

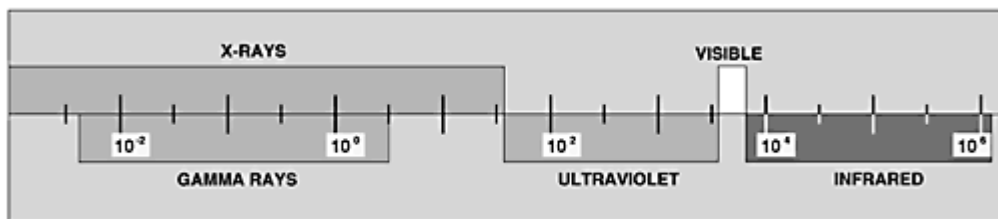
Chapter 1: The Radiographic Process

Nature of X-Rays

X-rays are a form of electromagnetic radiation (EMR), as is light. Their distinguishing feature is their extremely short wavelength--only about 1/10,000 that of light, or even less. This characteristic is responsible for the ability of x-rays to penetrate materials that absorb or reflect ordinary light.

X-rays exhibit all the properties of light, but in such a different degree as to modify greatly their practical behavior. For example, light is refracted by glass and, consequently, is capable of being focused by a lens in such instruments as cameras, microscopes, telescopes, and spectacles. X-rays are also refracted, but to such a very slight degree that the most refined experiments are required to detect this phenomenon. Hence, it is impractical to focus x-rays. It would be possible to illustrate the other similarities between x-rays and light but, for the most part, the effects produced are so different--particularly their penetration--that it is preferable to consider x-rays and gamma rays separately from other radiations. The figure below shows their location in the electromagnetic spectrum.

Figure 1: Portion of the electromagnetic spectrum. Wavelengths in angstrom units (1A = 10^{-8} cm = 3.937×10^{-9} inch)



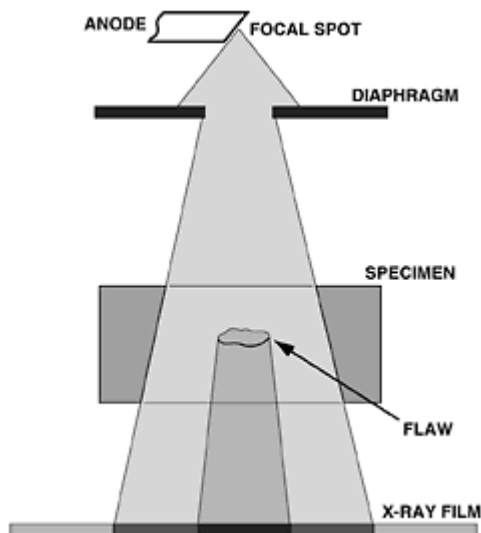
Nature of Gamma Rays

Gamma rays are similar in their characteristics to x-rays and show the same similarities to, and differences from, visible light as do x-rays. They are distinguished from x-rays only by their source, rather than by their nature. Gamma rays are emitted from the disintegrating nuclei of radioactive substances, and the quality (wavelength or penetration) and intensity of the radiation cannot be controlled by the user. Some gamma-ray-emitting radioactive isotopes, such as radium, occur naturally. Others, like cobalt 60, are artificially produced. In industrial radiography, the artificial radioactive isotopes are used almost exclusively as sources of gamma radiation.

Making a Radiograph

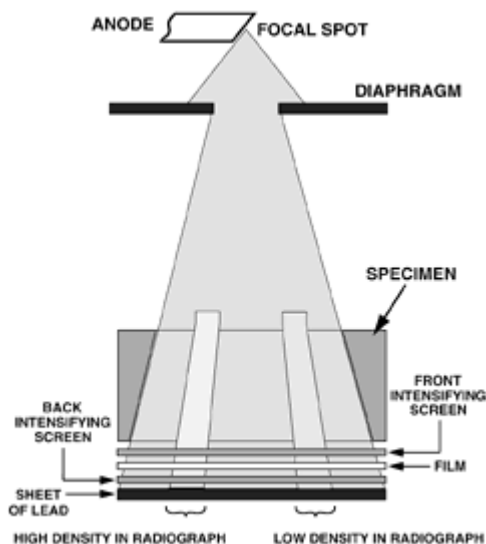
A radiograph is a photographic record produced by the passage of x-rays or gamma rays through an object onto a film. See the figure below. When film is exposed to x-rays, gamma rays, or light, an invisible change called a latent image is produced in the film emulsion. The areas so exposed become dark when the film is immersed in a developing solution, the degree of darkening depending on the amount of exposure. After development, the film is rinsed, preferably in a special bath, to stop development. The film is next put into a fixing bath, which dissolves the undarkened portions of the sensitive salt. It is then washed to remove the fixer and dried so that it may be handled, interpreted, and filed. The developing, fixing, and washing of the exposed film may be done either manually or in automated processing equipment.

Figure 2: Schematic diagram showing the fundamentals of a radiographic exposure. The dark region of the film represents the more penetrable part of the object; the light regions, the more opaque.



The diagram in figure 3 shows the essential features in the exposure of a radiograph. The focal spot is a small area in the x-ray tube from which the radiation emanates. In gamma radiography, it is the capsule containing the radioactive material, for example, cobalt 60, that is the source of radiation. In either case the radiation proceeds in straight lines to the object; some of the rays pass through and others are absorbed-the amount transmitted depending on the nature of the material and its thickness. For example, if the object is a steel casting having a void formed by a gas bubble, the void results in a reduction of the total thickness of steel to be penetrated. Hence, more radiation will pass through the section containing the void than through the surrounding metal. A dark spot, corresponding to the projected position of the void, will appear on the film when it is developed. Thus, a radiograph is a kind of shadow picture--the darker regions on the film representing the more penetrable parts of the object, and the lighter regions, those more opaque to x- or gamma-radiation.

Figure 3: Diagram of setup for making an industrial radiograph with x-rays.



Intensifying Screens

X-ray and other photographic films are sensitive to the direct action of the x-rays, but the photographic effect can be increased very appreciably, and exposure time can be decreased by the use of an intensifying screen in contact with each side of the film.

One form of intensifying screen consists of lead foil, or a thin layer of a lead compound evenly coated on a paper backing. Under the excitation of x-rays of short wavelength and gamma rays, lead is a good emitter of electrons, which expose the sensitive film, thus increasing the total photographic effect.

Another form of intensifying screen consists of a powdered fluorescent chemical—for example, calcium tungstate, mixed with a suitable binder and coated on cardboard or plastic. Its action depends on the fact that it converts some of the x-ray energy into light, to which the film is very sensitive.

The decision as to the type of screen to be used—or whether a screen is to be used at all—depends on a variety of circumstances, which will be discussed in more detail later.

Scattered Radiation

It is a property of all materials not only to absorb and transmit x-rays and gamma rays in varying degrees, but also to scatter them—as radiation of longer wavelength—in all directions. In radiography, the film receives scattered radiation from the object, the film holder, and any other material in the path of the primary x-ray beam. The effect is to diminish the contrast, detail, and clarity of the radiographic image. Lead screens, in contact with the film, lessen the relative effect of this longer-wavelength scattered radiation. Under some circumstances, a filter of copper or lead, placed between the x-ray tube and the object, or between the object and the film, diminishes the effect of scattered radiation on the film. A lead mask that limits the volume of matter exposed to the primary radiation is sometimes helpful in lessening scatter.

Types of Film

Several special types of x-ray film have been designed for the radiography of materials. Some types work best with lead screens, or without screens. Other types are intended primarily for use with fluorescent intensifying screens. X-ray films are commonly coated with emulsion on both sides of the support—the superposition of the radiographic images of the two emulsion layers doubles the density and hence greatly increases the speed. X-ray films coated on one side only (single-coated films) are available for use when the superposed images in two emulsions might cause confusion.

Chapter 2: X-Ray and Gamma-Ray Sources

Production of X-Rays

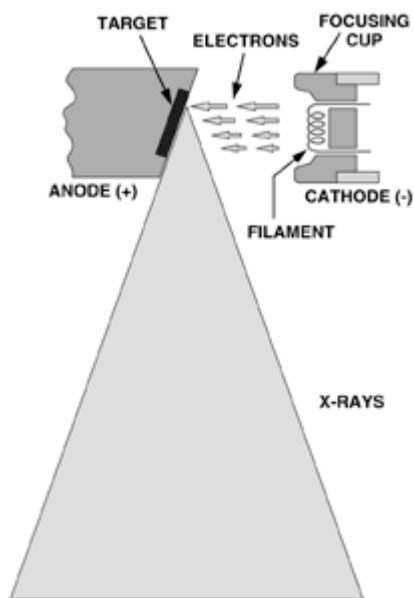
X-rays are produced when electrons, traveling at high speed, collide with matter or change direction. In the usual type of x-ray tube, an incandescent filament supplies the electrons and thus forms the cathode, or negative electrode, of the tube. A high voltage applied to the tube drives the electrons to the anode, or target. The sudden stopping of these rapidly moving electrons in the surface of the target results in the generation of x-radiation.

The design and spacing of the electrodes and the degree of vacuum are such that no flow of electrical charge between cathode and anode is possible until the filament is heated.

The X-Ray Tube

Figure 4 is a schematic diagram of the essential parts of an x-ray tube. The filament is heated by a current of several amperes from a low-voltage source, generally a small transformer. The focusing cup serves to concentrate the stream of electrons on a small area of the target, called the focal spot. This stream of electrons constitutes the tube current and is measured in milliamperes.

Figure 4: Schematic diagram of an x-ray tube.



The higher the temperature of the filament, the greater is its emission of electrons and the larger the resulting tube current. The tube current is controlled, therefore, by some device that regulates the heating current supplied to the filament. This is usually accomplished by a variable-voltage transformer, which energizes the primary of the filament transformer. Other conditions remaining the same, the x-ray output is proportional to the tube current.

Most of the energy applied to the tube is transformed into heat at the focal spot, only a small portion being transformed into x-rays. The high concentration of heat in a small area imposes a severe burden on the materials and design of the anode. The high melting point of tungsten

makes it a very suitable material for the target of an x-ray tube. In addition, the efficiency of the target material in the production of x-rays is proportional to its atomic number.¹ Since tungsten has a high atomic number, it has a double advantage. The targets of practically all industrial x-ray machines are made of tungsten.

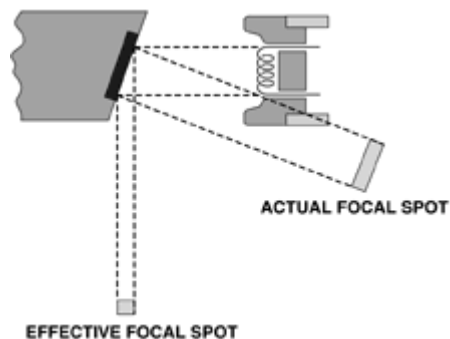
Cooling

Circulation of oil in the interior of the anode is an effective method of carrying away the heat. Where this method is not employed, the use of copper for the main body of the anode provides high heat conductivity, and radiating fins on the end of the anode outside the tube transfer the heat to the surrounding medium. The focal spot should be as small as conditions permit, in order to secure the sharpest possible definition in the radiographic image. However, the smaller the focal spot, the less energy it will withstand without damage. Manufacturers of x-ray tubes furnish data in the form of charts indicating the kilovoltages and milliamperages that may be safely applied at various exposure times. The life of any tube will be shortened considerably if it is not always operated within the rated capacity.

Focal-Spot Size

The principle of the line focus is used to provide a focal spot of small effective size, though the actual focal area on the anode face may be fairly large, as illustrated figure 5. By making the angle between the anode face and the central ray small, usually 20 degrees, the effective area of the spot is only a fraction of its actual area. With the focal area in the form of a long rectangle, the projected area in the direction of the central ray is square.

Figure 5: Diagram of a line-focus tube depicting the relation between actual focal-spot area (area of bombardment) and effective focal spot, as projected from a 20° anode.



Effects of Kilovoltage

As will be seen later, different voltages are applied to the x-ray tube to meet the demands of various classes of radiographic work. The higher the voltage, the greater the speed of the electrons striking the focal spot. The result is a decrease in the wavelength of the x-rays emitted and an increase in their penetrating power and intensity. It is to be noted that x-rays produced, for example, at 200 kilovolts contain all the wavelengths that would be produced at 100 kilovolts, and with greater intensity. In addition, the 200-kilovolt x-rays include some shorter wavelengths that do not exist in the 100-kilovolt spectrum at all. The higher voltage x-rays are used for the penetration of thicker and heavier materials.

Most x-ray generating apparatus consists of a filament supply and a high-voltage supply.

The power supply for the x-ray tube filament consists of an insulating *step-down* transformer. A variable-voltage transformer or a choke coil may serve for adjustment of the current supplied to the filament.

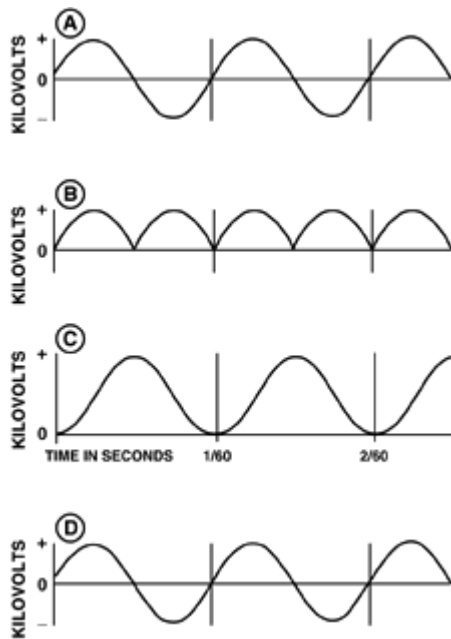
The high-voltage supply consists of a transformer, an autotransformer, and, quite frequently, a rectifier.

A transformer makes it possible to change the voltage of an alternating current. In the simplest form, it consists of two coils of insulated wire wound on an iron core. The coil connected to the source of alternating current is called the *primary* winding, the other the *secondary* winding. The voltages in the two coils are directly proportional to the number of turns, assuming 100 percent efficiency. If, for example, the primary has 100 turns, and the secondary has 100,000, the voltage in the secondary is 1,000 times as high as that in the primary. At the same time, the current in the coils is decreased in the same proportion as the voltage is increased. In the example given, therefore, the current in the secondary is only 1/1,000 that in the primary. A *step-up* transformer is used to supply the high voltage to the x-ray tube.

An autotransformer is a special type of transformer in which the output voltage is easily varied over a limited range. In an x-ray generator, the autotransformer permits adjustment of the primary voltage applied to the step-up transformer and, hence, of the high voltage applied to the x-ray tube.

The type of voltage *waveform* supplied by a high-voltage transformer is shown in part A of the figure 6 and consists of alternating pulses, first in one direction and then in the other. Some industrial x-ray tubes are designed for the direct application of the high-voltage waveform of part A of the figure below, the x-ray tube then acting as its own rectifier. Usually, however, the high voltage is supplied to a unit called a *rectifier*, which converts the pulses into the unidirectional form illustrated in part B of the figure below. Another type of rectifier may convert the waveform to that shown in part C of the figure below, but the general idea is the same in both cases—that is, unidirectional voltage is supplied to the x-ray tube. Sometimes a filter circuit is also provided that "smooths out" the voltage waves shown in parts B and C of the figure below, so that essentially constant potential is applied to the x-ray tube, part D of the figure below. Many different high-voltage waveforms are possible, depending on the design of the x-ray machine and its installation. Figure 6 shows idealized waveforms difficult to achieve in practical high-voltage equipment. Departures from these terms may vary in different x-ray installations. Since x-ray output depends on the entire waveform, this accounts for the variation in radiographic results obtainable from two different x-ray machines operating at the same value of peak kilovoltage.

Figure 6: Typical voltage waveforms of x-ray machines.

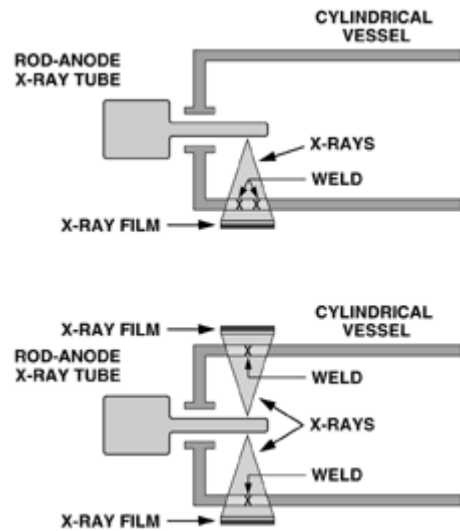


Tubes with the anodes at the end of a long extension cylinder are known as "rod-anode" tubes. The anodes of these tubes can be thrust through small openings (See Figure 7, top) to facilitate certain types of inspection. If the target is perpendicular to the electron stream in the tube, the x-radiation through 360 degrees can be utilized (See Figure 7, bottom), and an entire circumferential weld can be radiographed in a single exposure.

With tubes of this type, one special precaution is necessary. The long path of the electron stream down the anode cylinder makes the focusing of the electrons on the target very susceptible to magnetic influences. If the object being inspected is magnetized--for example, if it has undergone a magnetic inspection and has not been properly demagnetized--a large part of the electron stream can be wasted on other than the focal-spot area, and the resulting exposures will be erratic.

The foregoing describes the operation of the most commonly used types of x-ray equipment. However, certain high-voltage generators operate on principles different from those discussed.

Figure 7: Top: Rod-anode tube used in the examination of a plug weld. Bottom: Rod-anode tube with a 360° beam used to examine a circumferential weld in a single exposure.



Flash X-Ray Machines

Flash x-ray machines are designed to give extremely short (microsecond), extremely intense bursts of x-radiation. They are intended for the radiography of objects in rapid motion or the study of transient events (See "High Speed Radiography"). The high-voltage generators of these units give a very short pulse of high voltage, commonly obtained by discharging a condenser across the primary of the high-voltage transformer. The x-ray tubes themselves usually do not have a filament. Rather, the cathode is so designed that a high electrical field "pulls" electrons from the metal of the cathode by a process known as field emission, or cold emission. Momentary electron currents of hundreds or even thousands of amperes--far beyond the capacity of a heated filament--can be obtained by this process.

High-Voltage Equipment

The *betatron* may be considered as a high-voltage transformer, in which the secondary consists of electrons circulating in a doughnut-shaped vacuum tube placed between the poles of an alternating current electromagnet that forms the primary. The circulating electrons, accelerated to high speed by the changing magnetic field of the primary, are caused to impinge on a target within the accelerating tube.

In the *linear accelerator*, the electrons are accelerated to high velocities by means of a high-frequency electrical wave that travels along the tube through which the electrons travel.

Both the betatron and the linear accelerator are used for the generation of x-radiation in the multimillion-volt range.

Table I - Typical X-ray Machines and Their Applications

Maximum voltage (kV)	Screens	Applications and Approximate Thickness Limits
50	None	Thin sections of most metals; moderate thickness of graphite and beryllium; small electronic components; wood, plastics, etc.
150	None or lead foil	5-inch aluminum or equivalent. (See Table IV) 1-inch steel or equivalent.
	Fluorescent	1 1/2-inch steel or equivalent. (See Table IV)
300	Lead foil	3-inch steel or equivalent.
	Fluorescent	4-inch steel or equivalent.
400	Lead foil	3 1/2-inch steel or equivalent.
	Fluorescent	4 1/2-inch steel or equivalent.
1000	Lead foil	5-inch steel or equivalent.
	Fluorescent	8-inch steel or equivalent.
2000	Lead foil	8-inch steel or equivalent.
8 to 25 MeV	Lead foil	16-inch steel or equivalent.
	Fluorescent	20-inch steel or equivalent.

In the high-voltage electrostatic generator, the high voltage is supplied by static negative charges mechanically conveyed to an insulating electrode by a moving belt. Electrostatic generators are used for machines in the 1- and 2-million-volt range.

No attempt is made here to discuss in detail the various forms of electrical generating equipment. The essential fact is that electrons must be accelerated to very great velocities in order that their deceleration, when they strike the target, may produce x-radiation.

In developing suitable exposure techniques, it is important to know the voltage applied to the x-ray tube. It is common practice for manufacturers of x-ray equipment to calibrate their machines at the factory. Thus, the operator may know the voltage across the x-ray tube from the readings of the volt-meter connected to the primary winding of the high-voltage transformer.

Application of Various Types of X-Ray Apparatus

The various x-ray machines commercially available may be roughly classified according to their maximum voltage. The choice among the various classes will depend on the type of work to be done. Table I lists voltage ranges and applications of typical x-ray machines. The voltage ranges are approximate since the exact voltage limits of machines vary from one manufacturer to another. It should be emphasized that a table like the one table I can serve only as the roughest sort of guide, since x-ray machines differ in their specifications, and radiographic tasks differ in their requirements.

X-ray machines may be either fixed or mobile, depending on the specific uses for which they are intended. When the material to be radiographed is portable, the x-ray machine is usually permanently located in a room protected against the escape of x-radiation. The x-ray tube itself is frequently mounted on a stand allowing considerable freedom of movement. For the examination

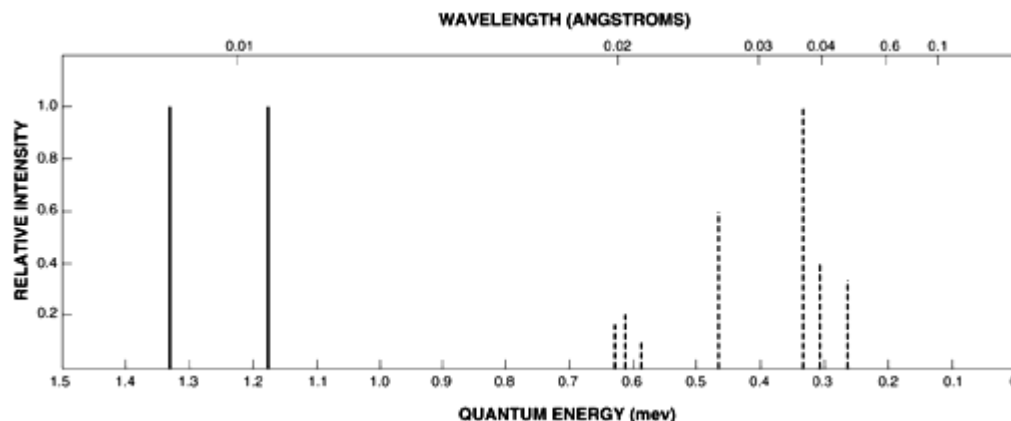
of objects that are fixed or that are movable only with great difficulty, mobile x-ray machines may be used. These may be truck-mounted for movement to various parts of a plant, or they may be small and light enough to be carried onto scaffolding, through manholes, or even self-propelled to pass through pipelines. Semiautomatic machines have been designed for the radiography of large numbers of relatively small parts on a "production line" basis. During the course of an exposure, the operator may arrange the parts to be radiographed at the next exposure, and remove those just radiographed, with an obvious saving in time.

Gamma-Ray Sources

Radiography with gamma rays has the advantages of simplicity of the apparatus used, compactness of the radiation source, and independence from outside power. This facilitates the examination of pipe, pressure vessels, and other assemblies in which access to the interior is difficult; field radiography of structures remote from power supplies; and radiography in confined spaces, as on shipboard.

In contradistinction to x-ray machines, which emit a broad band of wavelengths (see "X-rays"), gamma-ray sources emit one or a few discrete wavelengths. Figure 8 shows the gamma-ray spectrum of cobalt 60 and the principal gamma rays of iridium 192. (The most intense line in each spectrum has been assigned an intensity of 1.0.)

Figure 8: Gamma-ray spectrum of cobalt 60 (solid lines) and principal gamma rays of iridium 192 (dashed lines).



Note that gamma rays are most often specified in terms of the energy of the individual photon, rather than in the wavelength. The unit of energy used is the electron volt (eV)—an amount of energy equal to the kinetic energy an electron attains in falling through a potential difference of 1 volt. For gamma rays, multiples—kiloelectron volts (keV; 1 keV = 1,000 eV) or million electron volts (MeV; 1 MeV = 1,000,000 eV)—are commonly used. A gamma ray with an energy of 0.5 MeV (500 keV) is equivalent in wavelength and in penetrating power to the most penetrating radiation emitted by an x-ray tube operating at 500 kV. The bulk of the radiation emitted by such an x-ray tube will be much less penetrating (much softer) than this (see Figure 18). Thus the radiations from cobalt 60, for example, with energies of 1.17 and 1.33 MeV, will have a penetrating power (hardness) about equal to that of the radiation from a 2-million-volt x-ray machine.

For comparison, a gamma ray having an energy of 1.2 MeV has a wavelength of about 0.01 angstrom (A); a 120 keV gamma ray has a wavelength of about 0.1 angstrom.

The wavelengths (or energies of radiation) emitted by a gamma-ray source, and their relative intensities, depend *only* on the nature of the emitter. Thus, the radiation *quality* of a gamma ray source is not variable at the will of the operator.

The gamma rays from cobalt 60 have relatively great penetrating power and can be used, under some conditions, to radiograph sections of steel 9 inches thick, or the equivalent. Radiations from other radioactive materials have lower energies; for example, iridium 192 emits radiations roughly equivalent to the x-rays emitted by a conventional x-ray tube operating at about 600 kV.

The *intensity* of gamma radiation depends on the strength of the particular source used--specifically, on the number of radioactive atoms in the source that disintegrate in one second. This, in turn, is usually given in terms of curies ($1 \text{ Ci} = 3.7 \times 10^{10} \text{ s}^{-1}$). For small or moderate-sized sources emitting penetrating gamma rays, the intensity of radiation emitted from the source is proportional to the source activity in curies. The proportionality between the external gamma-ray intensity and the number of curies fails, however, for large sources or for those emitting relatively low-energy gamma rays. In these latter cases, gamma radiation given off by atoms in the middle of the source will be appreciably absorbed (*self-absorption*) by the overlying radioactive material itself. Thus, the intensity of the useful radiation will be reduced to some value below that which would be calculated from the number of curies and the radiation output of a physically small gamma-ray source.

A term often used in speaking of radioactive sources is *specific activity*, a measure of the degree of concentration of a radioactive source. Specific activity is usually expressed in terms of curies per gram. Of two gamma-ray sources of the same material and activity, the one having the greater specific activity will be the smaller in actual physical size. Thus, the source of higher specific activity will suffer less from self-absorption of its own gamma radiation. In addition, it will give less geometrical unsharpness in the radiograph or, alternatively, will allow shorter source-film distances and shorter exposures (See the calculation under "General Principles").

Gamma-ray sources gradually lose activity with time, the rate of decrease of activity depending on the kind of radioactive material (See Table II). For instance, the intensity of the radiation from a cobalt 60 source decreases to half its original value in about 5 years; and that of an iridium 192 source, in about 70 days. Except in the case of radium, now little used in industrial radiography, this decrease in emission necessitates more or less frequent revision of exposures and replacement of sources.

Table II - Radioactive Materials Used in Industrial Radiography

Radioactive Element	Half-Life	Energy of Gamma Rays (MeV)	Gamma-Ray Dosage Rate (roentgens ¹ per hour per curie at 1 metre)
Thulium 170	127 days	0.084 and 0.54 ²	--
Iridium 192	70 days	0.137 to 0.651 ³	0.55
Cesium 137	33 years	0.66	0.39
Cobalt 60	5.3 years	1.17 and 1.33	1.35

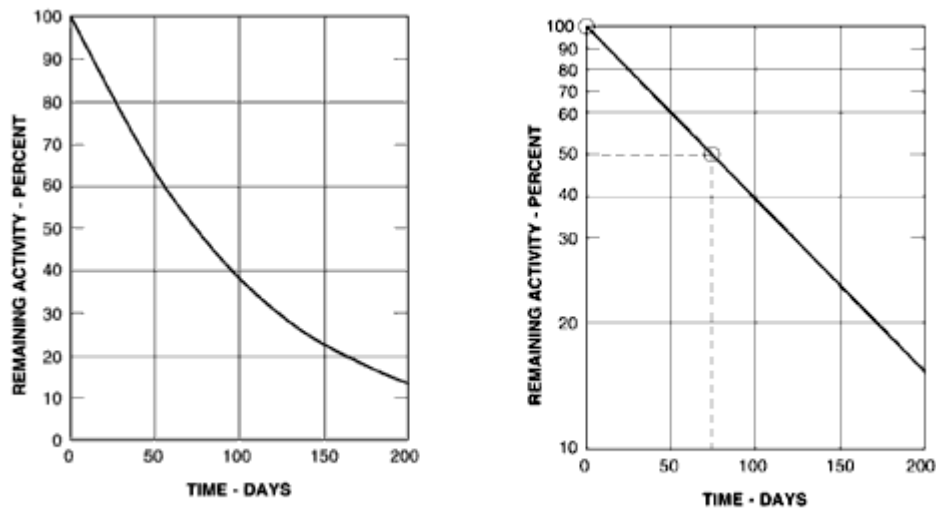
¹ The roentgen (R) is a special unit for x- and gamma-ray exposure (ionization of air): 1 roentgen = 2.58×10^{-4} coulombs per kilogram (Ckg-1). (The International Commission on Radiation Units and Measurements [ICRU] recommends that the roentgen be replaced gradually by the SI unit [Ckg-1] by about 1985.)

² These gamma rays are accompanied by a more or less intense background of much harder radiation. The proportion of hard radiation depends upon the chemical nature and physical size of the source.

³ Twelve gamma rays.

The exposure calculations necessitated by the gradual decrease in the radiation output of a gamma-ray source can be facilitated by the use of decay curves similar to those for indium 192 shown in figure 9. The curves contain the same information, the only difference being that the curve on the left shows activity on a linear scale, and the curve on the right, on a logarithmic scale. The type shown on the right is easier to draw. Locate point X, at the intersection of the half-life of the isotope (horizontal scale) and the "50 percent remaining activity" line (vertical scale). Then draw a straight line from the "zero time, 100 percent activity" point Y through point X.

Figure 9: Decay curves for iridium 192. Left: Linear plot. Right: Logarithmic plot.



It is difficult to give specific recommendations on the choices of gamma-ray emitter and source strength (See Figure 10). These choices will depend on several factors, among which are the type of specimen radiographed, allowable exposure time, storage facilities available, protective measures required, and convenience of source replacement. The values given in Table III for practical application are therefore intended only as a rough guide and in particular case will depend on the source size used and the requirements of the operation.

Figure 10: Typical industrial gamma-ray arrangement. Gamma-ray source in a combination "camera" and storage container.

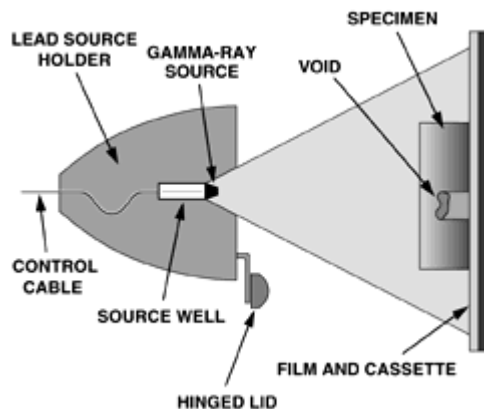


Table III - Industrial Gamma-Ray Sources and Their Applications

Source	Applications and Approximate Practical Thickness Limits
Thulium 170	Plastics, wood, light alloys. $\frac{1}{2}$ -inch steel or equivalent.
Iridium 192	$1\frac{1}{2}$ - to $2\frac{1}{2}$ -inch steel or equivalent.
Cesium 137	1 to $3\frac{1}{2}$ -inch steel or equivalent.
Cobalt 60	$2\frac{1}{2}$ - to 9-inch steel or equivalent.

¹The atomic number of an element is the number of protons in the nucleus of the atom, and is equal to the number of electrons outside the nucleus. In the periodic table the elements are arranged in order of increasing atomic number. Hydrogen has an atomic number of 1; iron, of 26; copper, of 29; tungsten, of 74; and lead of 82.

Chapter 3: Geometric Principles

A radiograph is a shadow picture of an object that has been placed in the path of an x-ray or gamma-ray beam, between the tube anode and the film or between the source of gamma radiation and the film. It naturally follows, therefore, that the appearance of an image thus recorded is materially influenced by the relative positions of the object and the film and by the direction of the beam. For these reasons, familiarity with the elementary principles of shadow formation is important to those making and interpreting radiographs.

General Principles

Since x-rays and gamma rays obey the common laws of light, their shadow formation may be explained in a simple manner in terms of light. It should be borne in mind that the analogy between light and these radiations is not perfect since all objects are, to a greater or lesser degree, transparent to x-rays and gamma rays and since scattering presents greater problems in radiography than in optics. However, the same geometric laws of shadow formation hold for both light and penetrating radiation.

Suppose, as in Figure 11A below, that there is light from a point L falling on a white card C, and that an opaque object O is interposed between the light source and the card. A shadow of the object will be formed on the surface of the card.

This shadow cast by the object will naturally show some *enlargement* because the object is not in contact with the card; the *degree of enlargement* will vary according to the relative distances of the object from the card and from the light source. The law governing the size of the shadow may be stated:

The diameter of the object is to the diameter of the shadow as the distance of the light from the object is to the distance of the light from the card.

Mathematically, the degree of enlargement may be calculated by use of the following equations:

$$\frac{S_o}{S_i} = \frac{D_o}{D_i} \text{ or } S_o = S_i \left(\frac{D_o}{D_i} \right)$$

where S_o is the size of the object; S_i is the size of the shadow (or the radiographic image); D_o the distance from source of radiation to object; and D_i the distance from the source of radiation to the recording surface (or radiographic film).

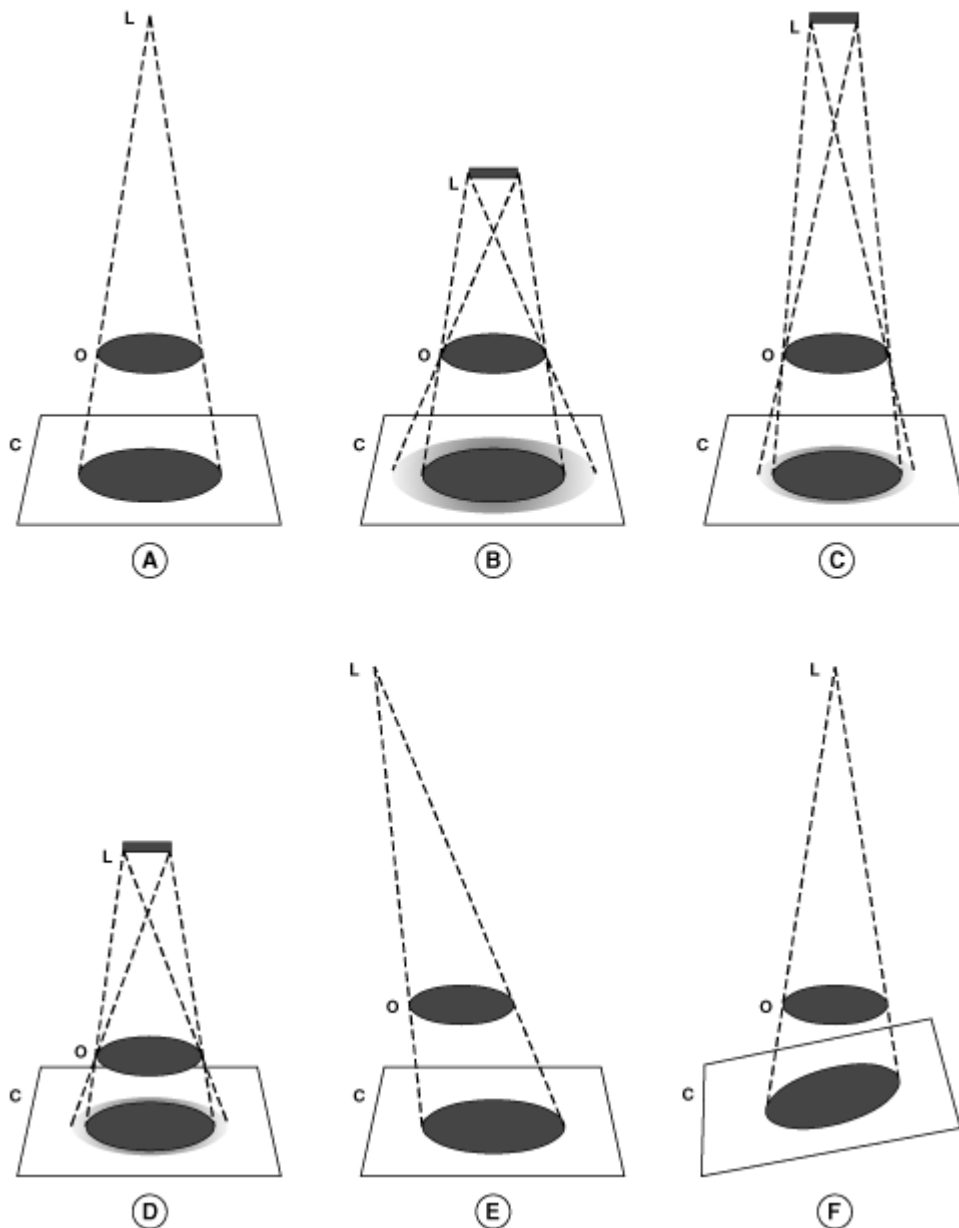
The degree of *sharpness* of any shadow depends on the size of the source of light and on the position of the object between the light and the card--whether nearer to or farther from one or the other. When the source of light is not a point but a small area, the shadows cast are not perfectly sharp (in Figure 11, B to D) because *each point* in the source of light casts its own shadow of the object, and each of these overlapping shadows is slightly displaced from the others, producing an ill-defined image.

The *form of the shadow* may also differ according to the angle that the object makes with the incident light rays. Deviations from the *true shape* of the object as exhibited in its shadow image are referred to as distortion.

Figure 11, A to F shows the effect of changing the size of the source and of changing the relative positions of source, object, and card. From an examination of these drawings, it will be seen that the following conditions must be fulfilled to produce the sharpest, truest shadow of the object:

1. The source of light should be small, that is, as nearly a point as can be obtained. Compare Figure 11, A and C.
2. The source of light should be as far from the object as practical. Compare Figure 11, B and C.
3. The recording surface should be as close to the object as possible. Compare Figure 11, B and D.
4. The light rays should be directed perpendicularly to the recording surface. See Figure 11, A and E.
5. The plane of the object and the plane of the recording surface should be parallel. Compare Figure 11, A and F.

Figure 11: Illustrating the general geometric principles of shadow formation as explained in these sections.

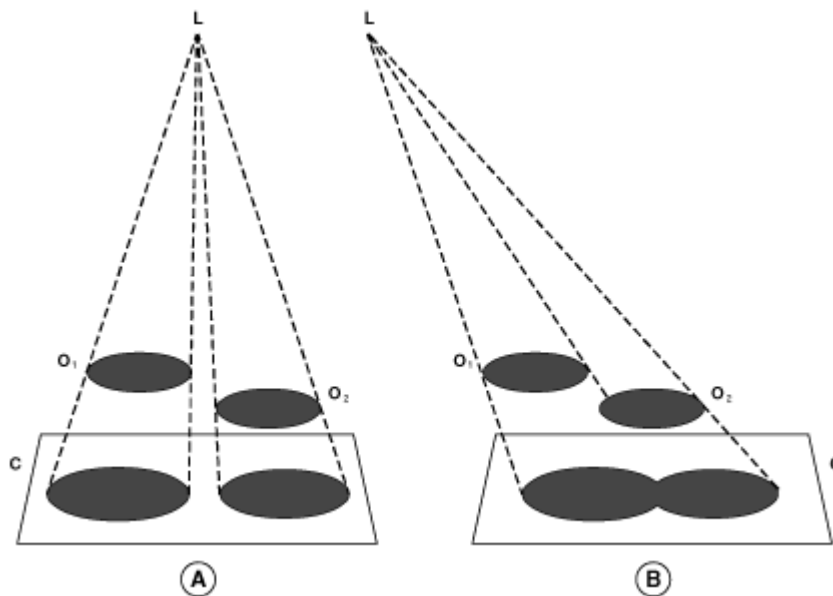


Radiographic Shadows

The basic principles of shadow formation must be given primary consideration in order to assure satisfactory sharpness in the radiographic image and essential freedom from distortion. A certain degree of distortion naturally will exist in every radiograph because some parts will always be farther from the film than others, the greatest magnification being evident in the images of those parts at the greatest distance from the recording surface (See Figure 11).

Note, also, that there is no distortion of shape in Figure 11E above--a circular object having been rendered as a circular shadow. However, under circumstances similar to those shown, it is possible that spatial relations can be distorted. In Figure 12 the two circular objects can be rendered either as two circles (See Figure 12A) or as a figure-eight-shaped shadow (See Figure 12B). It should be observed that both lobes of the figure eight have circular outlines.

Figure 12: Two circular objects can be rendered as two separate circles (A) or as two overlapping circles (B), depending on the direction of the radiation.



Distortion cannot be eliminated entirely, but by the use of an appropriate source-film distance, it can be lessened to a point where it will not be objectionable in the radiographic image.

Application To Radiography

The application of the geometric principles of shadow formation to radiography leads to five general rules. Although these rules are stated in terms of radiography with x-rays, they also apply to gamma-ray radiography.

1. The focal spot should be as small as other considerations will allow, for there is a definite relation between the size of the focal spot of the x-ray tube and the *definition* in the radiograph. A large-focus tube, although capable of withstanding large loads, does not permit the delineation of as much detail as a small-focus tube. Long source-film distances will aid in showing detail when a large-focus tube is employed, but it is advantageous to use the smallest focal spot permissible for the exposures required.

B and H in the Figure 13 show the effect of focal spot size on image quality. As the focal spot size is increased from 1.5 mm (B) to 4.0 mm (H), the definition of the radiograph starts to degrade. This is especially evident at the edges of the chambers, which are no longer sharp.

2. The distance between the anode and the material examined should always be as great as is practical. Comparatively long-source distances should be used in the radiography of thick materials to minimize the fact that structures farthest from the film are less sharply recorded than those nearer to it. At long distances, radiographic definition is improved and the image is more nearly the actual size of the object.
3. A to D in the Figure 13 show the effects of source-film distance on image quality. As the source-film distance is decreased from 68 inches (A) to 12 inches (D) the image becomes more distorted until at 12 inches it is no longer a true representation of the casting. This is particularly evident at the edges of the casing where the distortion is greatest.
4. The film should be as close as possible to the object being radiographed. In practice, the film--in its cassette or exposure holder--is placed in contact with the object.

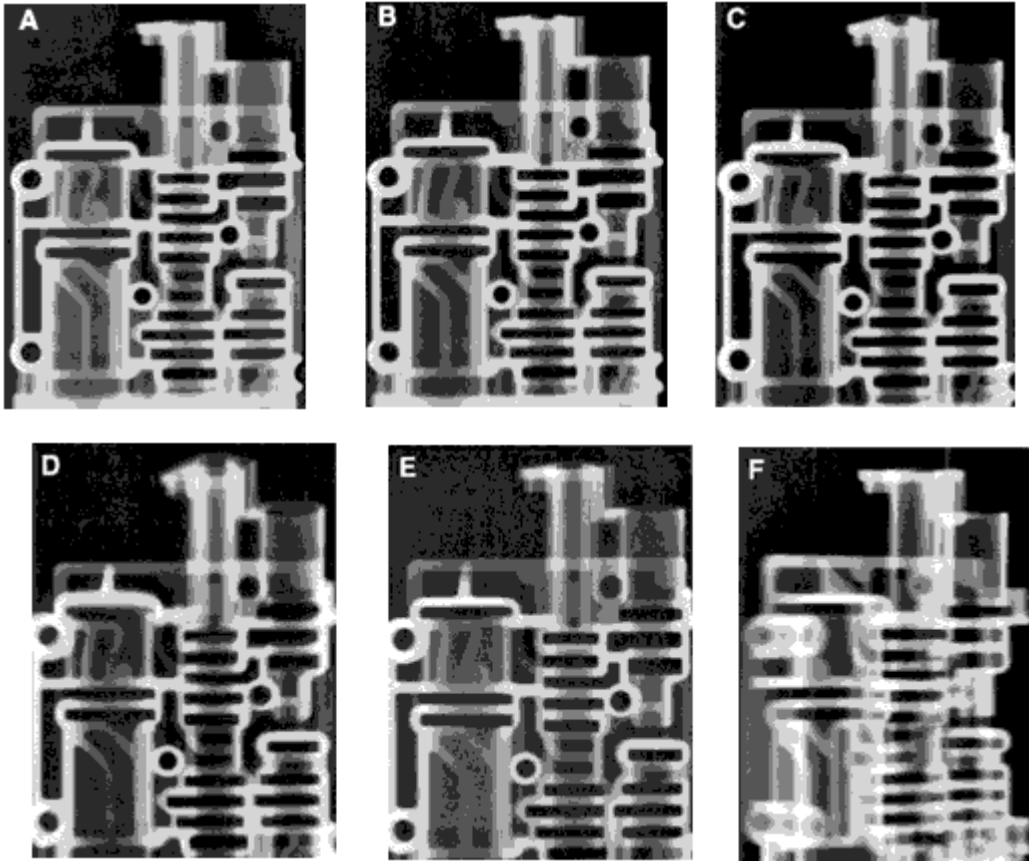
In B and E of Figure 13, the effects of object-film distance are evident. As the object-film distance is increased from zero (B) to 4 inches (E), the image becomes larger and the definition begins to degrade. Again, this is especially evident at the edges of the chambers that are no longer sharp.

5. The central ray should be as nearly perpendicular to the film as possible to preserve spatial relations.

As far as the shape of the specimen will allow, the plane of maximum interest should be parallel to the plane of the film.

Finally, in F and G of the Figure 13, the effects of object-film-source orientation are shown. When compared to B, image F is extremely distorted because although the film is perpendicular to the central ray, the casting is at a 45° angle to the film and spatial relationships are lost. As the film is rotated to be parallel with the casting (G), the spatial relationships are maintained and the distortion is lessened.

Figure 13: These graphics illustrate the effects on image quality when the geometric exposure factors are changed.



Calculation Of Geometric Unsharpness

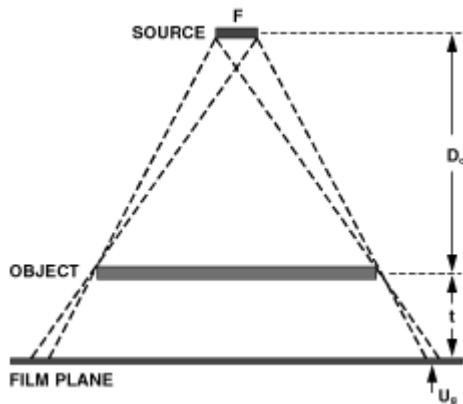
The width of the "fuzzy" boundary of the shadows in B, C, and D in the above figure is known as the *geometric unsharpness* (U_g). Since the geometric unsharpness can strongly affect the appearance of the radiographic image, it is frequently necessary to determine its magnitude.

From the laws of similar triangles, it can be seen (In Figure 14) that:

$$\frac{U_g}{F} = \frac{t}{D_o} \text{ or } U_g = F \left(\frac{t}{D_o} \right)$$

where U_g is the geometric unsharpness, F is the size of the radiation source, D_o is the source-object distance, and t is the object-film distance. Since the maximum unsharpness involved in any radiographic procedure is usually the significant quantity, the object-film distance (t) is usually taken as the distance from the *source side* of the specimen to the film.

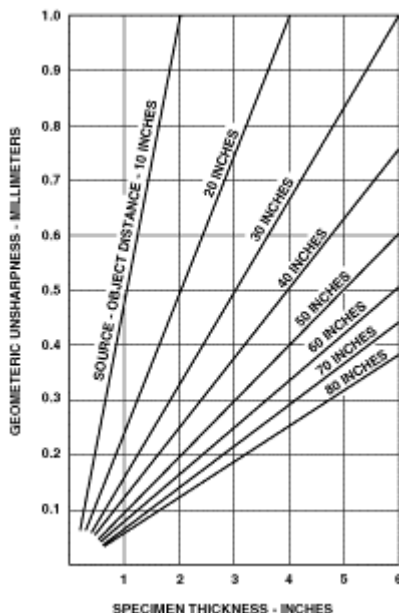
Figure 14: Geometric construction for determining geometric unsharpness (U_g).



D_o and t must be measured in the *same units*; inches are customary, but any other unit of length—say, centimetres—would also be satisfactory. So long as D_o and t are in the same units, the formula above will always give the geometric unsharpness U_g in whatever units were used to measure the dimensions of the source. The projected size of the focal spots of x-ray tubes are usually stated in millimetres, and U_g will also be in millimetres. If the source size is stated in inches, U_g will be in inches.

For rapid reference, graphs of the type shown in the figure below can be prepared by the use of the equation above. These graphs relate source-film distance, object-film distance and geometric unsharpness. Note that the lines of Figure 15 are all straight. Therefore, for each source-object distance, it is only necessary to calculate the value of U for a single specimen thickness, and then draw a straight line through the point so determined and the origin. It should be emphasized, however, that a separate graph of the type shown in Figure 15 must be prepared for each size of source.

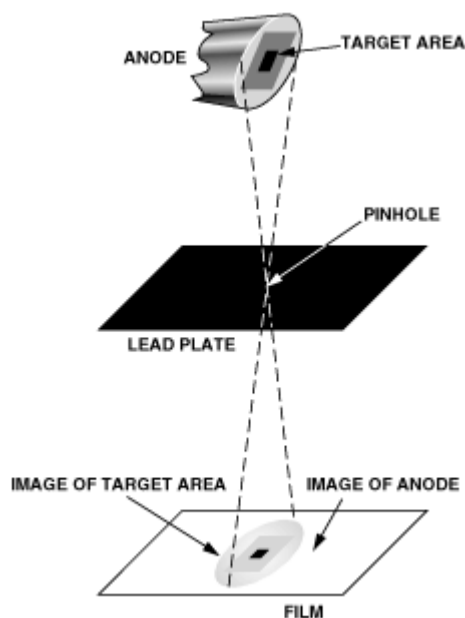
Figure 15: Graph relating geometric unsharpness (U_g) to specimen thickness and source-object distance, for a 5-millimetre source size.



Pinhole Projection Of Focal Spot

Since the dimensions of the radiation source have considerable effect on the sharpness of the shadows, it is frequently desirable to determine the shape and size of the x-ray tube focal spot. This may be accomplished by the method of pinhole radiography, which is identical in principle with that of the pinhole camera. A thin lead plate containing a small hole is placed exactly midway between the focal spot and the film, and lead shielding is so arranged that no x-rays except those passing through the pinhole reach the film (See Figure 16). The developed film will show an image that, for most practical radiographic purposes, may be taken as equal in size and shape to the focal spot (See Figure 17). If precise measurements are required, the measured dimensions of the focal-spot image should be decreased by twice the diameter of the pinhole.

Figure 16: Schematic diagram showing production of a pinhole picture of an x-ray tube focal spot.

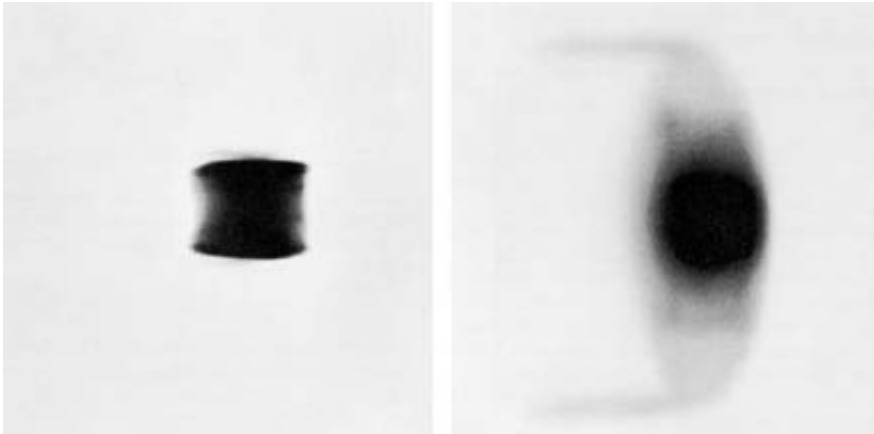


The method is applicable to x-ray tubes operating up to about 250 kV. Above this kilovoltage, however, the thickness of the lead needed makes the method impractical. (The entire focal spot cannot be "seen" from the film side of a small hole in a thick plate.) Thus the technique cannot be used for high-energy x-rays or the commonly used gamma-ray sources, and much more complicated methods, suitable only for the laboratory, must be employed.

A focus-film distance of 24 inches is usually convenient. Of course, the time of exposure will be much greater than that required to expose the film without the pinhole plate because so little radiation can get through such a small aperture. In general, a needle or a No. 60 drill will make a hole small enough for practical purposes.

A density in the image area of 1.0 to 2.0 is satisfactory. If the focal-spot area is overexposed, the estimate of focal-spot size will be exaggerated, as can be seen by comparing the two images in Figure 17.

Figure 17: Pinhole pictures of the focal spot of an x-ray tube. A shorter exposure (left) shows only focal spot. A longer exposure (right) shows, as well as the focal spot, some details of the tungsten button and copper anode stem. The x-ray images of these parts result from their bombardment with stray electrons.



Chapter 4: Factors Governing Exposure

Generally speaking, the density of any radiographic image depends on the amount of radiation absorbed by the sensitive emulsion of the film. This amount of radiation in turn depends on several factors: the total amount of radiation emitted by the x-ray tube or gamma-ray source; the amount of radiation reaching the specimen; the proportion of this radiation that passes through the specimen; and the intensifying action of the screens, if they are used. This chapter discusses the effects of these factors.

Radiation Emitted By Source

X-rays

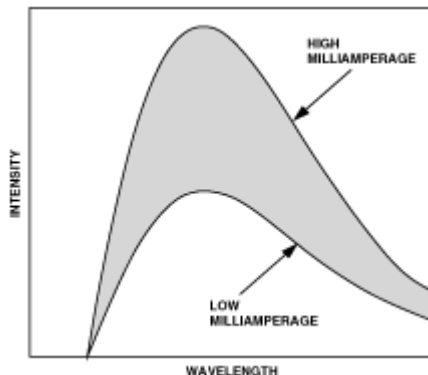
The total amount of radiation emitted by an x-ray tube depends on tube current (milliamperage), kilovoltage, and the time the tube is energized.

When other operating conditions are held constant, a change in milliamperage causes a change in the *intensity* of the radiation emitted, the intensity being approximately proportional to the milliamperage. The high voltage transformer saturation and voltage waveform can change with tube current, but a compensation factor is usually applied to minimize the effects of these changes. In normal industrial radiographic practice, the variation from exact proportionality is not serious and may usually be ignored.

Figure 18 shows spectral emission curves for an x-ray tube operated at two different currents, the higher being twice the lower. Therefore, *each wavelength* is twice as intense in one beam as in the other. Note that no wavelengths are present in one beam that are not present in the other. Hence, there is no change in x-ray quality or penetrating power.

As would be expected, the total amount of radiation emitted by an x-ray tube operating at a certain kilovoltage and milliamperage is directly proportional to the time the tube is energized.

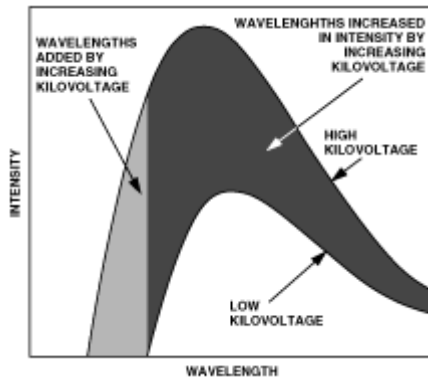
Figure 18: Curves illustrating the effect of a change in milliamperage on the intensity of an x-ray beam. (After Ulrey.)



Since the x-ray output is directly proportional to both milliamperage and time, it is directly proportional to their product. (This product is often referred to as the "exposure".) Algebraically, this may be stated $E = Mt$, where E is the exposure, M the tube current, and t the exposure time. Hence, the amount of radiation will remain constant if the exposure remains constant, no matter how the individual factors of tube current and exposure time are varied. This permits specifying x-ray exposures in terms of milliamperere-minutes or milliamperere-seconds, without stating the specific individual values of tube current and time.

The kilovoltage applied to the x-ray tube affects not only the quality but also the intensity of the beam. As the kilovoltage is raised, x-rays of shorter wavelength, and hence of more penetrating power, are produced. Figure 19 shows spectral emission curves for an x-ray tube operated at two different kilovoltages but at the same milliamperage. Note that, in the higher-kilovoltage beam, there are some shorter wavelengths that are absent from the lower-kilovoltage beam. Further, all wavelengths present in the lower-kilovoltage beam are present in the more penetrating beam, and in greater amount. Thus, raising the kilovoltage increases both the penetration and the intensity of the radiation emitted from the tube.

Figure 19: Curves illustrating the effect of a change in kilovoltage on the composition and intensity of an x-ray beam. (After Ulrey.)



Gamma Rays

The total amount of radiation emitted from a gamma-ray source during a radiographic exposure depends on the activity of the source (usually stated in curies) and the time of exposure. For a particular radioactive isotope, the intensity of the radiation is approximately proportional to the activity (in curies) of the source. If it were not for absorption of gamma rays within the radioactive material itself (see the discussion on self-absorption in "Gamma-Ray Sources") this proportionality would be exact. In normal radiographic practice, the range of source sizes used in a particular location is small enough so that variations from exact proportionality are not serious and may usually be ignored.

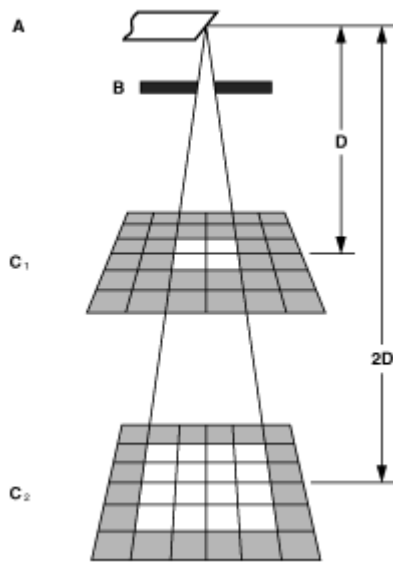
Thus, the gamma-ray output is directly proportional to both activity of the source and time, and hence is directly proportional to their product. Analogously to the x-ray exposure, the gamma-ray exposure E may be stated $E = Mt$, where M is the source activity in curies and t is the exposure time, the amount of gamma radiation remaining constant so long as the product of source activity and time remains constant. This permits specifying gamma-ray exposures in curie-hours without stating specific values for source activity or time.

Since gamma-ray energy is fixed by the nature of the particular radioactive isotope, there is no variable to correspond to the kilovoltage factor encountered in x-radiography. The only way to change penetrating power when using gamma rays is to change the source, i.e., cobalt 60 in place of iridium 192 (see Figure 8).

Inverse Square Law

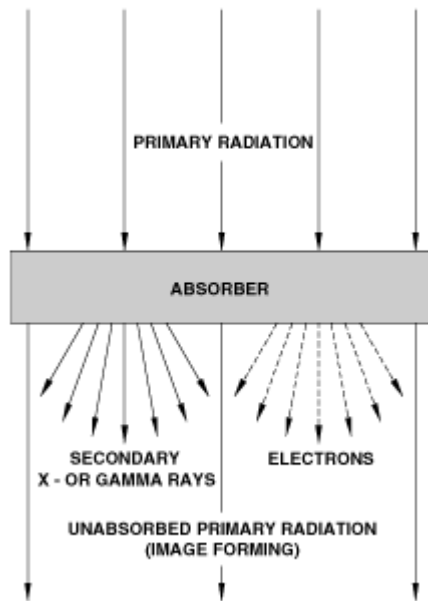
When the x-ray tube output is held constant, or when a particular radioactive source is used, the radiation intensity reaching the specimen is governed by the distance between the tube (or source) and the specimen, varying inversely with the square of this distance. The explanation that follows is in terms of x-rays and light, but it applies to gamma rays as well.

Figure 20: Schematic diagram illustrating the inverse square law.



Since x-rays conform to the laws of light, they diverge when they are emitted from the anode and cover an increasingly larger area with lessened intensity as they travel from their source. This principle is illustrated in the figure above. In this example, it is assumed that the intensity of the x-rays emitted at the anode A remains constant and that the x-rays passing through the aperture B cover an area of 4 square inches on reaching the recording surface C_1 , which is 12 inches (D) from the anode. Then, when the recording surface is moved 12 inches farther from the anode, to C_2 , so that the distance from the anode is 24 inches ($2D$), or twice its earlier value, the x-rays will cover 16 square inches—an area four times as great as that at C_1 . It follows, therefore, that the radiation per square inch on the surface at C_2 is only one-quarter of that at the level C_1 . Thus, the exposure that would be adequate at C_1 must be increased four times in order to produce at C_2 a radiograph of equal density. In practice, this can be done by increasing the time or by increasing the milliamperage.

Figure 21: Schematic diagram of some of the ways x- or gamma-ray energy is dissipated on passing through matter. Electrons from specimens are usually unimportant radiographically; those from lead foil screens are very important.



This inverse square law can be expressed algebraically as follows:

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

where I_1 and I_2 are the intensities at the distances D_1 and D_2 respectively.

Radiation Absorption In The Specimen

When x-rays or gamma rays strike an absorber (See Figure 21), some of the radiation is absorbed and another portion passes through undeviated. It is the intensity variation of the undeviated radiation from area to area in the specimen that forms the useful image in a radiograph. However, not all the radiation is either completely removed from the beam or transmitted. Some is deviated within the specimen from its original direction—that is, it is scattered and is nonimage-forming. This nonimage-forming scattered radiation, if not carefully controlled, will expose the film and thus tend to obscure the useful radiographic image. Scattered radiation and the means for reducing its effects are discussed in detail in "Scattered Radiation". Another portion of the energy in the original beam is spent in liberating electrons from the absorber. The electrons from the specimen are unimportant radiographically; those from lead screens, discussed in detail in "Radiographic Screens", are very important.

X-ray Equivalency

If industrial radiography were done with monoenergetic radiation, that is, with an x-ray beam containing but a single wavelength, and if there were no scattering, the laws of absorption of x-rays by matter could be stated mathematically with great exactness. However, since a broad band of wavelengths is used and since considerable scattered radiation reaches the film, the laws can be given only in a general way.

The x-ray absorption of a specimen depends on its thickness, on its density and, most important of all, on the atomic nature of the material. It is obvious that of two specimens of similar composition, the thicker or the more dense will absorb the more radiation, necessitating an

increase in kilovoltage or exposure, or both, to produce the same photographic result. However, the atomic elements in a specimen usually exert a far greater effect on x-ray absorption than either the thickness or the density. For example, lead is about 1.5 times as dense as ordinary steel, but at 220 kV, 0.1 inch of lead absorbs as much as 1.2 inches of steel. Brass is only about 1.1 times as dense as steel, yet, at 150 kV, the same exposure is required for 0.25 inch of brass as for 0.35 inch of steel. Table IV gives approximate radiographic equivalence factors. It should be emphasized that this table is only approximate and is intended merely as a guide, since it is based on a compilation of data from many sources. In a particular instance, the exact value of the radiographic equivalence factor will depend on the quality of the x-radiation and the thickness of the specimen. It will be noted from this table that the relative absorptions of the different materials are not constant but change with kilovoltage, and that as the kilovoltage increases, the differences between all materials tend to become less. In other words, as kilovoltage is increased, the radiographic absorption of a material is less and less dependent on the atomic numbers of its constituents.

Table IV: Approximate Radiographic Equivalence Factors

	X-rays								Gamma Rays			
Material	50 kV	100 kV	150 kV	220 kV	400 kV	1000 kV	2000 kV	4 to 25 MeV	Ir 192	Cs 137	Co 60	Radium
Magnesium	0.6	0.6	0.5	0.08								
Aluminum	1.0	1.0	0.12	0.18					0.35	0.35	0.35	0.40
2024 (aluminum) alloy	2.2	1.6	0.16	0.22					0.35	0.35	0.35	
Titanium			0.45	0.35								
Steel		12.	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
18-8 (steel) alloy		12.	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Copper		18.	1.6	1.4	1.4			1.3	1.1	1.1	1.1	1.1
Zinc			1.4	1.3	1.3			1.2	1.1	1.0	1.0	1.0
Brass*			1.4*	1.3*	1.3*	1.2*	1.2*	1.2*	1.1*	1.1*	1.1*	1.1*
Inconel X alloy		16.	1.4	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Zirconium			2.3	2.0		1.0						
Lead			14.	12.		5.0	2.5	3.0	4.0	3.2	2.3	2.0
Uranium				25.				3.9	12.6	5.6	3.4	

Aluminum is taken as the standard metal at 50 kV and 100 kV and **steel** at the higher voltages and gamma rays. The thickness of another metal is multiplied by the corresponding factor to obtain the approximate equivalent thickness of the standard metal. The exposure applying to this thickness of the standard metal is used.

Example: To radiograph 0.5 inch of copper at 220 kV, multiply 0.5 inch by the factor 1.4, obtaining an equivalent thickness of 0.7 inch of steel. Therefore, give the exposure required for 0.7 inch of steel.

*Tin or lead alloyed in the brass will increase these factors.

For x-rays generated at voltages upward of 1000 kV and for materials not differing too greatly in atomic number (steel and copper, for example), the radiographic absorption for a given thickness of material is roughly proportional to the density of the material. However, even at high voltages or with penetrating gamma rays, the effect of composition upon absorption cannot be ignored when dealing with materials that differ widely in atomic number. For instance, the absorption of lead for 1000 kV x-rays is about five times that of an equal thickness of steel, although its density is but 11/2 times as great.

The kilovoltage governs the penetrating power of an x-ray beam and hence governs the intensity of the radiation passing through the specimen. It is not possible, however, to specify a simple relation between kilovoltage and x-ray intensity because such factors as the thickness and the

kind of material radiographed, the characteristics of the x-ray generating apparatus, and whether the film is used alone or with intensifying screens exert a considerable influence on this relation. The following example illustrates this point:

Data from a given exposure chart indicate that radiographs of equal density can be made of 1/4-inch steel with either of the following sets of exposure conditions:

80 kilovolts, 35 milliamperes-minutes

120 kilovolt, 15 milliamperes-minutes

Thus, in this case, a 50 percent increase in kilovoltage results in a 23-*fold* increase in photographically effective x-ray intensity.

Two-inch aluminum can also be radiographed at these two kilovoltages. Equal densities will result with the following exposure relations:

80 kilovolts, 17 milliamperes-minutes

120 kilovolts, 2.4 milliamperes-minutes

In this case, the same increase in kilovoltage results in an increase of photographically effective x-ray intensity passing through the specimen of only *seven times*. Many other examples can be found to illustrate the extreme variability of the effect of kilovoltage on x-ray intensity.

Gamma-ray Equivalency

Essentially the same considerations apply to gamma-ray absorption, since the radiations are of similar nature. It is true that some radioactive materials used in industrial radiography emit radiation that is monoenergetic, or almost so (for example, cobalt 60 and cesium 137). However, even with these sources, scattering is dependent on the size, shape, and composition of the specimen, which prevents the laws of absorption from being stated exactly. For those gamma-ray emitters (for example, indium 192) that give off a number of discrete gamma-ray wavelengths extending over a wide energy range, the resemblance to the absorption of x-rays is even greater.

The gamma-ray absorption of a specimen depends on its thickness, density, and composition, as does its x-ray absorption. However, the most commonly used gamma-ray sources emit fairly penetrating radiations corresponding in their properties to high-voltage x-radiation. The table above shows that the absorptions of the various materials for penetrating gamma rays are similar to their absorptions for high-voltage x-rays--that is, the absorptions of materials fairly close together in atomic number are roughly proportional to their densities. As with high-voltage x-rays, this is not true of materials, such as steel and lead, that differ widely in atomic number.

Radiographic Screens

Another factor governing the photographic density of the radiograph is the intensifying action of the screens used. Intensifying screens and lead screens are fully discussed in "Radiographic Screens". It will suffice to state here that x-rays and gamma rays cause fluorescent intensifying screens to emit light that may materially lessen the exposure necessary to produce a given density. Lead screens emit electrons under the action of x-rays and gamma rays. The photographic effect of these electrons may permit a shorter exposure than would be required without lead screens.

Exposure Factor

The "exposure factor" is a quantity that combines milliamperage (x-rays) or source strength (gamma rays), time, and distance. Numerically the exposure factor equals

$$\frac{\text{milliamperes} \times \text{time}}{\text{distance}^2} \text{ for x-rays}$$

and $\frac{\text{curies} \times \text{time}}{\text{distance}^2} \text{ for gamma rays}$

Radiographic techniques are sometimes given in terms of kilovoltage and exposure factor, or radioactive isotope and exposure factor. In such a case, it is necessary to multiply the exposure factor by the square of the distance to be used in order to find, for example, the milliamperere-minutes or the curie-hours required.

Determination Of Exposure Factors

X-rays

The focus-film distance is easy to establish by actual measurement; the milliamperage can conveniently be determined by the milliammeter supplied with the x-ray machine; and the exposure time can be accurately controlled by a good time-switch. The tube voltage, however, is difficult and inconvenient to measure accurately. Furthermore, designs of individual machines differ widely, and may give x-ray outputs of a different quality and intensity even when operated at the same nominal values of peak kilovoltage and milliamperage.

Consequently, although specified exposure techniques can be duplicated satisfactorily in the factors of focus-film distance, milliamperage, and exposure time, one apparatus may differ materially from another in the kilovoltage setting necessary to produce the same radiographic density. Because of this, the kilovoltage setting for a given technique should be determined by trial on each x-ray generator. In the preliminary tests, published exposure charts may be followed as an approximate guide. It is customary for equipment manufacturers to calibrate x-ray machines at the factory and to furnish suitable exposure charts. For the unusual problems that arise, it is desirable to record in a logbook all the data on exposure and techniques. In this way, operators will soon build up a source of information that will make them more competent to deal with difficult situations.

For developing trial exposures, a standardized technique should always be used. If this is done, any variation in the quality of the trial radiographs may then be attributed to the exposure alone. This method obviates many of the variable factors common to radiographic work.

Since an increase of kilovoltage produces a marked increase in x-ray output and penetration (See Figure 19), it is necessary to maintain a close control of this factor in order to secure radiographs of uniform density. In many types of industrial radiography where it is desirable to maintain constant exposure conditions with regard to focus-film distance, milliamperage, and exposure time, it is common practice to vary the kilovoltage in accordance with the thickness of the material to be examined so as to secure proper density in the radiographic image. Suppose, for example, it is desired to change from radiographing 1 1/2-inch steel to radiographing 2-inch steel. The 2-inch steel will require more than 10 times the exposure in milliamperere-minutes at 170 kilovolts. However, increasing the kilovoltage to a little more than 200 will yield a comparable radiograph with the same milliamperere-minutes. Thus, kilovoltage is an important variable because economic considerations often require that exposure times be kept within fairly narrow limits. It is desirable, as a rule, to *use as low a kilovoltage as other factors will permit*. In the case of certain high-voltage x-ray machines, the technique of choosing exposure conditions may be somewhat modified. For

instance, the kilovoltage may be fixed rather than adjustable at the will of the operator, leaving only milliamperage, exposure time, film type, and focus-film distance as variables.

Gamma Rays

With radioactive materials, the variable factors are more limited than with x-rays. Not only is the quality of the radiation fixed by the nature of the emitter, but also the intensity is fixed by the amount of radioactive material in the particular source. The only variables under the control of operators, and the only quantities they need to determine, are the source-film distance, film type, and the exposure time. As in the case of x-radiography, it is desirable to develop trial exposures using the gamma-ray sources under standardized conditions and to record all data on exposures and techniques.

Contrast

In a radiograph, the various intensities transmitted by the specimen are rendered as different densities in the image. The density differences from one area to another constitute *radiographic contrast*. Any shadow or detail within the image is visible by reason of the contrast between it and its background of surrounding structures. Within appropriate limits, the greater the contrast or density differences in the radiograph, the more definitely various details will stand out. However, if overall contrast is increased too much, there is an actual loss in visibility of detail in both the thick and the thin regions of the specimen. The thick sections will be imaged at densities too low to be useful (See also Chapters 7 & 16) and the thin sections, at densities too high to be viewed on the available illuminators. This principle is fully illustrated in Figure 22, which shows two radiographs of a steel stepped wedge, one (A) exposed at a high tube voltage and the other (B) at a low voltage. It is apparent that in the middle tones the differentiation in the steps is greater in the low-voltage radiograph (B) than in the high-voltage radiograph (A). Near the end, however, the steps shown in A are much less apparent in B.

Figure 22: A: 220 kV exposure. B: 120 kV exposure. Radiographs of steel stepped wedge having a thickness range of 1/4 to 3/4 inch in 1/8-inch steps.



Radiographic contrast is a result of both subject contrast and film contrast. Subject contrast is governed by the range of radiation intensities transmitted by the specimen. A flat sheet of homogeneous material of nearly uniform thickness would have very low subject contrast. Conversely, a specimen with large variations in thickness, which transmits a wide range of

intensities, would have high subject contrast. Overall subject contrast could be defined as the ratio of the highest to the lowest radiation intensities falling on the film. Contrast is also affected by scattered radiation, removal of which increases subject contrast.

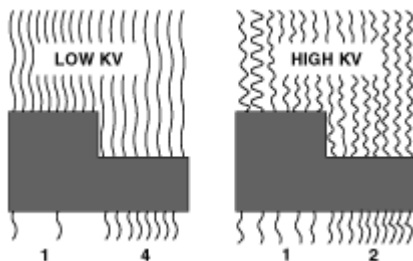
Choice Of Film

Different films have different contrast characteristics. Thus, a film of high contrast may give a radiograph of relatively low contrast if the subject contrast is very low; conversely, a film of low contrast may give a radiograph of relatively high contrast if the subject contrast is very high. *With any given specimen*, the contrast of the radiograph will depend on the kilovoltage of the x-rays or the quality of the gamma rays (See Figure 22), the contrast characteristic of the film, the type of screen, the density to which the radiograph is exposed, and the processing.

Radiographic Sensitivity

In the radiography of materials of approximately uniform thickness, where the range of transmitted x-ray intensities is small, a technique producing high contrast will satisfactorily render all portions of the area of interest, and the radiographic sensitivity¹ will be greater than with a technique producing low contrast. If, however, the part radiographed transmits a wide range of x-ray intensities, then a technique producing lower contrast may be necessary in order to record detail in all portions of radiographic sensitivity. (See Figure 23.) The interrelations among the various factors affecting radiographic sensitivity and detail visibility are discussed in the "Factors Affecting Image Quality" Table and the sections following it.

Figure 23: As kilovoltage increases, subject contrast decreases because more wavelengths penetrate the subject in both thick and thin sections, thus reducing the overall difference in exposure between the two.



Multiple Film Techniques

In the radiography of specimens transmitting too wide a range of intensities to be recorded by a single high-contrast film, high radiographic contrast can be obtained by loading the cassette with *two* high-contrast films of *different speeds*. The exposure conditions are so chosen that thick portions of the specimen are satisfactorily recorded on the faster, and thin portions on the slower film.

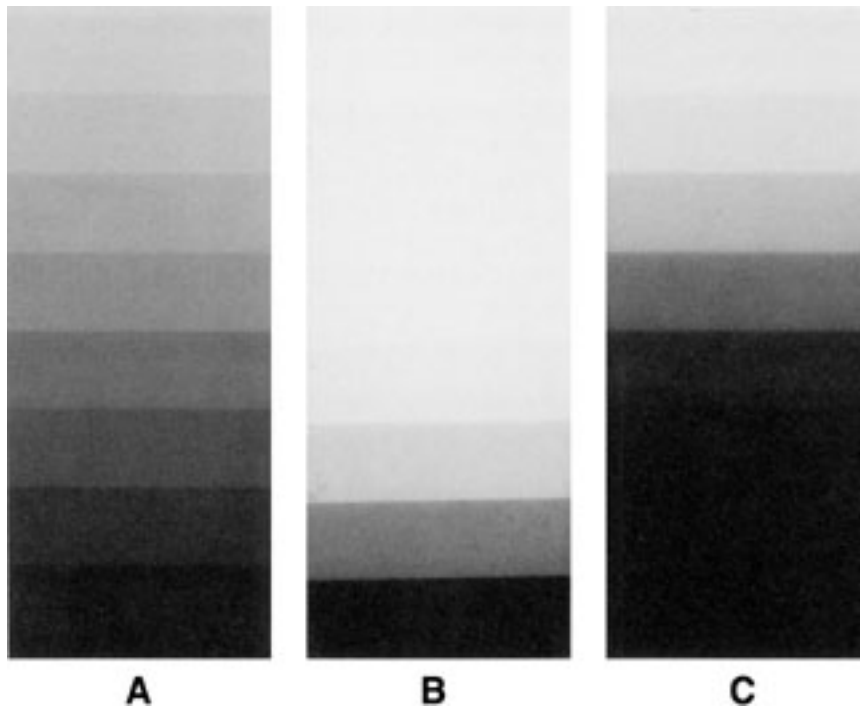
In Figure 24, A and B, the thicker portions of the stepped wedge (1/2 - 3/4 inch) are well recorded on a moderately fast film. In the B part of Figure 24, the thinner portions (3/8 - 1/2 inch) are recorded on a film of about one-quarter the speed exposed at the same time and in the same exposure holder. Had it been desired to render the whole of the stepped wedge in a single radiograph, the kilovoltage would have had to have been increased, which would have resulted in a decrease in subject contrast, and a consequent decrease in radiographic contrast (See Part C of Figure 24).

The technique need not be limited to only two films exposed simultaneously. In special cases, three or even more films can be used greatly expanding the range of thicknesses over which high contrast can be obtained with a single exposure.

A variation of this method is to load the cassette or film holder with two sheets of the same kind of film. With the proper exposure, details in the thick section of the specimen can be examined by viewing the two films superimposed with the images in register. The thin portions on the other hand, will be recorded on both films, either of which may be viewed alone.

Within the range of densities useful in practice, the contrasts of most industrial x-ray films increase continuously with increasing density. In the case of certain medical x-ray films that are occasionally used in industry, however, contrast first increases to a maximum with increasing density and then decreases. Thus, the contrast of a radiograph depends to a large extent on the density. This point is discussed in more detail in later sections.

Figure 24: A and B: Radiographs of stepped wedge made with a two-film technique showing thick portions (A) on a moderately fast film, and the thin portions (B) on a film about one-quarter the speed. C: Single radiograph at higher kilovoltage on the slower of the films. Note lower radiographic contrast in C.



Effects Of Processing

Film contrast increases with the degree of development up to a limit determined by the properties of both the film and the developer. For manual development, the development time should not be less than the minimum time recommended for the film-developer combination. Some films may be developed longer than this minimum time to obtain higher speed.

In automated processing, the recommended operating conditions of the processing machine are such that the maximum film contrast is obtained.

Radiographs of high contrast are likely to contain areas of high density in which detail cannot be seen with ordinary illumination. High-intensity illuminators, for viewing radiographs of high density, are commercially available.

¹"Radiographic sensitivity" refers to the size of the smallest detail that can be seen in a radiograph or to the ease with which the images of small details can be detected. In comparing radiographs of the same specimen, the one that renders details most clearly visible is said to have the highest radiographic sensitivity.