Chapter 15: Paper Radiography

To many radiographers and interpreters the words "radiograph" and "film" are synonymous. However, a combination of factors, among them, recurring silver shortages and rising costs of other nondestructive testing methods, have prompted increasing interest in the use of paper in industrial radiography. Developments in papers, screens, and processing techniques have resulted from the realization that radiographs on paper have distinct advantages to offer the user who will consider them, not in the context of x-ray film, but as the product of another recording medium, one which is to be viewed in an entirely different way.

Advantages of Paper Radiographs

What are some of the advantages of using paper in industrial radiography? For one, r*apid access*. A damp-dry radiograph can be put in the interpreter's hands in as little as 10 seconds after exposure. Moreover, radiographic paper, plus intensifying screens, plus proper exposure equals good *image quality*. With direct exposure, the image has acceptable subject contrast combined with wide latitude. *Convenience* and *economy* also enter the picture. The paper processor is portable, requires no plumbing connections and, in addition, has a low operating cost.

Applications for Paper Radiography

Where can you use paper radiographs in your nondestructive testing program? The applications are numerous. For instance, there are many stages in production that may require radiographic inspection *before* code or specification radiographs are made. This is a prime area for the use of paper in radiography. Other applications exist in foundries where in-process x-ray procedures are used to monitor practices of gating and risering; checking core positions in wax patterns; detecting shrinkage flaws, porosity, dross, or cavities in castings, and monitoring root passes; and subsequent weld passes for a variety of flaws.

Radiographs on paper also find application in checking circuit boards for proper assembly and absence of solder balls. In aircraft maintenance, paper radiographs can be used to inspect for water in honeycomb, foreign material in oil pumps, and for general survey work. Some other applications include on-site checking of pipelines, pressure vessels, and weldments; inspection in industries such as food processing, wood products, tires, seeds, and titanium reprocessing; bomb detection; and many types of survey radiography.

Factors Affecting Paper Radiographs

Although there are areas of similarity between radiographs on paper and radiographs on film, recognition of the differences between the two is, in some instances, the governing factor for the production of good paper radiographs. Paper requires more exposure control than film because it has less exposure latitude and a shorter density scale. On the other hand, both paper and film require control of scatter radiation in order to realize the most that is in the product.

Exposure Techniques

The fact that radiographic papers have a shorter density scale and less exposure latitude than industrial x-ray films demands more critical exposure parameters. There are, therefore, precise techniques for exposing these papers to achieve a properly exposed paper radiograph quickly. It is possible to choose a kilovoltage that will tend to yield an acceptable penetrameter sensitivity for a given metal and thickness range.

Processing Techniques

Radiographs on paper can be processed by stabilization, by automatic film processing, or manually.

Stabilization Processing

Stabilization processing is a method of producing radiographs on paper much faster than is possible by conventional develop-stop-fix-wash processing. The primary differences between stabilization processing and ordinary radiographic processing are in the speed and mechanism of development and in the method of treating the unexposed, light-sensitive silver halide left in the emulsion after development. Exposed paper processed by stabilization makes quality, ready-to-use radiographs available in seconds. These stabilized radiographs are not permanent, because the chemical reactions within the emulsion have been stopped only temporarily. They will, however, last long enough to serve a number of practical purposes.

In conventional processing, unused silver halide is dissolved by fixer and any traces of soluble silver compounds left after fixing are removed by washing. The resulting radiographs are stable for long periods. In stabilization processing, the silver halide is converted to compounds that are only temporarily stable and the radiographs have a limited keeping time. Stabilized radiographs often remain unchanged for many months if they are not exposed to strong light, high temperature, or excessive humidity. Commercial keeping quality can be achieved by fixing and washing if a longer-lasting record is desirable.

Papers designed for stabilization processing have developing agents in the paper emulsion. Development is achieved by applying an alkaline activator to the emulsion surface. The stabilizer is applied to neutralize the activator and to convert any remaining silver halide to *relatively* stable, colorless compounds. Ordinary photographic papers or x-ray films cannot be developed by this process because there are no developing agents present in either the emulsion or the activator. Stabilization papers with developing agents in the emulsion can also be hand-processed in x-ray processing chemicals.

Advantages of the Stabilization Process
In a stabilization process, a measure of radiographic stability is exchanged for some definite advantages.

Simplicity. The process is adaptable to uncomplicated mechanical systems.

Space Saving Darkroom. Space and plumbing needs are greatly reduced. In fact, some applications of the process do not require a darkroom.

Water Saving. Stabilized radiographs do not require washing.

Greater Uniformity. Mechanically processed radiographs have better day-to-day uniformity in density than those processed manually.

Successful Stabilization Processing
To realize the advantages of stabilization processing, there are a number of factors that must be taken into account.

Correct Exposure. This is essential because in this type of processing the developing time is constant.

Processor Maintenance. Follow the manufacturer's recommendations for cleaning and maintenance of the processor.

Capacity of Solutions. Don't overwork chemical solutions. Observe the manufacturer's recommendations in regard to capacity and renewal of solutions. Discard solutions--

1. When 150 square feet of radiographic paper has been processed
2. After 1 week regardless of the amount of paper processed
3. When a processed radiograph shows noticeable degradation
4. Dry Processing Trays. Check before loading them with chemicals. Some stabilization solutions are not compatible with water.

Avoid contamination of the activator with the stabilizer. This results in chemical fog on the radio- graphs. The smell of ammonia is an indication of contamination.

Do not wash stabilized radiographs unless they have been fixed in an ordinary fixing bath. Washing without fixing makes a stabilized radiograph sensitive to light.

Because stabilized radiographs are impregnated with chemicals, *do not file* them *in contact with processed x-ray films* or other valuable material. Stabilized radiographs that are to be kept for an *extended period of time* must be *fixed and washed* (post-stabilization processing).

Automated Processing

Some radiographic papers can be processed in specially modified automated film processors. However, papers designed for stabilization processing are not usually processible in film processors. Check the paper manufacturer's recommendations for specific processing information.

Radiographic paper cannot be intermixed with x-ray film for processing. Replenishment rates for paper are much lower than for film. Consequently, if film is intermixed with paper, the film will receive improper processing.

Manual Processing

Most radiographic papers can be processed manually. Check the manufacturer's recommendations for the specific processing chemicals, times, and temperatures required.

Viewing Paper Radiographs

A correctly exposed, properly processed radiograph on paper is only part of the story. To be useful in providing information, the radiograph must be viewed, and viewing radiographs on light-reflecting paper is entirely different from viewing radiographs on light-transmitting film. It is almost immediately apparent that some of the familiar methods of measurement and interpretation applicable to film are not relevant to the interpretation of paper radiographs.

Density--Transmission vs Reflection
When electromagnetic radiation--in the form of light, x-rays, or gamma rays--reacts with the sensitive emulsion of x-ray film or radiographic paper, the emulsion will show a blackening after it has been processed. The degree of blackening is defined as *density*. Up to this point, radiographic paper acts identically like film, but beyond this point, differences appear.

Density--Measurement
The density on transparent-based film is known as *transmission density*. D_T and is defined as the logarithm of the ratio of the incident light intensity, I_O (from the illuminator), on the radiograph, to the light intensity transmitted through the radiograph, I_T. The formula is:

$$D_T = \text{Log}\frac{I_O}{I_T}$$

Since this formula applies only to light-transmitting images, it cannot be applied to an opaque-based imaging material such as radiographic paper. Therefore, a slightly different means of measuring density is necessary, and this is called *reflection density*, D_R. Reflection density is defined as the logarithm of the ratio of incident light intensity, I_O, to the reflected light intensity, I_R from the image area. This formula is:

$$D_R = \text{Log}\frac{I_O}{I_R}$$

So, although the formula appears to be quite similar to that of transmission density, in practical application, reflection density measures the light reflected from the radiograph, not that which passes through. For example, reflection densities are measured by a *reflection densitometer*, and the familiar densitometer for measuring transmitted densities cannot be used.

To carry the discussion one step further, exposure is defined as the product of the quantity of radiation--measured in roentgens or other units--and time. In this respect, the exposure to radiographic paper is measured exactly the same as it is for x-ray film, although the order of magnitude of the exposure may be different. Reflection characteristic curves can be generated for radiographic paper. The difference between these curves and those for film is that transmission density values are used for x-ray film, while reflection densities are used for radiographic paper. Characteristic curves (which are also known as H & D curves) for paper have a shorter range of densities and usually a shorter log exposure scale.

Comparable Densities--Paper and Film
Interpreters could easily be led astray at this point by becoming involved in the purely objective relationship between reflection density and transmission density. They may theorize, for example, that under a given set of viewing conditions, reflection density of 0.7 appears to them to be similar to a transmission density of 2.0. In reality, the transmission density to reflection density relationship has no bearing upon where the same radiographic information is recorded on the film's transmission density scale as related to the paper's reflection density scale. The question really is--which densities contain the same information if x-ray film and radiographic paper are used to record the same image?

Given the correct intensity of illumination, it is universally believed that the most useful information is recorded on the essentially straight line portion of the characteristic curve. In fact, it is rather generally accepted that in industrial radiography the higher the density of a film radiograph, the better the visibility of tiny discontinuities limited mainly by the available intensity of the illuminator. Because of the essentially opaque base of paper radiographs and the shoulder effect of the H & D curve of paper, this concept cannot be applied to reflection densities.

A radiographic image on paper of the same image area of a subject will contain the same important image details as a radiograph on film. These details will be modified in density (and possibly in contrast) because the response is fundamentally different.

It must also be recognized, of course, that the *total range* of information capable of being recorded will be less on a paper radiograph because the reflection density scale is shorter than its x-ray film counterpart. For example, a reflection density of 2.0 on a paper radiograph is so black that detail is completely obscured.

In addition, because of the opaque nature of the paper base, the method of viewing reflected densities of images on paper is fundamentally different from the method for viewing transmitted

densities. Although these differences exist and must be recognized, the similarities in practical usage between film and paper radiographs are even more striking. *Good practice indicates that the exposure given to a radiographic paper is adjusted until the necessary and desirable details of the image are distributed along the available density scale of the paper within the constraints of optimum reflection viewing.*

If this is done correctly, it will be noticed that the important details will tend to be found in the mid-scale of subjective brightness provided by the density scale of the paper. This is strikingly similar to that of a film radiograph in which the details of a good image tend to be centered around the middle of the density scale (usually about 2.0). The center point, or aim point, then, is a significant factor for visualization of detail for both paper and film radiographs--even though the aim point may be a different value, and the densities may be reflected or transmitted.

Interpreting Paper Radiographs

Whether produced on film or on paper, a radiograph containing useful information must be viewed by an observer for the purpose of interpretation. The viewing process is, therefore, a subjective interpretation based on the variety of densities presented in the radiograph. To perform this function, the eye must obviously be capable of receiving the information contained in the image. Judgements, likewise, cannot be made if the details cannot be seen.

Viewing conditions are obviously of utmost importance in the interpretation of radiographs. As a general rule, extraneous reflections from, and shadows over, the area of interest must be avoided, and the general room illumination should be such that it does not impose any unnecessary eyestrain on the interpreter.

When following these general guidelines in viewing film radiographs, then, the light transmitted through the radiograph should be sufficient only to see the recorded details. *If the light is too bright, it will be blinding; if too dim, the details cannot be seen*. The general room illumination should be at approximately the same level as that of the light intensity transmitted through the radiograph to avoid shadows, reflections, and undue eyestrain.

The natural tendency is to view radiographs on paper, like a photograph, in normal available light. For simple cursory examination this can be done, but since normal available light might be anything from bright sunlight to a single, dim, light bulb, some guidelines are necessary. It has been found from practical experience that radiographic sensitivity can be greatly enhanced if the following guidelines for viewing are observed.

1. As noted in the general rule, all extraneous shadows or reflections in the viewing area of the radiograph that adversely affect the eyes must be avoided. In fact, *a darkened area, minimizing ambient lighting*, is desirable.
2. Since radiographs on paper must be viewed in *reflected light, several sources of reflected light* have been used successfully. One method is the use of *specular light* (light focused from a mirror-like reflector) directed at an angle of approximately 30° to the surface of the radiograph from the viewer's side, so that reflected light does not bother the eyes. Light that comes from a slide projector is specular light.

Other sources are the familiar high-intensity reading light, like a Tensor light, or a spotlight. Another type of light that has been found to be very effective is a circular *magnifying glass* illuminated around the periphery with a *circular fluorescent bulb*. When using this form of illumination, the paper radiograph should be inclined at an oblique angle to the light to produce the same specular lighting just discussed. These devices found in drafting rooms as well as medical examining rooms are usually mounted on some sort of adjustable stand, and have the advantage of low power magnification on the order of 3X to 5X. The magnifying glass should be

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such that it does not distort the image, but it does emphasize the fact that the graininess characteristics of paper radiographs are minimal.

Reflection density is different from transmission density. The difference is important in viewing and interpreting radiographs on paper, but presents no difficulty in procedure or visualization.

Chapter 16: Sensitometric Characteristics of X-ray Films

The Characteristic Curve

The relation between the exposure and the density in the processed radiograph is commonly expressed in the form of a characteristic curve, which correlates density with the logarithm of relative exposure.

Photographic density is dimensionless, since it is the logarithm of a dimensionless ratio. There are, therefore, no "units" of density. In this respect, it is similar to a number of other physical quantities, for example, pH, specific gravity, and atomic weight.

Contrast
The slope, or steepness, of the characteristic curve for x-ray film changes continuously along its length. (See "The Characteristic Curve".) The density difference corresponding to a difference in specimen thickness depends on the region of the characteristic curve on which the exposures fall. The steeper the slope of the curve in this region, the greater is the density difference, and hence the greater is the visibility of detail. (This assumes, of course, that the illuminator is bright enough so that a reasonable amount of light is transmitted through the radiograph to the eye of the observer.)

The increasing ease of visibility of detail with increasing steepness of the characteristic curve is demonstrated in Figure 113. Figure 113B and C of the figure below are radiographs of the test object shown in Figure 113A. The radiographs differ only in the milliampere-seconds used to make them, that is, on the portion of the characteristic curve on which the densities fall. The details are much more clearly visible on radiograph C than on B because C falls on the steeper high-density portion of the characteristic curve (where the film contrast is high), while B falls on the much flatter toe portion.

Figure 113: A: Representation of a photograph of the test object. B and C: Radiographs of the test object. The exposure time for C was greater than that for B, all other factors remaining constant. Note that the structure of the test object is more clearly seen in C, since it was made on a steeper portion of the characteristic curve.
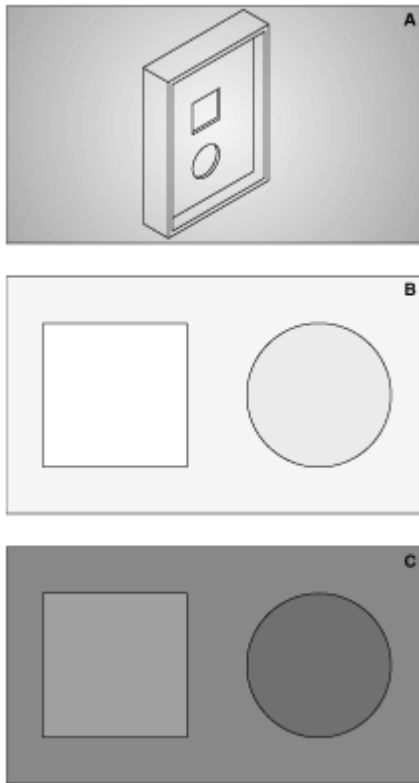
The type of example dealt with qualitatively, above, also lends itself to quantitative treatment.

The slope of a curve at any particular point may be expressed as the slope of a straight line drawn tangent to the curve at the point. When applied to the characteristic curve of a photographic material, the slope of such a straight line is called the gradient of the material at the particular density. A typical characteristic curve for a radiographic film is shown in the figure below. Tangents have been drawn at two points, and the corresponding gradients (ratios a/b, a'/b') have been evaluated. Note that the gradient varies from less than 1.0 in the toe to much greater than 1.0 in the high-density region.

Figure 114: Characteristic curve of a typical industrial x-ray film. Gradients have been evaluated at two points on the curve.
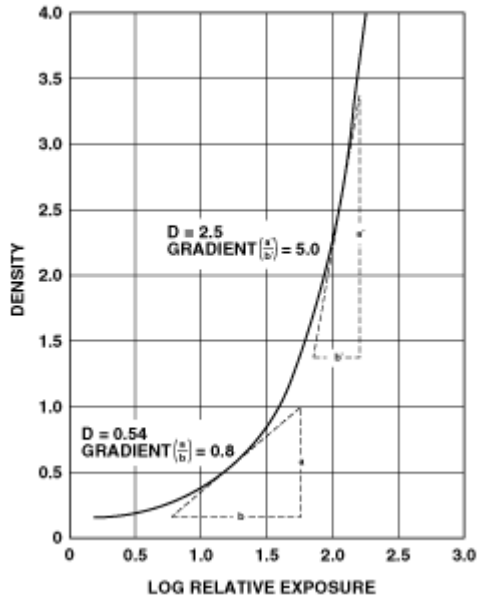
Now consider two slightly different thicknesses in a specimen. These transmit slightly different intensities of radiation to the film; in other words, there is a small difference in the logarithm of the relative exposure to the film in the two areas. Let us assume that at a certain kilovoltage the thinner section transmits 20 percent more radiation than the thicker. The difference in logarithm of relative exposure (Δ log E) is 0.08, and is independent of the milliamperage, exposure time, or source-film distance. If this specimen is now radiographed with an exposure that puts the developed densities on the toe of the characteristic curve where the gradient is 0.8, the x-ray intensity difference of 20 percent is represented by a density difference of 0.06 (See Figure 115). If the exposure is such that the densities fall on that part of the curve where the gradient is 5.0, the 20 percent intensity difference results in a density difference of 0.40.

Figure 115: Characteristic curve of a typical industrial x-ray film. Density differences corresponding to a 20 percent difference in x-ray exposure have been evaluated for the two values of gradient illustrated in Figure 114.
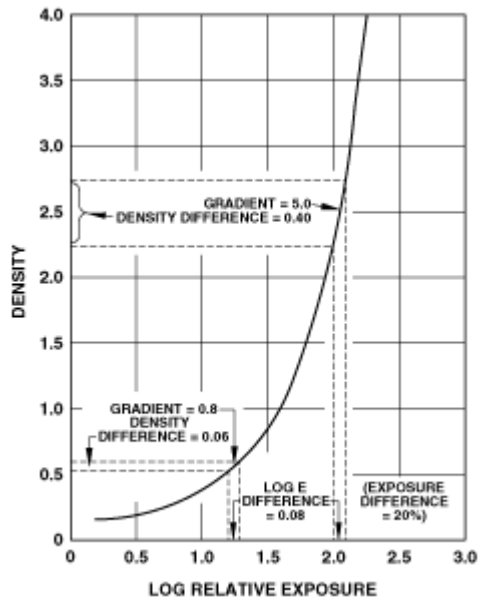
In general, if the gradient of the characteristic curve is greater than 1.0, the intensity ratios, or subject contrasts, of the radiation emerging from the specimen are exaggerated in the radiographic reproduction, and the higher the gradient, the greater is the degree of exaggeration. Thus, at densities for which the gradient is greater than 1.0, the film acts as a "constant amplifier". Similarly, if the gradient is less than 1.0, subject contrasts are diminished in the radiographic reproduction.

A minimum density is often specified for radiographs. This is not because of any virtue in a particular density, but rather because of the gradient associated with that density. The minimum useful density is that density at which the minimum useful gradient is obtained. In general, gradients lower than 2.0 should be avoided whenever possible.

The ability of the film to amplify subject contrast is especially significant in radiography with very penetrating radiations, which produce low subject contrast. Good radiographs depend on the enhancement of subject contrast by the film.

The direct x-ray characteristic curves of three typical x-ray films are shown in the first figure below. The gradients of these curves have been calculated, and are plotted in the second figure below against the density. It can be seen that the gradients of Films X and Y increase continuously up to the highest densities that can conveniently be used in radiography. This is the basis for the recommendation that with these films one should use the highest densities that the available illuminators allow to be viewed with ease. The gradient versus density curve of Film Z has a form different from the others in that the gradient increases, then becomes essentially constant over the density range of about 1.5 to 2.5, beyond which it decreases. With this film, the greatest density difference corresponding to a small difference in transmission of the specimen is obtained in the middle range of densities and the maximum, as well as the minimum, useful density is governed by the minimum gradient that can be tolerated.

Figure 116: Characteristic curves of three typical industrial x-ray film.
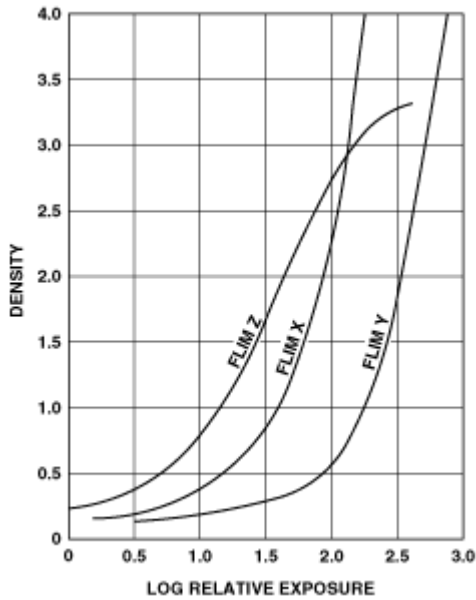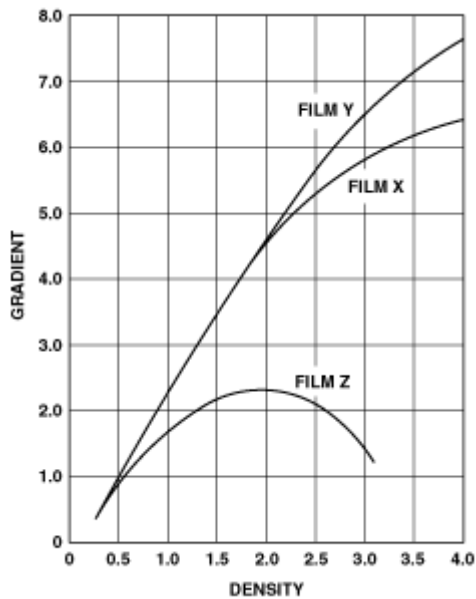

Figure 117: Gradient versus density curves of the typical industrial x-ray films, the characteristic curves of which are shown in Figure 116.

It is often useful to have a single number, rather than a curve as shown in the figure above, to indicate the contrast property of a film. This need is met by a quantity known as the *average gradient*, defined as the slope of a straight line joining two points of specified densities on the characteristic curve. In particular, the specified densities between which the straight line is drawn may be the maximum and minimum useful densities under the conditions of practical use. The average gradient indicates the average contrast properties of the film over this useful range; for a given film and development technique, the average gradient depends on the density range chosen. When high-intensity illuminators are available and high densities are used, the average gradient calculated for the density range 2.0 to 4.0 represents the contrast characteristics of the

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film fairly well. If high densities are for any reason not used, a density range of 0.5 to 2.5 is suitable for evaluation of this quantity. If intermediate densities are used, the average gradient can be calculated over another range of densities--1.0 to 3.0, for example.

Figure 118: Characteristic curve of a typical industrial x-ray film, with the average gradient calculated over two density ranges.

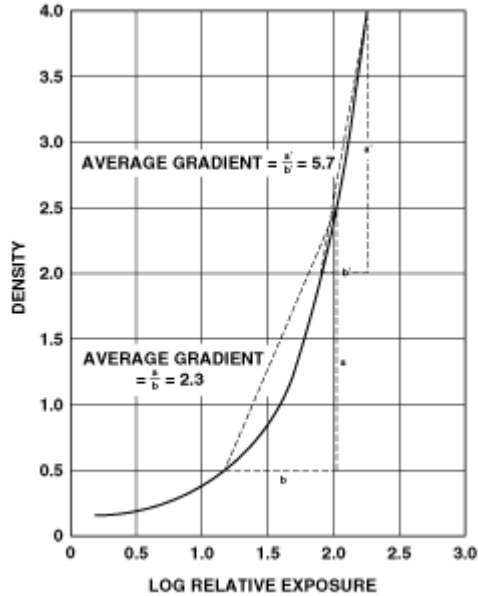
Figure 118shows the characteristic curve of a typical industrial x-ray film. The average gradients for this film over both the above density ranges are indicated. The table below gives average gradients of the typical x-ray films, the characteristic curves of which are shown in Figure 116. Since Film Z does not reach a density of 4.0, its average gradient cannot be given for the higher density range.

	Average Gradient	
Film	Density Range 0.5--2.5	Density Range 2.0--4.0
X	2.3	5.7
Y	2.6	6.3
Z	1.7	--

Experiments have shown that the shape of the characteristic curve is, for practical purposes, largely independent of the wavelength of x-radiation or gamma radiation. Therefore, a characteristic curve made with any radiation quality may be applied to exposures made with any other, to the degree of accuracy usually required in practice, and the same is true of values of gradient or average gradient derived from the curve.

The influence of kilovoltage or gamma-ray quality on contrast in the radiograph, therefore, is the result primarily of its effect on the subject contrast, and only very slightly, if at all, of any change in the contrast characteristics of the film. Radiographic contrast can also be modified by choice of a film of different contrast, or by use of a different density range with the same film. Contrast is also affected by the degree of development, but in industrial radiography, films are developed to their maximum, or nearly their maximum, contrast. In the early stages of development, both density and contrast increase quite rapidly with time of development (See "Effect Of Development Time

On Speed And Contrast"). However, to use manual processing as an example, the minimum recommended development time gives most of the available density and contrast. With certain of the direct x-ray film types, somewhat higher speed and, in same cases, slightly more contrast are gained by extending the development, but in no case should the maximum time recommended by the manufacturer be exceeded.

A special case arises when, for technical or economic reasons, there is a maximum allowable exposure time, that is, exposure time cannot be increased to take advantage of a higher film gradient at higher densities. In such a case, an increase in kilovoltage increases the radiation intensity penetrating the specimen, and hence the film is exposed to a higher density. This may result in an increase in radiographic contrast. An example may be taken from the exposures used to produce the exposure chart shown in Figure 44. The following table lists the densities obtained through the 1/2-inch to 5/8-inch sections, using an exposure of 8 mA-min.

kV	D_B $^1/_2$ in. steel	D_A $^5/_8$ in. steel	Radiographic Contrast D_B-D_A	Relative Radiographic Contrast
120	0.50	0.27	0.23	20
140	1.20	0.67	0.53	46
160	2.32	1.30	1.02	88
180	3.48	2.32	1.16	100

These data show that, when the exposure time is fixed, the density difference between the two sections increases, and hence the visibility of detail in this thickness range is also improved as the kilovoltage is raised. The improvement in visibility of detail occurs in spite of the decrease in the subject contrast caused by the increase in kilovoltage, and is the direct result of using higher densities where the gradient of the film is higher. Qualitatively, one may say that, in this particular case, the film contrast is increasing faster as a result of increased density than the subject contrast is decreasing as a result of increased kilovoltage. It should be emphasized again that this change in radiographic contrast resulting from a change in kilovoltage is not the result of a change in shape of the characteristic curve but rather the result of using a different portion of the characteristic curve--a portion where the slope is greater.

Speed
Film contrast depends on the *shape* of the characteristic curve. The other significant value obtained from the characteristic curve is the relative speed, which is governed by the location of the curve, along the log E axis, in relation to the curves of other films.

In Figure 16 the curves for the various x-ray films are spaced along the log relative exposure axis. The spacing of the curves arises from the differences in relative speed--the curves for the faster films lying toward the left of the figure, those for the slower films toward the right. From these curves, relative exposures to produce a fixed density can be read; the relative speeds are inversely proportional to these exposures. For some industrial radiographic purposes, a density of 1.5 is an appropriate level at which to compute relative speeds. However, the increasing trend toward high densities, with all radiographs viewed on high-intensity illuminators, makes a density of 2.5 more suitable for much industrial radiography. Relative speed values derived from the curves in Figure 116 for the two density levels are tabulated in the next table where Film X has arbitrarily been assigned a relative speed of 100 at both densities.

| Film	Density = 1.5		Density = 2.5	
	Relative Speed	Relative Exposure for D = 1.5	Relative Speed	Relative Exposure for D = 2.5
X	100	1.0	100	1.0
Y	24	4.2	26	3.9
Z	250	0.4	150	0.7

Note that the relative speeds computed at the two densities are not the same because of the differences in curve shape from one film to another. As would be expected from an inspection of these curves, this is most noticeable for Film Z.

Although the shape of the characteristic curve of a film is practically independent of changes in radiation quality, the location of the curve along the log relative exposure axis, with respect to the curve of another film, does depend on radiation quality. Thus, if curves of the type mentioned above were prepared at a different kilovoltage, the curves would be differently spaced, that is, the films would have different speeds relative to the film that was chosen as a standard of reference.

Density-Exposure Relation

The most common way of expressing the relation between film response and radiation intensity is the characteristic curve--the relation between the density and the *logarithm of the exposure*--which has been discussed above. If, however, density is plotted against *relative exposure* to x-rays or gamma rays--rather than against the logarithm of the exposure--in many cares there is a linear relation over a more or less limited density range (See Figure 119). If net density (that is, density above base density and fog), rather than gross density, is plotted against exposure, the straight line passes through the origin.

Figure 119: Density versus exposure curve for a typical industrial x-ray film exposed to direct x-rays or with lead screens. The density range over which a linear relationship exists between density and exposure depends on both the film type and the development.
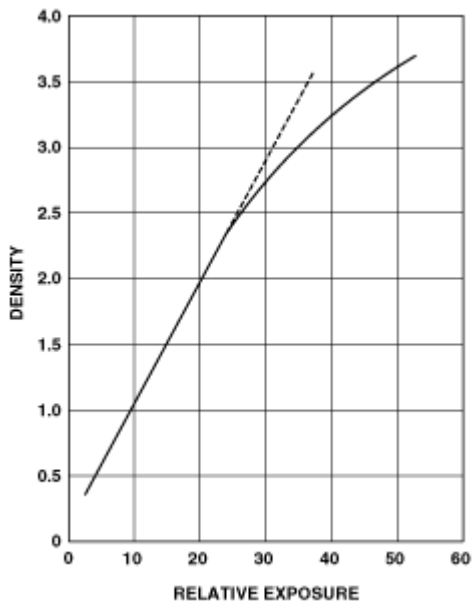
The linear relation cannot be assumed, however, but must be checked for the conditions involved in the particular application because the density range over which it is valid depends on the film

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used and on the processing conditions. The linear relation between density and exposure may be extremely useful, for instance, in the interpretation of diffraction patterns and the evaluation of radiation monitoring films, provided it is kept in mind that the linear range of the curve is limited.

Reciprocity Law Failure

The Bunsen-Roscoe reciprocity law states that the resultant of a photochemical reaction is dependent only on the *product* (I x t) of the radiation intensity (I) and the duration of the exposure (t), and is independent of the absolute values of either quantity. Applied to radiography, this means that the developed density in a film depends only on the *product* of x- or gamma-ray intensity reaching the film and the time of exposure.

The reciprocity law is valid for direct x-ray or gamma-ray exposures, or those made with lead foil screens, over a range of radiation intensities and exposure times much greater than those normally used in practice. It fails, however, for exposures to light and, therefore, for exposures using fluorescent intensifying screens. The magnitude of the differences that may be expected in practice are shown in an earlier table. Figure 120 shows a conventional reciprocity curve. (The data in the table were derived from a curve of this type.) The vertical axis in Figure 120 has been considerably expanded to make the curvature more apparent.

Figure 120: Reciprocity curve for light exposures. The corresponding curve for direct x-rays or lead screen exposures would be a straight line parallel to the log I axis.
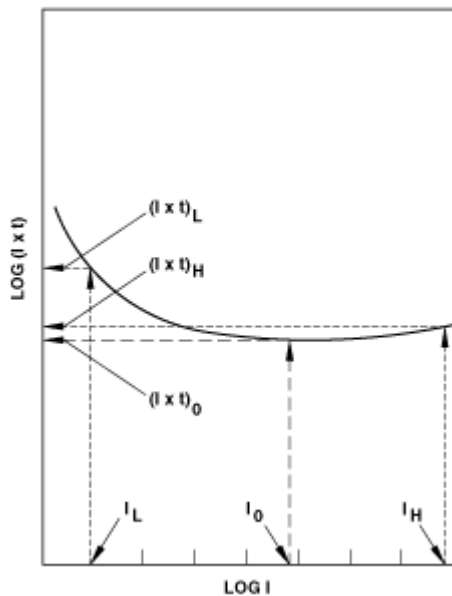
The logarithms of the exposures (I x t) that produce a given density are plotted against the logarithms of the individual intensities. It can be seen that for a particular intensity (I_O) the exposure $(I \times t)_O$ required to produce the given density is a minimum. It is for this intensity of light that the film is most efficient in its response. For light intensities higher (I_H) and lower (I_L) than I_O, the exposure required to produce the given density is greater than $(I \times t)_O$. Phrased differently, there is a certain intensity of light for which a particular film is most efficient in its response. In radiography with fluorescent screens, failure of the reciprocity law sometimes gives results that appear to be a failure of the inverse square law (See Table VI).

In most industrial radiography, the brightness of fluorescent intensifying screens is very low, and the exposures used lie on the left-hand branch of the curve shown in Figure 120. An exception is high-speed flash radiography in which the exposures lie to the right of the minimum.

See also "The Reciprocity Law".

Effect Of Development Time On Speed And Contrast

Although the shape of the characteristic curve is relatively insensitive to changes in x- or gamma-ray quality, it is affected by changes in degree of development. Degree of development, in turn, depends on the type of developer, its temperature, its degree of activity, and the time of development. Within certain limits, increased degree of development increases the speed and contrast of an x-ray film. If, however, development is carried too far, the speed of the film as based on a certain net density (density above base density and fog) ceases to increase and may even decrease. The fog increases and contrast may decrease.

Automated Processing
Automated processors and their associated chemicals are designed to give the optimum degree of development. All the variables, listed in the above paragraph, that affect the degree of development are controlled and kept constant by the processor. The responsibilities of the operator are to keep the machine clean and to make sure that temperatures, replenishment rates, and the like are maintained at the proper levels.

Manual Processing
In manual processing, however, all the processing variables are under the control of the operator. Although all are important in the production of the final radiograph, those associated with development are particularly so. The following discussion is therefore devoted to the effects of development variables, in the context of manual processing.

Figure 121 shows the characteristic curves of a typical industrial x-ray film developed for a series of times in developer at 68°F. It can be seen that as development time increases, the characteristic curve grows progressively steeper (contrast increasing) and moves progressively to the left (speed increasing). Note that the curves for 2 and 10 minutes represent development techniques that would never be encountered in practice. They are included here merely as extreme examples.

Figure 121: Characteristic curves of a typical industrial x-ray film, developed for 2, 3, 5, 8, and 10 minutes.
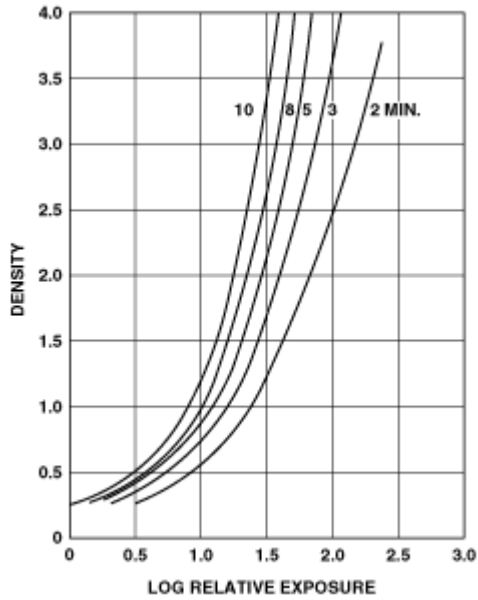
From the curves shown in Figure 121, values of relative speed and *average gradient* can be derived as explained earlier. These values, and fog, are plotted against development time in Figure 122. Curves of these quantities plotted against developer temperature, with development time held constant, show a similar form. At the maximum recommended development time of 8 minutes, the film used in this example has reached its maximum contrast, and further development would cause a decrease in film contrast, rather than an increase.

Figure 122: Time-speed and time-average gradient curves derived from the characteristic curves of Figure 121. The time-fog curve for the same development conditions is shown.
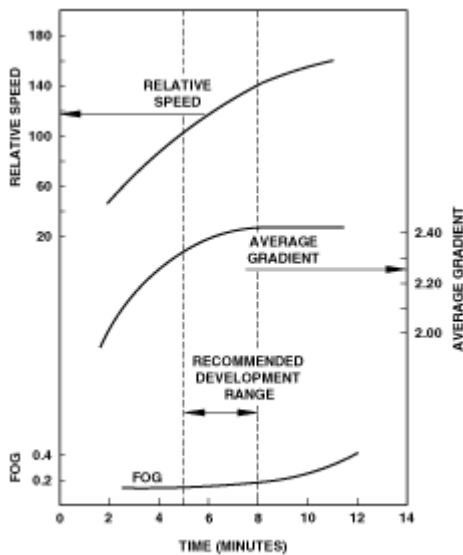
Curves of the type shown in Figure 122 depend on the particular film considered. Some films, for instance, increase very little in average gradient when the development time is increased from 5 to 8 minutes, the main effect being an increase in film speed. A practical point, however, should

be noted here. Although the average gradient of a film (*film contrast*) may be unaffected by a change of development time, increased development time may result in an increase in *radiographic contrast*, that is, density differences in the radiograph. This is illustrated by the figure below in which are plotted the characteristic curves of a typical industrial x-ray film for 5 and 8 minutes' development. These curves are of the same shape, indicating that the average gradients are the same for both times of development. The lateral spacing along the logarithm of relative exposure axis is a measure of the speed increase resulting from the increased development.

Figure 123: Portions of the characteristic curves of a typical industrial x-ray film developed for 5 and 8 minutes. Density differences corresponding to pairs of exposures differing by 25 percent are shown for each development time. (The scale of the figure is expanded from that of earlier figures for ease of illustration.)
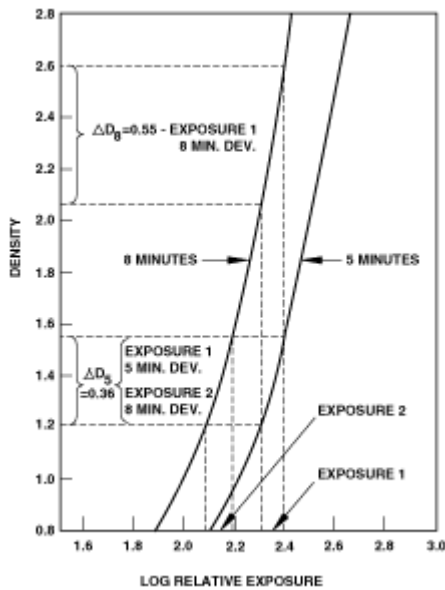
Consider two slightly different thicknesses in a specimen, one transmitting 25 percent more x-radiation than the other. The difference in log relative exposure between the two areas of the specimen (Δ log E) is 0.10. With a certain exposure time (Exposure 1), a radiograph developed for 5 minutes has a density of 0.36 (ΔD_5) between the two areas. On a radiograph given the same exposure but developed for 8 minutes, the density difference is 0.55 (ΔD_8). If, however, the exposure time is decreased to just compensate for the increased film speed at 8 minutes' development (Exposure 2), the log relative exposures corresponding to the two areas of the specimen are moved to the left, although the spacing between them (in terms of log exposure) remains constant. In this latter case, the density difference for 8 minutes development is the same as that for 5 minutes, that is, 0.36. This, of course, is merely a further illustration of the fact that the density difference corresponding to a certain difference in relative x-ray exposure depends on the region of the characteristic curve where the exposures fall.

X-Ray Spectral Sensitivity

As has been pointed out, the shape of the characteristic curve of an x-ray film is unaffected, for practical purposes, by the wavelength (energy) of the x-rays or gamma rays to which the film is exposed. However, the *sensitivity* of the film, in terms of the number of roentgens required to produce a given density, is strongly affected by the energy (wavelength) of the exposing radiation.

Figure 124 shows the number of roentgens needed to produce a density of 1.0 on a particular x-ray film under certain processing conditions. (Exposures were made without screens, either fluorescent or lead.)

The spectral sensitivity curves for all x-ray films have roughly the same general features as the curves shown in Figure 124. Details, among them the ratio of maximum to minimum sensitivity, differ from type to type of film, however.

The spectral *sensitivity* of a film, or differences in spectral sensitivity between two films, need rarely be considered in industrial radiography. Usually, such changes in sensitivity are automatically taken into account in the preparation of exposure charts See "Preparing An Exposure Chart") and of tables of relative film speeds. The spectral sensitivity of a film is, of course, very important in radiation monitoring, because in this case an evaluation of the number of roentgens incident on the film is required.

Figure 124: Typical x-ray spectral sensitivity curve of an x-ray film, showing the number of roentgens required to produce a density of 1.0 for various radiation qualities. Other films will have curves of similar shape, but shifted up or down depending on the properties of the film and the development technique used. (After Wilsey, Radiography, 56:229, 1951.)
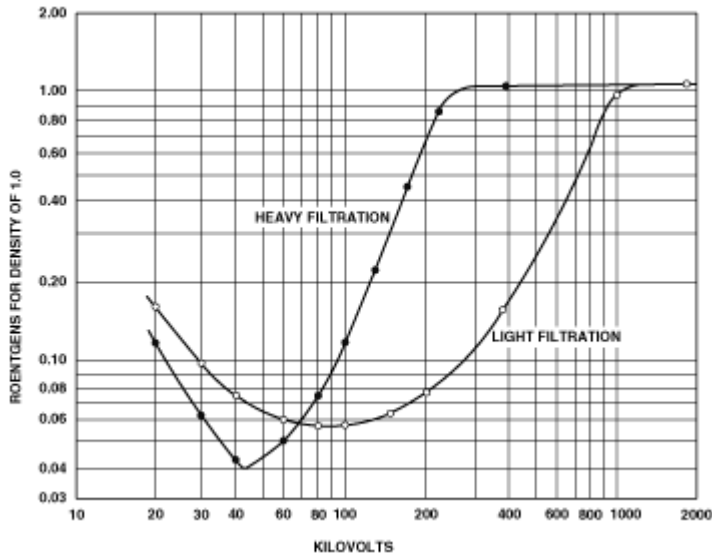
Chapter 17: Film Graininess; Signal-to-Noise Ratio in Radiographs

Graininess

Graininess is defined as the visual impression of nonuniformity of density in a radiographic (or photographic) image. With fast films exposed to high-kilovoltage radiation, the graininess is easily apparent to the unaided vision; with slow films exposed to low-kilovoltage x-rays, moderate magnification may be needed to make it visible. In general, graininess increases with increasing film speed and with increasing energy of the radiation.

The "clumps" of developed silver, which are responsible for the impression of graininess do not each arise from a single developed photographic grain. That this cannot be so can be seen from size consideration alone. The particle of black metallic silver arising from the development of a single photographic grain in an industrial x-ray film (See Figure 69) is rarely larger than 0.001 mm (0.00004 inch) and usually even less. This is far below the limits of unaided human vision.

Rather, the visual impression of graininess is caused by the random, statistical grouping of these individual silver particles. Each quantum (photon) of x-radiation or gamma radiation absorbed in the film emulsion exposes one or more of the tiny crystals of silver bromide of which the emulsion is composed (See Figure 67). These "absorption events" occur at random and even in a uniform x-ray beam, the number of absorption events will differ from one tiny area of the film to the next for purely statistical reasons. Thus, the exposed grains will be randomly distributed; that is, their numbers will have a statistical variation from one area to the next.

In understanding this effect, a simple analogy--a long sidewalk on a rainy day--will be of assistance. The sidewalk corresponds to the film and the raindrops to the x-ray photons absorbed in it. (Only those *absorbed* by the film are considered because only those that are absorbed have a photographic effect.) First, consider what happens in a downpour so hard that there is an *average* of 10,000 drops per block or square of the sidewalk. It would not be expected, however, that each square would receive precisely this average number of 10,000 drops. Since the raindrops fall at random, only a few or perhaps none of the squares would receive precisely 10,000 drops. Some would receive more than 10,000 and others less. In other words, the actual number of drops falling on any particular square will most likely differ from the average number of drops per square along the whole length of the sidewalk. The laws of statistics show that the *differences* between the actual numbers and the average number of drops can be described in terms of probability. If a large number of blocks is involved, the actual number of raindrops on 68 percent of the block, will differ from the average by no more than 100 drops or ±1 percent of the average.[1] The remaining 32 percent will differ by more than this number. Thus, the differences in "wetness" from one block of sidewalk to another will be small and probably unnoticeable.

This value of 100 drops holds only for an average of 10,000 drops per square. Now consider the same sidewalk in a light shower in which the average number of drops per square is only 100. The same statistical laws show that the deviation from the average number of drops will be 10 or ±10 percent of the average. Thus, differences in wetness from one square to the next will be much more noticeable in a light shower (±10 percent) than they are in a heavy downpour (±1 percent).

Now we will consider these drops as x-ray photons absorbed in the film. With a very slow film, it might be necessary to have 10,000 photons absorbed in a small area to produce a density of, for example, 1.0. With an extremely fast film it might require only 100 photons in the same area to

produce the same density of 1.0. When only a few photons are required to produce the density, the random positions of the absorption events become visible in the processed film as film graininess. On the other hand, the more x-ray photons required, the less noticeable the graininess in the radiographic image, all else being equal.

It can now be seen how film speed governs film graininess. In general, the silver bromide crystals in a slow film are smaller than those in a fast film, and thus will produce less light-absorbing silver when they are exposed and developed. Yet, at low kilovoltages, one absorbed photon will expose one grain, of whatever size. Thus, more photons will have to be absorbed in the slower film than in the faster to result in a particular density. For the slower film, the situation will be closer to the "downpour" case in the analogy above and film graininess will be lower.

The increase in graininess of a particular film with increasing kilovoltage can also be understood on this basis. At low kilovoltages each absorbed photon exposes one photographic grain; at high kilovoltages one photon will expose several, or even many, grains. At high kilovoltages, then, fewer absorption events will be required to expose the number of grains required for a given density than at lower kilovoltages. The fewer absorption events, in turn, mean a greater relative deviation from the average, and hence greater graininess.

It should be pointed out that although this discussion is on the basis of direct x-ray exposures, it also applies to exposures with lead screens. The agent that actually exposes a grain is a high-speed electron arising from the absorption of an x- or gamma-ray photon. The silver bromide grain in a film cannot distinguish between an electron that arises from an absorption event within the film emulsion and one arising from the absorption of a similar photon in a lead screen.

The quantum mottle observed in radiographs made with fluorescent intensifying screens has a similar statistical origin. In this case, however, it is the numbers of photons absorbed in the screens that are of significance.

Signal-To-Noise Ratio

The statistical reasoning used above has an application in considering the radiographic recording of small details. Again, the discussion will be in terms of direct x-ray exposures to industrial radiographic films, but the same principles apply to exposures with lead screens.

Because of the random spatial distribution of the photons absorbed in the film, the exposure to any small area of a film in a uniform beam of radiation is likely to differ by a small amount from the exposure to another area of the same size. This "noise" naturally interferes with the visibility of a small or faint detail, because the image of the detail may be lost in the density variations arising statistically.

It can be shown that for a given small area (A) on a uniformly exposed film, the noise (σD)--that is, the standard deviation of density--is proportional to the square root of the exposure to the film.[2] For this discussion it will be convenient to state the exposure in terms of the number (N) of photons absorbed in the film within the small area, A, being considered. Those photons not absorbed have no photographic effect.

This can be stated mathematically:

$$\text{NOISE} = \sigma D \propto \sqrt{N}$$

The "signal" transmitted to the film by a detail of area A in the object being radiographed is the difference (ΔN) between the number of photons reaching the film through the detail and the average number reaching similar areas of film outside the detail image. This signal is proportional to the exposure or

$$\text{SIGNAL} = \triangle N \propto N$$

The ratio of signal to noise has a profound bearing on the minimum size of detail that can be seen. It has been shown that for threshold visibility of detail, this signal-to-noise ratio must be at least 5.

An example can be given to illustrate how the information content of a radiograph depends on exposure--that is, depends on the number of x-ray photons involved in forming the image. Consider a penetrameter on a flat steel plate (See Figure 125). The penetrameter has a single hole, the image of which is to be made visible in the radiograph. The area of the hole (A) will be the unit of area. Suppose that in a 0.01-second exposure, for example, an average of 100 of the photons per unit area (A) transmitted through the plate and penetrameter body interact with the film to form an image. In the area of the hole, however, assume that an average of 101 photons interact with the film in the same time. Thus the "signal" that it is hoped to detect--the excess of radiation through the hole above that in the background--is one photon. But, the standard deviation of the number of photons in the background is the square root of 100, or 10. In this case, it would be impossible to detect the signal (the image of the penetrameter hole) because the "noise" is ten times as great as the signal.

Figure 125
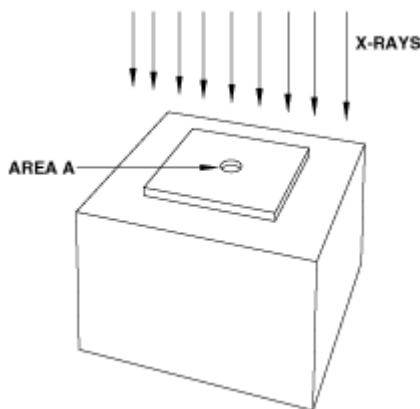
It will now be interesting to see what happens when the number of photons that are absorbed in the film is increased. This can be done by increasing the exposure time above the 0.01 second originally assumed in this example. The table below shows the conditions for a series of increasing times. "Background" is the number of absorbed photons per "hole area" beneath plate and penetrameter; "signal" is the excess of absorbed photons through the hole.

Exposure Time (seconds)	Background	Signal	Noise	Signal - Noise Ratio
0.01	100	1	$\sqrt{100}$	0.1
0.1	1,000	10	$\sqrt{1,000}$	0.316
1.0	10,000	100	$\sqrt{10,000}$	1
10.0	100,000	1,000	$\sqrt{100,000}$	3.16
30.0	300,000	3,000	$\sqrt{300,000}$	5.5
100.0	1,000,000	10,000	$\sqrt{1,000,000}$	10

Since threshold visibility of a detail is not achieved until the signal-to-noise ratio is at least 5, the penetrameter hole would not be visible until an exposure of 30 seconds (in this example) had

been reached. If the exposure were extended to 100 seconds, visibility of the detail would be more certain, because the signal-to-noise ratio would be increased to 10.

Suppose, now, there were two conventional industrial radiographic films, one of which gave a density of 2.0 for 300,000 absorbed photons over the area A of the penetrameter hole (exposure of 30 seconds in the example used), and the other about one-third the speed, requiring 1,000,000 photons absorbed over the same area to give the same density. The penetrameter hole would be much more visible on the slower film, because of the better signal-to-noise ratio. Indeed, it can be said that the slower film gives a better image because it requires more radiation to produce the image. In many instances, with the exposure required for the slower film, a hole about one-third the area (about 0.55 the diameter) of the original hole would be at the threshold of visibility.

In the preceding discussion nothing has been said about film contrast. Actually, of course, both adequate film contrast and a sufficiently high signal-to-noise ratio are essential to the visibility of a particular detail in a radiograph. If the densities involved fall on the toe of the characteristic curve where the film contrast is very low, the image of the detail will be invisible to the observer, no matter what the signal-to-noise ratio might be. Further, suppose that an exposure were made, the densities of which fell on the shoulder of the characteristic curve for Film Z. Again, the image of the detail might be invisible to the observer, because of low film contrast. Decreasing the exposure time would make use of a steeper portion of the characteristic curve (giving higher film contrast) and produce a better radiograph. To sum up, increasing film contrast will increase the ease with which the image of a small detail can be visualized, provided always that the signal-to-noise ratio is above the required minimum.

Conversely, however, it can be stated that no increase in film contrast will make an image visible if the signal-to-noise ratio is inadequate. An increase in the film contrast with no change in exposure (that is, with no change in signal-to-noise ratio) will merely increase both the density variations due to noise and those due to the desired image, with no improvement in visibility of the detail. Suppose, for example, that a radiograph were made on Film Y at a density of 0.5 (See Figure 116), and that the signal-to-noise ratio for a particular small penetrameter hole were very low--say 2. Changing to Film X, with all other conditions remaining the same, would give a higher film contrast. However, the signal-to-noise ratio would remain the same--namely 2--and the image of the penetrameter hole would continue to be lost in the random density fluctuations of the background.

[1]A statistician refers to these values as the standard deviation (±100 drops) or the relative deviation (±1 percent) from the average. They are calculated by taking the square root of the average. Thus, if the average number is 10,000, as in this illustration, the deviation from the average is the square root of 10,000 or ±100. In turn, 100 is 1 percent of the 10,000, so the relative deviation is ±1 percent. Standard deviation is usually symbolized by the small Greek sigma (σ).

[2]This is true for conditions under which each absorbed photon exposes one or more photographic grains--that is, when energy is not "wasted" on grains already exposed by a previous photon. This does not occur until a significant fraction of the total number of grains has been exposed. Most industrial x-ray films have such a large number of grains that wastage of energy from this cause occurs only at high densities.

Chapter 18: The Photographic Latent Image

As shown in Figures 67 and 68, a photographic emulsion consists of a myriad of tiny crystals of silver halide--usually the bromide with a small quantity of iodide--dispersed in gelatin and coated on a support. The crystals--or photographic grains--respond as individual units to the successive actions of radiation and the photographic developer.

The *photographic latent image* may be defined as that radiation-induced change in a grain or crystal that renders the grain readily susceptible to the chemical action of a developer.

To discuss the latent image in the confines of this site requires that only the basic concept be outlined. A discussion of the historical development of the subject and a consideration of most of the experimental evidence supporting these theories must be omitted because of lack of space.

It is interesting to note that throughout the greater part of the history of photography, the nature of the latent image was unknown or in considerable doubt. The first public announcement of Daguerre's process was made in 1839, but it was not until 1938 that a reasonably satisfactory and coherent theory of the formation of the photographic latent image was proposed. That theory has been undergoing refinement and modification ever since.

Some of the investigational difficulties arose because the formation of the latent image is a very subtle change in the silver halide grain. It involves the absorption of only one or a few photons of radiation and can therefore affect only a few atoms, out of some 10^9 or 10^{10} atoms in a typical photographic grain. The latent image cannot be detected by direct physical or analytical chemical means.

However, even during the time that the mechanism of formation of the latent image was a subject for speculation, a good deal was known about its physical nature. It was known, for example, that the latent image was localized at certain discrete sites on the silver halide grain. If a photographic emulsion is exposed to light, developed briefly, fixed, and then examined under a microscope (See Figure 126), it can be seen that development (the reduction of silver halide to metallic silver) has begun at only one or a few places on the crystal. Since small amounts of silver sulfide on the surface of the grain were known to be necessary for a photographic material to have a high sensitivity, it seemed likely that the spots at which the latent image was localized were local concentrations of silver sulfide.

Figure 126: Electron micrograph of exposed, partially developed, and fixed grains, showing initiation of development at localized sites on the grains (1µ = 1 micron = 0.001 mm).
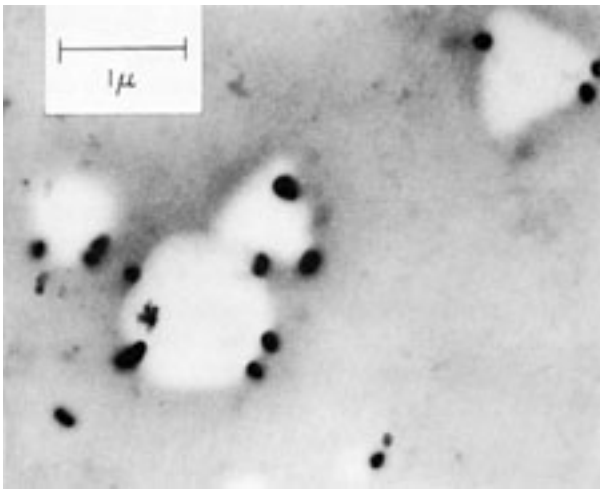
It was further known that the material of the latent image was, in all probability, silver. For one thing, chemical reactions that will oxidize silver will also destroy the latent image. For another, it is a common observation that photographic materials given prolonged exposure to light darken spontaneously, without the need for development. This darkening is known as the print-out image. The printout image contains enough material to be identified chemically, and this material is metallic silver. By microscopic examination, the silver of the print-out image is discovered to be localized at certain discrete areas of the grain (See Figure 127), just as is the latent image.

Figure 127: Electron micrograph of photolytic silver produced in a grain by very intense exposure to light.
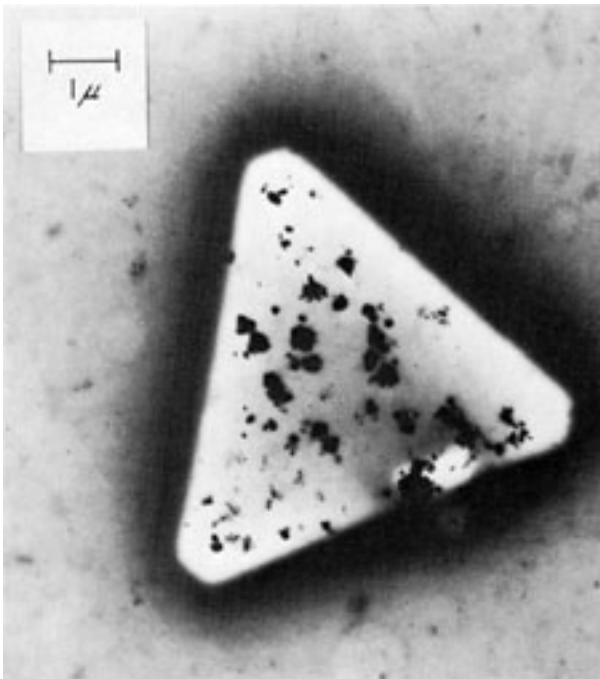
Thus, the change that makes an exposed photographic grain capable of being transformed into metallic silver by the mild reducing action of a photographic developer is a concentration of silver atoms--probably only a few--at one or more discrete sites on the grain. Any theory of latent-image formation must account for the way that light photons absorbed at random within the grain can produce these isolated aggregates of silver atoms. Most current theories of latent-image formation are modifications of the mechanism proposed by R. W. Gurney and N. F. Mott in 1938.

In order to understand the Gurney-Mott theory of the latent image, it is necessary to digress and consider the structure of crystals--in particular, the structure of silver bromide crystals.

When solid silver bromide is formed, as in the preparation of a photographic emulsion, the silver atoms each give up one orbital electron to a bromine atom. The silver atoms, lacking one negative charge, have an effective positive charge and are known as silver ions (Ag^+). The bromine atoms, on the other hand, have gained an electron--a negative charge--and have become bromine ions (Br^-). The "plus" and "minus" signs indicate, respectively, one fewer or one more electron than the number required for electrical neutrality of the atom.

A crystal of silver bromide is a regular cubical array of silver and bromide ions, as shown schematically in Figure 128. It should be emphasized that the "magnification" of the figure is very great. An average grain in an industrial x-ray film may be about 0.00004 inch in diameter, yet will contain several billions of ions.

Figure 128: A silver bromide crystal is a rectangular array of silver (Ag+) and bromide (Br-) ions.

o AG⁺ION
◯ BR⁻ION
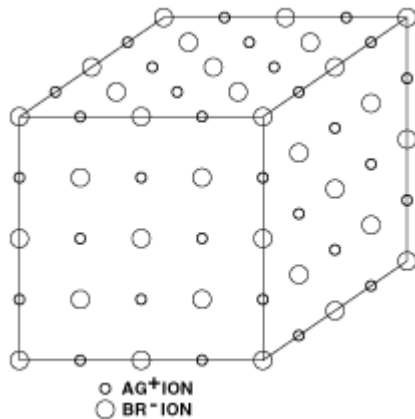
A crystal of silver bromide in a photographic emulsion is--fortunately--not perfect; a number of imperfections are always present. First, within the crystal, there are silver ions that do not occupy the "lattice position" shown in the figure above, but rather are in the spaces between. These are known as interstitial silver ions (See Figure 129). The number of the interstitial silver ions is, of course, small compared to the total number of silver ions in the crystal. In addition, there are distortions of the uniform crystal structure. These may be "foreign" molecules, within or on the crystal, produced by reactions with the components of the gelatin, or distortions or dislocations of the regular array of ions shown in Figure 128. These may be classed together and called "latent-images sites."

Figure 129: "Plain view" of a layer of ions of a crystal similar to that of the previous figure. A latent-image site is shown schematically, and two interstitial silver ions are indicated.
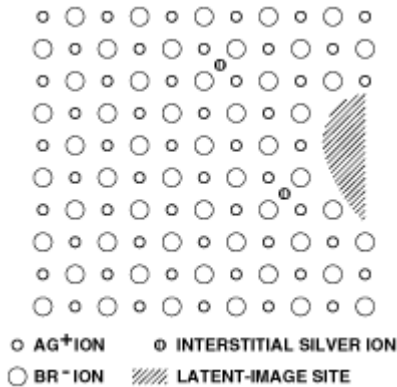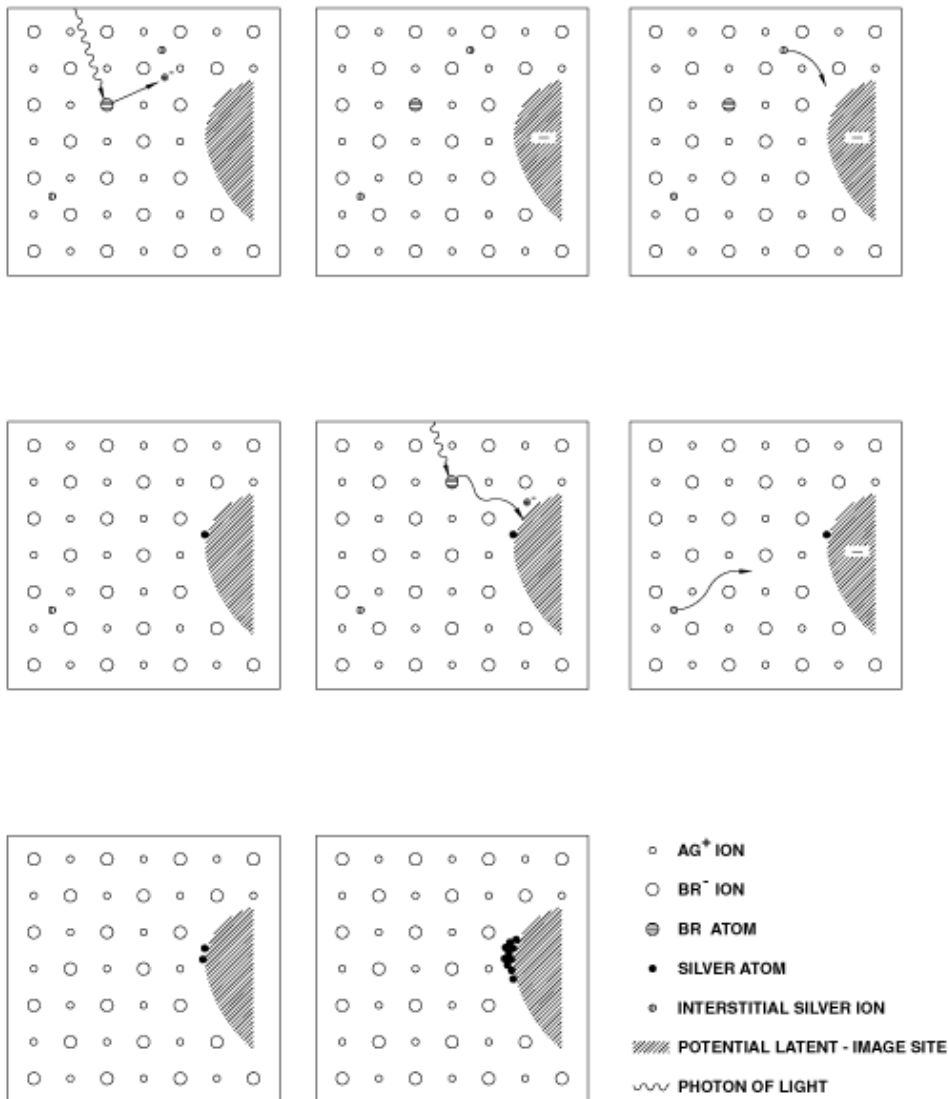

The Gurney-Mott theory envisions latent-image formation as a two-stage process. It will be discussed first in terms of the formation of the latent image by light, and then the special considerations of direct x-ray or lead foil screen exposures will be covered.

The Gurney-Mott Theory

When a photon of light of energy greater than a certain minimum value (that is, of wavelength less than a certain maximum) is absorbed in a silver bromide crystal, it releases an electron from a bromide (Br-) ion. The ion, having lost its excess negative charge, is changed to a bromine atom. The liberated electron is free to wander about the crystal (See Figure 130). As it does, it may encounter a latent image site and be "trapped" there, giving the latent-image site a negative electrical charge. This first stage of latent-image formation--involving as it does transfer of electrical charges by means of moving electrons--is the electronic conduction stage.

Figure 130: Stages in the development of the latent image according to the Gurney-Mott theory.

○	AG⁺ ION
◯	BR⁻ ION
⊖	BR ATOM
●	SILVER ATOM
○	INTERSTITIAL SILVER ION
▨	POTENTIAL LATENT - IMAGE SITE
∿	PHOTON OF LIGHT

The negatively charged trap can then attract an interstitial silver ion because the silver ion is charged positively (See Figure 130C). When such an interstitial ion reaches a negatively charged trap, its charge is counteracted, an atom of silver is deposited at the trap, and the trap is "reset" (See Figure 130D). This second stage of the Gurney-Mott mechanism is termed the ionic condition stage, since electrical charge is transferred through the crystal by the movement of ions--that is, charged atoms. The whole cycle can recur several, or many, times at a single trap, each cycle involving absorption of one photon and addition of one silver atom to the aggregate. (See Figure 130, E to H)

In other words, this aggregate of silver atoms is the latent image. The presence of these few atoms at a single latent-image site makes the whole grain susceptible to the reducing action of the developer. In the most sensitive emulsions, the number of silver atoms required may be less than ten.

The mark of the success of a theory is its ability to provide an understanding of previously inexplicable phenomena. The Gurney-Mott theory and those derived from it have been notably successful in explaining a number of photographic effects. One of these effects--reciprocity-law failure--will be considered here as an illustration.

Low-intensity reciprocity-law failure (See left branch of the curve in Figure 120) results from the fact that several atoms of silver are required to produce a stable latent image. A single atom of silver at a latent-image site (See Figure 130D) is relatively unstable, breaking down rather easily into an electron and a positive silver ion. Thus, if there is a long interval between the formation of the first silver atom and the arrival of the second conduction electron (See Figure 130E), the first silver atom may have broken down, with the net result that the energy of the light photon that produced it has been wasted. Therefore, increasing light intensity from very low to higher values increases the efficiency, as shown by the downward trend of the left-hand branch of the curve in Figure 120, as intensity increases.

High-intensity reciprocity-law failure (See right branch of the curve of Figure 120) is frequently a consequence of the sluggishness of the ionic process in latent-image formation (See Figure 130). According to the Gurney-Mott mechanism, a trapped electron must be neutralized by the movement of an interstitial silver ion to that spot (See Figure 130D) before a second electron can be trapped there (See Figure 130E); otherwise, the second electron is repelled and may be trapped elsewhere. Therefore, if electrons arrive at a particular sensitivity center faster than the ions can migrate to the center, some electrons are repelled, and the center does not build up with maximum efficiency. Electrons thus denied access to the same traps may be trapped at others, and the latent image silver therefore tends to be inefficiently divided among several latent-image sites. (This has been demonstrated by experiments that have shown that high-intensity exposure produces more latent image within the volume of the crystal than do either low- or optimum-intensity exposures.) Thus, the resulting inefficiency in the use of the conduction electrons is responsible for the upward trend of the right-hand branch of the curve.

X-Ray Latent Image

In industrial radiography, the photographic effects of x-rays and gamma rays, rather than those of light, are of the greater interest.

At the outset it should be stated that the agent that actually exposes a photographic grain, that is, a silver bromide crystal in the emulsion, is not the x-ray photon itself, but rather the electrons--photoelectric and Compton--resulting from the absorption event. It is for this reason that direct x-ray exposures and lead foil screen exposures are similar and can be considered together.

The most striking differences between x-ray and visible-light exposures to grains arise from the difference in the amounts of energy involved. The absorption of a single photon of light transfers a very small amount of energy to the crystal. This is only enough energy to free a *single* electron from a bromide (Br-) ion, and several successive light photons are required to render a single grain developable. The passage through a grain of an electron, arising from the absorption of an x-ray photon, can transmit hundreds of times more energy to the grain than does the absorption of a light photon. Even though this energy is used rather inefficiently, in general the amount is sufficient to render the grain traversed developable--that is, to produce within it, or on it, a stable latent image.

As a matter of fact, the photoelectric or Compton electron, resulting from absorption or interaction of a photon, can have a fairly long path in the emulsion and can render several or many grains developable. The number of grains exposed per photon interaction can vary from 1 grain for x-radiation of about 10 keV to possibly 50 or more grains for a 1 meV photon. However, for 1 meV and higher energy photons, there is a low probability of an interaction that transfers the total energy to grains in an emulsion. Most commonly, high photon energy is imparted to several

electrons by successive Compton interactions. Also, high-energy electrons pass out of an emulsion before all of their energy is dissipated. For these reasons there are, on the average, 5 to 10 grains made developable per photon interaction at high energy.

For comparatively low values of exposure, each increment of exposure renders on the average the same number of grains developable, which, in turn, means that a curve of net density versus exposure is a straight line passing through the origin (See Figure 131). This curve departs significantly from linearity only when the exposure becomes so great that appreciable energy is wasted on grains that have already been exposed. For commercially available fine-grain x-ray films, for example, the density versus exposure curve may be essentially linear up to densities of 2.0 or even higher.

Figure 131: Typical net density versus exposure curves for direct x-ray exposures.
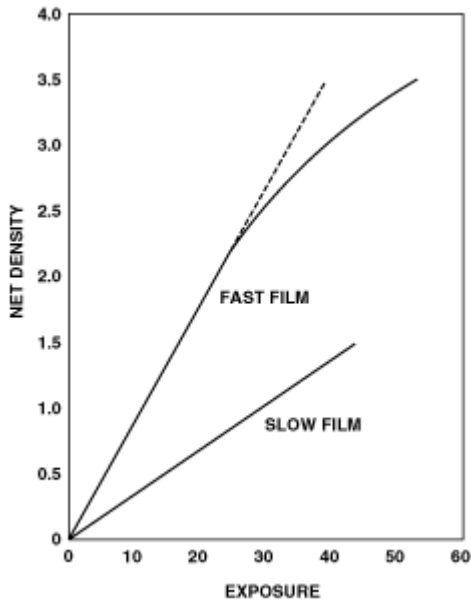
The fairly extensive straight-line relation between exposure and density is of considerable use in photographic monitoring of radiation, permitting a saving of time in the interpretation of densities observed on personnel monitoring films.

It the D versus E curves shown in Figure 131 are replotted as characteristic curves (D versus log E), both characteristic curves are the same shape (See Figure 132) and are merely separated along the log exposure axis. This similarity in toe shape has been experimentally observed for conventional processing of many commercial photographic materials, both x-ray films and others.

Figure 132: Characteristic curves plotted from the data in Figure 131.
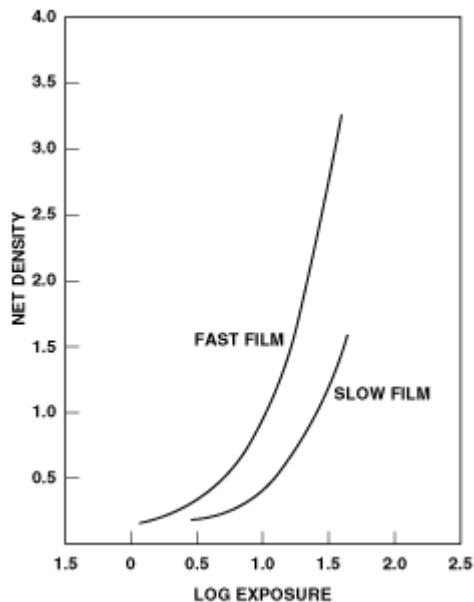
Because a grain is completely exposed by the passage of an energetic electron, all x-ray exposures are, as far as the *individual* grain is concerned, extremely short. The actual time that an x-ray-induced electron is within a grain depends on the electron velocity, the grain dimensions, and the "squareness" of the hit. However, a time of the order of 10^{-13} second is representative. (This is in distinction to the case of light where the "exposure time" for a single grain is the interval between the arrival of the first photon and that of the last photon required to produce a stable latent image.)

The complete exposure of a grain by a single event and in a very short time implies that there should be no reciprocity-law failure for direct x-ray exposures or for exposures made with lead foil screens. The validity of this has been established for commercially available film and conventional processing over an extremely wide range of x-ray intensities. That films can satisfactorily integrate x-, gamma-, and beta-ray exposures delivered at a wide range of intensities is one of the advantages of film as a radiation dosimeter.

In the discussion on reciprocity-law failure it was pointed out that a very short, very high intensity exposure to light tends to produce latent images in the interior of the grain. Because x-ray exposures are also, in effect, very short, very high intensity exposures, they too tend to produce internal, as well as surface, latent images.
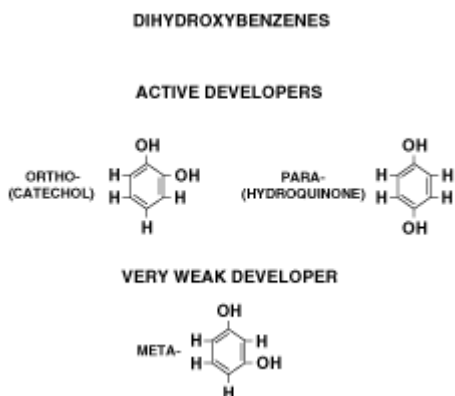
Development

Many materials discolor on exposure to light--a pine board or the human skin, for example--and thus could conceivably be used to record images. However, most such systems reset to exposure on a "1:1" basis, in that one photon of light results in the production of one altered molecule or atom. The process of development constitutes one of the major advantages of the silver halide system of photography. In this system, a few atoms of photolytically deposited silver can, by development, be made to trigger the subsequent chemical deposition of some 10^9 or 10^{10} additional silver atoms, resulting in an amplification factor of the order of 10^9 or greater. The amplification process can be performed at a time, and to a degree, convenient to the user and, with sufficient care, can be uniform and reproducible enough for the purposes of quantitative measurements of radiation.

Development is essentially a chemical reduction in which silver halide is reduced or converted to metallic silver in order to retain the photographic image, however, the reaction must be limited largely to those grains that contain a latent image. That is, to those grains that have received more than a certain minimum exposure to radiation. Compounds that can be used as photographic developing agents, therefore, are limited to those in which the reduction of silver halide to metallic silver is catalyzed (or speeded up) by the presence of the metallic silver of the latent image. Those compounds that reduce silver halide in the absence of a catalytic effect by the latent image are not suitable developing agents because they produce a uniform overall density on the processed film.

Many practical developing agents are relatively simple organic compounds (See Figure 133) and, as shown, their activity is strongly dependent on molecular structure as well as on composition. There exist empirical rules by which the developing activity of a particular compound may often be predicted from a knowledge of its structure.

Figure 133: Configurations of dihydroxybenzene, showing how developer properties depend on structure.

The simplest concept of the role of the latent image in development is that it acts merely as an electron-conducting bridge by which electrons from the developing agent can reach the silver ions on the interior face of the latent image. Experiment has shown that this simple concept is inadequate to explain the phenomena encountered in practical photographic development. Adsorption of the developing agent to the silver halide or at the silver-silver halide interface has been shown to be very important in determining the rate of direct, or chemical, development by most developing agents. The rate of development by hydroquinone (See Figure 133), for example, appears to be relatively independent of the area of the silver surface and instead to be governed by the extent of the silver-silver halide interface.

The exact mechanisms by which a developing agent acts are relatively complicated, and research on the subject is very active.

The broad outlines, however, are relatively clear. A molecule of a developing agent can easily give an electron to an exposed silver bromide grain (that is, to one that carries a latent image), but not to an unexposed grain. This electron can combine with a silver (Ag+) ion of the crystal, neutralizing the positive charge and producing an atom of silver. The process can be repeated many times until all the billions of silver ions in a photographic grain have been turned into metallic silver.

The development process has both similarities to, and differences from, the process of latent-image formation. Both involve the union of a silver ion and an electron to produce an atom of metallic silver. In latent image formation, the electron is freed by the action of radiation and

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combines with an interstitial silver ion. In the development process, the electrons are supplied by a chemical electron-donor and combine with the silver ions of the crystal lattice.

The physical shape of the developed silver need have little relation to the shape of the silver halide grain from which it was derived. Very often the metallic silver has a tangled, filamentary form, the outer boundaries of which can extend far beyond the limits of the original silver halide grain (See Figure 134). The mechanism by which these filaments are formed is still in doubt although it is probably associated with that by which filamentary silver can be produced by vacuum deposition of the silver atoms from the vapor phase onto suitable nuclei.

Figure 134: Electron micrograph of a developed silver bromide grain.

The discussion of development has thus far been limited to the action of the developing agent alone. However, a practical photographic developer solution consists of much more than a mere water solution of a developing agent. The function of the other common components of a practical developer are the following:

An Alkali
The activity of developing agents depends on the alkalinity of the solution. The alkali should also have a strong buffering action to counteract the liberation of hydrogen ions--that is, a tendency toward acidity--that accompanies the development process. Common alkalis are sodium hydroxide, sodium carbonate, and certain borates.

A Preservative
This is usually a sulfite. One of its chief functions is to protect the developing agent from oxidation by air. It destroys certain reaction products of the oxidation of the developing agent that tend to catalyze the oxidation reaction. Sulfite also reacts with the reaction products of the development process itself, thus tending to maintain the development rate and to prevent staining of the photographic layer.

A Restrainer
A bromide, usually potassium bromide, is a common restrainer or antifoggant. Bromide ions decrease the possible concentration of silver ions in solution (by the common-ion effect) and also, by being adsorbed to the surface of the silver bromide grain, protect unexposed grains from the action of the developer. Both of these actions tend to reduce the formation of fog.

Commercial developers often contain other materials in addition to those listed above. An example would be the hardeners usually used in developers for automatic processors.

Chapter 19: Protection

One of the most important considerations in the x-ray or gamma-ray laboratory is the provision and exercise of adequate safeguards for the personnel. Only the general principles of the necessary protective precautions are discussed in the following.

For details, obtain and carefully study the pertinent National Bureau of Standards Handbooks, publications from the National Council on Radiation Protection and Measurement, the Atomic Energy Commission regulations, and the state and local codes. It is essential that new installations be constructed in compliance with the provisions of applicable codes and that existing installations be checked to make certain that they meet all requirements. It is desirable, and under some circumstances obligatory, to have a qualified radiation expert examine the radiation installation and protective measures. In addition, some state and local codes require that radiation-producing equipment be registered.

Any of the body tissues may be injured by excessive exposure to x-rays or gamma rays--the blood, the lens of the eye, and some internal organs being particularly sensitive. Unless exposure to x-rays or gamma rays is kept at a minimum, the cumulative effect may cause injury to the body, and it is essential that workers in the radiographic department be adequately protected against radiation at all times. Furthermore, protective measures should be so arranged that persons in nearby areas are also safe. Precautions should be particularly observed when radiography is done in the work areas of the shop rather than in a specially constructed department.

Protection Against X-Rays

Exposure may be caused by the direct beam from the x-ray tube target or by scattered radiation arising from objects in the direct beam. Therefore, while exposures are being made, operators should always be protected by sufficient lead, or its equivalent, shielding them from the x-ray beam, the part being radiographed, and any other matter exposed to the x-rays.

Protection can be provided in a number of ways, depending on the x-ray installation and the use to which it is put. Whenever possible, protective measures should be built in as permanent features of the installation. Preferably, the x-ray generator and the work should be enclosed in a room or cabinet, with the necessary protection incorporated in the walls.

The common method is to locate the x-ray tube within a room completely lined with lead of a sufficient thickness to provide adequate protection. All the controls are located outside the room.

In the placing of equipment and the design of protective enclosures, keep certain principles in mind. Careful application of these principles adds to the safety of the personnel, and may decrease cost.

Both safety and economy benefit if the amount of radiation that must be absorbed in the outside wall of the enclosure is kept to a minimum. To this end, the distance from the x-ray tube target to any occupied space should be as great as possible. Further, if the nature of the work permits, the direct beam should never be pointed in the direction of occupied areas.

Ideally, the lead housing around the x-ray tube should protect against all primary radiation except the useful beam, although this is not always feasible in practice. The useful beam itself should be limited in cross section by the use of cones, diaphragms, or other devices.

If there are parts of the x-ray room that, because of the design of the equipment, can never be exposed to direct radiation, certain economies in the installation of protective material are

possible. Where *only* scattered radiation can reach a protective wall, less protection is necessary, since the intensity of the scattered radiation is much lower than that of the primary. When advantage is taken of these economies, great care must be exercised in rearranging equipment, lest it become possible to direct the full intensity of the x-ray beam against a wall that contains protection against the *scattered radiation only*.

Where large numbers of relatively small parts are inspected, the protection may be in a more compact form such as a lead-lined hood surrounding the x-ray tube, the specimens, and the film holder, completely enclosing them for the duration of the exposure. When the exposure is completed, the hood is opened to allow the removal of the radiographed parts and the placement of a new batch. The electrical controls are interlocked so that the x-ray tube cannot be turned on until the hood is closed.

The protective material, usually lead, in the walls of the enclosure, whether it be a room or a cabinet, should be of sufficient thickness to reduce the exposure in all occupied areas to the lowest value possible or economically feasible. Under no circumstances should the exposure to personnel exceed that permitted by the pertinent regulations, and a lower level than this should be sought whenever possible.

In some cases, it may be possible for the personnel of an x-ray department, or other employees, to be exposed to the radiation from more than one x-ray machine. In such cases, the amount of protection must be increased to a point where the total exposure in any occupied area is within the prescribed radiation limits.

If the object being radiographed is too large or heavy to be brought to the x-ray machine, the radiography must be done in the shop. Under such conditions, special precautions are necessary. These include a completely lead-lined booth large enough to accommodate the x-ray machine controls, the operator, and his assistants. The booth may be completely enclosed, or open on one side. In any event, the exposure within it should be very carefully measured. Lead cones on the x-ray machine should be used to confine the x-ray beam to a certain direction and to the minimum angle that can be used. Portable screens should be provided to protect workers nearby. Guard rails or ropes and warnings should be used to keep others at a safe distance.

In field radiography, protection is usually obtained by distance. Care should be taken to see that all personnel are far enough away from the radiation source to insure safety.

Material And Construction For Protection Against X-Rays

Lead is the most common material used to provide protection against x-rays. It combines high protective efficiency with low cost and easy availability. In most cases, recommendations on protective measures are given in terms of lead thicknesses.

When using lead for protection, care must be taken to avoid any leaks in the shielding. This means that adjacent lead sheets should be over-lapped, not merely butted, even if the sheets are to be burned together throughout the whole length of the joint. The heads of any nails or screws that pass through the lead should be carefully covered with lead. Extra precautions should be taken at those points where water pipes, electrical conduits, or ventilating ducts pass through the walls of the x-ray room. For small conduits and pipes, it is usually sufficient to provide a lead sheathing around the pipe for some distance on one side of the lead protective barrier in the wall. This sheath should be continuous and be very carefully joined, by a burned joint, to the lead in the wall. Better protection is afforded by having a right-angle bend in the pipe either inside or outside the x-ray room and covering it with a lead sheath to a point well beyond the right-angle bend. The sheath should be carefully joined to the lead in the wall. In the case of a large opening for ventilation, lead baffles will stop x-rays, but permit the passage of air. When a large ventilating

duct is brought into the x-ray room, two right-angled bends covered with lead will prevent the escape of x-rays.

If the x-ray room is on the lowest floor of a building, the floor of the room need not be completely protected. The lead protection in the wall should not stop at the floor level, however. An "apron" of lead, continuous with the protection within the wall, should be placed in the floor, extending inward from all four walls. The purpose of this apron is to prevent x-rays from escaping from the room by penetrating the floor and then scattering upward outside the protective barrier. An alternative is to extend the lead protection in the walls downward for some distance below floor level. The same considerations apply to the ceiling if the x-ray room is located on the top floor of a building. Of course, if there is occupied space above or below the x-ray room, the ceiling or door of the x-ray room must have full radiation protection over its whole area.

Although lead is the most common material for x-ray protection, other materials may be used. In particular, structural walls of concrete or brick may afford considerable protection and may reduce the thickness, and therefore the cost, of the lead required. Above 400 kV, concrete is most used as protective material. The thicknesses of lead required at these potentials are so great that fastening the lead to the walls becomes a serious problem, and concrete is often used because of the ease of construction. In new construction, the use of concrete may have economic advantages even for protection against radiations generated at kilovoltages well below 400. State and local codes should be examined, and any installations checked for compliance with their requirements.

Protection Against Gamma Rays

Most gamma-ray emitters used in industry are artificial radioactive isotopes; the procurement, use, handling, storage, and the like are controlled directly by the United States Atomic Energy Commission, or indirectly by state radiation control laws approved by the Atomic Energy Commission. It is essential, therefore, that these codes be followed rigorously.

Gamma rays may be very penetrating. For instance, one-half inch of lead reduces the intensity of the gamma rays of cobalt 60 only about 50 percent. This makes the problems of protection somewhat different from those encountered in protection against moderate-voltage x-rays in general, it is not feasible to provide safety from gamma rays solely by means of a protective barrier. Therefore, distance or a combination of distance and protective material is usually required. When radioactive materials are not in use, protection is usually obtained by keeping them in thick lead containers, because in this case the total amount of lead needed is not great.

Because of the great thicknesses of protective materials required for shielding some gamma-ray sources, distance is the most economical method of protection while the source is in use. A danger zone should be roped off around the location of the radioactive material, and personnel should be forbidden to enter this zone except to put the source in position or return it to its safe. Suitable conspicuous signs should be provided to warn away the casual passersby. Tables are available that give data for calculating the distances from various amounts of radioactive material at which a radiation hazard exists.

It must be kept in mind that the presence of a large mass of scattering material, for example, a wall, will materially increase the gamma-ray exposure. This increase may be as much as 50 percent of the exposure as calculated without the presence of scattering material. Thus, to be sure that the radiation protection is adequate, factors other than distance must be kept in mind when considering personnel protection from gamma rays.

Precautions must be taken in shipping radioactive materials, not only to protect those who handle them in transit but also to prevent the fogging of photographic materials that may be transported in the same vehicle. The Interstate Commerce Commission has established regulations

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governing the rail shipments of radioactive isotopes. These provide in part; that the package shall have such internal shielding that the gamma radiation does not exceed 10 milliroentgens (mR) per hour at a distance of 3 feet from the outside of the container; that the radiation intensity at any readily accessible surface of the package shall not be over 200 mR per hour; that the package shall carry a prescribed label; and that shipping conditions be such that unprocessed photographic film traveling in the same vehicle shall be protected from damage throughout the transit period.

Packages meeting these requirements often consist of a central lead container for the radioactive isotope surrounded by a wooden or other box of such dimensions that the radiation at any readily accessible surface is less than 200 mR per hour. It is advisable to preserve the original package in case it is again necessary to ship the source.