techniques for computed tomography. The usefulness of CT is based upon the capability to fashion a reconstruction of lots of data, to give a two-dimensional image, with three-dimensional information superimposed. The final three-dimensional map is based on observation of information from all the slices in the test object. The three-dimensional superposition is available by manipulating all the stored digital information. Reconstruction of density differences or other parameters for volume elements within the entire object is possible, and the results are satisfying to viewers because of the presentation as three-dimensional, similar to what people envision. Thus, computed tomography permits decisions to be made for NDE without developing novel comparisons of observed displays and the counterpart in the real world for good evaluation.

* Modern techniques that have enhanced the usefulness of CT include application of the new algorithms and statistical studies. Algorithms are mathematical expressions for reconstructing the CT images. Newer algorithms use transform methods that enable speed of operation. These are more powerful than the previous matrix inversion methods, and finite series expansion methods, although each of the three has advantages. Statistical methods can provide guidance as to which generation scanning technique should be utilized and to select appropriate detection equipment and control. Details of the subjects above are beyond the scope of this handbook. More discussion can be found in ASTM E1441, Standard Guide for Computed Tomography (CT) Imaging.

5.5 IMAGE QUALITY INDICATORS AND STANDARDS

5.5.1 IQI's and standards for radiography. Penetrameters (image quality indicators) are often considered a standard to be used in radiography. In section 5.3, penetrameters were said to measure "radiographic quality" and to provide "a check on the radiographic technique." Therefore, penetrameters are very important, and do determine to a high degree the potential effectiveness of a particular radiograph. They are not, however, always sufficient. They do not always represent actual defects or all the variables being sought. For these reasons, there are special cases where specimens with known defects or flaws, both in the acceptable and unacceptable range, are used as true standards. One of the most critical points in radiographic work is the interpretation of the radiograph. Because radiographs are shadowgraphs, with three-dimensional data compressed onto two dimensions, often with specific geometric distortions and with many possible non-specimen related indications, interpretation by experienced and knowledgeable viewers is often critical. The use of true standards is usually a great help in guiding the interpretation as well as confirming the adequacy of the basic x-ray procedure.

Usually a series of radiographs that exhibit the types and sizes of flaws and/or acceptable variables are assembled. These radiographs are collectively called "radiographic acceptance standards." The radiographic viewer then has the task of comparing and deciding if the radiographs being inspected meet or exceed these radiographic standards. Several representative sets of standards are published by ASTM for certain aluminum, magnesium, copper, tin, and steel alloys.

* 5.5.2 IQI's and standards for radioscopy. Blocks with known defects incorporated into them, in conjunction with IQI's, can be used to define the quality of a radioscopic system. IQI's developed for radiography may be utilized for initial radioscopic inspection. Wire or plaque type IQI's are recommended when no calibration blocks are available. Wire type IQI's should be used in a manner emphasizing the least sensitive direction. IQI's can be used where dynamic effects are present, but only if they are part of the overall system. Calibration blocks that incorporate defects and simulate the motion of test objects in the system are better standards, since they incorporate system performance. Many radioscopic inspection procedures involve motions that may mask defects in certain areas. Similar defects can be shown by experimenting with calibration blocks. Various filtering schemes can then be advantageously used to show these defects, and enhance the image in the location determined.

* Reference radioscopic images (or electronic images) are being produced in digital form to provide comparison of display of specific known defects, in order to be useful when parts with unknown defects are inspected in the spectroscopic system. The above results are also directly related to control of the image quality of the presentation system. Additional information on the effect of pixel size on image presentation for reference radiological images is also used for such standardization.

5.6 APPLICATIONS

5.6.1 Applications for radiography. Radiography is extensively used in the inspection of castings, welds, and forgings. Radiography is used in the inspection of finished parts as well as raw stock to verify completeness of assembly and the absence of cracks or other material flaws. Radiography is used in the medical profession and in research. Flash radiographic units are used for in-motion studies. Normally, radiographic exposure times are measured in minutes, but when exposures must be made of a moving subject, such as a bullet or projectile in flight, the exposure time must be extremely short to prevent blurring of the image. Flash radiography provides these short exposure times; short enough to find application even in ballistic studies.

The main limitations in radiographic applications are: 1) access to both sides of the part to be inspected is required, 2) the part must not be too thick to penetrate (a function of the beam energy available, etc.), 3) the variable must provide an observable contrast (normally a two percent contrast is a reasonable minimum), and 4) all safety requirements must be met. Therefore, where extremely thick parts are involved, where designs prevent access to both sides, where variables are very small, or where safety can not be assured, radiography may not be a reasonable choice. As development in ultrasonics occurs, the medical area will be supplementing x-rays with ultrasonics for safety reasons.

* 5.6.2 Applications for radioscopy. Radioscopy is used for inspection of the same types of structures/material as radiography is useful for. Radioscopy has advantages when non-symmetrical structures are being looked at, because of the three-dimensional capability when using mechanical motion of the objects observed.

Radioscopy has advantages when looking at thin and delicate parts such as electronic components, often even when these are readily inspected by fixed position film radiography. The three-dimensional aspects of many of the configurations that need to be looked at by non-film techniques do require flexibility when low kilovoltage sources and appropriate complex detector selection are used.

One application that is being used more frequently is high power microfocus x-ray imaging. Effective focal spot size of the order of 10 microns with sufficient beam intensity and energy to perform imaging on sections up to the equivalent of 1/2 inch of steel are possible. Geometric magnifications up to 500 x have been attained with sharpness sufficient for many critical inspections.

High speed digital archival systems are currently being designed to efficiently store and retrieve the high quality images produced by microfocus projection imaging. Making records on videotape is straightforward and is a useful archival method today.

* 5.6.3 Applications for computed tomography. Computed tomography allows depth of defects to be determined. It can show small, specific clusters of defects that give information not available from standard radiography. In some applications, such as castings, this information is available for

permitting judgment as to failure possibility. Acceptance criteria are more easily applied to test objects with knowledge of specific defects and their locations than for a two-dimensional map that shows a combination of defects in this format. Real-time radioscopy offers improvement over straight film radiography, but still cannot give exact depth information, except for some experimental programs.

Some more sophisticated radiological methods such as stereo microradiography and various three-dimensional relatives of CT, such as digital radiography and laminography should also be considered for various applications. Cost can be a significant factor. However, economic analysis may show benefits due to confidence in predictions of failure as well as confidence in defect analysis. Less frequent inspection requirements during in-use operation may actually make use of the CT method result in savings, as well as result in greater confidence in using the objects or structures that have been inspected.

5.7 SPECIFIC GUIDELINES

In general, guidelines for radiology are well established and only a few additional comments are necessary in this section. This is partially due to the number of years radiology has existed as an inspection method with no major changes in principles, but also, because radiology does entail some dangers, those associated with x-ray work are by necessity well trained. Therefore, the following guidelines are somewhat superficial and are more of a review than a presentation of new material.

There is one warning. Because radiology is a well established method, it is often abused. It is often used even when it does not provide information on the quality of a product. Radiography is not an answer to every problem. It should not be automatically applied just because it is available.

5.7.1 Guidelines for designers. Probably the most difficult concept for a designer to understand is some of the limitations of radiography. Radiographs can produce extremely sharp, finely detailed, views. This ability is called "definition" or sharpness of view. But the sharpness of view is of no value unless there is contrast, and contrast requires a significant change in the total density of adjoining paths of the radiating beam. If a change in a variable from one point to another on a specimen results in much less than a 2 percent change in the total beam intensity, then it will be difficult for radiography to detect this difference. A designer needs to appreciate this limitation when he is considering specifying a radiographic method. The importance of lining up the expected defect in the direction of the beam path is entirely due to this need to establish contrast. Once this principle is understood, the other limitations (access to both sides, finite thickness limits, safety, etc.) are usually well understood and acknowledged.

The difficulty of the interpretation of the radiograph is another area that designers often overlook. Only experience seems adequate to impress upon individuals that shadowgraphs are limited in the degree of information they present, and experience in interpretation is a necessity for acceptable confidence and reliability.

5.7.2 Guidelines for production engineers. The main drive for Production Engineers is efficiency, and, for radiographic work, efficiency means short exposure times, fast turnaround times, and the least delay on the production line. Safety requirements often involve exposure during night shifts when fewer personnel are around and the least delay to the line may be experienced. The fast exposure times required in this drive for efficiency minimizes the contrast of the radiograph. Therefore, under production conditions, the use of penetrameters are a must to ensure that contrast is not being lost.

5.7.3 Guidelines for quality assurance personnel. Because radiography is a standard routine, Q.A. often relies upon routine methods for all radiographic work. The need for real standards (specimens with real flaws) and not just exposure standards (penetrameters) or sets of radiographs as radiographic acceptance standards must constantly be kept in mind. For some inspections the verification with real flaws is vital, both for exposure control as well as for proper interpretations of the radiographs.

(1) Procedures must be established and enforced to insure only experienced, qualified people perform the radiographic inspection function.

(2) For complex mechanisms and assemblies, QA personnel must determine that the desired feature of interest is actually capable of being radiographically observed and is not confused with some other feature.

(3) Where radiographic requirements and standards have been established for x-ray film, a change to fluoroscopy or other filmless methods should only be made with extreme caution. Many of the characteristics implicit in the film method (high detail, permanent records, ability to backtrack and review, transportability of data) are not always satisfactorily provided with a non-film method.

(4) Accept/reject criteria should be verified and clearly defined and presented to the x-ray inspector. Only the designer is in a position to evaluate the significance of a particular defect or condition in a product.

5.7.4 Guidelines for NDT engineers. The NDT Engineer has great influence in the quality versus time conflict that might exist in radiographic work. Many times the use of dual packs, the combining of films having different speeds into one exposure shot, will allow different thicknesses to be examined by the one setup. The use of single-side emulsion film must be considered by the engineer if extra fine, magnified details are sought. The final quality of all radiographic film methods depends upon the development of the film. If out-of-date film, or improper development solutions, or other inadequate development methods are used, the results will be as unacceptable as if improper exposures were used. The cause of a particular difficulty is not always obvious. Therefore, the radiographic engineer must keep knowledgeable of several interrelating activities if he is to be truly successful.

5.7.5 Guidelines for NDT technicians. One of the most important attributes for a radiographic technician to develop is the habit of safety. When one works in a regularly maintained x-ray vault, safety interlocks usually exist to ensure some degree of safety. However, because there usually are times when work must be done in other locations and times when interlocks fail, it is imperative that the NDT technician adopts habits that will ensure his safety under all conditions.

An x-ray technician should never enter an exposure area with the equipment turned on even though interlocks are provided. The use of gamma ray sources is even more dangerous to the technician since safety interlocks are less likely to be present. The technician is entirely responsible for his own safety under these circumstances.

A technician must be observant of details. All variances from normal conditions should be noted and brought to the attention of the NDT Engineer. The placement of penetrameters and markers in each exposure must be carefully accomplished, with double checks on the proper placement of film, filters, screens, and masking materials when required.

5.8 SAFETY

This section covers basic radiographic safety procedures, protection devices, and detection equipment. It is not an interpretation of government regulations nor can it be considered a complete safety guide. The radiographer is obligated to know all current regulations and to keep personally aware of all changes in these regulations. Most of the effects of radiation on the human body are known and predictable. Radiation safety practices are based on these effects and the characteristics of radiation. Since radiation cannot be detected by any of the human senses, and its damaging effects do not become immediately apparent, personal protection is dependent upon detection devices and adequate shielding. The United States Nuclear Regulatory Commission (USNRC) (formerly U.S. Atomic Energy Commission) enforces safety regulations covering the handling and use of radioisotopes. The United States Department of Transportation, the Civil Aeronautics Board, and the United States Coast Guard enforce safety regulations covering the transportation of radioactive material. The various states have similar regulations covering use, handling, and transportation of radioactive material and machine sources of radiation. All of these regulations are designed to limit radiation exposure to safe levels, and to afford protection for the general public. This government emphasis on safety practices indicates the mandatory nature of sure and certain safety practices in all radiation areas. The radiographer who is a licensee of the USNRC or who is employed by a licensee must have knowledge of, and comply with, all pertinent regulations. Radiography can be safe, but only as safe as those working with it make it safe. Radiographic tests shall be performed under protected conditions such that personnel shall not receive a whole-body radiation dosage exceeding the maximum permitted by city, state, or national codes.

5.8.1 Units of radiation measurements and maximum dosages. For radiation safety purposes, the cumulative effect upon the human body of radiation exposure is of primary concern. Since the damaging effects of radiation to living cells are dependent upon both the type and the energy of the radiation to which they are exposed, it is impractical only to measure radiation quantitatively. For this reason, exposure is first measured in physical terms; then, a factor allowing for the relative biological effectiveness of different types and energies of radiation is applied.

The units used to measure radiation exposure are defined as follows:

a. Roentgen. The roentgen (r) is the unit measure of x- or gamma radiation in air. It is defined as the quantity of radiation that will produce one electrostatic unit (esu) of charge in one cubic centimeter of air at standard pressure and temperature. One roentgen of radiation represents the absorption by ionization of approximately 83 ergs of radiation energy per gram of air. In practical application, the milliroentgen (mr), one thousandth of a roentgen, is often used. The roentgen is a physical measurement of x- and gamma radiation quantity.

b. Rad. The rad (radiation absorbed dose) is the unit of measurement of radiation. It represents an absorption of 100 ergs of energy per gram of material, at the place of incidence. The roentgen applies only to x- and gamma rays; the rad applies to absolute dose of any type of radiation in any medium.

c. Rbe. The value assigned to various types of radiation, determined by the radiation's effect on the human body, is called relative biological effectiveness (rbe). Rbe values have been calculated by the National Committee on Radiation Protection as shown in Table 5.8(1).

TABLE 5.8(1). RBE values.

RADIATION	RBE
X-RAY	1
GAMMA RAY	1
BETA PARTICLES	1
THERMAL NEUTRONS	5
FAST NEUTRONS	10
ALPHA PARTICLES	20

d. Rem. The roentgen equivalent man (rem) is the unit used to define the biological effect of radiation on man. It represents the absorbed dose in rads multiplied by the relative biological effectiveness of the radiation absorbed.

Radiation safety levels are established in terms of rem dose. The calculating of rem dose of x- and gamma radiation is simplified by two facts: (1) the roentgen dose is equivalent to the rad dose, and (2) the rbe of both x- and gamma radiation is one. A measurement of dose thus is rad equivalent and then equivalent to a measurement of rem dose.

It is impossible to safeguard radiographic personnel from all exposure to radiation. Permissible dose is defined by the International Commission on Radiation Units (ICRU) as, ". . . the dose of ionizing radiation that, in the light of present knowledge, is not expected to cause appreciable bodily injury to a person at any time during his lifetime." Maximum permissible dose (mpd) is the numerical value of the highest permissible dose, under prescribed conditions of exposure, stated in units of time. Currently accepted mpd, established through experience, is contained in USNRC regulations on Standards for Protection Against Radiation. Maximum radiation dose, in any period of one calendar quarter, to an individual in a restricted area, is normally limited to 1-1/4 rem. Maximum permissible dose per year must not average over 5 rem for each year past the age 18. An average weekly dose of 100 mrem is within dose level tolerances. Under certain circumstances defined by cognizant government regulatory bodies, exposures up to 3 rem per calendar quarter may be permitted. Applicable radiation safety publications are issued by the National Bureau of Standards, the International and National Committee on Radiation Protection, the USNRC, and state authorities. The radiographer should be cognizant of the information in the "NRC Licensing Guide for Industrial Radiography," which is available from the U.S. Government Printing Office. For under 18 and the general public, .5 rem is the limit.

It should be emphasized again that regardless of limits that are set for allowable radiation exposures, the general policy is to avoid all unnecessary exposure to ionizing radiation.

This policy is referred to as the "as low as reasonably achievable" (ALARA) principle by the Nuclear Regulatory Commission (10CFR20.1C). The commission expects that its licensees will make every reasonable effort to maintain exposures to radiation as far below the limits as is reasonably achievable. Specific recommendations for implementing this policy are contained in NRC Regulatory Guides 8.8 (primarily for nuclear power stations), 8.1 (and an associated detailed report, NUREG-0267, for medical institutions), and 8.10. Some of the measures listed as indicators of a commitment by management to an ALARA policy include promulgation of the policy in statements and instructions to personnel; review of exposures and operating procedures to examine compliance with ALARA; and training programs including periodic reviews or testing of the understanding of workers on how radiation protection relates to their jobs.

5.8.2 Principles of protection against radiation. Three main principles govern safety practices for controlling body exposure to radiation: 1) time, 2) distance, and 3) shielding. Safe radiographic techniques and radiographic installations are designed by applying these three principles:

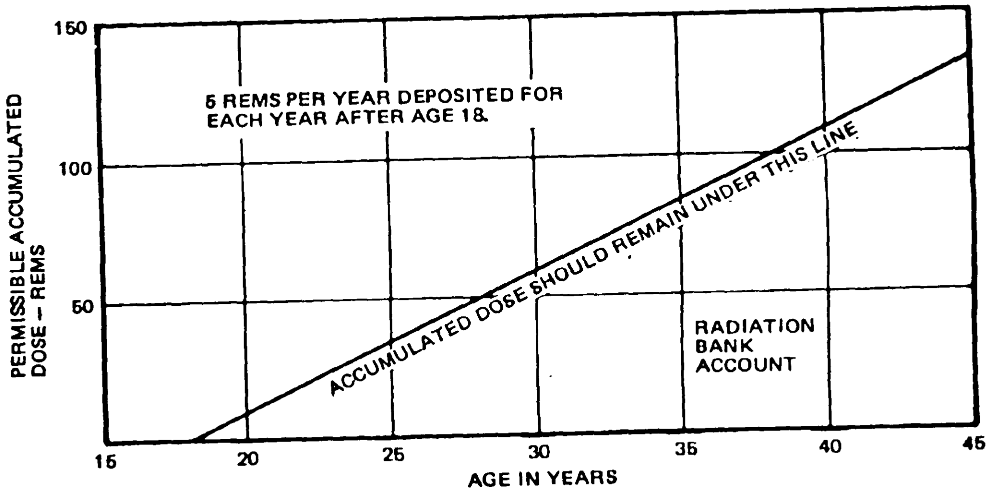


FIGURE 5.8(1). Banking concept.

a. Allowable Working Time. The amount of radiation absorbed by the human body is directly proportional to the time the body is exposed. A person receiving 2 mr in one minute at a given point in a radiation field would receive 10 mr in five minutes. Allowable working time is calculated by measuring radiation intensity and substituting in the following equation:

$$\text{Allowable working time in hr/wk} = \frac{\text{permissible exposure in mr/wk}}{\text{exposure rate in mr/hr}} \qquad (1)$$

b. Working Distance. The greater the distance from a radiation source, the lower the exposure received. The inverse square law is used to calculate radiation intensities at various distances from a source. The inverse square law is expressed as:

$$\frac{I_1}{I} = \frac{D^2}{(D_1)^2} \qquad (2)$$

where I_1 and I are intensities at D_1 and D respectively.

Intensity and dose rate calculations based on the inverse square law should never be accepted as exact. Radiation intensity at any point is the sum of the primary radiation and the secondary (scatter) radiation at that point. Therefore, the actual radiation will normally be greater than that calculated by this equation. Safety should always be established by actual measurements of the radiation level and not just by theoretical calculations.

c. Shielding. Lead, steel, iron, and concrete are materials commonly used as shielding to reduce radiation exposure to personnel. Since all of the energy of x- or gamma radiation cannot be stopped by shielding, it is practical to measure shielding efficiency in terms of half-value layers. The half-value layer is that amount of shielding which will stop half of the radiation energy. See table 5.2(2). Similarly, shielding efficiency is often measured in tenth-value layers. A tenth-value layer is that amount of shielding which will stop nine-tenths of the radiation of a given intensity. Half- and tenth-value layers are, in all cases, determined by experiment and actual measurement. The radiographer should rely on actual measurement to determine the effectiveness of any shielding.

Wherever practicable, a working area should consist of a room completely lined with lead, steel, iron or concrete of sufficient thickness for protection. Concrete is the most commonly used material. If the construction of such a room is not feasible, then the equipment should be housed in a suitably shielded cabinet, large enough to also house the specimens under test. x-ray machine controls should be located outside the exposure area. To reduce the possibility of excessive radiation in occupied spaces, the exposure area should be as isolated as conditions permit. If neither a room nor a cabinet is available, any combination of shielding that safely encloses the radiation equipment, specimen, and the film is acceptable. It is not always practical to bring the specimen to the shielded exposure area. When radiography must be accomplished under this circumstance, the three safety factors (time, distance, and shielding) must be taken into account. Safe distances, in relation to exposure, must be determined, and adequately marked guard rails or ropes placed to enclose the radiation area. Sufficient shielding must be placed to protect the radiographer and others who must remain in the vicinity. When radiography is practiced outside a designated shielded exposure area the simplest, most effective safety consideration is distance. All personnel must be kept at a safe distance from the radiation source.

Theoretically, the lead housing around an x-ray tube effectively shields, to safe levels, all primary radiation except the useful beam. Practically, this is not always the case, and the only way to assure the safeness of an x-ray tube is to measure leakage (unwanted) radiation around it. To limit the unwanted radiation, the area of primary radiation should be fixed by a cone or diaphragm at the tube head.

Certain gamma radiations can be very penetrating, and the required protective shielding can be excessively thick and heavy. Gamma radiation cannot be shut off, and protection must be provided at all times.

Shielding is the primary protection from gamma rays. The penetrating capability of gamma radiation makes it impractical to rely only on shielding for protection during gamma radiography; a combination of distance and shielding is usually employed. The radiation danger zone is roped off and clearly marked with conspicuous signs, and only those persons making the radiograph are permitted in the zone. The extent of the danger zone is based on calculations of safe distance as determined by the source strength. In calculating the area of the danger zone, the possible effects of scatter radiation are considered and the calculations are confirmed by intensity measurements.

The continuous gamma radiation from radioisotopes necessitates strict accountability of radioactive sources. When not in use they are stored in conspicuously labelled, lead vaults and/or depleted uranium 238. After every use, intensity measurements are taken to ensure that the source is safely housed, and the storage pig is not permitting leakage radiation.

5.8.3 USNRC rules and regulations. Handling, storage, and use of radioisotopes are regulated by the USNRC. The regulations are published in the Code of Federal Regulations, Title 10, Chapter I, parts 20, 21, 30, 31 and 34. Part 34 of the Code is also published in the NRC Licensing Guide. The following regulations are subject to change and are presented for familiarization purposes only.

Limitations on individual dosages are specified in table 5.8(2).

Doses greater than specified in the table may be permitted provided: 1) during any calendar quarter the dose to the whole body does not exceed 3 rems; 2) the dose to the whole body, when added to the accumulated occupational dose to the whole body, does not exceed 5 (N-18) rems where "N" equals the individual's age in years at his last birthday; and 3) the individual's accumulated occupational dose has been recorded on Form NRC-4 or equivalent and the concerned individual has signed the form. Note This is being replaced by an annual limit of 5 rems.

TABLE 5.8(2). Exposure limits in restricted areas.

	REMS PER CALENDAR QUARTER
WHOLE BODY, HEAD AND TRUNK; ACTIVE BLOOD-FORMING ORGANS; LENS OF EYES; OR GONADS	1-1/4
HANDS AND FOREARMS: FEET AND ANKLES	18-3/4
SKIN OF WHOLE BODY	7-1/2

Form NRC-5, Current Occupational External Radiation Exposure, must be completed quarterly and is the source of the information recorded on Form NRC-4.

Minors are not allowed to work in restricted areas. Regulations to protect minors specify that no individual under 18 years of age is permitted to receive dosages exceeding 10 percent of the limits specified in table 5.8(2).

Under approved circumstances, a limited amount of radiation is permitted in unrestricted areas. Exposure limits in unrestricted areas are listed in table 5.8(3). These dosage limits are based on an individual being continually present in the area and thus the exposure limits represent maximum radiation levels permitted.

Personnel monitoring equipment must be used by:

a. Individuals entering restricted areas who receive, or may receive, dosage in any calendar quarter in excess of 25 percent of the applicable value specified in table 5.8(2).

b. Individuals under 18 years of age entering restricted areas who receive, or may receive, dosage in any calendar quarter in excess of 5 percent of the applicable value specified in table 5.8(2).

c. Individuals who enter high radiation areas.

During radiographic operations, radiographers and their assistants shall wear radiation monitoring devices such as film badges or thermoluminescence dosimeters (TLD) and either pocket dosimeters or pocket chambers. Pocket dosimeters and chambers shall be capable of measuring doses from zero to 200 milliroentgens. They shall be read daily and the indicated dose shall be recorded. If a pocket chamber or dosimeter is discharged beyond its range, the film badge of the individual shall be processed immediately.

TABLE 5.8(3). Exposure limits in unrestricted areas.

TIME	MILLIREMS
1 HOUR	2
7 CONSECUTIVE DAYS	100
1 CALENDAR YEAR	500

The radiation "Warning" symbol is shown in figure 5.8(1). Signs bearing this symbol must be placed in conspicuous places in all exposure areas, and on all containers in which radioactive materials are transported, stored, or used. On each sign the word "Caution," or the word "Danger," must appear. Other wording required is determined by specific sign use. Area signs bear the phrases, "Radiation Area," "High Radiation Area," or "Airborne Radioactivity Area," as appropriate. If a dose equal to or greater than 2 milliroentgens/hr has been established in an area, a warning sign must be posted. Containers of radioactive materials and areas housing such containers must be marked with signs or labels bearing the radiation symbol and the words "Radioactive Material(s)." Special tags bearing the radiation symbol and the phrase, "Danger-Radioactive Material-Do Not Handle. Notify Civil Authorities If Found," must be attached to sealed sources not fastened to, or contained in, an exposure device.

Specific regulations provide standards for isotope cameras and other isotope exposure devices. Protective standards designed to protect personnel from sealed sources when they are in the fully shielded position are as follows:

a. Radiologic exposure devices measuring less than four inches from the sealed source storage position to any exterior surface of the device shall have no radiation level in excess of 50 milliroentgens per hour at six inches from any exterior surface of the device.

b. Radiologic exposure devices measuring a minimum of four inches from the sealed source storage position to any exterior surface of the device, and all storage containers for sealed sources or for radiographic exposure devices, shall have no radiation level in excess of 200 milliroentgens per hour at one meter from any exterior surface.

For radiologic operations, it is required that calibrated and operable radiation survey instruments (meters) be available. The meters used shall have a range such that two milliroentgens per hour through one roentgen per hour can be measured. It is not necessary that any one meter be capable of measuring the entire required range.

Specific regulations for required isotope radiation surveys are as follows:

a. No isotope radiologic operation shall be conducted unless calibrated and operable radiation survey instrumentation is available and used at each site where radiographic exposures are made.

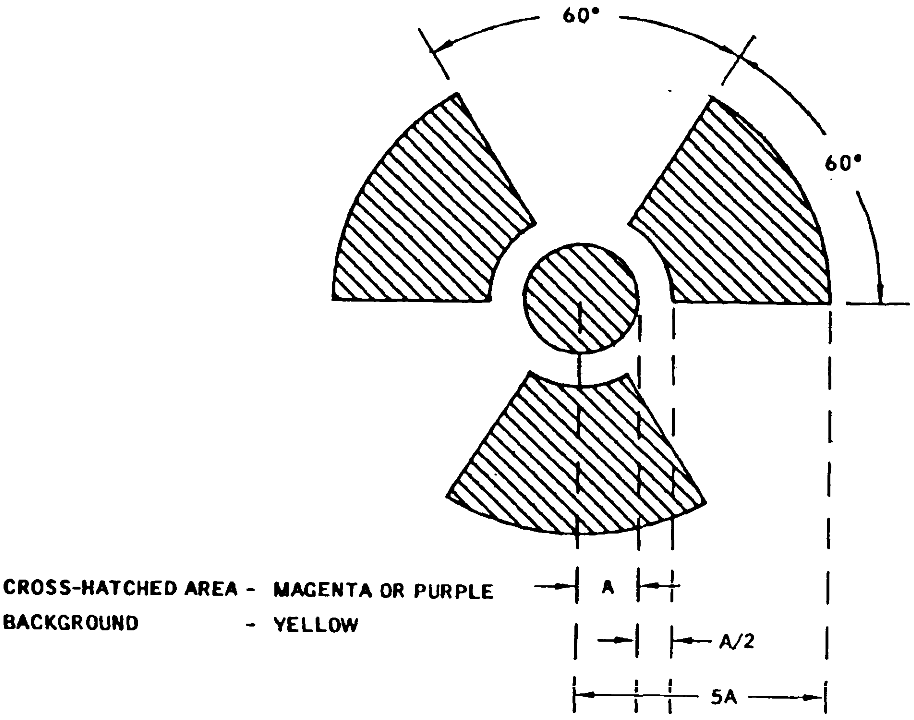


FIGURE 5.8(2). Radiation symbol.

b. Physical radiation measurements (a radiation survey) shall be made after each isotope radiographic exposure operation to determine that the sealed source has been returned to its shielded condition.

c. A physical radiation survey shall be made to determine that each sealed source is in its shielded condition prior to securing the radiographic exposure device and storage container.

5.8.4 Radiation detection and measurement instruments. Based on the characteristic effects of radiant energy on matter, various techniques are employed in detection and measurement devices. Chemical and photographic detection methods are used, as well as methods which measure the excitation effect of radiation on certain materials. In radiography, however, the instruments most commonly used for radiation detection and measurement rely on the ionization produced in a gas by radiation. Since the hazard of radiation is calculated in terms of total dose and dose rate, the instruments used for detection and measurement logically fall into two categories: instruments that measure total dose and exposure, such as pocket dosimeters, pocket chambers, and film badges; and instruments that measure dose rate(radiation intensity), such as ionization chambers and Geiger counters. These last two instruments are known as survey meters.

The pocket dosimeter (figure 5.8(2)) is a small device approximately the size of a fountain pen. Its operation is based on two principles: 1) like electrical charges repel each other; and 2) radiation causes ionization in a gas. The essential parts of the dosimeter are the metal cylinder, the metal-coated quartz fiber electrode consisting of a fixed section and a movable section, the transparent scale, and the lens. The electrode and the cylinder form an electroscope. When a potential (from an external source of voltage) is applied between the electrode and the cylinder, the electrode gains a positive charge and the cylinder a negative charge. Simultaneously, the movable portion of the electrode moves away from the fixed portion since they are mutually repellent, each carrying a positive charge. The transparent scale and the lens are so placed that, when the scale is viewed through the lens, the movable portion of the electrode appears as the indicator on the scale. When the dosimeter is properly charged, the indicator will be at zero on the scale and the dosimeter is ready for use.

When a dosimeter is placed in an area of radiation, ionization takes place in the cylinder chamber. Negative ions are attracted to the electrode and positive ions to the cylinder. As the positive charge on the electrode becomes neutralized, the repellent force between the fixed and movable portions decreases. The movable portion moves toward the fixed portion in an amount proportional to the ionization action. Since the quantity of ionization is determined by the quantity of radiation, the displacement of the movable portion of the electrode is a direct measure of the radiation. Pocket dosimeters are designed with a sensitivity that permits them to be scaled in dose/exposure from 0 to 200 milliroentgens.

The film badge (figure 5.8(3)) consists of a small film holder equipped with thin lead or cadmium filters, in which is inserted special x-ray film. The badge is designed to be worn by an individual when in radiation areas, and is not to be otherwise exposed. After a period of time, usually two weeks, the film is removed and developed by standard techniques. The density of the processed film is proportional to the radiation received. By use of a densitometer the density of the film is compared to that of a set of control films. Through this comparison, an estimate of the amount of radiation received by the individual who wore the badge is made. Film badges and dosimeters each record total radiation received and serve as a check on each other.

Because of the number of instruments that would be required, and the excessive amount of time necessary for their use, dosimeters and pocket chambers cannot be readily used for radiation area surveys. Such surveys require an instrument capable of obtaining and presenting an instantaneous measurement of radiation intensity. Two such instruments are in common use: the ionization chamber instrument and the Geiger counter.

Ionization chamber instruments basically consist of an ionization chamber containing two electrodes: a power supply, usually a battery, which is connected across the electrodes; and an ammeter connected in series with the power supply. When the instrument is exposed to radiation, ionization takes place in the chamber. Individual ions are attracted to the electrode of opposite potential, and upon reaching the electrode become neutral by removing a charge from the battery. The flow of current from the battery required to

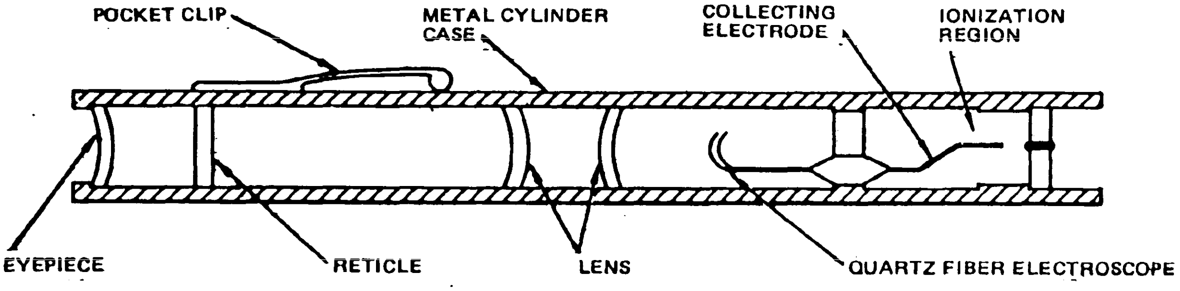


FIGURE 5.8(3). Pocket dosimeter cross-section (typical).

neutralize the ions is measured by the meter, which is calibrated in terms of milliroentgens or roentgens. The meter may be calibrated in physical quantities because the flow of current is proportional to the ionization caused by the radiation. In this manner, radiation intensity (dosage rate) is measured. Ionization chamber instruments attain an accuracy of ±15 percent except in low radiation intensity areas. In areas of low intensity radiation, sufficient ionization current is not generated to indicate accurately on the meter. Radiation intensity measurements in areas of low radiation intensity are usually made with Geiger counters.

Geiger counters utilize a Geiger-Muller tube as an ionization chamber in a high sensitivity radiation detecting device. The voltage difference between the tube anode and cathode, and the gas within the tube create an environment wherein any ionizing event is multiplied into many such events. The secondary ionizations are caused by the action of the electrons produced in the first ionization event. This phenomenon of a single ionization producing many in a fraction of a millisecond is known as gas multiplication. The resultant amplified pulse of electrical energy is used to cause an audible indication, deflect a meter, or light a lamp. Geiger counters are accurate to ±15 percent for the quality of radiation to which they are calibrated. They are extremely useful as detection instruments particularly for gross contamination surveys, but are not intended to be accurate measurers of dose rate. In areas of high radiation intensity, Geiger counters have a tendency to block out, and the meter will indicate a false zero reading. For this reason, in areas of suspected high radiation intensity, chamber instruments should be used.

Area alarm systems consist of one or more sensing elements, usually ionization chambers, whose output is fed to a central alarm meter. The meter is preset so that an audible alarm is sounded, or a visual indication is given (lighted lamp), when permissible radiation levels are exceeded. Area alarm systems are often used in gamma radiography.

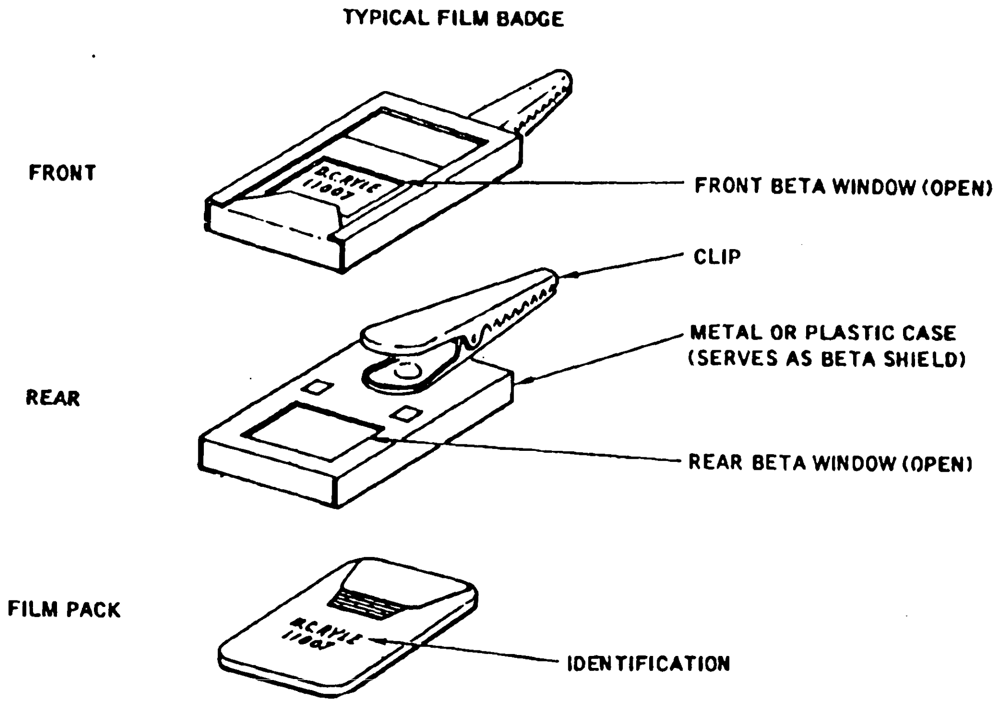


FIGURE 5.8(4). Film badge (typical).

5.8.5 Electrical safety. The radiographer must comply with safe electrical procedures when working with x-ray equipment. Modern x-ray machines use high voltage circuits. Permanently installed x-ray facilities are designed so that personnel trained in safe practices will encounter few electrical hazards; however, portable x-ray equipment requires certain electrical precautions.

Whenever x-ray equipment is being operated or serviced, the following precautions, applicable to either permanent or portable installations, should be observed:

a. Do not turn power on until the setup for exposure is completed.

b. Ensure that grounding instructions are complied with.

c. Regularly check power cables for signs of wear. Replace when necessary.

d. Avoid handling power cables when power is ON.

e. If power cables must be handled with power ON, use safety equipment such as rubber gloves, rubber mats, and insulated high-voltage sticks.

f. Ensure that condensers are completely discharged before checking any electrical circuit.

If common-sense precautions are observed, there are few electrical hazards in the use of x-ray equipment.

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