Chapter 5: Radiographic Screens

When an x-ray or gamma-ray beam strikes a film, usually less than 1 percent of the energy is absorbed. Since the formation of the radiographic image is primarily governed by the absorbed radiation, more than 99 percent of the available energy in the beam performs no useful photographic work. Obviously, any means of more fully utilizing this wasted energy, without complicating the technical procedure, is highly desirable. Two types of radiographic screens are used to achieve this end--lead and fluorescent. Lead screens, in turn, take two different forms. One form is sheets of lead foil, usually mounted on cardboard or plastic, which are used in pairs in a conventional cassette or exposure holder. The other consists of a lead compound (usually an oxide), evenly coated on a thin support. The film is placed between the leaves of a folded sheet of this oxide-coated material with the oxide in contact with the film. The combination is supplied in a sealed, lightproof envelope.

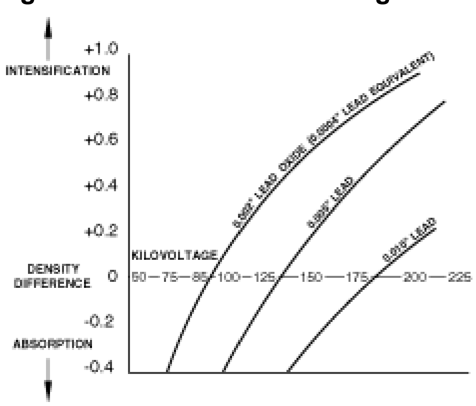
Lead Foil Screens

For radiography in the range 150 to 400 kV, lead foil in direct contact with both sides of the film has a desirable effect on the quality of the radiograph. In radiography with gamma rays and with x-rays below 2,000 kV, the front lead foil need be only 0.004 to 0.006 inch thick; consequently its absorption of the primary beam is not serious. The back screen should be thicker to reduce backscattered radiation. Such screens are available commercially. The choice of lead screen thicknesses for multimillion-volt radiography is much more complicated, and the manufacturers of the equipment should be consulted for their recommendations.

Effects of Lead Screens

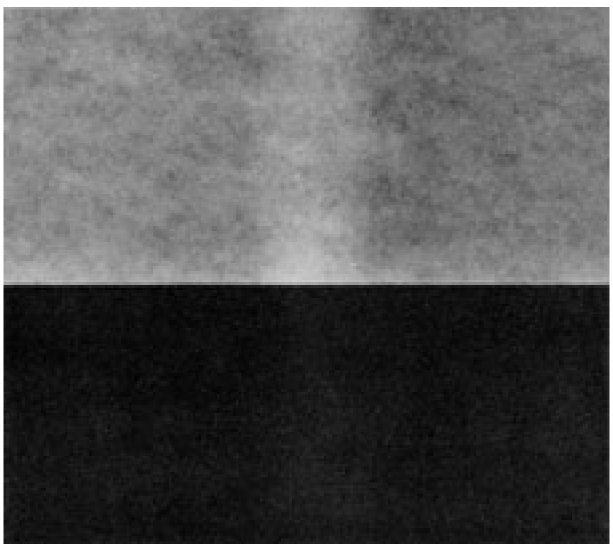
Lead foil in direct contact with the film has three principal effects: (1) It increases the photographic action on the film, largely by reason of the electrons emitted and partly by the secondary radiation generated in the lead. (2) It absorbs the longer wavelength scattered radiation more than the primary. (3) It intensifies the primary radiation more than the scattered radiation. The differential absorption of the secondary radiation and the differential intensification of the primary radiation result in diminishing the effect of scattered radiation, thereby producing greater contrast and clarity in the radiographic image. This reduction in the effect of the scattered radiation decreases the total intensity of the radiation reaching the film, thereby lessening the net intensification factor of the screens. The absorption of primary radiation by the front lead screen also diminishes the net intensifying effect, and, if the incident radiation does not have sufficient penetrating power, the actual exposure required may be even greater than without screens. At best, the exposure time is one half to one third of that without screens, but the advantage of screens in reducing scattered radiation still holds.

Figure 25: Effects of kilovoltage on intensification properties of lead screens.



The quality of the radiation necessary to obtain an appreciable intensification from lead foil screens depends on the type of film, the kilovoltage, and the thickness of the material through which the rays must pass. (See Figure 25) In the radiography of aluminum, for example, using a 0.005-inch front screen and a 0.010-inch back screen, the thickness of aluminum must be about 6 inches and the kilovoltage as high as 160 kV to secure any advantage in exposure time with lead screens. In the radiography of steel, lead screens begin to give appreciable intensification with thicknesses in the neighborhood of 1/4 inch, at voltages of 130 to 150 kV. In the radiography of 11/4 inches of steel at about 200 kV, lead screens permit an exposure of about one third of that without screens (intensification factor of 3). With cobalt 60 gamma rays, the intensification factor of lead screens is about 2. Lead foil screens, however, do not detrimentally affect the definition or graininess of the radiographic image to any material degree so long as the lead and the film are in intimate contact.

Figure 26: Upper area shows decreased density caused by paper between the lead screen and film. An electron shadow picture of the paper structure has also been introduced.



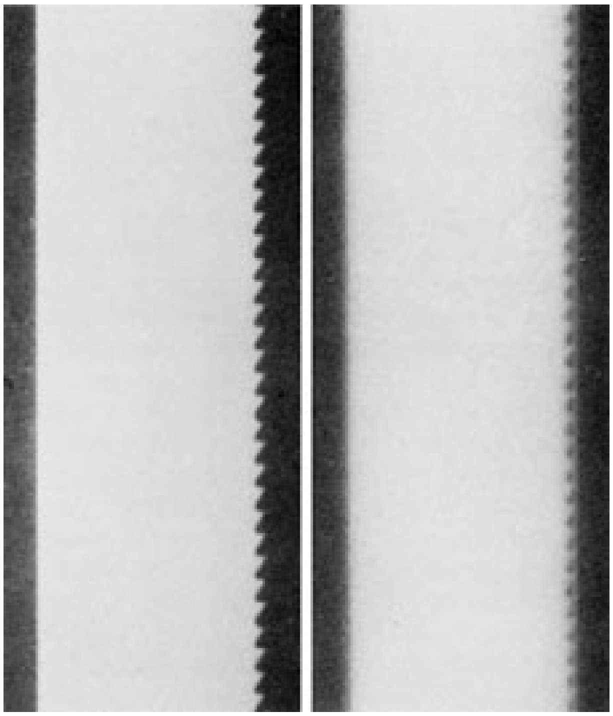
Lead foil screens diminish the effect of scattered radiation, particularly that which undercuts the object (See "Scattered Radiation"), when the primary rays strike the portions of the film holder or cassette outside the area covered by the object.

Scattered radiation from the specimen itself is cut almost in half by lead screens, contributing to maximum clarity of detail in the radiograph; this advantage is obtained even under conditions where the lead screen makes necessary an increase in exposure. A more exhaustive discussion of scattered radiation will be found in "Scattered Radiation".

In radiography with gamma rays or high-voltage x-rays, films loaded in metal cassettes without screens are likely to record the effect of secondary electrons generated in the lead-covered back of the cassette. These electrons, passing through the felt pad on the cassette cover, produce a mottled appearance because of the structure of the felt. Films loaded in the customary lead-backed cardboard exposure holder may also show a pattern of the structure of the paper that lies between the lead and the film (See Figure 26.). To avoid these effects, film should be enclosed between double lead screens, care being taken to ensure good contact between film and screens. Thus, lead foil screens are essential in practically all radiography with gamma rays or million-volt x-rays. If, for any reason, screens cannot be used with these radiations, use a lightproof paper or cardboard holder *with no metal backing*.

Contact between the film and the lead foil screens is essential to good radiographic quality. Areas in which contact is lacking produce "fuzzy" images, as shown in (See Figure 27).

Figure 27: Good contact between film and lead foil screens gives a sharp image (left). Poor contact results in a fuzzy image (right).



Selection and Care of Lead Screens
Lead foil for screens must be selected with extreme care. Commercially pure lead is satisfactory. An alloy of 6 percent antimony and 94 percent lead, being harder and stiffer, has better resistance to wear and abrasion. Avoid tin-coated lead foil, since irregularities in the tin cause a variation in the intensifying factor of the screens, resulting in mottled radiographs. Minor blemishes do not affect the usefulness of the screen, but large "blisters" or cavities should be avoided.

Most of the intensifying action of a lead foil screen is caused by the electrons emitted under x-ray or gamma-ray excitation. Because electrons are readily absorbed even in thin or light materials, the surface must be kept free of grease and lint which will produce light marks on the radiograph. Small flakes of foreign material--for example, dandruff or tobacco--will likewise produce light spots on the completed radiograph. For this same reason, protective coatings on lead foil screens are not common. Any protective coating should be thin, to minimize the absorption of electrons and keep the intensification factors as high as possible, and uniform so that the intensification factor will be uniform. (In addition, the coating should not produce static electricity when rubbed against or placed in contact with film--See Figure 28.)

Figure 28: Static marks resulting from poor film-handling techniques. Static marks may also be treelike or branching.

Deep scratches on lead foil screens, on the other hand, will result in dark lines (See Figures 29 and 30).

You can remove grease and lint from the surface of lead foil screens with a mild household detergent or cleanser and a soft, lint-free cloth. If the cleanser is one that dries to a powder, carefully remove all the powder to prevent its getting into the cassette or exposure holder. The screens must be completely dry before use; otherwise, the film will stick to them. If more thorough cleaning is necessary, very gently rub the screens with the finest grade of steel wool. If this is done carefully, the shallow scratches left by steel wool will not produce dark lines in the radiograph.

Films may be fogged if left between lead foil screens longer than is reasonably necessary, particularly under conditions of high temperature and humidity. When screens have been freshly cleaned with an abrasive; this effect will be increased; hence, delay prolonged contact between film and screens for 24 hours after cleaning.

Figure 29: The number of electrons emitted per unit surface of the lead is essentially uniform. Therefore, more electrons can reach the film in the vicinity of a scratch, resulting in a dark line on the radiograph. (For illustrative clarity, electron paths have been shown as straight and parallel; actually, the electrons are emitted diffusely.)

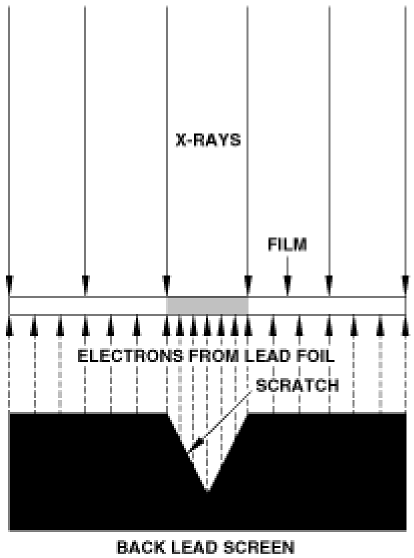
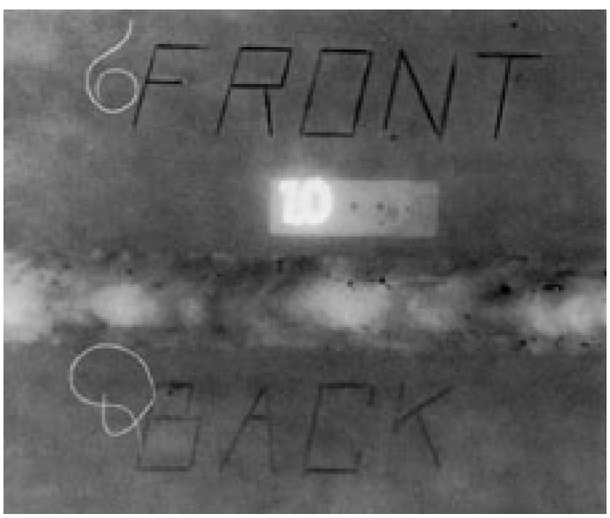


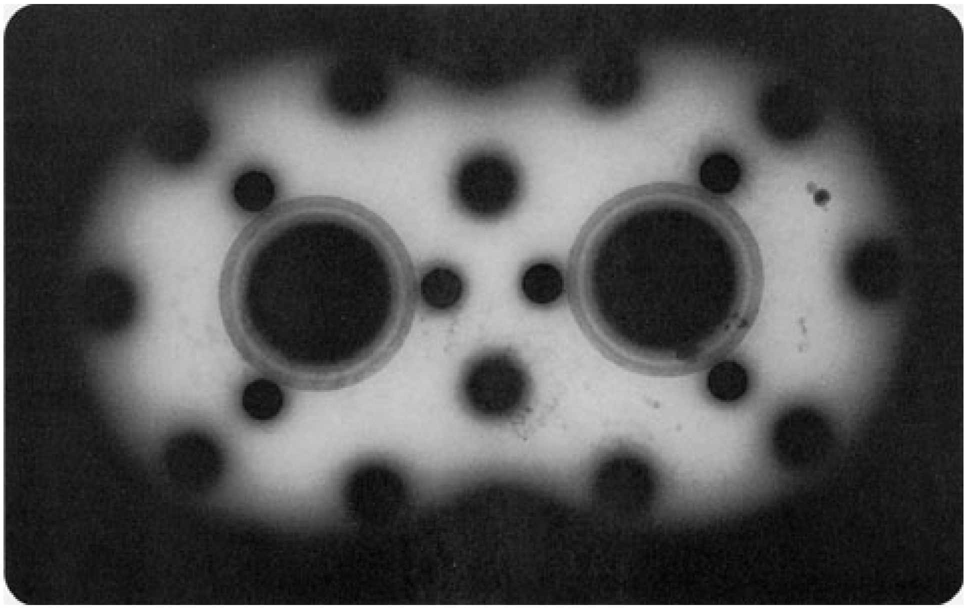
Figure 30: The words "Front" and "Back" were scratched in the surface of front and back lead foil screens before radiographing a 1-inch welded steel plate. Hairs placed between the respective screens and the film show as light marks preceding the scribed words.



Indications for Use of Lead Foil Screens
Lead foil screens have a wide range of usefulness. They permit a reduction in exposure time with thicknesses of metal greater than about ¼ inch of steel and kilovoltages in excess of about 130. Their use is recommended in all cases where they exhibit this intensifying action. However, they may be employed in some cases where they do not permit a reduction, but even necessitate an increase in the exposure time. The chief criterion should be the quality of the radiograph. Lead screens should be used whenever they improve radiographic quality (See Figure 31).

The number of electrons emitted per unit surface of the lead is essentially uniform. Therefore, more electrons can reach the film in the vicinity of a scratch, resulting in a dark line on the radiography. (For illustrative clarity, electron paths have been shown as straight and parallel; actually, the electrons are emitted diffusely.)

Figure 31: Lead foil screens remove scatter and increase radiographic contrast. Specimen is 1/4-inch steel radiographed at 120 kV. Above: Without screens. Below: With lead foil screens. Although in this case lead foil screens necessitate some increase in exposure, they greatly improve radiographic quality.



Lead Oxide Screens

Films packaged with lead screens in the form of lead-oxide-coated paper, factory sealed in light tight envelopes, have a number of advantages. One of these is convenience--the time-consuming task of loading cassettes and exposure holders is avoided, as are many of the artifacts that can arise from the careless handling of film.

Another advantage is cleanliness. This is particularly important in the radiography of those specimens in which heavy inclusions are serious. Light materials--hair, dandruff, tobacco ash--between the lead screen and the film will produce low-density indications on the radiograph. These can easily be confused with heavy inclusions in the specimen. The factory-sealed combination of film and lead oxide screens, manufactured under the conditions of extreme cleanliness necessary for all photographic materials, avoids all difficulties on this score and obviates much of the re-radiography that formerly was necessary. A further advantage is the flexibility of the packets, which makes them particularly valuable when film must be inserted into confined spaces.

Such packets may be used in the kilovoltage range of 100 to 300 kV. In many cases, the integral lead oxide screens will be found to have a somewhat higher intensification factor than conventional lead foil screens. They will, however, remove less scattered radiation because of the smaller effective thickness of lead in the lead oxide screen.

Scatter removal and backscatter protection equivalent to that provided by conventional lead foil screens can be provided by using conventional lead foil screens *external* to the envelope. Such screens can be protected on *both* surfaces with cardboard or plastic, and thus can be made immune to most of the accidents associated with handling. With this technique, the full function of lead foil screens ran be retained while gaining the advantages of cleanliness, convenience, and screen contact.

Indications for Use of Lead Oxide Screens
Films packaged in this manner may be used in the kilovoltage range from 100 to 300 kV, particularly in those circumstances in which cleanliness is important and where good film-screen contact would otherwise be difficult to obtain.

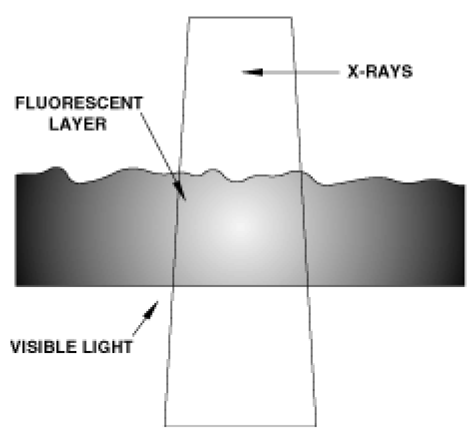
Fluorescent Screens

Certain chemicals fluoresce, that is, have the ability to absorb x-rays and gamma rays and immediately emit light. The intensity of the light emitted depends on the intensity of the incident radiation. The phosphors are finely powdered, mixed with a suitable binder, and coated in a thin, smooth layer on a special cardboard or plastic support.

For the exposure, the film is clamped firmly between a pair of these screens. The photographic effect on the film, then, is the sum of the effects of the x-rays and of the light emitted by the screens. A few examples will serve to illustrate the importance of intensifying screens in reducing exposure time. In medical radiography, the exposure is from 1/10 to 1/60 as much with fluorescent intensifying screens as without them. In other words, the *intensification factor* varies from 10 to 60, depending on the kilovoltage and the type of screen used. In the radiography of 1/2-inch steel at 150 kV, a factor as high as 125 has been observed, and in the radiography of 3/4-inch steel at 180 kV factors of several hundred have been obtained experimentally. Under these latter conditions, the intensification factor has about reached its maximum, and it diminishes both for lower voltage and thinner steel and for higher voltage and thicker steel. Using cobalt 60 gamma rays for very thick steel, the factor may be 10 or less.

Limitations
Despite their great effect in reducing exposure time, fluorescent screens are used in industrial radiography only under special circumstances. This is in part because they give poor definition in the radiograph, compared to a radiograph made directly or with lead screens. The poorer definition results from the spreading of the light emitted from the screens, as shown in Figure 32. The light from any particular portion of the screen spreads out beyond the confines of the x-ray beam that excited the fluorescence. This spreading of light from the screens accounts for the blurring of outlines in the radiograph.

Figure 32: Diagram showing how the light and ultraviolet radiation from a typical fluorescent screen spreads beyond the x-ray beam that excites the fluorescence.



The other reason fluorescent screens are used relatively little in industrial radiography is because they produce *screen mottle* on the finished radiograph. This mottle is characteristic in appearance, very much larger in scale and much "softer" in outline than the graininess associated with the film itself. It is not associated with the actual structure of the screen, that is, it is not a result of the size of the fluorescent crystals themselves or of any unevenness in their dispersion in the binder.

Rather, screen mottle is associated with purely statistical variations in the numbers of absorbed x-ray photons from one tiny area of the screen to the next. The fewer the number of x-ray photons involved, the stronger the appearance of the screen mottle. This explains, for example, why the screen mottle produced by a particular type of screen tends to become greater as the kilovoltage of the radiation increases. The higher the kilovoltage, the more energetic, on the average, are the x-ray photons. Therefore, on absorption in the screen, a larger "burst" of light is produced. The larger the bursts, the fewer that are needed to produce a given density and the greater are the purely statistical variations in the number of photons from one small area to the next. (See "Signal-To-Noise Ratio".)

Intensifying screens may be needed in the radiography of steel thicknesses greater than about 2 inches at 250 kV, 3 inches at 400 kV, and 5 inches at 1,000 kV.

Fluorescent screens are not employed with gamma rays as a rule since, apart from the screen mottle, failure of the reciprocity law (see "The Reciprocity Law" and "Reciprocity Law Failure") results in relatively low intensification factors with the longer exposure times usually necessary in gamma-ray radiography. In the radiography of light metals, fluorescent screens are rarely necessary; but, should they be required, the best choice would be fluorescent screens of the slowest type compatible with an economical exposure time--if possible, those designed specifically for sharpness definition in medical radiography.

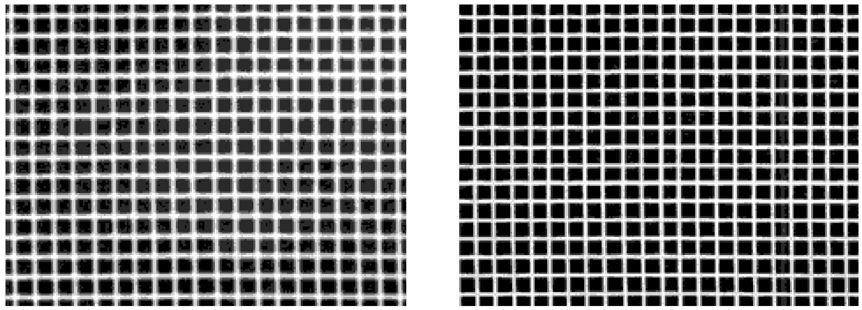
At kilovoltages higher than those necessary to radiograph about 1/2 inch of steel, the fastest available screens are usually employed, since the major use of fluorescent intensifying screens is to minimize the exposure time.

There are few radiographic situations in which a speed higher than that of the fastest film designed for direct exposure with lead screens is required but which do not demand the maximum in speed given by fluorescent intensifying screens used with a film intended for that application. In such cases a high-speed, direct-exposure film may be used with fluorescent screens. The speed of this combination will be intermediate between those of the two first-mentioned combinations. However, the contrast and the maximum density will be higher than that obtained with a film designed for fluorescent-screen exposure, and the screen mottle will be less because of the lower speed of the screen-film combination.

Mounting of Fluorescent Screens

Intensifying screens are usually mounted in pairs in a rigid holder, called a cassette, so that the fluorescent surface of each screen is in direct contact with one of the emulsion surfaces of the film. Intimate contact of the screens and the film over their entire area is essential, because poor contact allows the fluorescent light to spread and produce a blurred image as shown in Figure 33, left.

Figure 33: The sharpness of the radiographic image depends on the contact between the intensifying screens and the film. In the radiographs of a wire mesh test object, the one (left) shows the fuzzy image produced by poor film-screen contact; the other (right), made with good contact, resulted in a sharp image.



As a rule, the mounting of screens is done by the x-ray dealer, who is equipped to provide this service in accordance with the manufacturer's recommendations. If the screens are mounted by the purchaser, care must be exercised to avoid physical unevenness that would result from any thick or uneven binding material. The adhesive must not cause discoloration of the screens--even a small degree of discoloration will reduce their effective speed--nor can the adhesive be such as to cause fogging of the film.

Care of Screens
Fluorescent light from intensifying screens obeys all the laws of light and cannot pass through opaque bodies as do x-rays. To prevent extraneous shadows caused by absorption of the fluorescent light by foreign matter during exposure, dust and dirt particles must not be allowed to collect between the film and screen surfaces, and stains on the screens must be avoided. Cleanliness of the order desirable for handling film and screens is sometimes difficult to maintain, but much can be done by stressing its need and eliminating carelessness.

Whenever it can he avoided, fluorescent intensifying screens should not be exposed to the full intensity of the primary beam when making a radiograph. In extreme cases, in which very high intensity primary x-radiation falls directly on the screen-film combination, the screens may become discolored or an afterglow, which will show up on subsequent radiographs, may be produced. If the specimen more than covers the screen area or if proper marking is provided, there is no difficulty from this source.

As a matter of routine, all cassettes should he tested periodically to check the contact between the screens and the film. This can be done easily by mounting a piece of wire screening (any size mesh from 1/16 inch to 1/4 inch is satisfactory) so that it lies fairly flat. The cassette is then loaded with a film, the wire screening is placed on the exposure side of the cassette, and a flash exposure is made. If there are areas of poor contact, the result will be as shown in the figure above, left. If there is proper contact, the shadow of the wire mesh will be sharply outlined (See Figure 33, right).

Close-up viewing of wire-mesh contact tests can be a very fatiguing visual task. A better and more comfortable way is for the observer to stand about 15 feet from the illuminator and look for the dark areas of the pattern, which are indicative of poor contact. Viewing is even easier and the dark areas show up more definitely if the radiograph is viewed at an angle of about 45 degrees, or if a thin sheet of light-diffusing material is put over the radiograph. Wearers of glasses often find it advantageous to remove them while viewing tests.

Fluorescent intensifying screens may be stored in the processing room but must be kept away from chemicals and other sources of contamination. The sensitive surfaces should not be touched, because the images of finger marks and dust particles may show in the radiograph and interfere with accurate interpretation. Fluorescent screens usually have a transparent protective coating. This coating reduces the abrasion of the active surfaces and facilitates the removal of dirt and smudges from the screens. Every effort should be made to avoid soiling fluorescent screens. Should they become dirty, they must be carefully cleaned according to the manufacturer's recommendations. Do not use common cleaning and bleaching agents because their chemical composition may cause damage to the screens or fog the sensitive film emulsion.

The use of thin cellulose sheets for protecting the active surface of intensifying screens is particularly objectionable, because any separation between screen and film has an adverse effect on definition in the radiograph. Furthermore, under dry atmospheric conditions, merely opening the cassette is liable to produce static electrical discharges between the sheets and the film. The result will be circular or tree-like black marks in the radiograph.

Indications for Use of Fluorescent Screens
Using fluorescent intensifying screens reduces exposure time greatly. As a corollary to this, it is easier to take radiographs of relatively thick specimens with x-ray machines of moderate power. For instance, using fluorescent intensifying screens, 3 inches of steel may be radiographed at 250 kV with a reasonable exposure time.

Fluorescent intensifying screens give rise to the phenomenon of screen mottle, and give poorer definition in the radiograph compared to a radiograph made directly or with lead screens. Thus, as a general rule, use fluorescent screens only when the exposure necessary without them would be prohibitive.

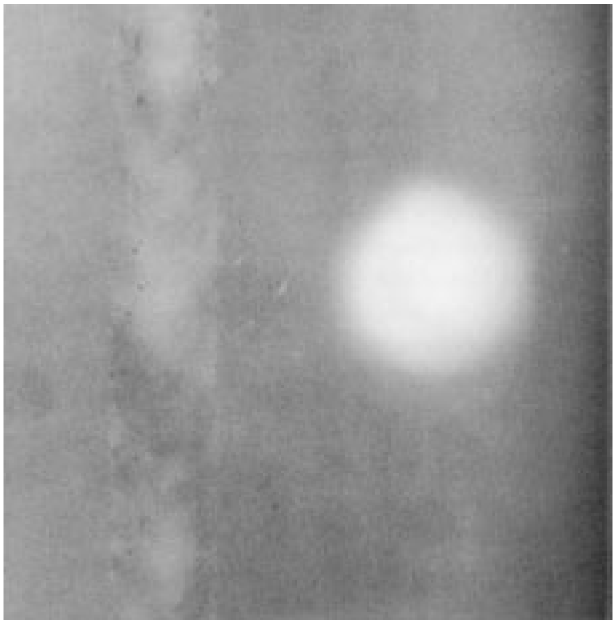
Cassettes And Film Holders

When intensifying or lead foil screens are used, good, uniform contact between screens and film is of prime importance. The use of vacuum cassettes is the most certain way of obtaining such intimate contact. Rigid, spring-back cassettes are also satisfactory, provided they are tested for satisfactory screen contact at reasonable intervals.

Cardboard or thin plastic exposure holders are less expensive, easier to handle in large numbers, and are flexible compared to rigid cassettes. However, if screens are to be used in them, special precautions must be taken to assure good contact. The exact means used will depend on the object radiographed. Exposure holders may be pressed or clamped against the specimen, or the weight of the specimen or the flexing of the holder as it is bent to fit some structure may provide adequate contact.

Two points should be noted, however. First, these methods do not guarantee *uniform* contact, and hence the definition of the image may vary from area to area of the film. This variation of definition may not be obvious and may cause errors in the interpretation of the radiograph. Second, such holders do not always adequately protect the film and screens from mechanical damage. A projection on the film side of the specimen may cause relatively great pressure on a small area of the film. Projections on the specimen may also give rise to pressure artifacts on the radiograph when paper wrapped films are used. This may produce a light or dark pressure mark in the finished radiograph (See Figure 34) which may be mistaken for a flaw in the specimen.

Figure 34: Low density (right) is a pressure mark, caused by a heavy object dropped on the film holder before exposure.



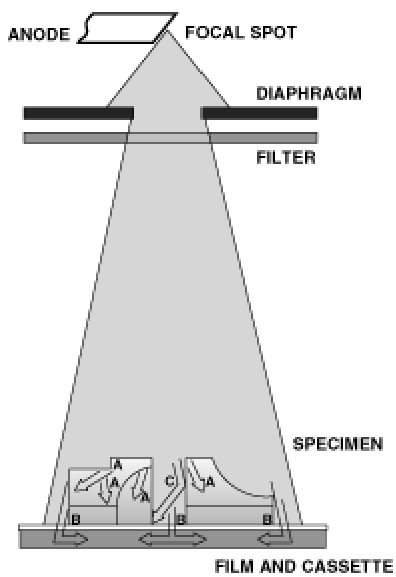
Chapter 6: Scattered Radiation

When a beam of x-rays or gamma rays strikes any object, some of the radiation is absorbed, some is scattered, and some passes straight through. The electrons of the atoms constituting the object scatter radiation in all directions, much as light is dispersed by a fog. The wavelengths of much of the radiation are increased by the scattering process, and hence the scatter is always somewhat "softer," or less penetrating, than the unscattered primary radiation. Any material--whether specimen, cassette, tabletop, walls, or floor--that receives the direct radiation is a source of scattered radiation. Unless suitable measures are taken to reduce the effects of scatter, it will reduce contrast over the whole image or parts of it.

Scattering of radiation occurs, and is a problem, in radiography with both x-rays and gamma rays. In the material that follows, the discussion is in terms of x-rays, but the same general principles apply to gamma radiography.

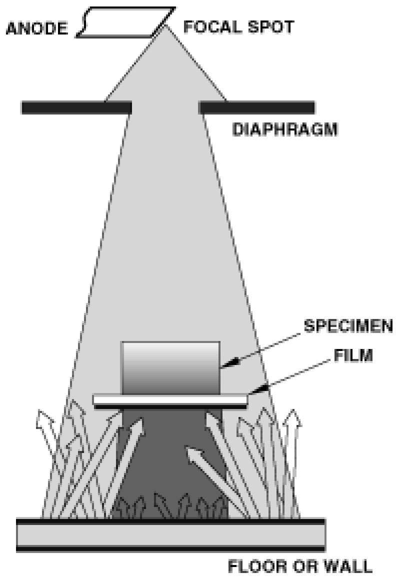
In the radiography of thick materials, scattered radiation forms the greater percentage of the total radiation. For example, in the radiography of a 3/4-inch thickness of steel, the scattered radiation from the specimen is almost twice as intense as the primary radiation; in the radiography of a 2-inch thickness of aluminum, the scattered radiation is two and a half times as great as the primary radiation. As may be expected, preventing scatter from reaching the film markedly improves the quality of the radiographic image.

Figure 35: Sources of scattered radiation. A: Transmitted scatter. B: Scatter from cassette. C: "Reflection" scatter.



As a rule, the greater portion of the scattered radiation affecting the film is from the specimen under examination (A in Figure 35). However, any portion of the film holder or cassette that extends beyond the boundaries of the specimen and thereby receives direct radiation from the x-ray tube also becomes a source of scattered radiation, which can affect the film. The influence of this scatter is most noticeable just inside the borders of the image (B in Figure 35). In a similar manner, primary radiation striking the film holder or cassette through a thin portion of the specimen will cause scattering into the shadows of the adjacent thicker portions. Such scatter is called undercut. Another source of scatter that may undercut a specimen is shown as C in the figure above. If a filter is used near the tube, this too will scatter x-rays. However, because of the distance from the film, scattering from this source is of negligible importance. Any other material, such as a wall or floor, on the film side of the specimen may also scatter an appreciable quantity of x-rays back to the film, especially if the material receives the direct radiation from the x-ray tube or gamma-ray source (See Figure 36). This is referred to as backscattered radiation.

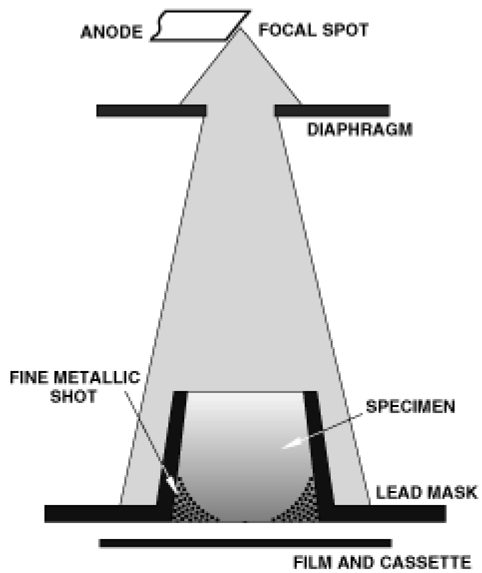
Figure 36: Intense backscattered radiation may originate in the floor or wall. Coning, masking, or diaphragming should be employed. Backing the cassette with lead may give adequate protection.



Reduction Of Scatter

Although scattered radiation can never be completely eliminated, a number of means are available to reduce its effect. The various methods are discussed in terms of x-rays. Although most of the same principles apply to gamma-ray radiography, differences in application arise because of the highly penetrating radiation emitted by most common industrial gamma-ray sources. For example, a mask (See Figure 37) for use with 200 kV x-rays could easily be light enough for convenient handling. A mask for use with cobalt 60 radiation, on the other hand, would be thick, heavy, and probably cumbersome. In any event, with either x-rays or gamma rays, the means for reducing the effects of scattered radiation must be chosen on the basis of cost, convenience, and effectiveness.

Figure 37: The combined use of metallic shot and a lead mask for lessening scattered radiation is conducive to good radiographic quality. If several round bars are to be radiographed, they may be separated with lead strips held on edge on a wooden frame and the voids filled with fine shot.



Lead Foil Screens

Lead screens, mounted in contact with the film, diminish the effect on the film of scattered radiation from all sources. They are beyond doubt the least expensive, most convenient, and most universally applicable means of combating the effects of scattered radiation. Lead screens lessen the scatter reaching the films regardless of whether the screens permit a decrease or necessitate an increase in the radiographic exposure. The nature of the action of lead screens is discussed more fully in "Radiographic Screens".

Many x-ray exposure holders incorporate a sheet of lead foil in the back for the specific purpose of protecting the film from backscatter. This lead will not serve as an intensifying screen, first, because it usually has a paper facing, and second because it often is not lead of "radiographic quality". If intensifying screens are used with such holders, *definite means must be provided to insure good contact.*

X-ray film cassettes also are usually fitted with a sheet of lead foil in the back for protection against backscatter. Using such a cassette or film holder with gamma rays or with million-volt x-rays, the film should always be enclosed between double lead screens; otherwise, the secondary radiation from the lead backing is sufficient to penetrate the intervening felt or paper and cast a shadow of the structure of this material on the film, giving a granular or mottled appearance. This effect can also occur at voltages as low as 200 kV unless the film is enclosed between lead foil or fluorescent intensifying screens. (See Figure 26.)

Masks and Diaphragms

Scattered radiation originating in matter outside the specimen is most serious for specimens that have high absorption for x-rays, because the scattering from external sources may be large compared to the primary image-forming radiation that reaches the film through the specimen. Often, the most satisfactory method of lessening this scatter is to use cutout diaphragms or some other form of mask mounted over or around the object radiographed. If many specimens of the same article are to be radiographed, it may be worthwhile to cut an opening of the same shape, but slightly smaller, in a sheet of lead and place this on the object. The lead serves to reduce the exposure in surrounding areas to a negligible value and therefore to eliminate scattered radiation from this source. Since scatter also arises from the specimen itself, it is good practice wherever possible, to limit the cross an x-ray beam to cover only the area of the specimen that is of interest in the examination.

For occasional pieces of work where a cutout diaphragm would not be economical, barium clay packed around the specimen will serve the same purpose. The clay should be thick enough so that the film density under the clay is somewhat less than that under the specimen. Otherwise, the clay itself contributes appreciable scattered radiation.

It may be advantageous to place the object in aluminum or thin iron pans and to use a liquid absorber, provided the liquid chosen will not damage the specimen. A combined saturated solution of lead acetate and lead nitrate is satisfactory.

WARNING! Harmful if swallowed. Harmful if inhaled. Wash thoroughly after handling. Use only with adequate ventilation.

To prepare this solution, dissolve approximately 31/2 pounds of lead acetate in 1 gallon of hot water. When the lead acetate is in solution, add approximately 3 pounds of lead nitrate.

Because of its high lead content this solution is a strong absorber of x-rays. In masking with liquids, be sure to eliminate bubbles that may be clinging to the surface of the specimen.

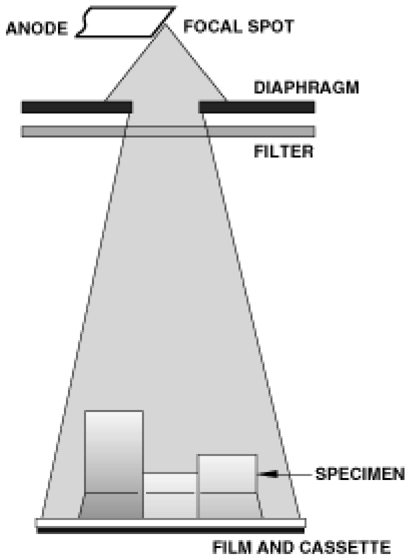
One of the most satisfactory arrangements, combining effectiveness and convenience, is to surround the object with copper or steel shot having a diameter of about 0.01 inch or less (See Figure 37). This material "flows" without running badly. It is also very effective for filling cavities in irregular objects, such as castings, where a normal exposure for thick parts would result in an overexposure for thinner parts. Of course, it is preferable to make separate exposures for thick and thin parts, but this is not always practical.

In some cases, a lead diaphragm or lead cone on the tube head may be a convenient way to limit the area covered by the x-ray beam. Such lead diaphragms are particularly useful where the desired cross section of the beam is a simple geometric figure, such as a circle, square, or rectangle.

Filters
In general, the use of filters is limited to radiography with x-rays. A simple metallic filter mounted in the x-ray beam near the x-ray tube (See Figure 38) may adequately serve the purpose of eliminating overexposure in the thin regions of the specimen and in the area surrounding the part. Such a filter is particularly useful to reduce scatter undercut in cases where a mask around the specimen is impractical, or where the specimen would be injured by chemicals or shot. Of course, an increase in exposure or kilovoltage will be required to compensate for the additional absorption; but, in cases where the filter method is applicable, this is not serious unless the limit of the x-ray machine has been reached.

The underlying principle of the method is that the addition of the filter material causes a much greater change in the amount of radiation passing through the thin parts than through the thicker parts. Suppose the shape of a certain steel specimen is as shown in Figure 38 and that the thicknesses are 1/4 inch, 1/2 inch, and 1 inch. This specimen is radiographed first with no filter, and then with a filter near the tube.

Figure 38: A filter placed near the x-ray tube reduces subject contrast and eliminates much of the secondary radiation, which tends to obscure detail in the periphery of the specimen.



Column 3 of the table below shows the percentage of the original x-ray intensity remaining after the addition of the filter, assuming both exposures were made at 180 kV. (These values were derived from actual exposure chart data.)

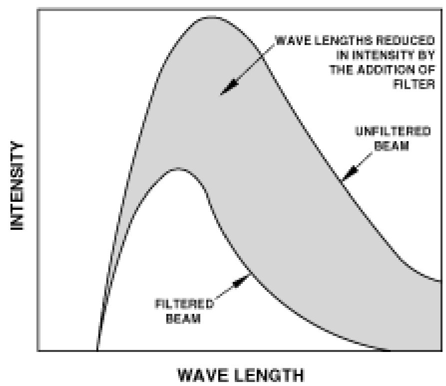
Region	**Specimen Thickness (inches)**	**Percentage of Original X-ray Intensity Remaining After Addition of a Filter**
Outside specimen	0	less than 5%
Thin section	$^1/_4$	about 30%
Medium section	$^1/_2$	about 40%
Thick section	1	about 50%

Note that the greatest *percentage change* in x-ray intensity is under the thinner parts of the specimen and in the film area immediately surrounding it. The filter reduces by a large ratio the x-ray intensity passing through the thin sections or sticking the cassette around the specimen, and hence reduces the undercut of scatter from these sources. Thus, *in regions of strong undercut*, the contrast is *increased* by the use of a filter since the only effect of the undercutting scattered radiation is to obscure the desired image. In regions where the undercut is negligible, a filter has the effect of *decreasing* the contrast in the finished radiograph.

Although frequently the highest possible contrast is desired, there are certain instances in which too much contrast is a definite disadvantage For example, it may be desired to render detail visible in all parts of a specimen having wide variations of thickness. If the exposure is made to give a usable density under the thin part, the thick region may be underexposed. If the exposure is adjusted to give a suitable density under the thick parts, the image of the thin sections may be grossly overexposed.

A filter reduces excessive subject contrast (and hence radiographic contrast) by hardening the radiation. The longer wavelengths do not penetrate the filter to as great an extent as do the shorter wavelengths. Therefore, the beam emerging from the filter contains a higher proportion of the more penetrating wavelengths. Figure 39 illustrates this graphically. In the sense that a more penetrating beam is produced, filtering is analogous to increasing the kilovoltage. However, it requires a comparatively large change in kilovoltage to change the hardness of an x-ray beam to the same extent as will result from adding a small amount of filtration.

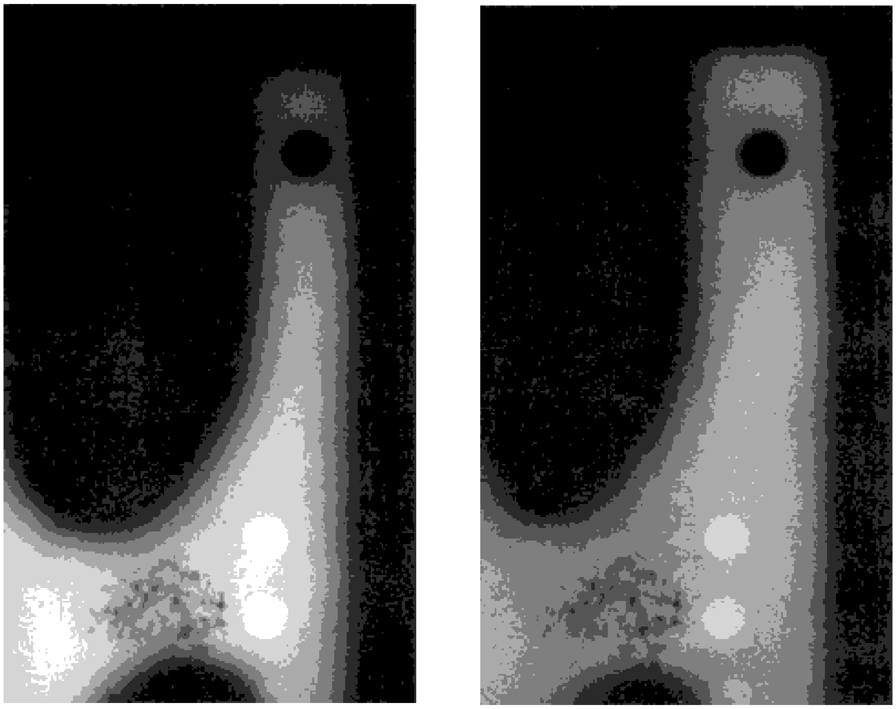
Figure 39: Curves illustrating the effect of a filter on the composition and intensity of an x-ray beam.



Although filtering reduces the total quantity of radiation, most of the wavelengths removed are those that would not penetrate the thicker portions of the specimen in any case. The radiation removed would only result in a high intensity in the regions around the specimen and under its thinner sections, with the attendant scattering undercut and overexposure. The harder radiation obtained by filtering the x-ray beam produces a radiograph of lower contrast, thus permitting a wider range of specimen thicknesses to be recorded on a single film than would otherwise be possible.

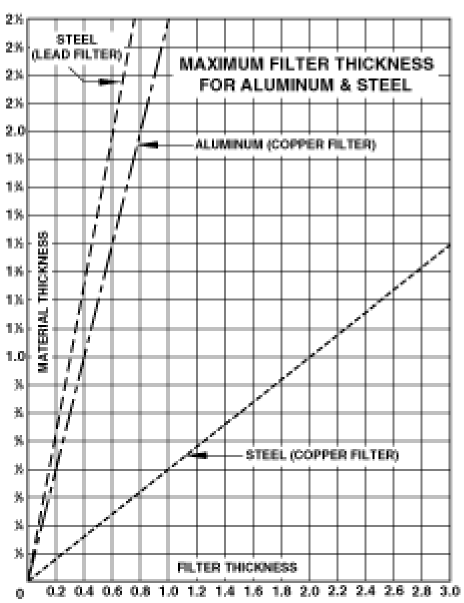
Thus, a filter can act either to increase or to decrease the net contrast. The contrast and penetrameter visibility (See "Film Graininess, Screen Mottle") are *increased* by the removal of the scatter that undercuts the specimen (See Figure 40) and *decreased* by the hardening of the original beam. The nature of the individual specimen will determine which of these effects will predominate or whether both will occur in different parts of the same specimen.

Figure 40: Sections of a radiograph of an unmasked 11/8-inch casting, made at 200 kV without filtration (left), and as improved by filtration at the tube (right).



The choice of a filter material should be made on the basis of availability and ease of handling. For the same filtering effect, the thickness of filter required is less for those materials having higher absorption. In many cases, copper or brass is the most useful, since filters of these materials will be thin enough to handle easily, yet not so thin as to be delicate. (See Figure 41)

Figure 41: Maximum filter thickness for aluminum and steel.



Definite rules as to filter thicknesses are difficult to formulate exactly because the amount of filtration required depends not only on the material and thickness range of the specimen, but also on the distribution of material in the specimen and on the amount of scatter undercut that it is desired to eliminate. In the radiography of aluminum, a filter of copper about 4 percent of the greatest thickness of the specimen should prove the thickest necessary. With steel, a copper filter should ordinarily be about 20 percent, or a lead filter about 3 percent, of the greatest specimen thickness for the greatest useful filtration. The foregoing values are maximum values, and, depending on circumstances, useful radiographs can often be made with far less filtration.

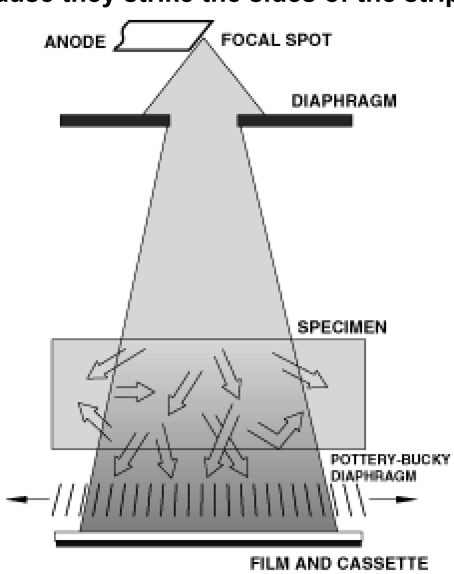
In radiography with x-rays up to at least 250 kV, the 0.005-inch front lead screen customarily used is an effective filter for the scatter from the bulk of the specimen. Additional filtration between specimen and film only tends to contribute additional scatter from the filter itself. The scatter undercut can be decreased by adding an appropriate filter at the tube as mentioned before (See also Figures 40). Although the filter near the tube gives rise to scattered radiation, the scatter is emitted in all directions, and since the film is far from the filter, scatter reaching the film is of very low intensity.

Further advantages of placing the filter near the x-ray tube are that specimen-film distance is kept to a minimum and that scratches and dents in the filter are so blurred that their images are not apparent on the radiograph.

Grid Diaphragms

One of the most effective ways to reduce scattered radiation from an object being radiographed is through the use of a Potter-Bucky diaphragm. This apparatus (See Figure 42) consists of a moving grid, composed of a series of lead strips held in position by intervening strips of a material transparent to x-rays. The lead strips are tilted, so that the plane of each is in line with the focal spot of the tube. The slots between the lead strips are several times as deep as they are wide. The parallel lead strips absorb the very divergent scattered rays from the object being radiographed, so that most of the exposure is made by the primary rays emanating from the focal spot of the tube and passing between the lead strips. During the course of the exposure, the grid is moved, or oscillated, in a plane parallel to the film as shown by the black arrows in Figure 42. Thus, the shadows of the lead strips are blurred out so that they do not appear in the final radiograph.

Figure 42: Schematic diagram showing how the primary x-rays pass between the lead strips of the Potter-Bucky diaphragm while most of the scattered x-rays are absorbed because they strike the sides of the strips.



The use of the Potter-Bucky diaphragm in industrial radiography complicates the technique to some extent and necessarily limits the flexibility of the arrangement of the x-ray tube, the specimen, and the film. Grids can, however, be of great value in the radiography of beryllium more than about 3 inches thick and in the examination of other low-absorption materials of moderate and great thicknesses. For these materials, kilovoltages in the medical radiographic range are used, and the medical forms of Potter-Bucky diaphragms are appropriate. Grid ratios (the ratio of height to width of the *openings* between the lead strips) of 12 or more are desirable.

The Potter-Bucky diaphragm is seldom used elsewhere in the industrial field, although special forms have been designed for the radiography of steel with voltages as high as 200 to 400 kV. These diaphragms are not used at higher voltages or with gamma rays because relatively thick lead strips would be needed to absorb the radiation scattered at these energies. This in turn would require a Potter-Bucky diaphragm, and the associated mechanism, of an uneconomical size and complexity.

Mottling Caused By X-Ray Diffraction

A special form of scattering caused by x-ray diffraction (See "X-Ray Diffraction") is encountered occasionally. It is most often observed in the radiography of fairly thin metallic specimens whose grain size is large enough to be an appreciable fraction of the part thickness. The radiographic appearance of this type of scattering is mottled and may be confused with the mottled appearance sometimes produced by porosity or segregation. It can be distinguished from these conditions by making two successive radiographs, with the specimen rotated slightly (1 to 5 degrees) between exposures, about an axis perpendicular to the central beam. A pattern caused by porosity or segregation will change only slightly; however, one caused by diffraction will show a marked change. The radiographs of some specimens will show a mottling from both effects, and careful observation is needed to differentiate between them.

The basic facts of x-ray diffraction are given in "X-Ray Diffraction". Briefly, however, a relatively large crystal or grain in a relatively thin specimen may in some cases "reflect" an appreciable portion of the x-ray energy falling on the specimen, much as if it were a small mirror. This will result in a light spot on the developed radiograph corresponding to the position of the particular crystal and may also produce a dark spot in another location if the diffracted, or "reflected," beam strikes the film. Should this beam strike the film beneath a thick part of the specimen, the dark spot may be mistaken for a void in the thick section. This effect is not observed in most industrial radiography, because most specimens are composed of a multitude of very minute crystals or grains, variously oriented; hence, scatter by diffraction is essentially uniform over the film area. In addition, the directly transmitted beam usually reduces the contrast in the diffraction pattern to a point where it is no longer visible on the radiograph.

The mottling caused by diffraction can be reduced, and in some cases eliminated, by raising the kilovoltage and by using lead foil screens. The former is often of positive value even though the radiographic contrast is reduced. Since definite rules are difficult to formulate, both approaches should be tried in a new situation, or perhaps both used together.

It should be noted, however, that in same instances, the presence or absence of mottling caused by diffraction has been used as a rough indication of grain size and thus as a basis for the acceptance or the rejection of parts.

Scattering In 1- And 2-Million-Volt Radiography

Lead screens should always be used in this voltage range. The common thicknesses, 0.005-inch front and 0.010-inch back, are both satisfactory and convenient. Some users, however, find a

0.010-inch front screen of value because of its greater selective absorption of the scattered radiation from the specimen.

Filtration at the tube offers no improvement in radiographic quality. However, filters at the film improve the radiograph in the examination of uniform sections, but give poor quality at the edges of the image of a specimen because of the undercut of scattered radiation from the filter itself. Hence, filtration should not be used in the radiography of specimens containing narrow bars, for example, no matter what the thickness of the bars in the direction of the primary radiation. Further, filtration should be used only where the film can be adequately protected against backscattered radiation.

Lead filters are most convenient for this voltage range. When thus used between specimen and film, filters are subject to mechanical damage. Care should be taken to reduce this to a minimum, lest filter defects be confused with structures in or on the specimen. In radiography with million-volt x-rays, specimens of uniform sections may be conveniently divided into three classes. Below about 11/2 inches of steel, filtration affords little improvement in radiographic quality. Between 11/2 and 4 inches of steel, the thickest filter, up to 1/8-inch lead, which at the same time allows a reasonable exposure time, may be used. Above 4 inches of steel, filter thicknesses may be increased to1/4 inch of lead, economic considerations permitting. It should be noted that in the radiography of extremely thick specimens with million-volt x-rays, fluorescent screens (See "Fluorescent Screens") may be used to increase the photographic speed to a point where filters can be used without requiring excessive exposure time.

A very important point is to block off all radiation except the useful beam with heavy (1/2-inch to 1-inch) lead at the anode. Unless this is done, radiation striking the walls of the x-ray room will scatter back in such quantity as to seriously affect the quality of the radiograph. This will be especially noticeable if the specimen is thick or has parts projecting relatively far from the film.

Multimillion-Volt Radiography

Techniques of radiography in the 6- to 24-million-volt range are difficult to specify. This is in part because of the wide range of subjects radiographed, from thick steel to several feet of mixtures of solid organic compounds, and in part because the sheer size of the specimens and the difficulty in handling them often impose limitations on the radiographic techniques that can be used.

In general, the speed of the film-screen combination increases with increasing thickness of front and back lead screens up to at least 0.030 inch. One problem encountered with screens of such great thickness is that of screen contact. For example, if a conventional cardboard exposure holder is supported vertically, one or both of the heavy screens may tend to sag away from the film, with a resulting degradation of the image quality. Vacuum cassettes are especially useful in this application and several devices have been constructed for the purpose, some of which incorporate such refinements as automatic preprogrammed positioning of the film behind the various areas of a large specimen.

The electrons liberated in lead by the absorption of multimegavolt x-radiation are very energetic. This means that those arising from fairly deep within a lead screen can penetrate the lead, being scattered as they go, and reach the film. Thus, when thick screens are used, the electrons reaching the film are "diffused," with a resultant deleterious effect on image quality. Therefore, when the highest quality is required in multimillion-volt radiography, a comparatively thin front screen (about 0.005 inch) is used, and the back screen is eliminated. This necessitates a considerable increase in exposure time. Naturally, the applicability of the technique depends also on the amount of backscattered radiation involved and is probably not applicable where large amounts occur.

Chapter 7: Arithmetic of Exposure

Relations Of Milliamperage (Source Strength), Distance, And Time

With a given kilovoltage of x-radiation or with the gamma radiation from a particular isotope, the three factors governing the exposure are the milliamperage (for x-rays) or source strength (for gamma rays), time, and source-film distance. The numerical relations among these three quantities are demonstrated below, using x-rays as an example. The same relations apply for gamma rays, provided the number of curies in the source is substituted wherever milliamperage appears in an equation.

The necessary calculations for any changes in focus-film distance (D), milliamperage (M), or time (T) are matters of simple arithmetic and are illustrated in the following example. As noted earlier, kilovoltage changes cannot be calculated directly but must be obtained from the exposure chart of the equipment or the operator's logbook.

All of the equations shown on these pages can be solved easily for any of the variables (mA, T, D), using one basic rule of mathematics: If one factor is moved across the equals sign (=), it moves from the numerator to the denominator or vice versa.

EXAMPLE: $\frac{A}{B} = \frac{C}{D}$

TO SOLVE FOR B:

① $\frac{A}{B} = \frac{C}{D}$ ② $A = \frac{BC}{D}$ ③ $AD = BC$ ④ $\frac{AD}{C} = B$

○ = **MOVE THIS VALUE NEXT IN THE DIRECTION INDICATED BY THE ARROW**

We can now solve for any unknown by:

1. Eliminating any factor that remains constant (has the same value and is in the same location on both sides of the equation).
2. Simplifying the equation by moving the unknown value so that it is alone on one side of the equation in the numerator.
3. Substituting the known values and solving the equation.

Milliamperage-Distance Relation

The milliamperage employed in any exposure technique should be in conformity with the manufacturer's rating of the x-ray tube. In most laboratories, however, a constant value of milliamperage is usually adopted for convenience.

Rule: *The milliamperage (M) required for a given exposure is directly proportional to the square of the focus-film distance (D).* The equation is expressed as follows:

$$M_1 : M_2 :: D_1^2 : D_2^2 \quad \text{OR} \quad \frac{M_1}{M_2} = \frac{D_1^2}{D_2^2}$$

Example: Suppose that with a given exposure time and kilovoltage, a properly exposed radiograph is obtained with 5mA (M_1) at a distance of 12 inches (D_1), and that it is desired to increase the sharpness of detail in the image by increasing the focus-film distance to 24 inches (D_2). The correct milliamperage (M_2) to obtain the desired radiographic density at the increased distance (D_2) may be computed from the proportion:

$$M_1 : M_2 :: D_1^2 : D_2^2 \quad \text{OR} \quad \frac{M_1}{M_2} = \frac{D_1^2}{D_2^2}$$

When very low kilovoltages, say 20 kV or less, are used, the x-ray intensity decreases with distance more rapidly than calculations based on the inverse square law would indicate because of absorption of the x-rays by the air. Most industrial radiography, however, is done with radiation so penetrating that the air absorption need not be considered. These comments also apply to the time-distance relations discussed below.

Time-Distance Relation
Rule: *The exposure time (T) required for a given exposure is directly proportional to the square of the focus-film distance (D). Thus:*

To solve for either a new Time (T_2) Or a new Distance (D_2), simply follow the steps shown in the example above.

$$T_1 : T_2 :: D_1^2 : D_2^2 \quad \text{OR} \quad \frac{T_1}{T_2} = \frac{D_1^2}{D_2^2}$$

Tabular Solution of Milliamperage-Time and Distance Problems
Problems of the types discussed above may also be solved by the use of a table similar to Table V. The factor between the new and the old exposure time, milliamperage, or milliamperage-minute (mA-min) value appears in the box at the intersection of the column for the new source-film distance and the row for the old source-film distance.

Suppose, for example, a properly exposed radiograph has an exposure of 20 mA-min with a source-film distance of 30 inches and you want to increase the source-film distance to 45 inches in order to decrease the geometric unsharpness in the radiograph. The factor appearing in the box at the intersection of the column for 45 inches (new source-film distance) and the row for 30 inches (old source-film distance) is 2.3. Multiply the old milliampere-minute value (20) by 2.3 to give the new value--46 mA-min.

Note that some approximation is involved in the use of such a table, since the values in the boxes are rounded off to two significant figures. However, the errors involved are always less than 5 percent and, in general, are insignificant in actual practice.

Further, a table like Table V obviously cannot include all source-film distances, because of limitations of space. However, in any one radiographic department, only a few source-film distances are used in the great bulk of the work, and a table of reasonable size can be constructed involving only these few distances.

Milliamperage-Time Relation
Rule: *The milliamperage (M) required for a given exposure is inversely proportional to the time (T):*

Another way of expressing this is to say that for a given set of conditions (voltage, distance, etc), the product of milliamperage and time is constant for the same photographic effect.

$$M_1 : M_2 :: T_2 : T_1 \quad \text{OR} \quad \frac{M_1}{M_2} = \frac{T_2}{T_1}$$

Thus, $M_1T_1 = M_2T_2 = M_3T_3 = C$, a constant.

This is commonly referred to as the reciprocity law. (Important exceptions are discussed below.)

To solve for either a new time (T_2) or a new milliamperage (M_2), simply follow the steps shown in the example in "Milliamperage-Distance Relation".

Table V: Milliamperage-Time and Distance Relations

Old Dist./ New Dist.	**25°**	**30°**	**35°**	**40°**	**45°**	**50°**	**55°**	**60°**	**65°**	**70°**	**75°**	**80°**
25 min.	1.0	1.4	2.0	2.6	3.2	4.0	4.8	5.6	6.8	7.8	9.0	10.0
30 min.	0.70	1.0	1.4	1.8	2.3	2.8	3.4	4.0	4.8	5.4	6.3	7.1
35 min.	0.51	0.74	1.0	1.3	1.6	2.0	2.5	3.0	3.4	4.0	4.	5.2
40 min.	0.39	0.56	0.77	1.0	1.3	1.6	1.9	2.2	2.6	3.1	3.5	4.0
45 min.	0.31	0.45	0.60	0.79	1.0	1.2	1.5	1.8	2.1	2.4	2.8	3.2
50 min.	0.25	0.36	0.49	0.64	0.81	1.0	1.2	1.4	1.7	2.0	2.2	2.6
55 min.	0.21	0.30	0.40	0.53	0.67	0.83	1.0	1.2	1.4	1.6	1.9	2.1
60 min.	0.17	0.25	0.34	0.44	0.56	0.69	0.84	1.0	1.2	1.4	1.6	1.8
65 min.	0.15	0.21	0.29	0.38	0.48	0.59	0.72	0.85	1.0	1.2	1.3	1.5
70 min.	0.13	0.18	0.25	0.33	0.41	0.51	0.62	0.74	0.86	1.0	1.1	1.3
75 min.	0.11	0.16	0.22	0.28	0.36	0.45	0.54	0.64	0.75	0.87	1.0	1.1
80 min.	0.10	0.14	0.19	0.25	0.32	0.39	0.47	0.56	0.66	0.77	0.88	1.0

The Reciprocity Law

In the sections immediately preceding, it has been assumed that exact compensation for a decrease in the time of exposure can be made by increasing the milliamperage according to the relation $M_1T_1 = M_2T_2$. This may be written $MT = C$ and is an example of the general photochemical law that the same effect is produced for IT = constant, where I is intensity of the radiation and T is the time of exposure. It is called the *reciprocity law and is true for direct x-ray and lead screen exposures*. For exposures to light, it is not quite accurate and, since some radiographic exposures are made with the light from fluorescent intensifying screens, the law cannot be strictly applied.

Errors as the result of assuming the validity of the reciprocity law are usually so small that they are not noticeable in examples of the types given in the preceding sections. Departures may be apparent, however, if the intensity is changed by a factor of 4 or more. Since intensity may be changed by changing the source-film distance, failure of the reciprocity law may appear to be a violation of the inverse square law. Applications of the reciprocity law over a wide intensity range sometimes arise, and the relation between results and calculations may be misleading unless the possibility of failure of the reciprocity law is kept in mind. Failure of the reciprocity law means that the *efficiency* of a light-sensitive emulsion in utilizing the light energy depends on the light *intensity*. *Under the usual conditions of industrial radiography, the number of milliampere-minutes required for a properly exposed radiograph made with fluorescent intensifying screens increases as the x-ray intensity decreases, because of reciprocity failure.*

If the milliamperage remains constant and the x-ray intensity is varied by changing the focus-film distance, the compensating changes shown in Table VI should be made in the exposure time.

Table VI gives a rough estimate of the deviations from the rules given in the foregoing section that are necessitated by failure of the reciprocity law for exposures with fluorescent intensifying screens. It must be emphasized that the figures in column 3 are only approximate. The exact values of the factors vary widely with the intensity of the fluorescent light and with the density of the radiograph.

When distance is held constant, the milliamperage may be increased or decreased by a factor of 2, and the new exposure time may be calculated by the method shown in "Time-Distance Relation", without introducing errors caused by failure of the reciprocity law, which are serious in practice.

Logarithms

Since logarithms are used a great deal in the following section, a brief discussion of them is included here. Some handbooks and intermediate algebra texts give a more detailed treatment.

Before discussing logarithms, it is necessary to define the term "power". The power of a number is the product obtained when the number is multiplied by itself a given number of times. Thus, 10 = 10 x 10 = 1000; 5 = 5^2 x 5 = 25. In the first example, 1000 is the third power of 10; in the second, 25 is the second power of 5, or 5 raised to the second power. The superscript figure 2 is known as the *exponent*. Fractional exponents are used to denote roots.

FOR EXAMPLE:

$$n^{\frac{a}{b}} = \sqrt[b]{n^a}\ ;\ 16^{\frac{1}{2}} = \sqrt{16} = 4$$

$$10^{2.50} = 10^{\frac{5}{2}} = \sqrt[2]{10^5} = 316$$

NEGATIVE EXPONENTS INDICATE RECIPROCALS OF POWERS.

THUS:

$$n^{-a} = \frac{1}{n^a}\ ;\ 10^{-2} = \frac{1}{10^2} = \frac{1}{100} = 0.01$$

The *common logarithm* of a number is the exponent of the power to which 10 must be raised to give the number in question. For example, the logarithm of 100 is 2. The logarithm of 316 equals 2.50, or log 316 = 250; the logarithm of 1000 equals 3, or log 1000 = 3. It is also said that 1000 is the antilogarithm of 3 or antilog 3 = 1000.

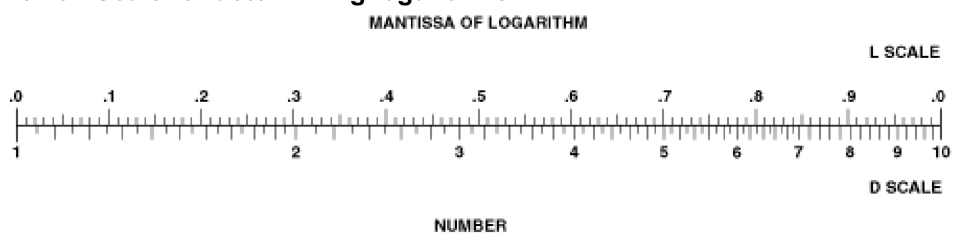
Table VI: Approximate Corrections for Reciprocity Law Failure

Distance Increased by	(Direct and Lead Screen Exposures) Exposure Time Multiplied by[1]	(Fluorescent Screen Exposures) Exposure Time Multiplied by[1]
25%	1.6	about 2
50%	2.3	about 4
100%	4.0	about 8
Distance Decreased by		
20%	0.62	about 0.5
33%	0.43	about 0.2
50%	0.25	about 0.1

[1]Column 2 shows the changes necessitated by the inverse square law only. Column 3 shows the combined effects of the inverse square law and failure of the reciprocity law.

Logarithms consist of two parts: A decimal which is always positive, called the *mantissa*; and an integer which may be positive or negative, called the *characteristic*. In the case of log 316 = 2.50, .50 is the mantissa and 2 is the characteristic. The mantissa may be found by reference to a table of logarithms, by the use of a slide rule (D and L scales), or by reference to the figure below. Regardless of the location of the decimal point, the logarithms of all numbers having the same figures in the same order will have the same mantissa.

Figure 43: Scale for determining logarithms.



The characteristic of the logarithm is determined by the location of the decimal point in the number. If the number is greater than one, the characteristic is positive and its numerical value is one *less* than the number of digits to the left of the decimal point. If the number is less than one (for example, a decimal fraction), the characteristic is negative and has a numerical value of one *greater* than the number of zeros between the decimal paint and the first integer. A negative characteristic of 3 is written either as 3...to indicate that only the characteristic is negative, or as 7...-10.

From Figure 43, we see that the mantissa of the logarithm of 20 is 0.30. The characteristic is 1.

log 20 = 1.30
log 40 = 1.60
log 80 = 1.90
log 160 = 2.20
log 200 = 2.30
log 2000 = 3.30
log 20000 = 4.30
log 0.2 = $\bar{1}$.30 or 9.30 - 10
log 0.02 = $\bar{2}$.30 or 8.30 - 10

The preceding table illustrates a very important property of logarithms. Note that when a series of numbers increases by a constant *factor*, for example, the series 20, 40, 80, 160 or the series 20, 200, 2,000, 20,000, the logarithms have a constant *difference*, in these cases 0.30 and 1.00, respectively. In other words, a constant *increase* in the logarithm of a number means a constant *percentage increase* in the number itself.

Photographic Density

Photographic density refers to the quantitative measure of film blackening. When no danger of confusion exists, photographic density is usually spoken of merely as *density*. Density is defined by the equation:

$$D = \log \frac{I_o}{I_t}$$

where D is density, I_o is the light intensity incident on the film and It is the light intensity transmitted.

The tabulation below illustrates some relations between transmittance, percent transmittance, opacity, and density.

This table shows that an increase in density of 0.3 reduces the light transmitted to one-half its former value. In general, since density is a logarithm, a certain *increase* in density always corresponds to the same *percentage decrease* in transmittance.

TRANS-MITTANCE $\left(\frac{I_t}{I_o}\right)$	PERCENT TRANS-MITTANCE $\left(\frac{I_t}{I_o} \times 100\right)$	OPACITY $\left(\frac{I_o}{I_t}\right)$	DENSITY $\left(\log \frac{I_o}{I_t}\right)$
1.0	100	1	0
0.50	50	2	0.3
0.25	25	4	0.6
0.10	10	10	1.0
0.01	1	100	2.0
0.001	0.1	1,000	3.0
0.0001	0.01	10,000	4.0

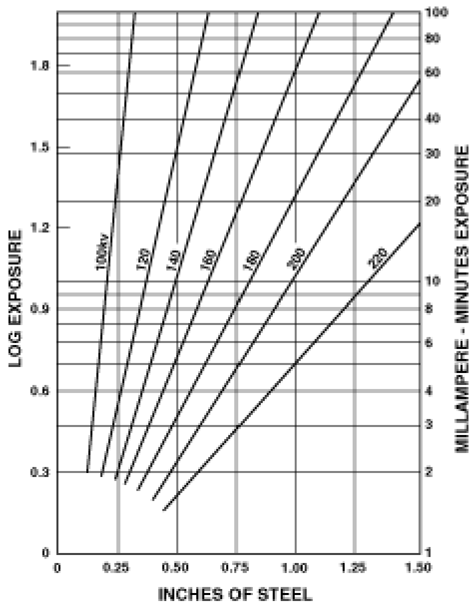
Densitometers

A densitometer is an instrument for measuring photographic densities. A number of different types, both visual and photoelectric, are available commercially. For purposes of practical industrial radiography, there is no great premium on high accuracy of a densitometer. A much more important property is reliability, that is, the densitometer should reproduce readings from day to day.

X-Ray Exposure Charts

An exposure chart is a graph showing the relation between material thickness, kilovoltage, and exposure. In its must common form, an exposure chart resembles Figure 44. These graphs are adequate for determining exposures in the radiography of uniform plates, but they serve only as rough guides for objects, such as complicated castings, having wide variations of thickness.

Figure 44: Typical exposure chart for steel. This chart may be taken to apply to Film X (for example), with lead foil screens, at a film density of 1.5. Source-film distance, 40 inches.



Exposure charts are usually available from manufacturers of x-ray equipment. Because, in general, such charts cannot be used for different x-ray machines unless suitable correction factors are applied, individual laboratories sometimes prepare their own.

Preparing An Exposure Chart

A simple method for preparing an exposure chart is to make a series of radiographs of a pile of plates consisting of a number of steps. This "step tablet" or stepped wedge, is radiographed at several different exposure times at each of a number of kilovoltages. The exposed films are all processed under conditions identical to those that will later be used for routine work. Each radiograph consists of a series of photographic densities corresponding to the x-ray intensities transmitted by the different thicknesses of metal. A certain density, for example, 1.5, is selected as the basis for the preparation of the chart. Wherever this density occurs on the stepped-wedge radiographs, there are corresponding values of thickness, milliampere-minutes, and kilovoltage. It is unlikely that many of the radiographs will contain a value of exactly 1.5 in density, but the correct thickness for this density can be found by interpolation between steps. Thickness and milliampere-minute values are plotted for the different kilovoltages in the manner shown in Figure 44.

Another method, requiring fewer stepped wedge exposures but more arithmetical manipulation, is to make one step-tablet exposure at each kilovoltage and to measure the densities in the processed stepped-wedge radiographs. The exposure that would have given the chosen density (in this case 1.5) under any particular thickness of the stepped wedge can then be determined from the characteristic curve of the film used (See "The Characteristic Curve"). The values for thickness, kilovoltage, and exposure are plotted as described in the figure above.

Note that thickness is on a linear scale, and that milliampere-minutes are on a logarithmic scale. The logarithmic scale is not necessary, but it is very convenient because it compresses an otherwise long scale. A further advantage of the logarithmic exposure scale is that it usually allows the location of the points for any one kilovoltage to be well approximated by a straight line.

Any given exposure chart applies to a set of specific conditions. These fixed conditions are:

1. The x-ray machine used
2. A certain source-film distance
3. A particular film type
4. Processing conditions used
5. The film density on which the chart is based
6. The type of screens (if any) that are used

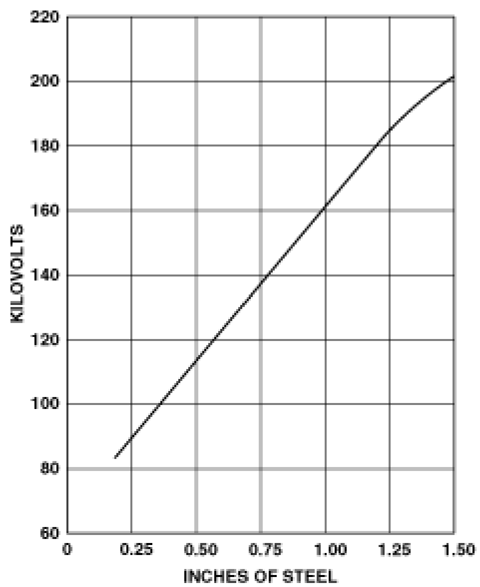
Only if the conditions used in making the radiograph agree in all particulars with those used in preparation of the exposure chart can values of exposure be read directly from the chart. Any change requires the application of a correction factor. The correction factor applying to each of the conditions listed previously will be discussed separately.

1. It is sometimes difficult to find a correction factor to make an exposure chart prepared for one x-ray machine applicable to another. Different x-ray machines operating at the same nominal kilovoltage and milliamperage settings may give not only different intensities but also different qualities of radiation.
2. A change in source-film distance may be compensated for by the use of the inverse square law or, if fluorescent screens are used, by referring to the earlier table. Some exposure charts give exposures in terms of "exposure factor" rather than in terms of milliampere-minutes or milliampere-seconds. Charts of this type are readily applied to any value of source-film distance.
3. The use of a different type of film can be corrected for by comparing the difference in the amount of exposure necessary to give the same density on both films from relative exposure charts such as those shown in Figure 47.
    - For example, to obtain a density of 1.5 using Film Y, 0.6 more exposure is required than for Film X.
    - This log exposure difference is found on the L scale and corresponds to an exposure factor of 3.99 on the D scale. (Read directly below the log E difference.) Therefore, in order to obtain the same density on Film Y as on Film X, multiply the original exposure by 3.99 to get the new exposure. Conversely, if going from Film Y to Film X, divide the original exposure by 3.99 to obtain the new exposure.
    - You can use these procedures to change densities on a single film as well. Simply find the log E difference needed to obtain the new density on the film curve; read the corresponding exposure factor from the chart; then multiply to increase density or divide to decrease density.
4. A change in processing conditions causes a change in effective film speed. If the processing of the radiographs differs from that used for the exposures from which the chart was made, the correction factor must be found by experiment.
5. The chart gives exposures to produce a certain density. If a different density is required, the correction factor may be calculated from the film's characteristic curve (See "The Characteristic Curve").
6. If the type of screens is changed, for example from lead foil to fluorescent, it is easier and more accurate to make a new exposure chart than to attempt to determine correction factors.

Sliding scales can be applied to exposure charts to allow for changes in one or more of the conditions discussed, with the exception of the first and the last. The methods of preparing and using such scales are described in detail later on.

In some radiographic operations, the exposure time and the source-film distance are set by economic considerations or on the basis of previous experience and test radiographs. The tube current is, of course, limited by the design of the tube. This leaves as variables only the thickness of the specimen and the kilovoltage. When these conditions exist, the exposure chart may take a simplified form as shown in Figure 45, which allows the kilovoltage for any particular specimen thickness to be chosen readily. Such a chart will probably be particularly useful when uniform sections must be radiographed in large numbers by relatively untrained persons. This type of exposure chart may be derived from a chart similar to Figure 44 by following the horizontal line corresponding to the chosen milliampere-minute value and noting the thickness corresponding to this exposure for each kilovoltage. These thicknesses are then plotted against kilovoltage.

Figure 45: Typical exposure chart for use when exposure and distance are held constant and kilovoltage is varied to conform to specimen thickness. Film X (Figure 47 for example), exposed with lead foil screens to a density of 1.5. Source-film distance, 40 inches; exposure, 50 mA-min.



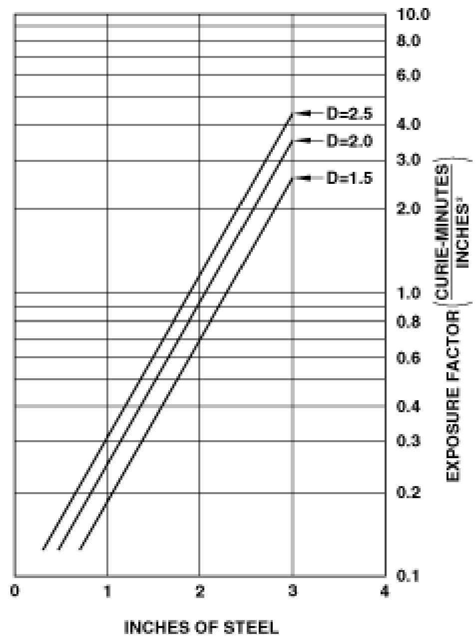
Gamma-Ray Exposure Charts

The figure below shows a typical gamma-ray exposure chart. It is somewhat similar to the next to Figure 46.

However, with gamma rays, there is no variable factor corresponding to the kilovoltage. Therefore, a gamma-ray exposure chart contains one line, or several parallel lines, each of which corresponds to a particular film type, film density, or source-film distance. Gamma-ray exposure guides are also available in the form of linear or circular slide rules. These contain scales on which can be set the various factors of specimen thickness, source strength and source-film distance, and from which exposure time can be read directly.

Sliding scales can also be applied to gamma-ray exposure charts of the type in the figure below to simplify some exposure determinations. For the preparation and use of such scales, see "Sliding Scales For Exposure Charts".

Figure 46: Typical gamma-ray exposure chart for iridium 192, based on the use of Film X (Figure 47 for example).



The Characteristic Curve

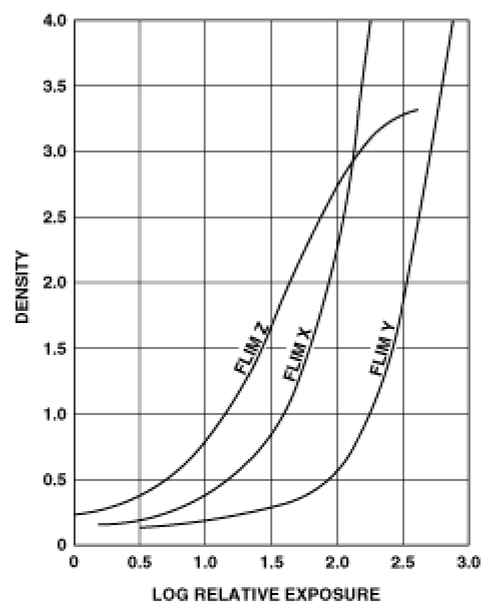
The characteristic curve, sometimes referred to as the sensitometric curve or the H and D curve (after Hurter and Driffield who, in 1890, first used it), expresses the relation between the exposure applied to a photographic material and the resulting photographic density. The characteristic curves of three typical films, exposed between lead foil screens to x-rays, are given in Figure 47. Such curves are obtained by giving a film a series of known exposures, determining the densities produced by these exposures, and then plotting density against the logarithm of relative exposure.

Relative exposure is used because there are no convenient units, suitable to all kilovoltages and scattering conditions, in which to express radiographic exposures. Hence, the exposures given a film are expressed in terms of some particular exposure, giving a relative scale. In practical radiography, this lack of units for x-ray intensity or quantity is no hindrance. The use of the logarithm of the relative exposure, rather than the relative exposure itself, has a number of advantages. It compresses an otherwise long scale. Furthermore, in radiography, ratios of exposures or intensities are usually more significant than the exposures or the intensities themselves. Pairs of exposures having the same ratio will be separated by the same interval on the log relative exposure scale, no matter what their absolute value may be. Consider the following pairs of exposures.

Relative Exposure	Log Relative Exposure	Interval in Log Relative Exposure
1	0.0	0.70
5	0.70	
2	0.30	0.70
10	1.00	
30	1.48	0.70
150	2.18	

This illustrates another useful property of the logarithmic scale. Figure 43 shows that the antilogarithm of 0.70 is 5, which is the ratio of each pair of exposures. Hence, to find the ratio of *any* pair of exposures, it is necessary only to find the antilog of the log E (logarithm of relative exposure) interval between them. Conversely, the log exposure interval between any two exposures is determined by finding the logarithm of their ratio.

Figure 47: Characteristic curves of three typical x-ray films, exposed between lead foil screens.



As Figure 47 shows, the slope (or steepness) of the characteristic curves is continuously changing throughout the length of the curves. The effects of this change of slope on detail visibility are more completely explained in "The Characteristic Curve". It will suffice at this point to give a qualitative outline of these effects. For example, two slightly different thicknesses in the object radiographed transmit slightly different exposures to the film. These two exposures have a certain small log E interval between them, that is, have a certain ratio. The difference in the densities corresponding to the two exposures depends on just where on the characteristic curve they fall, and the steeper the slope of the curve, the greater is this density difference. For example, the curve of Film Z (See Figure 47), is steepest in its middle portion. This means that a certain log E interval in the middle of the curve corresponds to a greater density difference than the same log E interval at either end of the curve. In other words, the film contrast is greatest where the slope of the characteristic curve is greatest. For Film Z, as has been pointed out, the region of greatest slope is in the central part of the curve. For Films X and Y, however, the slope--and hence the film contrast continuously increases throughout the useful density range. The curves of most industrial x-ray films are similar to those of Films X and Y.

Use Of The Characteristic Curve

The characteristic curve can be used to solve quantitative problems arising in radiography, in the preparation of technique charts, and in radiographic research. Ideally, characteristic curves made under the radiographic conditions actually encountered should be used in solving practical problems. However, it is not always possible to produce characteristic curves in a radiographic department, and curves prepared elsewhere must be used. Such curves prove adequate for many purposes although it must be remembered that the shape of the characteristic curve and the speed of a film relative to that of another depend strongly on developing conditions. The accuracy attained when using "ready-made" characteristic curves is governed largely by the similarity between the developing conditions used in producing the characteristic curves and those for the film, whose densities are to be evaluated.

A few examples of the quantitative use of characteristic curves are worked out below. In the examples below, D is used for density and log E for the logarithm of the relative exposure.

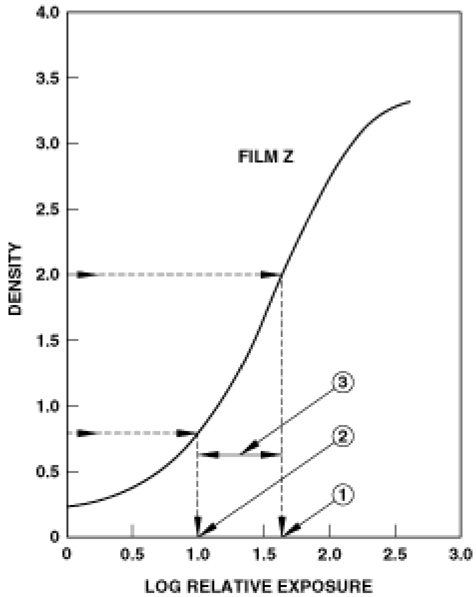
Example 1: Suppose a radiograph made on Film Z (See Figure 48) with an exposure of 12 mA-min has a density of 0.8 in the region of maximum interest. It is desired to increase the density to 2.0 for the sake of the increased contrast there available.

1. Log E at D = 2.0 is 1.62
2. Log E at D = 0.8 is 1.00
3. Difference in log E is 0.62

Antilogarithm of this difference is 4.2

Therefore, the original exposure is multiplied by 4.2 giving 50 mA-min to produce a density of 2.0.

Figure 48: Circled numerals in the figure correspond to the items in Example 1.



Example 2: Film X has a higher contrast than Film Z at D = 2.0 (See Figure 49) and also a finer grain. Suppose that, for these reasons, it is desired to make the radiograph on Film X with a density of 2.0 in the same region of maximum interest.

4. Log E at D = 2.O for Film X is 1.91

5. Log E at D = 2.0 for Film Z is 1.62

6. Difference in log E is 0.29

Antilogarithm of this difference is 1.95

Therefore, the exposure for D = 2.0 on Film Z is multiplied by 1.95 giving 97.5 mA-min, for a density of 2.0 on Film X.

Figure 49: Characteristic curves of two x-ray films exposed with lead foil screens. Circled numerals in the figure correspond to the items in Example 2.

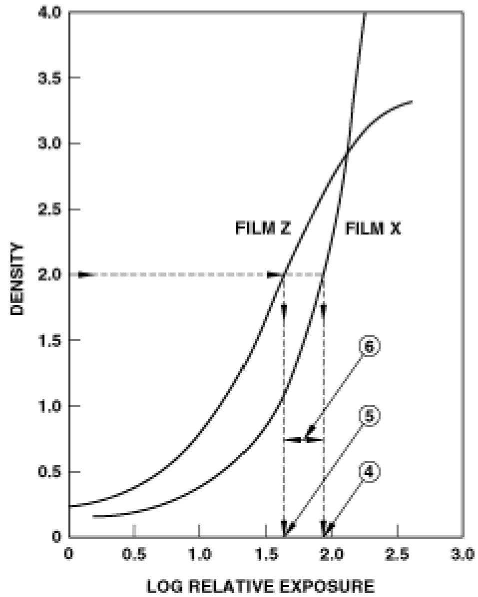
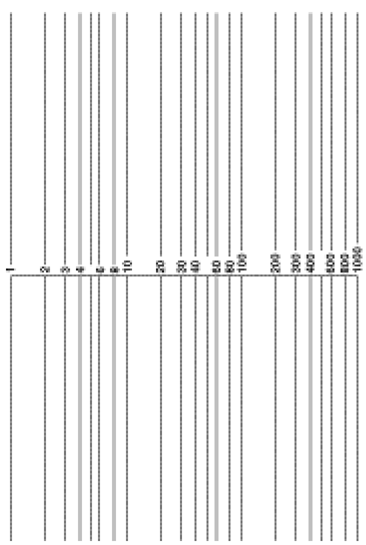


Figure 50: Form of transparent overlay of proper dimensions for use with the characteristic curves in the solution of exposure problems. The use of the overlay and curves is demonstrated below.



Graphical Solutions To Sensitometric Problems

Many of the problems in the foregoing section can be solved graphically. One method involves the use of a transparent overlay (See Figure 50) superimposed on a characteristic curve. Another method involves the use of a nomogram-like chart in Figure 54. In general, the overlay method requires less arithmetic but more equipment than the nomogram method. The nomogram method usually requires somewhat more arithmetic but no equipment other than a diagram similar to Figure 54 and a ruler or straightedge.

Graphical solutions of either type are often sufficiently accurate for the purposes of practical industrial radiography.

Overlay Methods
An example of a transparent overlay is shown in the Figure 50. The numbers on the horizontal line are exposure values. They can be taken, for example to be milliampere-minutes, milliampere-seconds, curie-minutes, curie-hours, or an exposure factor. Further, all numbers on the line can be multiplied by the same value, without affecting the use of the device. For instance, multiplying by 10 makes the scale go from 10 to 10,000 (rather than from 1 to 1,000) of whatever exposure unit is convenient. Note that the overlay must be made to fit the characteristic curves with which it is to be used, since it is essential for the horizontal scales of both characteristic curves and overlay to agree.

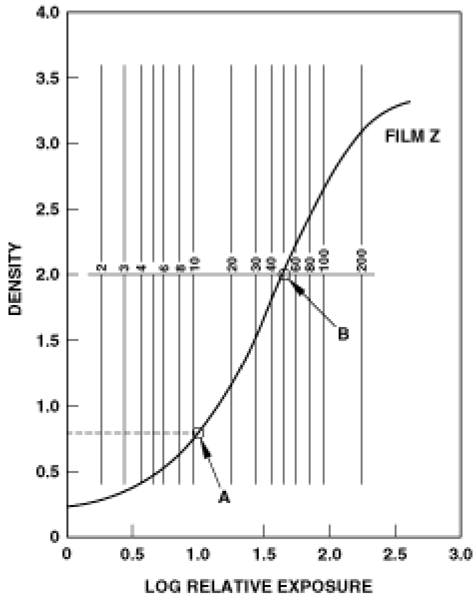
The use of the overlay will be demonstrated by solving again some of the same problems used as illustrations in the foregoing section. Note that the vertical lines on the overlay must be parallel to the vertical lines on the graph paper of the characteristic curve, and the horizontal line must be parallel to the horizontal lines on the graph paper.

Example 1: Suppose a radiograph made on Film Z with an exposure of 12 mA-min has a density of 0.8 in the region of maximum interest. It is desired to increase the density to 2.0 for the sake of the increased contrast there available.

Locate the intersection of the line for the original density of 0.8 with the characteristic curve of Film Z (Point A in Figure 51). Superimpose the transparent overlay on the curve, so that the vertical line for the original exposure--12 mA-min--passes through point A and the horizontal line overlies the line for the desired final density of 2.0. The new exposure, 50 mA-min, is read at the intersection of the characteristic curve with the horizontal line of the overlay (Point B in Figure 51).

The method of solution would be the same if the new density were lower rather than higher than the old. The vertical line corresponding to the old exposure would pass through the characteristic curve at the point of the old density. The horizontal line of the overlay would pass through the desired new density. The new exposure would be read at the intersection of the characteristic curve and the horizontal line of the overlay.

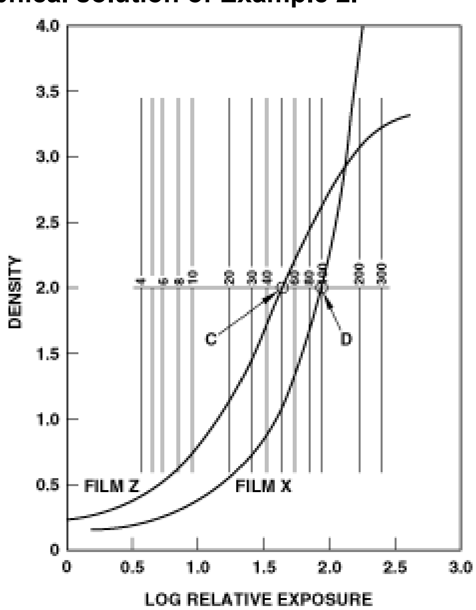
Figure 51: Characteristic curve of Film Z. Transparent overlay of the figure above positioned for the graphical solution of Example 1.



Example 2: Film X has a higher contrast at D = 2.0 than Film Z and also has a finer grain. Suppose that, for these reasons, it is desired to make the aforementioned radiograph on Film X with a density of 2.0 in the same region of maximum interest.

Superimpose the overlay on the characteristic curve so that the horizontal line coincides with the horizontal line for a density of 2.0, and position the overlay from left to right so that the curve for Film Z cuts the line at the original exposure of 50 mA-min (Point C in Figure 52). Read the new exposure of 97.5 mA-min at the point at which the curve for Film X cuts the horizontal line (Point D in Figure 52).

Figure 52: Characteristic curves of Films X and Z. Transparent overlay positioned for the graphical solution of Example 2.



Example 3: The types of problems given in Examples 1 and 2 above are often combined in actual practice. Suppose, for example, that a radiograph was made on Film X with an exposure of 20 mA-min and that a density of 1.0 was obtained. Then suppose that a radiograph at the same kilovoltage but on Film Y at a density of 2.5 is desired for the sake of the higher contrast and the lower graininess obtainable. The problem can be solved in a single step.

Locate the intersection of the original density of 1.0 and the characteristic curve of Film X (Point E in Figure 53) for the original exposure--20 mA-min--passes through point # and the horizontal line coincides with the line for the new density of 2.5. The new exposure of 220 mA-min is read from point F (See Figure 53), the intersection of the horizontal line and the characteristic curve of Film Y.

Figure 53: Characteristic curves of Films X and Y. Transparent overlay positioned for the graphical solution of Example 3.

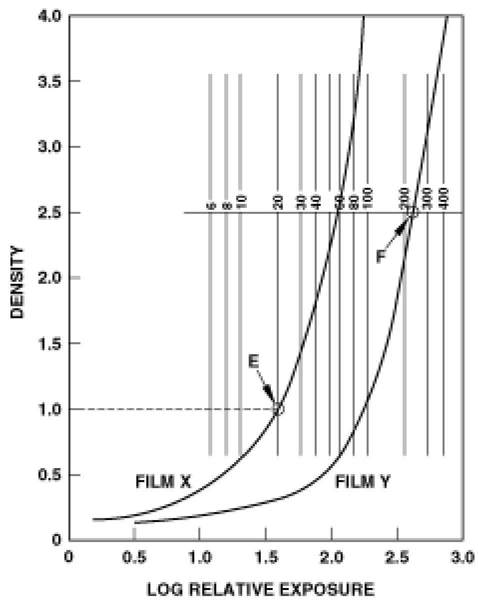
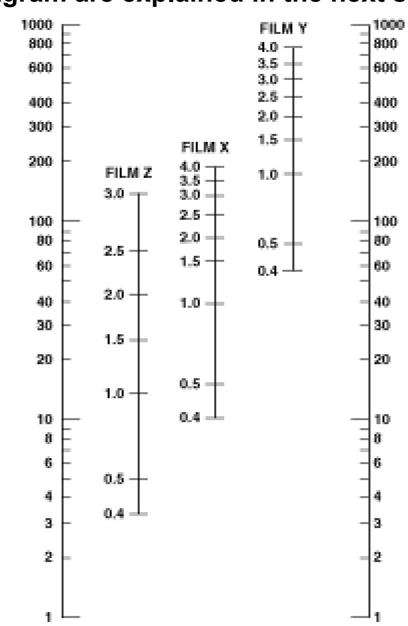


Figure 54: Typical nomogram for solution of exposure calculations. The uses of the diagram are explained in the next section.



Nomogram Methods
In Figure 54, the scales at the far left and far right are *relative* exposure values. They do not represent milliampere-minutes, curie-hours, or any other exposure unit; they are to be considered merely as multiplying (or dividing) factors, the use of which is explained below. Note, also, that these scales are identical, so that a ruler placed across them at the same value will intersect the vertical lines, in the center of the diagram, at right angles.

On the central group of lines, each labeled with the designation of a film whose curve is shown in the Figure 47, the numbers represent densities.

The use of Figure 54 will be demonstrated by a re-solution of the same problems used as illustrations in both of the preceding sections. Note that in the use of the nomogram, the straightedge must be placed so that it is at right angles to all the lines--that is, so that it cuts the outermost scales on the left and the right at the same value.

Example 1: Suppose a radiograph made on Film Z (See Figure 47) with an exposure of 12 mA-min has a density of 0.8 in the region of maximum interest. It is desired to increase the density to 2.0 for the sake of the increased contrast there available.

Place the straightedge across Figure 54 so that it cuts the Film Z scale at 0.8. The reading on the outside scales is then 9.8. Now move the straightedge upward so that it cuts the Film Z scale at 2.0; the reading on the outside scales is now 41. The original exposure (12 mA-min) must be multiplied by the ratio of these two numbers--that is, by 41/9.8 = 4.2. Therefore, the new exposure is 12 x 4.2 mA-min or 50 mA-min.

Example 2: Film X has a higher contrast than Film Z at D = 2.0 (See Figure 47) and also lower graininess. Suppose that, for these reasons, it is desired to make the aforementioned radiograph on Film X with a density of 2.0 in the same region of maximum interest.

Place the straightedge on Figure 54 so that it cuts the scale for Film Z at 2.0. The reading on the outside scales is then 41, as in Example 1. When the straightedge is placed across the Film X scale at 2.0, the reading on the outside scale is 81. In the previous example, the exposure for a density of 2.0 on Film Z was found to be 50 mA-min. In order to give a density of 2.0 on Film X, this exposure must be multiplied by the ratio of the two scale readings just found--81/41 = 1.97. The new exposure is therefore 50 x 1.97 or 98 mA-min.

Example 3: The types of problems given in Examples 1 and 2 are often combined in actual practice. Suppose, for example, that a radiograph was made on Film X (See Figure 47) with an exposure of 20 mA-min and that a density of 1.0 was obtained. A radiograph at the same kilovoltage on Film Y at a density of 2.5 is desired for the sake of the higher contrast and the lower graininess obtainable. The problem can be solved graphically in a single step.

The reading on the outside scale for D = 1.0 on Film X is 38. The corresponding reading for D = 2.5 on Film Y is 420. The ratio of these is 420/38 = 11, the factor by which the original exposure must be multiplied. The new exposure to produce D = 2.5 on Film Y is then 20 x 11 or 220 mA-min.

Sliding Scales For Exposure Charts

An exposure chart is an exceedingly useful radiographic tool. However, as pointed out in "Preparing An Exposure Chart", it has the limitations of applying only to a specific set of radiographic conditions. These are:

1. The x-ray machine used

2. A certain source-film distance
3. A particular type of film
4. Processing conditions used
5. The film density on which the chart is based
6. The type of screens (if any) that are used

Only if the conditions used in practice agree in every particular with those used in the production of the exposure chart can exposures be read directly from the chart. If one or more of the conditions are changed, a correction factor must be applied to the exposure as determined from the chart. Correction factors to allow for differences between one x-ray machine and another, or between one type of screen and another, are best determined by experiment--often a new exposure chart must be made. Changes in the other four conditions, however, can in many cases be calculated, making use of the characteristic curve of the films involved or of the inverse square law.

Numerical work involved in these corrections can often be avoided by the use of sliding scales affixed to the exposure chart. The preparation of these sliding scales will be facilitated (1) if the exposure chart has a logarithm of exposure (or of relative exposure) scale along one vertical boundary and (2) if the horizontal (exposure) lines are available on a transparent overlay (See Figure 55), on which the spacing of the lines corresponds to those in Figure 44. These overlays can be made by tracing from the exposure chart involved onto exposed, fixed-out, x-ray film or any stiff transparent plastic material.

Note that arrowheads are printed on the Figures 55 and 56. When these coincide, the exposures read from the chart are those corresponding to the conditions under which the chart was made.

The material that follows describes the technique of modifying the exposure chart in the earlier figure, to allow for changes in radiographic conditions 2 through 5 above. The sections below are numbered to correspond to the list in "Preparing An Exposure Chart".

Figure 55: Pattern of transparent overlay for exposure chart of Figure 44.

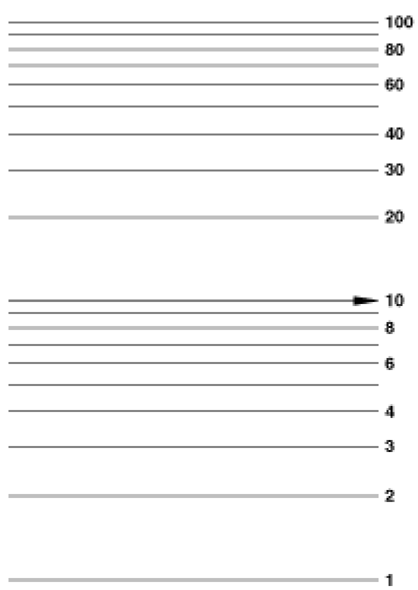
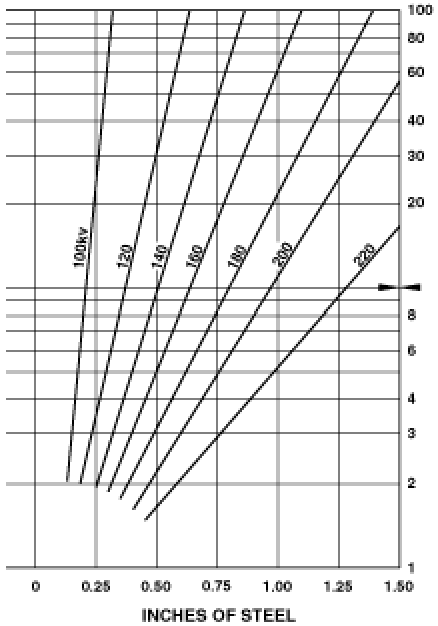


Figure 56: Transparent overlay positioned over the exposure chart in such a way as to duplicate that in an earlier figure. Thus, it applies to Film X a density of 1.5 and a source-film distance of 40 inches.



2. *Source-film distance*. Since the intensity of the radiation varies inversely with the square of the source-film distance, the exposure must vary directly with the square of the distance if a constant density on the radiograph is to be maintained. If source-film distance is to be changed, therefore, the exposure scale on the chart must be shifted vertically a distance that is in accord with the law.

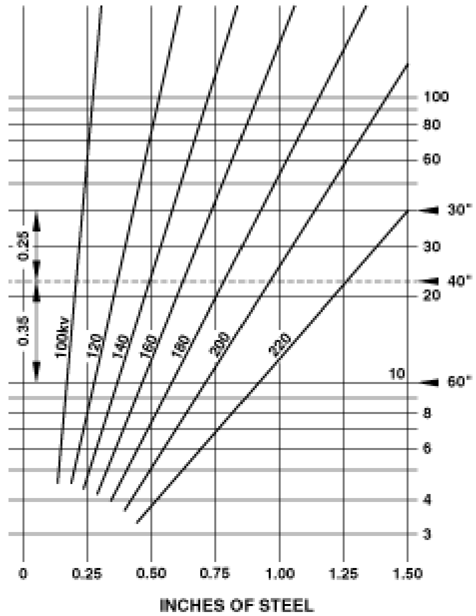
The chart of Figure 44 was made using a 40-inch source-film distance. Assume that it is desired to make the chart applicable to distances of 30 and 60 inches as well. Note that column 2 of the table below is calculated from the inverse square law *and that the ratio is taken so that it is always greater than 1*. (This is done merely for convenience, it being easier to work with logarithms of numbers greater than 1 than with logarithms of decimal fractions.) The logarithms in column 3 can be found in Figure 43, with a slide rule, or in a table of logarithms.

Distance	Intensity Ratio (relative to 40 in.)	Logarithm of Intensity Ratio
30 in.	1.78[1]	0.25
60 in.	2.25[2]	0.35

[1]Intensity greater than that at 40 inches by this factor.
[2]Intensity less than that at 40 inches by this factor.

A mark is put on the margin of the exposure chart a log E *interval* of 0.25 above the printed arrow. When the transparent overlay is displaced upward to this position, exposures for a 30-inch focus-film distance can be read directly. Similarly, a mark is put a log E *interval* of 0.35 below the printed arrow. The overlay, in this position, gives the exposures required at a source-film distance of 60 inches. In the figure below, the exposure chart and overlay are shown in this position.

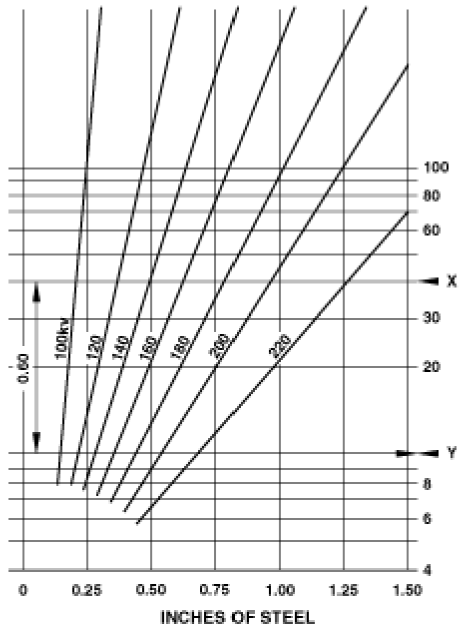
Figure 57: Overlay positioned so as to make the exposure chart and the nomogram apply to a source-film distance of 60 inches, rather than 40 inches. See No. 2, "Source-film distance".



3. *Film type*. Changes required by the use of a film different from that for which the exposure chart was prepared can be made by a somewhat similar procedure. Using the characteristic curve shown in an earlier figure and the method described in Example 2 in "Overlay Methods" and "Nomogram Methods", it can be found that Film Y requires four times more exposure than does Film X to produce a density of 1.5. The logarithm of 4.0 is 0.60 (See Figure 53). A mark is put on the margin of the exposure chart a log exposure *interval* of 0.60 below the printed arrow. When the transparent overlay is in this position, exposures for Film Y can be read directly. The Figure 58 shows this arrangement.

If the new film were faster than the one for which the chart was prepared, the same general procedure would be followed. The relative exposure required for the new film would be taken *so that it was greater than 1*, and the logarithm of this number would indicate the log E *interval* by which the new mark would be placed above the printed arrow on the chart.

Figure 58: Overlay positioned so as to make the exposure chart and the nomogram apply to Film Y rather than to Film X. See No. 3, "Film type", above.



4. *Changes in processing conditions.* It is difficult to make simple corrections for gross changes in processing conditions, because such changes affect both the speed and the contrast of the film, often to a marked degree (See "Effect Of Development Time On Speed And Contrast").

For the sake of both economy and radiographic quality, avoid large departures from recommended times and temperatures.

However, in manual processing of some industrial x-ray films, the development time may be increased, for example, from 5 to 8 minutes at 68° F. The longer development may result in speed increases that are frequently useful in practice, with little or no change in the shape of the characteristic curve--that is, with little or no change in film contrast. Exposure charts and nomograms of the types shown earlier can be made to apply to both development times. Assume, for instance, that increasing the development time of Film X from 5 to 8 minutes at 68° F results in a 20 percent gain in speed. The ratio of exposures required to achieve the same density would be 1:1.2. The logarithm of 1.2 is 0.08. A mark at log E *interval* of 0.08 above the arrow printed on the exposure chart would allow the overlay to be positioned so that exposures for a development time of 8 minutes could be read directly.

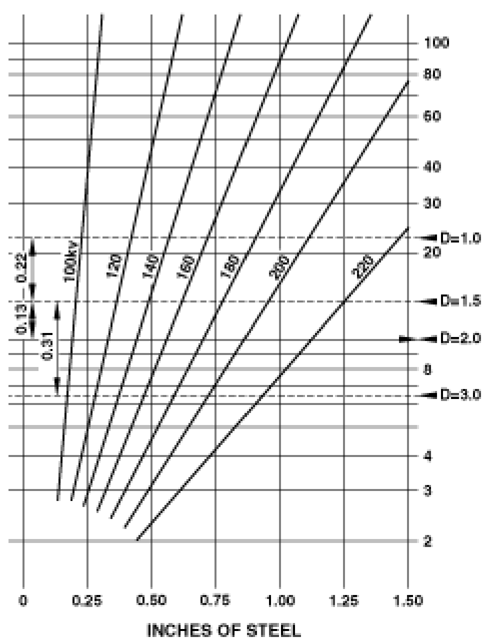
5. *Film density.* Exposure charts apply only to a single density of the processed radiograph. However, by the use of data from the characteristic curve of the film, it is possible to supply a sliding scale that can make the exposure chart applicable to any densities desired.

Figure 44 was drawn for a density of 1.5. Let us assume that it is desired to make this chart applicable to densities of 1.0, 2.0, and 3.0 also. The second column of the tabulation below is obtained from the characteristic curve of Film X in Figure 47.

Density	Log Relative Exposure	Difference of Log Relative Exposure
1.0	1.57	+ 0.22
1.5	1.79	0
2.0	1.92	- 0.13
3.0	2.10	- 0.31

The values in column 3 are the differences between the logarithm of relative exposure required to produce the density for which the chart was originally drawn (in this case 1.5) and the logarithm of exposure required for the desired density. They represent the log E *intervals* that the "exposure" grid of the exposure chart must be shifted up or down to give exposures that will result in the lower or higher densities. Plus signs indicate that the added marks on the margin should be above that printed on the chart; minus signs, that the added marks are to be below. Figure 59 shows the chart with the transparent overlay positioned to directly read exposures required to give a density of 2.0.

Figure 59: Overlay positioned so as to make the exposure chart and the nomogram apply to a density of 2.0, rather than 1.5. See No. 5, "Film density".



Estimating Exposures For Multithickness Specimens

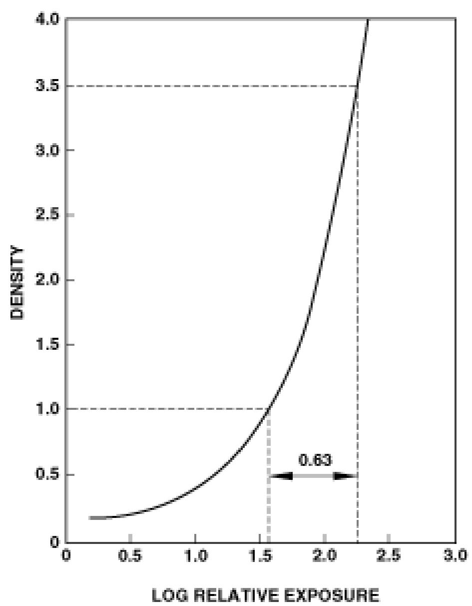
A minimum acceptable density for radiographs is often specified, not because of any virtue in the particular density, but because the slope of the characteristic curve (and hence the film contrast) below a certain point is too low for adequate rendition of detail. Similarly, a maximum acceptable density is often designated because either the film contrast is lower at high densities or detail cannot be seen on the available illuminators if the density is above a certain value.

The problem of radiographing a part having several thicknesses is one of using the available density range most efficiently. In other words, the kilovoltage and exposure should be adjusted so that the image of the thinnest part has the maximum acceptable density, and the thickest has the minimum. Exposure charts alone, although adequate for the radiography of uniform plates, can serve only as rough guides for articles having considerable variation in thickness. Previous experience is a guide, but even when a usable radiograph has been obtained, the question remains as to whether or not it is the best that could be achieved.

A quantitative method for finding such exposures combines information derived from the exposure chart and the characteristic curve of the film used. The procedure is outlined below:

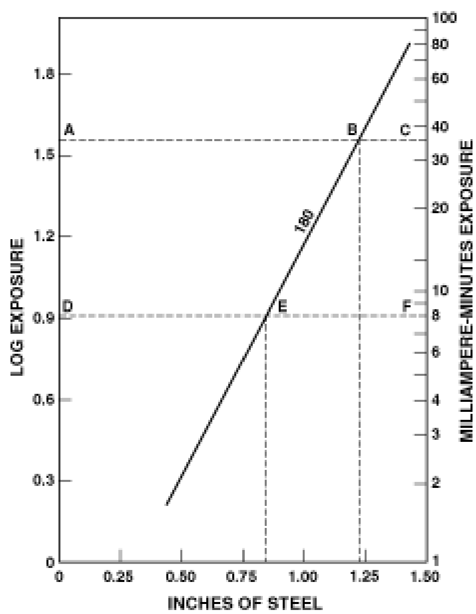
Assume that 1.0 is the lowest acceptable density on Film X (See Figure 47) and that 3.5 is the highest. As shown in the figure below, this density interval corresponds to a certain log exposure interval, in this case 0.63.

Figure 60: Characteristic curve of Film X. Dotted lines show how the log E interval corresponding to a certain density interval (in this case 1.0 to 3.5) can be found.



The antilog of 0.63 is 4.3, which means that 4.3 times more exposure is required to produce a density of 3.5 than of 1.0. It is therefore desired that the thinnest portion of the object to be radiographed transmit exactly 4.3 times more radiation than the thickest part, so that with the proper adjustment of radiographic exposure, all parts of the object will be rendered within the density range 1.0 to 3.5. The ratios of x-ray intensities transmitted by different portions of the object will depend on kilovoltage; examination of the exposure chart of the x-ray machine reveals the proper choice of kilovoltage. For example, in the chart shown in the figure below, the 180 kV line shows that a thickness range of about 7/8 to about 11/4 inches of steel corresponds to an exposure ratio of 35 mA-min to 8 mA-min, or 4.3, which is the ratio required. The next problem is to determine the radiographic exposure needed. The chart shown below gives the exposure to produce a density of 1.0 on Film X. Since it is desired to produce a density 1.0 under the thick section (11/4 inches), the exposure time would be 35 mA-min.

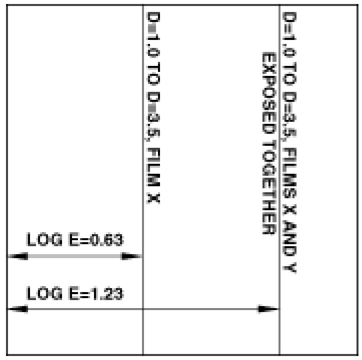
Figure 61: Abridged form of the exposure chart derived from a previous figure, but showing exposures at 180 kV to produce a density of 1.0 on Film X. Dotted lines indicate the metal thickness corresponding to the log E interval of the figure above. If the separation of lines ABC and DEF is maintained, they can be moved up and down the chart. They will then mark off a large number of thickness ranges on the various kilovoltage lines, all of which will completely fill the density range which has been assumed to be useful.



A simple means for applying this method to routine work is as follows:

Parallel lines are drawn on a transparent plastic sheet, such as a fixed-out x-ray film, in the manner shown in the figure below. The spacing between the base line and the line immediately above is the log relative exposure interval for Film X between D = 1.0 and D = 3.5. *It is laid off to the same scale as the ordinate (vertical) scale of the exposure chart*. Similarly, the distance from the baseline to any other line parallel to it can be made to correspond to the log relative exposure interval for other density limits and films. This transparent guide is moved up and down on the exposure chart with its lines parallel to the thickness axis. The two guidelines being used form a rectangle with the two vertical lines of the exposure chart that mark the thickness limits of the specimen. The correct kilovoltage is the one whose graph intersects diagonally opposite comers of the rectangle. If the film type used is the one for which the chart was prepared, the correct exposure is indicated at the intersection of the upper guide line with the exposure scale (Point C Figure 1). If a different film is used, a suitable correction factor obtained either from tables of relative speeds or by the method described in Example 2 in "Overlay Methods" and "Nomogram Methods", must be applied to the exposure as determined from the chart.

Figure 62: System of lines drawn on a transparent sheet to be used in connection with an exposure chart for estimating radiographic exposures for multithickness specimens.



If there is only one graph on a gamma-ray exposure chart, this procedure will indicate limiting thicknesses of material that can be radiographed within the prescribed density limits.

On a chart of the type Figure 46, which has lines for various densities, the thickness range that can be radiographed in a single exposure can be read directly. For example, the same exposure (exposure factor = 0.7) will give a density of 1.5 through 2 inches of steel and a density of 2.5 through about 11/2 inches of steel.

Use Of Multiple Films

If the chart shows that the thickness range is too great for a single exposure under any condition, it may be used to select two different exposures to cover the range. Another technique is to load the cassette with two films of different speed and expose them simultaneously, in which case the chart may be used to select the exposure. The log relative exposure range for two films of different speed, when used together in this manner, is the difference in log exposure between the value at the low-density end of the faster film curve and the high-density end of the slower film curve. Figure 47 shows that when Films X and Y are used, the difference is 1.22, which is the difference between 1.57 and 2.79. It is necessary that the films be close enough together in speed so that their curves will have some "overlap" on the log E axis.

Limitations Of Exposure Charts

Although exposure charts are useful industrial radiographic tools, they must be used with some caution. They will, in most cases, be adequate for routine practice, but they will not always show the precise exposure required to radiograph a given thickness to a particular density.

Several factors have a direct influence on the accuracy with which exposures can be predicted. Exposure charts are ordinarily prepared by radiographing a stepped wedge. Since the proportion of scattered radiation depends on the thickness of material and, therefore, on the distribution of the material in a given specimen, there is no assurance that the scattered radiation under different parts will correspond to the amount under the same thickness of the wedge. In fact, it is unreasonable to expect exact correspondence between scattering conditions under two objects the thicknesses of which are the same but in which the distribution of material is quite different. The more closely the distribution of metal in the wedge resembles that in the specimen the more accurately the exposure chart will serve its purpose. For example, a narrow wedge would approximate the scattering conditions for specimens containing narrow bars.

Although the lines of an exposure chart are normally straight, they should in most cases be curved--concave downward. The straight lines are convenient approximations, suitable for most practical work, but it should be recognized that in most cases they are only approximations. The degree to which the conventionally drawn straight line approximates the true curve will vary, depending on the radiographic conditions, the quality of the exposing radiation, the material radiographed, and the amount of scattered radiation reaching the film.

In addition, time, temperature, degree of activity, and agitation of the developer are all variables that affect the shape of the characteristic curve and should therefore be standardized. When, in hand processing, the temperature or the activity of the developer does not correspond to the original conditions, proper compensation can be made by changing the time according to methods described in "Control of Temperature and Time". Automated processors should be carefully maintained and cleaned to achieve the most consistent results. In any event, the greatest of care should always be taken to follow the recommended processing procedures.

Chapter 8: Radiographic Image Quality and Detail Visibility

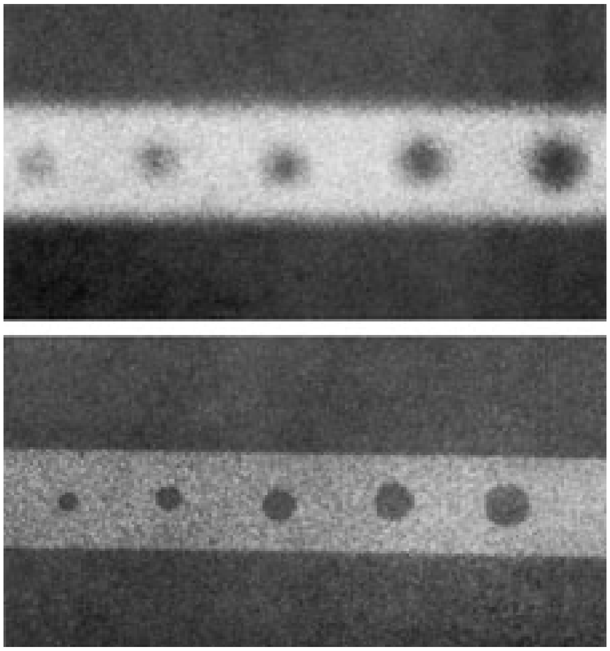
Because the purpose of most radiographic inspections is to examine a specimen for inhomogeneity, a knowledge of the factors affecting the visibility of detail in the finished radiograph is essential. The summary chart below shows the relations of the various factors influencing image quality and radiographic sensitivity, together with page references to the discussion of individual topics. For convenience, a few important definitions will be repeated.

<table>
<tr><th colspan="4">Factors Affecting Image Quality</th></tr>
<tr><th colspan="4">Radiographic Image Quality</th></tr>
<tr><th colspan="2">Radiographic Contrast</th><th colspan="2">Definition</th></tr>
<tr><th>Subject Contrast</th><th>Film Contrast</th><th>Geometric Factors</th><th>Film Graininess, Screen Mottle Factors</th></tr>
<tr>
<td>Affected by:
A - Absorption differences in specimen (thickness, composition, density)
B - Radiation wavelength
C - Scattered radiation

Reduced by:
1 - Masks and diaphragms
2 - Filters
3 - Lead screens
4 - Potter-Bucky diaphragm</td>
<td>Affected by:
A - Type of Film
B - Degree of development (type of developer, time and temperature of development, activity of developer, degree of agitation)
C - Density
D - Type of screens (fluorescent vs lead or none)</td>
<td>Affected by:
A - Focal-spot size
B - Source-film distance
C - Specimen-film distance
D - Abruptness of thickness changes in specimen
E - Screen-film contact
F - Motion of specimen</td>
<td>Affected by:
A - Type of Film
B - Type of screen
C - Radiation wavelength
D - Development</td>
</tr>
</table>

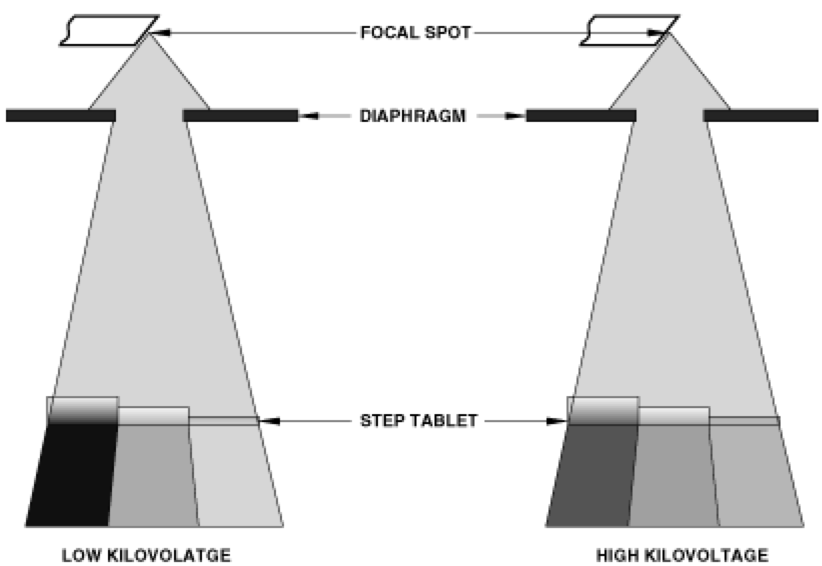
Radiographic sensitivity is a general or qualitative term referring to the size of the smallest detail that can be seen in a radiograph, or to the ease with which the images of small details can be detected. Phrased differently, it is a reference to the amount of information in the radiograph. Note that radiographic sensitivity depends on the combined effects of two independent sets of factors. One is radiographic contrast (the density difference between a small detail and its surroundings) and the other is definition (the abruptness and the "smoothness" of the density transition). See Figure 63.

Figure 63: Advantage of higher radiographic contrast (left) is largely offset by poor definition. Despite lower contrast (right), better rendition of detail is obtained by improved definition.



Radiographic contrast between two areas of a radiograph is the difference between the densities of those areas. It depends on both subject contrast and film contrast. Subject contrast is the ratio of x-ray or gamma-ray intensities transmitted by two selected portions of a specimen. (See Figure 64.) Subject contrast depends on the nature of the specimen, the energy (spectral composition, hardness, or wavelengths) of the radiation used, and the intensity and distribution of the scattered radiation, but is independent of time, milliamperage or source strength, and distance, and of the characteristics or treatment of the film.

Figure 64: With the same specimen, the lower-kilovoltage beam (left) produces higher subject contrast than does the higher-kilovoltage beam (right).



Film contrast refers to the slope (steepness) of the characteristic curve of the film. It depends on the type of film, the processing it receives, and the density. It also depends on whether the film is exposed with lead screens (or direct) or with fluorescent screens. Film contrast is independent, for most practical purposes, of the wavelengths and distribution of the radiation reaching the film, and hence is independent of subject contrast.

Definition refers to the sharpness of outline in the image. It depends on the types of screens and film used, the radiation energy (wavelengths, etc), and the geometry of the radiographic setup.

Subject Contrast

Subject contrast decreases as kilovoltage is increased. The decreasing slope (steepness) of the lines of the exposure chart (See Figure 44) as kilovoltage increases illustrates the reduction of subject contrast as the radiation becomes more penetrating. For example, consider a steel part containing two thicknesses, 3/4 inch and 1 inch, which is radiographed first at 160 kV and then at 200 kV.

KV	INCH THICKNESS	EXPOSURE TO GIVE D = 1.5 mA-MIN	RELATIVE INTENSITY	RATIO OF INTENSITIES
160	3/4	18.5	3.8	3.8
	1	70.0	1.0	
200	3/4	4.9	14.3	2.5
	1	11.0	5.8	

In the table above, column 3 shows the exposure in milliampere-minutes required to reach a density of 1.5 through each thickness at each kilovoltage. These data are from the exposure chart mentioned above. It is apparent that the milliampere-minutes required to produce a given density at any kilovoltage are inversely proportional to the corresponding x-ray intensities passing through the different sections of the specimen. Column 4 gives these relative intensities for each kilovoltage. Column 5 gives the ratio of these intensities for each kilovoltage.

Column 5 shows that, at 160 kV, the intensity of the x-rays passing through the 3/4-inch section is 3.8 times greater than that passing through the 1-inch section. At 200 kV, the radiation through the thinner portion is only 2.5 times that through the thicker. Thus, as the kilovoltage increases, the *ratio* of x-ray transmission of the two thicknesses decreases, indicating a lower subject contrast.

Film Contrast

The dependence of film contrast on density must be kept in mind when considering problems of radiographic sensitivity. In general the contrast of radiographic films, except those designed for use with fluorescent screens, increases continuously with density in the usable density range. Therefore, for films that exhibit this continuous increase in contrast, the best density, or upper limit of density range, to use is the highest that can conveniently be viewed with the illuminators available. Adjustable high-intensity illuminators that greatly increase the maximum density that can be viewed are commercially available.

The use of high densities has the further advantage of increasing the range of radiation intensities that can be usefully recorded on a single film. This in turn permits, in x-ray radiography, the use of lower kilovoltage, with resulting increase in subject contrast and radiographic sensitivity.

Maximum contrast of screen-type films is at a density of about 2.0. Therefore, other things being equal, the greatest radiographic sensitivity will be obtained when the exposure is adjusted to give this density.

Film Graininess, Screen Mottle

(See also "Film Graininess; Signal-to-Noise Ratio in Radiographs".)

The image on an x-ray film is formed by countless minute silver grains, the individual particles being so small that they are visible only under a microscope. However, these small particles are grouped together in relatively large masses, which are visible to the naked eye or with a magnification of only a few diameters. These masses result in the visual impression called *graininess*.

All films exhibit graininess to a greater or lesser degree. In general, the slower films have lower graininess than the faster. Thus, Film Y (Figure 47) would have a lower graininess than Film X.

The graininess of all films increases as the penetration of the radiation increases, although the rate of increase may be different for different films. The graininess of the images produced at high kilovoltages makes the slow, inherently fine-grain films especially useful in the million- and multimillion-volt range. When sufficient exposure can be given, they are also useful with gamma rays.

The use of lead screens has no significant effect on film graininess. However, graininess is affected by processing conditions, being directly related to the degree of development. For instance, if development time is increased for the purpose of increasing film speed, the graininess of the resulting image is likewise increased. Conversely, a developer or developing technique that results in an appreciable decrease in graininess will also cause an appreciable loss in film speed. However, adjustments made in development technique to compensate for changes in temperature or activity of a developer will have little effect on graininess. Such adjustments are made to achieve the same degree of development as would be obtained in the fresh developer at a standard processing temperature, and therefore the graininess of the film will be essentially unaffected.

Another source of the irregular density in uniformly exposed areas is the screen mottle encountered in radiography with the fluorescent screens. The screen mottle increases markedly as hardness of the radiation increases. This is one of the factors that limits the use of fluorescent screens at high voltage and with gamma rays.

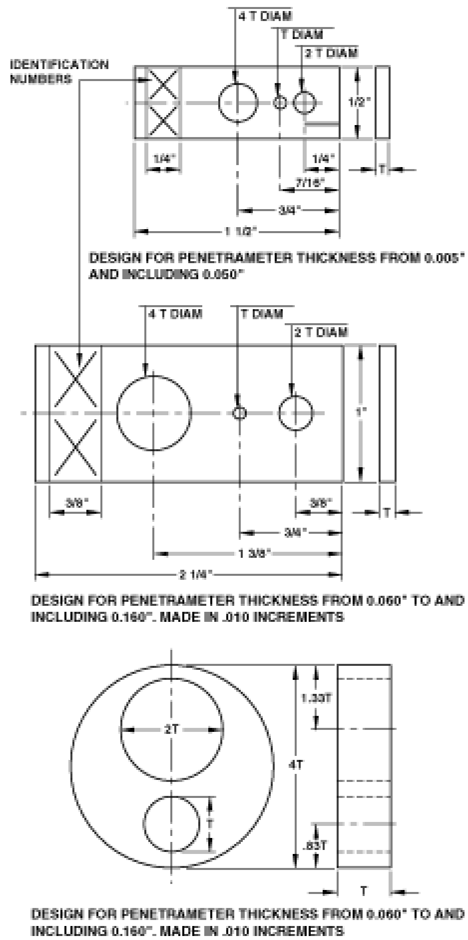
Penetrameters

A standard test piece is usually included in every radiograph as a check on the adequacy of the radiographic technique. The test piece is commonly referred to as a penetrameter in North America and an Image Quality Indicator (IQI) in Europe. The penetrameter (or IQI) is made of the same material, or a similar material, as the specimen being radiographed, and is of a simple geometric form. It contains some small structures (holes, wires, etc), the dimensions of which bear some numerical relation to the thickness of the part being tested. The image of the penetrameter on the radiograph is permanent evidence that the radiographic examination was conducted under proper conditions.

Codes or agreements between customer and vendor may specify the type of penetrameter, its dimensions, and how it is to be employed. Even if penetrameters are not specified, their use is advisable, because they provide an effective check of the overall quality of the radiographic inspection.

Hole Type Penetrameters
The common penetrameter consists of a small rectangular piece of metal, containing several (usually three) holes, the diameters of which are related to the thickness of the penetrameter (See Figure 65).

Figure 65: American Society for Testing and Materials (ASTM) penetrameter (ASTM E 142-68).



The ASTM (American Society for Testing and Materials) penetrameter contains three holes of diameters T, 2T, and 4T, where T is the thickness of the penetrameter. Because of the practical difficulties in drilling minute holes in thin materials, the minimum diameters of these three holes are 0.010, 0.020, and 0.040 inches, respectively. These penetrameters may also have a slit similar to the ASME penetrameter described below. Thick penetrameters of the hole type would be very large, because of the diameter of the 4T hole. Therefore, penetrameters more than 0.180 inch thick are in the form of discs, the diameters of which are 4 times the thickness (4T) and which contain two holes of diameters T and 2T. Each penetrameter is identified by a lead number showing the thickness in thousandths of an inch.

The ASTM penetrameter permits the specification of a number of levels of radiographic sensitivity, depending on the requirements of the job. For example, the specifications may call for a radiographic sensitivity level of 2-2T. The first symbol (2) indicates that the penetrameter shall be 2 percent of the thickness of the specimen; the second (2T) indicates that the hole having a diameter twice the penetrameter thickness shall be visible on the finished radiograph. The quality level 2-2T is probably the one most commonly specified for routine radiography. However, critical components may require more rigid standards, and a level of 1-2T or 1-1T may be required. On the other hand, the radiography of less critical specimens may be satisfactory if a quality level of 2-4T or 4-4T is achieved. The more critical the radiographic examination--that is, the *higher* the level of radiographic sensitivity required--the *lower* the numerical designation for the quality level.

Some sections of the ASME (American Society of Mechanical Engineers) Boiler and Pressure Vessel Code require a penetrameter similar in general to the ASTM penetrameter. It contains three holes, one of which is 2T in diameter, where T is the penetrameter thickness. Customarily, the other two holes are 3T and 4T in diameter, but other sizes may be used. Minimum hole size is 1/6 inch. Penetrameters 0.010 inch, and less, in thickness also contain a slit 0.010-inch wide and 1/4 inch long. Each is identified by a lead number designating the thickness in thousandths of an inch.

Equivalent Penetrameter Sensitivity
Ideally, the penetrameter should be made of the same material as the specimen. However, this is sometimes impossible because of practical or economic difficulties. In such cases, the penetrameter may be made of a radiographically similar material--that is, a material having the same radiographic absorption as the specimen, but one of which it is easier to make penetrameters. Tables of radiographically equivalent materials have been published wherein materials having similar radiographic absorptions are arranged in groups. In addition, a penetrameter made of a particular material may be used in the radiography of materials having *greater* radiographic absorption. In such a case, there is a certain penalty on the radiographic testers, because they are setting for themselves more rigid radiographic quality standards than are actually required. The penalty is often outweighed, however, by avoidance of the problems of obtaining penetrameters of an unusual material or one of which it is difficult to make penetrameters.

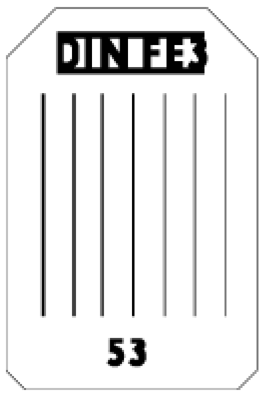
In some cases, the materials involved do not appear in published tabulations. Under these circumstances the comparative radiographic absorption of two materials may be determined experimentally. A block of the material under test and a block of the material proposed for penetrameters, equal in thickness to the part being examined, can be radiographed side by side on the same film with the technique to be used in practice. If the density under the proposed penetrameter materials is equal to or greater than the density under the specimen material, that proposed material is suitable for fabrication of penetrameters.

In practically all cases, the penetrameter is placed on the source side of the specimen--that is, in the least advantageous geometric position. In some instances, however, this location for the penetrameter is not feasible. An example would be the radiography of a circumferential weld in a long tubular structure, using a source positioned within the tube and film on the outer surface. In such a case a "film-side" penetrameter must be used. Some codes specify the film-side penetrameter that is equivalent to the source-side penetrameter normally required. When such a specification is not made, the required film-side penetrameter may be found experimentally. In the example above, a short section of tube of the same dimensions and materials as the item under test would be used to demonstrate the technique. The required penetrameter would be used on the source side, and a range of penetrameters on the film side. If the penetrameter on the source side indicated that the required radiographic sensitivity was being achieved, the image of the smallest visible penetrameter hole in the film-side penetrameters would be used to determine the penetrameter and the hole size to be used on the production radiograph.

Sometimes the shape of the part being examined precludes placing the penetrameter on the part. When this occurs, the penetrameter may be placed on a block of radiographically similar material of the same thickness as the specimen. The block and the penetrameter should be placed as close as possible to the specimen.

Wire Penetrameters
A number of other penetrameter designs are also in use. The German DIN (Deutsche Industrie-Norm) penetrameter (See Figure 66) is one that is widely used. It consists of a number of wires, of various diameters, sealed in a plastic envelope that carries the necessary identification symbols. The thinnest wire visible on the radiograph indicates the image quality. The system is such that only three penetrameters, each containing seven wires, can cover a very wide range of specimen thicknesses. Sets of DIN penetrameters are available in aluminum, copper, and steel. Thus a total of nine penetrameters is sufficient for the radiography of a wide range of materials and thicknesses.

Figure 66: DIN (German) penetrameter (German Standard DIN 54109).



Comparison of Penetrameter Design
The hole type of penetrameter (ASTM, ASME) is, in a sense, a "go no-go" gauge; that is, it indicates whether or not a specified quality level has been attained but, in most cases, does not indicate whether the requirements have been exceeded, or by how much. The DIN penetrameter on the other hand is a series of seven penetrameters in a single unit. As such, it has the advantage that the radiographic quality level achieved can often be read directly from the processed radiograph.

On the other hand, the hole penetrameter can be made of any desired material but the wire penetrameter is made from only a few materials. Therefore, using the hole penetrameter, a quality level of 2-2T may be specified for the radiography of, for example, commercially pure aluminum and 2024 aluminum alloy, even though these have appreciably different compositions and radiation absorptions. The penetrameter would, in each case, be made of the appropriate material. The wire penetrameters, however, are available in aluminum but not in 2024 alloy. To achieve the same quality of radiographic inspection of equal thicknesses of these two materials, it would be necessary to specify different wire diameters--that for 2024 alloy would probably have to be determined by experiment.

Special Penetrameters
Special penetrameters have been designed for certain classes of radiographic inspection. An example is the radiography of small electronic components wherein some of the significant factors are the continuity of fine wires or the presence of tiny balls of solder. Special image quality indicators have been designed consisting of fine wires and small metallic spheres within a plastic block, the whole covered on top and the bottom with steel approximately as thick as the case of the electronic component.

Penetrameters and Visibility of Discontinuities
It should be remembered that even if a certain hole in a penetrameter is visible on the radiograph, a cavity of the same diameter and thickness may not be visible. The penetrameter holes, having sharp boundaries, result in an abrupt, though small, change in metal thickness whereas a natural cavity having more or less rounded sides causes a gradual change. Therefore, the image of the penetrameter hole is sharper and more easily seen in the radiograph than is the image of the cavity. Similarly, a fine crack may be of considerable extent, but if the x-rays or gamma rays pass from source to film along the thickness of the crack, its image on the film may not be visible because of the very gradual transition in photographic density. Thus, a penetrameter is used to indicate the quality of the radiographic technique and not to measure the size of cavity that can be shown.

In the case of a wire image quality indicator of the DIN type, the visibility of a wire of a certain diameter does not assure that a discontinuity of the same cross section will be visible. The human eye perceives much more readily a long boundary than it does a short one, even if the density difference and the sharpness of the image are the same.

Viewing And Interpreting Radiographs

The examination of the finished radiograph should be made under conditions that favor the best visibility of detail combined with a maximum of comfort and a minimum of fatigue for the observer. To be satisfactory for use in viewing radiographs, an illuminator must fulfill two basic requirements. First, it must provide light of an intensity that will illuminate the areas of interest in the radiograph to their best advantage, free from glare. Second, it must diffuse the light evenly over the entire viewing area. The color of the light is of no optical consequence, but most observers prefer bluish white. An illuminator incorporating several fluorescent tubes meets this requirement and is often used for viewing industrial radiographs of moderate density.

For routine viewing of high densities, one of the commercially available high-intensity illuminators should be used. These provide an adjustable light source, the maximum intensity of which allows viewing of densities of 4.0 or even higher.

Such a high-intensity illuminator is especially useful for the examination of radiographs having a wide range of densities corresponding to a wide range of thicknesses in the object. If the exposure was adequate for the greatest thickness in the specimen, the detail reproduced in other thicknesses can be visualized with illumination of sufficient intensity.

The contrast sensitivity of the human eye (that is, the ability to distinguish small brightness differences) is greatest when the surroundings are of about the same brightness as the area of interest. Thus, to see the finest detail in a radiograph, the illuminator must be masked to avoid glare from bright light at the edges of the radiograph, or transmitted by areas of low density. Subdued lighting, rather than total darkness, is preferable in the viewing room. The room illumination must be such that there are no troublesome reflections from the surface of the film under examination.

Chapter 9: Industrial X-ray Films

Modern x-ray films for general radiography consist of an emulsion--gelatin containing a radiation-sensitive silver compound--and a flexible transparent, blue-tinted base. Usually, the emulsion is coated on both sides of the base in layers about 0.0005 inch thick. (See Figures 67 and 68) Putting emulsion on both sides of the base doubles the amount of radiation-sensitive silver compound, and thus increases the speed. At the same time, the emulsion layers are thin enough so that developing, fixing, and drying can be accomplished in a reasonable time. However, some films for radiography in which the highest detail visibility is required have emulsion on only one side of the base.

Figure 67: The silver bromide grains of an x-ray film emulsion (2,500 diameters). These grains have been dispersed to show their shape and relative sizes more clearly. In an actual coating, the crystals are much more closely packed.

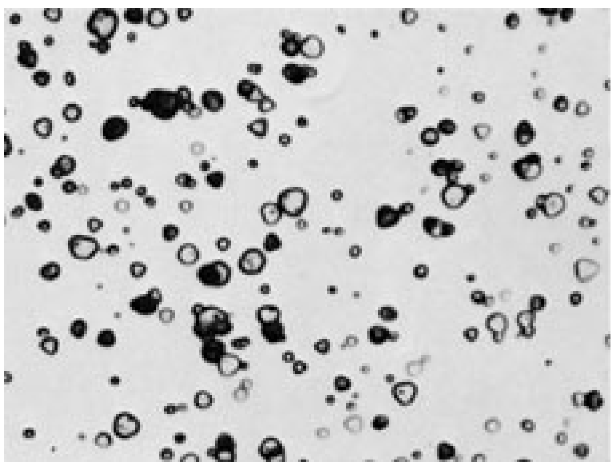
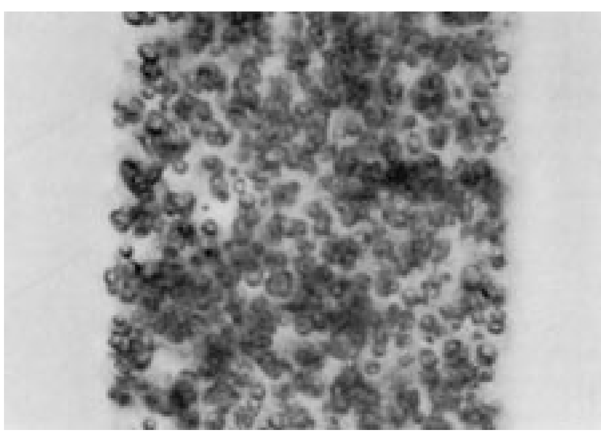
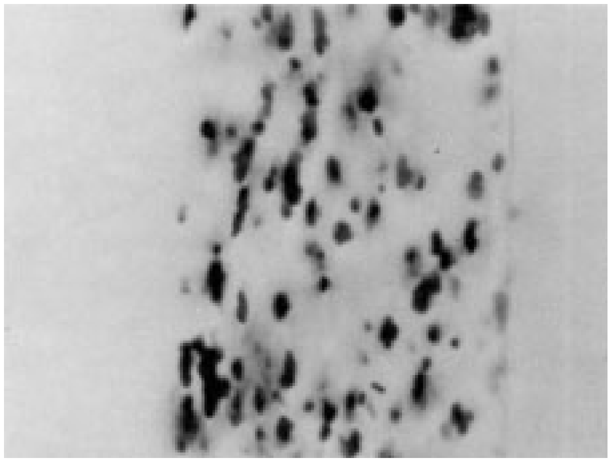


Figure 68: Cross section of the unprocessed emulsion on one side of an x-ray film. Note the large number of grains as compared to the developed grains of the Figure 69 this one.



When x-rays, gamma rays, or light strike the grains of the sensitive silver compound in the emulsion, a change takes place in the physical structure of the grains. This change is of such a nature that it cannot be detected by ordinary physical methods. However, when the exposed film is treated with a chemical solution (called a *developer*), a reaction takes place, causing the formation of black, metallic silver. It is this silver, suspended in the gelatin on both rides of the base, that constitutes the image. (See Figure 69) The details of this process are discussed in greater length later. Although an image may be formed by light and other forms of radiation, as well as by gamma rays or x-rays, the properties of the latter two are of a distinct character, and, for this reason, the sensitive emulsion must be different from those used in other types of photography.

Figure 69: Cross section showing the distribution of the developed grains in an x-ray film emulsion exposed to give a moderate density.



Selection Of Films For Industrial Radiography

Industrial radiography now has many widely diverse applications. There are many considerations in obtaining the best radiographic results, for example:

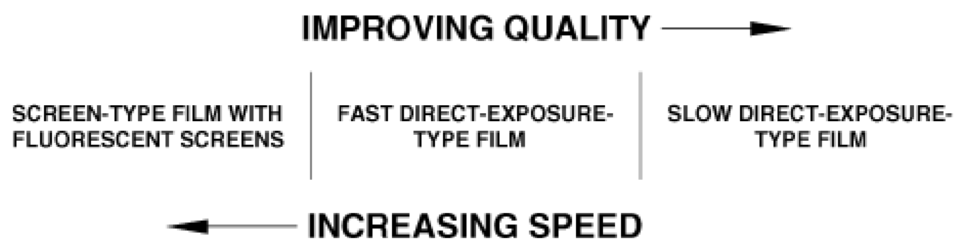
- the composition, shape, and size of the part being examined--and, in some cases, its weight and location as well
- the type of radiation used--whether x-rays from an x-ray machine or gamma rays from a radioactive material
- the kilovoltages available with the x-ray equipment
- the intensity of the gamma radiation
- the kind of information sought--whether it is simply an overall inspection or the critical examination of some especially important portion, characteristic, or feature
- the resulting relative emphasis on definition, contrast, density, and the time required for proper exposure

All of these considerations are important in the determination of the most effective combination of radiographic technique and x-ray film.

The selection of a film for the radiography of any particular part depends on the thickness and material of the specimen and on the voltage range of the available x-ray machine. In addition, the choice is affected by the relative importance of high radiographic quality or short exposure time. Thus, an attempt must be made to balance these two opposing factors. As a consequence, it is not possible to present definite rules on the selection of a film. If high quality is the deciding factor, a slower and hence finer grained film should be substituted for a faster one--for instance, for the radiography of steel up to 1/4-inch thick at 120-150 kV. Film Y (See Figure 47) might be substituted for Film X. If short exposure times are essential, a faster film (or film-screen combination) can be used. For example, 11/2-inch steel might be radiographed at 200 kV using fluorescent screens and a film particularly sensitive to blue light, rather than a direct exposure film with lead screens.

Figure 70 indicates the direction that these substitutions take. The "direct exposure" films may be used with or without lead screens, depending on the kilovoltage and on the thickness and shape of the specimen. (See "Radiographic Screens".)

Figure 70: Change in choice of film, depending on relative emphasis on high speed or high radiographic quality.



Fluorescent intensifying screens must be used in radiography requiring the highest possible photographic speed (see "Fluorescent Screens"). The light emitted by the screens has a much greater photographic action than the x-rays either alone or combined with the emission from lead screens. To secure adequate exposure within a reasonable time, screen-type x-ray films sandwiched between fluorescent intensifying screens are often used in radiography of steel in thicknesses greater than about 2 inches at 250 kV and more than about 3 inches at 400 kV.

Film Packaging

Industrial x-ray films are available in a number of different types of packaging, each one ideally suited to particular classes of radiography.

Sheet Films
Formerly, x-ray films were available only in individual sheets, and this form is still the most popular packaging. Each sheet of film may be enclosed in an individual paper folder (interleaved). The choice between the interleaved and non-interleaved films is a matter of the user's preference. When no-screen techniques are used, the interleaving paper can be left on the film during exposure, providing additional protection to the film against accidental fogging by light or marking by moist fingertips. In addition, many users find the interleaving folders useful in filing the finished radiographs, protecting them against scratches and dirt during handling, and providing a convenient place for notes and comments about the radiograph.

Envelope Packing
Industrial x-ray films are also available in a form in which each sheet is enclosed in a folder of interleaving paper sealed in a light tight envelope. The film can be exposed from either side without removing it from the envelope. A rip strip makes it easy to remove the film in the darkroom for processing. This form of packaging has the advantage that the time-consuming process of darkroom loading of cassettes and film holders is eliminated. The film is completely protected from finger marks and dirt until the time the film is removed from the envelope for processing.

Envelope Packing with Integral Lead Oxide Screens
The main feature of this type of packaging is that the sheet of film is an envelope is enclosed between two lead oxide screens which are in direct contact with the film. This form of packaging affords great convenience in material handling in an industrial x-ray department. As pointed out in "Lead Oxide Screens", it provides the advantage of cleanliness. This is particularly important where heavy inclusions in the specimen are significant. The use of film in this packaging prevents the images of such inclusions from being confused with artifacts caused by dust, cigarette ash,

and the like being introduced between film and screen during darkroom handling. The time-consuming process of loading and unloading cassettes and film holders is avoided.

Roll Films

In the radiography of circumferential welds in cylindrical specimens, in the examination of the joints of a complete frame of an aircraft fuselage, and the like, long lengths of film permit great economies. The film is wrapped around the outside of the structure and the radiation source is positioned on the axis inside allowing the examination of the entire circumference to be made with a single exposure. Long rolls of film are also convenient for use in mechanized exposure holders for the repetitive radiography of identical specimens or for step-and-repeat devices in which radiation source and film holder move in synchronism along an extended specimen.

Handling Of Film

X-ray film should always be handled carefully to avoid physical strains, such as pressure, creasing, buckling, friction, etc. The normal pressure applied in a cassette to provide good contacts is not enough to damage the film. However, whenever films are loaded in semiflexible holders and external clamping devices are used, care should be taken to be sure that this pressure is uniform. If a film holder bears against a few high spots, such as occur on an unground weld, the pressure may be great enough to produce desensitized areas in the radiograph. This precaution is particularly important when using envelope-packed films.

Marks resulting from contact with fingers that are moist or contaminated with processing chemicals, as well as crimp marks, are avoided if large films are always grasped by the edges and allowed to hang free. A convenient supply of clean towels is an incentive to dry the hands often and well. Use of envelope-packed films avoids these problems until the envelope is opened for processing. Thereafter, of course, the usual precautions must be observed.

Another important precaution is to avoid drawing film rapidly from cartons, exposure holders, or cassettes. Such care will help materially to eliminate objectionable circular or treelike black markings in the radiograph, the results of static electric discharges.

The interleaving paper should be removed before the film is loaded between either lead or fluorescent screens. When using exposure holders in direct exposure techniques, however, the paper should be left on the film for the added protection that it provides. At high voltage, direct-exposure techniques, electrons emitted by the lead backing of the cassette or exposure holder may reach the film through the intervening paper or felt and record an image of this material on the film. This effect is avoided by the use of lead or fluorescent screens. In the radiography of light metals, direct-exposure techniques are the rule, and the paper folder should be left on interleaved film when loading it in the exposure holder.

The ends of a length of roll film factory-packed in a paper sleeve should be sealed in the darkroom with black pressure-sensitive tape. The tape should extend beyond the edges of the strip 1/4 to 1/2 inch, to provide a positive light tight seal.

Identifying Radiographs

Because of their high absorption, lead numbers or letters affixed to the subject furnish a simple means of identifying radiographs. They may also be used as reference marks to determine the location of discontinuities within the specimen. Such markers can be conveniently fastened to the object with adhesive tape. A code can be devised to minimize the amount of lettering needed. Lead letters are commercially available in a variety of sizes and styles. The thickness of the letters chosen should be great enough so that their image is clearly visible on exposures with the most penetrating radiation routinely used. Under some circumstances it may be necessary to put the lead letters on a radiation-absorbing block so that their image will not be "burned out". The block should be considerably larger than the legend itself.

Shipping Of Unprocessed Films

If unprocessed film is to be shipped, the package should be carefully and conspicuously labeled, indicating the contents, so that the package may be segregated from any radioactive materials. It should further be noted that customs inspection of shipments crossing international boundaries sometimes includes fluoroscopic inspection. To avoid damage from this cause, packages, personal baggage, and the like containing unprocessed film should be plainly marked, if possible, and the attention of inspectors drawn to their contents.

Storage Of Unprocessed Film

With x-rays generated up to 200 LV, it is feasible to use storage compartments lined with a sufficient thickness of lead to protect the film. At higher kilovoltages, protection becomes increasingly difficult; hence, film should be protected not only by the radiation barrier for protection of personnel but also by increased distance from the source.

At 100 kV, a 1/8-inch thickness of lead should normally be adequate to protect film stored in a room adjacent to the x-ray room if the film is not in the line of the direct beam. At 200 kV, the lead thickness should be increased to 1/4 inch.

With million-volt x-rays, films should be stored beyond the concrete or other protective wall at a distance at least five times farther from the x-ray tube than the area occupied by personnel. The storage period should not exceed the times recommended by the manufacturer.

Medical x-ray films should be stored at approximately 12 times the distance of the personnel from the million-volt x-ray tube, for a total storage period *not exceeding two weeks*.

In this connection, it should be noted that the shielding requirements for films given in National Bureau of Standards Handbook 76 "Medical X-Ray Protection Up to Three Million Volts" and National Bureau of Standards Handbook 93 "Safety Standard for Non-Medical X-Ray and Sealed Gamma-Ray Sources, Part 1 General" are not adequate to protect the faster types of x-ray films in storage.

Gamma Rays
When radioactive material is not in use, the lead container in which it is stored helps provide protection for film. In many cases, however, the storage container for gamma-ray source will not provide completely satisfactory protection to stored x-ray film. In such cases, to prevent fogging, a sufficient distance should separate the emitter and the stored film. The conditions for the safe storage of x-ray film in the vicinity of gamma-ray emitters are given in Tables VII and VIII.

Table VII: Cobalt 60 Storage Conditions for Film Protection

Source Strength in Curies	1	5	10	25	50	100
Distance from Film Storage in Feet	**Lead Surrounding Source, in Inches[1]**					
25	5.5	7.0	7.5	8.0	8.5	9.0
50	4.5	6.0	6.5	7.0	7.5	8.0
100	3.5	5.0	5.5	6.0	6.5	7.0
200	2.5	4.0	4.5	5.0	5.5	6.0
400	1.5	3.0	3.5	4.0	4.5	5.0

Table VIII: Iridium 192 Storage Conditions for Film Protection

Output R/hr at 1 metre	1	2	5	10	25	50
Source Strength in Curies	**2**	**5**	**12.5**	**25**	**75**	**150**
Distance from Film Storage in Feet	**Lead Surrounding Source, in Inches[1]**					
25	1.70	1.85	2.15	2.35	2.50	2.70
50	1.35	1.50	1.85	2.00	2.15	2.35
100	1.00	1.15	1.50	1.70	1.85	2.00
200	0.70	0.85	1.15	1.35	1.50	1.70
400	0.35	0.50	0.85	1.00	1.15	1.35

[1]Lead thickness rounded off to nearest half-value thickness.

These show the necessary emitter-film distances and thicknesses of lead that should surround the various gamma-ray emitters to provide protection of stored film. These recommendations allow for a slight but harmless degree of fog on films when stored for the recommended periods.

The lead thicknesses and distances in tables above are considered the minimum tolerable.

To apply the cobalt 60 table to radium, values for source strength should be multiplied by 1.6 to give the grams of radium in a source that will have the same gamma-ray output and hence will require the same lead protection. This table can be extended to larger or smaller source sizes very easily. The half-value layer, in lead, for the gamma rays of radium or cobalt 60 is about 1/2 inch. Therefore, if the source strength is doubled or halved, the lead protection should be increased or decreased by 1/2 inch.

The table can also be adapted to storage times longer than those given in the tabulation. If, for example, film is to be stored in the vicinity of cobalt 60 for twice the recommended time, the protection recommendations for a source *twice* as large as the actual source should be followed.

Iridium 192 has a high absorption for its own gamma radiation. This means that the external radiation from a large source is lower, per curie of activity, than that from a small source.

Therefore, protection requirements for an iridium 192 source should be based on the radiation output, in terms of roentgens per hour at a known distance. The values of source strength, in curies, are merely a rough guide, and should be used only if the radiation output of the source is unknown. The table above can be extended to sources having higher or lower radiation outputs than those listed. The half-value layer of iridium 192 radiation in lead is about 1/6 inch. Therefore, if the radiation output is doubled or halved, the lead thicknesses should be respectively increased or decreased by 1/6 inch.

Tables VII and VII are based on the storage of a particular amount of radioactive material in a single protective lead container. The problem of protecting film from gamma radiation becomes more complicated when the film is exposed to radiation from several sources, each in its own housing. Assume that a radiographic source is stored under the conditions required by Tables VII and VII (for example, a 50-curie cobalt 60 source, in a 6.5-inch lead container 100 feet from the film storage). This combination of lead and distance would adequately protect the film from the gamma radiation for the storage times given in the tables. However, if a second source, identical with the first and in a similar container, is stored alongside the first, the radiation level at the film will be doubled. Obviously, then, if there are several sources in separate containers, the lead protection around each or the distance from the sources to the film must be increased over the values given in the tables.

The simplest method of determining the film protection required for several sources is as follows. Multiply the actual total strength of the source in each container by the number of separate containers. Then use these assumed source strengths to choose lead thicknesses and distances Tables VII and VIII, and apply the values so found for the protection around each of the actual sources. For instance, assume that in a particular radiographic department there are two source containers, both at 100 feet from the film storage area. One container holds 50 curies of cobalt 60 and the other an iridium 192 source whose output is 5 roentgens per hour at 1 metre (5 rhm). Since there are two sources, the 5 curies of cobalt 60 will require the protection needed for a "solitary" 100-curie source, and the iridium 192 source will need the same protection as if a source whose output is 10 rhm were alone irradiating the stored film. The thicknesses of lead needed are shown to be 7.0 inches for the 50 curies of cobalt 60 (Table VII) and 1.7 inches for the iridium 192 whose emission is 5 rhm (Table VIII).

This method of determining the protective requirements when multiple sources must be considered is based on two facts. First, if several sources, say four, simultaneously irradiate stored film, the exposure contributed by each must be only one-quarter that which would be permissible if each source were acting alone--in other words, the gamma-ray attenuation must be increased by a factor of four. Second, any combination of source strength, lead thickness, and distance given in Tables VII and VIII results in the same gamma-ray dose rate--about 0.017 mr per hour--being delivered to the film location. Thus, to determine conditions that would reduce the radiation from a particular source to one-quarter the value on which Tables BII and VIII are based, it is only necessary to use the conditions that are set up for a source four times the actual source strength.

Heat, Humidity, and Fumes

During packaging, most x-ray films are enclosed in a moisture proof container that is hermetically sealed and then boxed. As long as the seal is unbroken, the film is protected against moisture and fumes. Because of the deleterious effect of heat, all films should be stared in a cool, dry place and ordered in such quantities that the supply of film on hand is renewed frequently.

Under no circumstances should opened boxes of film be left in a chemical storage room or in any location where there is leakage of illuminating gas or any other types of gases, or where there is a possibility of contact with formalin vapors, hydrogen sulfide, ammonia, or hydrogen peroxide.

Packages of sheet film should be stored on edge--that is, with the plane of the film vertical. They should *not* be stacked with the boxes horizontal because the film in the bottom boxes can be damaged by the impact of stacking or by the weight of boxes above. In addition, storing the boxes on edge makes it simpler to rotate the inventory--that is, to use the older films first.

Storage Of Exposed And Processed Film

Archival Keeping
Many factors affect the storage life of radiographs. One of the most important factors is residual thiosulfate (from the fixer chemicals) left in the radiograph after processing and drying. For archival storage1, ANSI PH1.41 specifies the amount of residual thiosulfate (as determined by the methylene blue test) to be a maximum level of 2 micrograms/cm^2 on each side of coarse-grain x-ray films. For short-term storage requirements, the residual thiosulfate content can be at a higher level, but this level is not specified. Washing of the film after development and fixing, therefore, is most important. The methylene blue test and silver densitometric test are laboratory procedures to be performed on *clear areas* of the processed film.

The following ANSI documents[2] may be used as an aid in determining storage conditions:

1. ANSI PH1.41, Specifications for Photographic Film for Archival Records, Silver Gelatin Type on Polyester Base
2. ANSI PH1.43, Practice for Storage of Processed Safety Photographic Film
3. ANSI PH4.20, Requirements for Photographic Filing Enclosures for Storing Processed Photographic Films, Plates, and Papers
4. ANSI PH4.8, Methylene Blue Method for Measuring Thiosulfate and Silver Densitometric Method for Measuring Residual Chemicals in Film, Plates, and Papers
5. ANSI N45.2.9, Quality Assurance Records for Nuclear Power Plants, Requirements for Collection, Storage and Maintenance of

Commercial Keeping

Since definite retention times for radiographs are often specified by applicable codes, archival keeping may not always be necessary. Recent studies3 have indicated that industrial x-ray films, with a residual thiosulfate ion level of up to 5 micrograms/cm^2, per side (as measured by the methylene blue method described in ANSI PH4.8) [4], should retain their information for at least 50 years when stored at 0 to 24°C (32 to 75°F) and a relative humidity of 30 to 50 percent. Peak temperatures for short time periods should not exceed 32°C (90°F) and the relative humidity should not exceed 60 percent. Storage conditions in excess of these ranges tend to reduce image stability. The extent of reduced image stability is very difficult to define, due to the great number of conditions that could exist outside of the above suggested storage condition ranges. It should be noted that this does not imply that industrial x-ray films with a total residual thiosulfate content of 5 micrograms/cm^2, per side, will have archival keeping characteristics. It does, however, suggest that these films will fulfill the needs of most current users of industrial x-ray film requiring a storage life of 50 years or less.

Additional Storage Suggestions

Regardless of the length of time a radiograph is to be kept, these suggestions should be followed to provide for maximum stability of the radiographic image:

1. Avoid storage in the presence of chemical fumes.
2. Avoid short-term cycling of temperature and humidity.
3. Place each radiograph in its own folder to prevent possible chemical contamination by the glue used in making the storage envelope (negative preserver). Several radiographs may be stored in a single storage envelope if each is in its own interleaving folder.
4. Never store unprotected radiographs in bright light or sunlight.

5. Avoid pressure damage caused by stacking a large number of radiographs in a single pile, or by forcing more radiographs than can comfortably fit into a single file drawer or shelf.

Other recommendations can be found in ANSI PH1.43.

[1]A term commonly used to describe the keeping quality of x-ray film, defined by the American National Standards Institute as "Archival Storage--Those storage conditions suitable for the preservation of photographic film having permanent value." This term is not defined in years in ANSI documents, but only in residual thiosulfate content (residual fixer) for archival storage.

[2]These documents may be obtained from the American National Standards Institute, Inc., 1430 Broadway, New York, NY 10018.

[3]These studies, called Arrhenius tests, are relatively short-term, elevated-temperature tests conducted under carefully controlled conditions of temperature and humidity that simulate the effects of natural aging.

[4]The methylene blue and silver densitometric methods produce data as a combination of both sides of double-coated x-ray film.