Conf-356-10

(1,d)

FACTORS IN RADIOGRAPHY AT ENERGIES BELOW 400 kvp[a]

GMELIN REFERENCE NUMBER
AED-Conf- 63-223-3

R. W. McClung
Metals and Ceramics Division
Oak Ridge National Laboratory[b]
Oak Ridge, Tennessee

MASTER

INTRODUCTION

Although radiography is one of the oldest nondestructive testing methods, it is still very much a necessary part of current technology. Some of the more common applications are assembly evaluation, dimensional gaging, and flaw detection in castings, weldments, and other fabricated shapes. In short, radiography is applied to a host of inspection problems in which an internal evaluation is desired on an optically opaque material. A very large number of papers and books have been written on the subject, both from practical and theoretical viewpoints. The material contained in the Nondestructive Testing Handbook (1) as well as the bibliography compiled by Isenburger (2) provides a thorough coverage of industrial radiographic practice.

There are several major factors in a radiographic technique which affect the attainment of optimum results. These include the radiation source, specimen, film-screen combination, film processing, and their mutual relationships. Changes in each of these can have a significant effect on the radiographic contrast and resolution of the film used as the detector. This discussion is intended as a general review of radiographic practice with emphasis on the effect of variations in the principal factors at energies

---

[a] This paper is one of a series of three requested to serve as an integrated survey of industrial radiography.

[b] Operated for the U. S. Atomic Energy Commission by Union Carbide Corporation.

Facsimile Price $ 2.60
Microfilm Price $ .98

Available from the
Office of Technical Services
Department of Commerce
Washington 25, D. C.

1963 ASM Metals/Materials Show
Cleveland, Ohio
October 21-25, 1963

LEGAL NOTICE

below 400 kvp. Obviously it will not be possible to cover every facet or give complete details of the procedure. The cited publications can be used as reference material for those wishing more detailed information.

BASIC PRINCIPLES

As x-rays pass through a specimen, they will be attenuated in accordance with the relationship

$$I = I_o e^{-\mu p x}$$

where

I = transmitted x-ray intensity,
I_o = initial x-ray intensity,
μ = mass attenuation coefficient,
p = density, and
x = thickness.

The value of the mass attenuation coefficient, μ, (which in general decreases with decreasing atomic number) is dependent upon the energy (kilovoltage) of the x-ray being used; that is, the lower the energy the larger the coefficient. From this it is evident that there will be a greater proportion of transmitted energy for higher x-ray energies, lower atomic number materials, lower densities, and thinner sections. Figure 1 relates this to radiographic practice. The specimen is placed so that x-rays of a given energy range may impinge upon it. A film containing a radiation-sensitive emulsion is placed behind the specimen so that those rays passing through the specimen may be detected. Variations in the intensity of x-rays passing through the specimen will cause a corresponding change in the amount of photochemical reaction in the emulsion. For instance, the discontinuity shown in Fig. 1 represents an effective decrease in specimen thickness, allowing an increased x-ray intensity at that point with subsequent increased film reaction. In general, the attainment of a useful radiograph depends upon the selection of the proper conditions of x-ray energy, exposure, and film to produce visible variations in film reaction for small, localized changes in section thickness. Since each of the factors necessary to produce a radiograph has an effect on the completed film, an understanding of each is necessary.

SINGLE FACTORS

Source

X-rays are generated in an x-ray tube by the focusing of an electron beam upon a metal target after acceleration through a high voltage potential. Some of the electron energy is converted by the target to x-rays with energies varying in energy downward from that of the accelerating voltage. One of the most common x-ray tube target materials is tungsten, although other materials are occasionally used. The x-ray tube is generally housed in a container designed and shielded in such a way to allow a usable portion of the x-ray to be emitted only in selected directions. The maximum intensity of the electron beam (and subsequently the x-rays) per unit area of the target is limited by the ability to remove the heat (another by-product of the electron-beam bombardment). From this very brief description, it is evident that an x-ray source has several characteristics which significantly affect the radiographic procedure.

1. As the accelerating voltage of the electron is changed, there will be a corresponding change in the range of x-ray energies and the transmission or penetrating capability.

2. The focusing of the electrons into a certain size focal spot on the target material limits the maximum x-ray intensity and fixes the size of the x-ray source itself. The former can be directly related to the required amount of exposure time to achieve the desired amount of photochemical reaction or "blackening" of the detector film; the latter is a factor in the degree of sharpness in the projected "shadow" of the specimen. More will be said about each of these factors. In general, for a given x-ray tube, the target material and focal spot size (or sizes) are fixed, there being control only on accelerating voltage and beam-current intensity.

Specimen

Unlike most of the other factors to be discussed, there is generally very little that can be done about the selection of the specimen. It is generally thrust upon the radiographer with the cryptic request, "X-ray it!" and, on occasion, with no understanding of the "why." These being so frequently the circumstances, it is in order to take a quick look at the specimen and to remember "what it is that we're a-doin!" As noted earlier, a film record is being obtained of variations in thickness in the specimen as they affect x-ray transmission. Since voids or other such flaws reduce the amount of material through which the x-rays must pass, these constitute an effective thickness change. Three-dimensional flaws such as porosity, gas holes, etc., are best suited for radiographic detection since there will be somewhat equivalent response regardless of the orientation of the x-ray beam (other things being equal).

This is reflected in the very widespread usage and excellent results of radiographic inspection of welds, castings, and other such items in which such flaws may be found. However, "two-dimensional" flaws such as cracks, laminations, etc., are quite orientation-sensitive being, in general, nondetectable when the x-ray beam is perpendicular to the plane of the flaw, detectable when the beam is parallel to the flaw, and having varying degrees of detectability at other angles between the extremes according to the "thickness" of the discontinuity in the direction parallel with the x-rays. These factors indicate the necessity of knowing something about the fabrication history of the specimen and the suspected flaw types and orientation. This would allow the optimum specimen orientation to be chosen and, in some instances, might indicate that radiography would be an unprofitable exercise. For some configurations having a designed variation in thickness, it may be necessary to make more than one radiographic exposure varying the specimen orientation and the condition of x-ray exposure to obtain the best results on contrast and defect resolution according to the section thickness.

Film

The most common mode of detecting and subsequently displaying the variation in transmitted x-ray intensity is the use of film with an unstable emulsion which is sensitive to electromagnetic radiation such as x-rays. The photosensitive emulsion, usually silver halide-bearing, undergoes a change in physical structure when it receives the radiation. Subsequent chemical processing (developing) produces a reaction which allows the gradation of reaction zone to be viewed.

In general, radiographic film can be classified according to two factors — speed and quality. The film speed, as its name implies, is indicative of the relative amount of radiation exposure necessary to produce a certain amount of film blackening. Quality, a more complex factor, includes film graininess and the contrast which can be achieved for a given change in specimen thickness. In general, for faster speed, the quality will be lower (less contrast and more graininess).

The film is, of course, quite sensitive to visible light and, because of this, must be protected throughout its handling until the final chemical processing has removed its capability to undergo change under the effects of radiation. In most common procedures, all film handling is in darkrooms except for the time immediately preceding, during, and after the x-ray exposure. During this period it is encased in a holder (cassette) which is opaque to visible light but relatively transparent to x-rays.

Film Processing

After the radiographic film has been exposed to the x-rays, chemical processing is employed to allow viewing of the latent image produced by the variation in impinging x-ray intensities. The common steps include the use of a developer solution which reduces the exposed silver halide crystals to metallic silver, rinsing in an acid bath to stop the developing action, and then a "fixing" operation to remove the unreacted photosensitive crystals. Subsequent operations include washing to remove residual chemicals, perhaps a wetting agent to improve the drying characteristics, and finally film drying.

The degree of developing by a standard-strength solution on the reacted crystals is a function of both time of development and temperature of the solution. For consistent results both time and temperature should be standardized. The most commonly recommended values are 68 F with a 5-min developing time. Decreased time or temperature will result in less development of the image. Increased development, due either to slight increases in solution temperature or developing time, can afford increased film contrast but, in general, at the sacrifice of resolution because of increased graininess in the processed film.

COMBINED FACTORS

Source-Specimen

The specimen is the principal factor in the selection of source-operation conditions. As mentioned in the basic principles, for reasonable exposure times, the higher the atomic number and the greater the thickness of the specimen the higher will be the required energy of the x-ray beam. For example, Fig. 2 relates the required x-ray energy for varying thicknesses of type 316 stainless steel with all other factors of exposure time, film, achieved film density, etc., remaining constant. Figure 3 shows the change in exposure time to achieve constant film density as the energy is varying on several thicknesses of the same steel. As a first approximation, it is desirable to use the lowest x-ray energy consistent with achievement of adequate film density in a reasonable exposure time. The lower energy allows greater contrast or discrimination for small thickness changes associated with defects. Of course, there may be times when a slightly higher energy may be optimum. For instance, with specimens of varying thickness, the lowest energy may produce so much contrast that all areas cannot be viewed on a single film. However, if adequate sensitivity can be achieved, it may be possible to increase the energy such that a slightly reduced contrast and greater latitude will allow the entire specimen to be interpreted.

Source-Specimen-Film

Figure 4 will assist the description of effects due to variation of the relative spacing between source, specimen, and film. The image of an object (discontinuity) can be considered as the shadow caused by the impinging x-rays. As the object moves closer to the source and away from the film (decreasing the $\frac{d}{t}$ ratio), its image will be magnified. Also, since the x-ray source has a finite area and each point on the source casts its own shadow, the overlapping of images at the edge produces a band (denoted "P") in which the image is poorly defined. The width of the band of unsharpness decreases with decreasing source size and with increasing $\frac{d}{t}$ ratio (as shown in Fig. 4b). This latter consideration demonstrates the need for a large $\frac{d}{t}$ ratio which is achieved by placing the specimen as near the film as possible and using large source-to-film distances. This is limited, of course, by practical considerations of exposure time since the divergent x-ray beam obeys the inverse square law; that is, the x-ray intensity per unit area varies inversely as the square of the distance. Therefore, to achieve comparable x-ray film densities, the exposure times will vary as the square of the distance. For example, if the distance is doubled, the exposure requirements are 2^2 or four times the original.

Source-Film

As mentioned previously, with more intense x-ray beams or with longer exposure times, more film blackening will occur. This can be readily expressed by the characteristic curve shown in Fig. 5 which relates the logarithm of x-ray exposure to the film density. The slope of the curve provides an indication of the contrast which can be obtained for unit change in exposure intensity on the film (as might be caused by small thickness changes or the presence of voids within a specimen). As seen in this curve, there will be less contrast at the lower and higher densities with best contrast occurring at intermediate densities. Characteristic curves for other film may show that the best contrast will be obtained at the highest densities compatible with radiographic viewing.

A less well-recognized effect is that of the relative response of the x-ray film as a function of the relative energy of the x-ray beam. Figure 6 (taken from the Nondestructive Testing Handbook, p. 16.23) illustrates this for a screen-type film by indicating the relative amount of radiation to produce a film density of 1 as the energy changes. This correction generally has been made in the preparation of exposure charts.

The factors mentioned thus far relate x-ray intensity and energy to the achieved density. Another necessary consideration is the effect of the x-ray energy on the "graininess" of the film. "Grain" is the result of a clumping of the silver particles released during the exposure to radiation. Contributing factors to the clumping or graininess include radiation scatter in the film and the fact that the photoelectrons which are produced by the interaction between the x-rays and the atoms in the film emulsion diffuse or spread in the emulsion — the higher the x-ray energy the greater the range of electron diffusion. What does this mean on a radiograph? Simply, that the x-rays passing through a specimen and impinging on a single point on the film will, by scatter and electron diffusion, affect a small area around that point, thereby producing a diffuse image. Therefore, as the energy increases, this factor of unsharpness will likewise increase. If the inherent unsharpness is the largest factor (and is controlling), the resolution will become poorer; that is, the minimum detectable discontinuity will be larger. This exposes a potential pitfall into which the unwary may step. In an attempt to gain better resolution, a change may be made from fine grain to very fine grain film — a logical step. However, to avoid paying the penalty of increased exposure time at the same energy, the energy may be increased sufficiently to achieve the desired film density without increased exposure time. Because of the subsequent increase in graininess, the gain in resolution is decreased. The results of a simple test will illustrate the problem. A plate containing a number of holes of varying depth and diameter was radiographed on a fine-grain film to a density of approximately 2.0. A 5-min exposure was required and the shallowest hole detectable was 0.016-in. diam × 0.006 in. deep and the smallest diameter was 0.008 in. × 0.019 in. deep. The same plate was radiographed on a very fine-grained film; a 20-min exposure was required to achieve a comparable density (other factors held constant); and the comparable detectable hole sizes were 0.012-in. diam × 0.005 in. deep and 0.006-in. diam × 0.019 in. deep. However, when the x-ray energy was increased to allow a 5-min exposure on the very fine-grained film, the hole sizes increased to 0.013-in. diam × 0.006 in. deep and 0.006-in. diam × 0.019 in. deep. Figure 7 provides more detailed information of the intermediate sizes which were detectable.

Film-Screens

It is quite common to use lead screens in the film holder in close proximity to the film. This can serve several functions. One such use is to serve as an intensifier for the x-ray action. It has been noted that the response of film to x-rays is affected by the relative energy of the rays. A partial explanation utilizes the relation noted earlier.

$$I = I_o e^{-\mu p x} .$$

As the energy of the x-rays increases, more are transmitted through the film with no interaction. This inefficiency can be somewhat offset by the use of heavy metal screens. These act as efficient absorbers for the x-rays, emitting photoelectrons and softer (lower energy) scattered secondary radiation which are more easily absorbed by the film. If the metal (usually lead) screen is in intimate contact with the film, both primary and secondary radiation impinge upon the same areas and no image blurring is produced. However, if intimate contact is not maintained, image quality can be severely degraded. The secondary radiation can produce a significant increase in the film response at higher energies allowing shorter exposure time. The improvement decreases with decreasing energy until (at approximately 110 kvp) the use of lead screens can require the same and even longer exposure times. Figure 8 indicates the crossover observed in a series of radiographs on 1/4 in. of 300 series steel made at varying energies both with and without 0.005-in.-thick lead screens. A fine-grained film and a constant potential x-ray unit were used. Near the crossover point there may be a slight decrease in contrast with lead screens because of preferential absorption of the softer beam components.

SCATTER

It should not be concluded from the foregoing that the use of lead screens can serve no useful purpose at the lower energies. Although not beneficial as intensifying screens, they can still be very profitable as filters for scattered radiation. When an x-ray beam strikes a material, some of its energy is transmitted through the specimen and a portion is converted to lower energy radiation which is "scattered" in all directions as shown in Fig. 9. This "scattered" radiation will produce film blackening, and since it can quite easily be more than that from the primary image-forming beam, scatter can seriously shadow, undercut, or otherwise degrade the image of interest. The use of lead screens (on both sides of the film) will preferentially absorb a greater portion of the scattered x-rays and can significantly improve the desired image. Several precautions need to be recognized before a decision is made to use lead screens as "filters" at the lower energies. In addition to their effect on the scattered radiation, the screens will also attenuate the primary radiation, increasing the required exposure time and preferentially absorbing more of the softer components of the broad spectrum of x-ray energies present in the beam. The latter will, of course, reduce the attainable contrast. On specimens with large thickness differences (subject contrast), this may be acceptable and, on occasion, perhaps desirable.

In summary, lead intensifying screens are generally desirable at x-ray energies greater than approximately 110-120 kvp because of the reduced exposure time and diminished scatter. At lower energies, screens should be used sparingly because of the increased exposure time but may be employed to reduce severe scattering problems, if adequate image contrast can still be maintained. A practice formed by many is the use of a lead screen behind the film. In this position, it has no effect on the primary beam striking the film but can be effective against scatter from other materials behind the specimen and film.

Another approach is frequently used to reduce the harmful effects of scatter, particularly on irregular shapes or parts with rapidly changing cross section. This involves the use of masking material on or around the specimen to act as an attenuator or thickness supplement. Figure 10 illustrates the use of a snug-fitting mask used to improve radiographic quality in the radiographic examination of closure welds on nuclear reactor fuel rods.

SPECIAL TECHNIQUES FOR LOWEST ENERGIES

The previous discussions have been concerned with the most common forms of radiography at energies below 400 kvp. On the extreme lower end of the spectrum, some of the practices are inadequate for optimum results. For instance, at energies below approximately 50 kvp more consideration should be given to the filtering effect of the film holder on the x-ray energy. At energies below about 25 kvp, the air atmosphere can become an effective attenuator and filter for the x-rays – changing the energy spectrum and increasing the exposure time. Steps which have been taken at these energies to achieve better radiographic quality have included the use of thin beryllium windows in the x-ray tube, interposition of a helium chamber to displace the air atmosphere, and the use of bare-film, darkroom exposure techniques (3). These techniques are of particular value in the radiography of such light materials as beryllium, graphite, and thin sections of aluminum. These modifications coupled with the use of very high-resolution photographic emulsions and optical magnification for viewing can permit the observation of detail much less than 0.001 in. in thin sections.

SUMMARY AND CONCLUSIONS

The various facets of radiography at energies below 400 kvp have been reviewed singly and in combination. In each case, the variations in the several factors have been noted as they affect the attained radiographic contrast and sensitivity. The generalized conclusions are summarized below:

Radiographic Contrast

Increased Contrast	Decreased Contrast
Lower x-ray energies	Higher x-ray energies
More thickness variation	Less thickness variation
Finer grain film	Coarser grain film
Decreased scatter	More scatter
Longer processing	Shorter processing
Less filtration of beam	More filtration

Radiographic Sharpness or Resolution

Increased	Decreased
Larger $\frac{d}{t}$ ratios	Smaller $\frac{d}{t}$ ratios
Smaller focal spots	Larger focal spots
Finer grained film	Coarser grain film
Lower x-ray energies	Higher x-ray energies
Better film-screen contact	Poor film-screen contact
Decreased scatter	Increased scatter
Shorter film developing	Long film developing
Thinner specimens	Thicker specimens
Higher contrast	Lower contrast

Radiographic contrast denotes those factors which will affect the difference in film blackening across a radiograph. Radiographic sharpness or resolution denotes those factors which affect the ability to detect discontinuities as a function of their absolute size, not as a percent of specimen thickness. Both summaries indicate trends, some of which have very real limits beyond which further improvement of the quality cannot be obtained. Most experienced radiographers can immediately cite cases or areas in which these generalizations are not valid, but it is felt that they can be useful for most operations.

The factors noted for improved resolution or image sharpness are not simply additive. Previous studies in photography, fluoroscopy, and radiography indicate that the total unsharpness varies as the cube root of the sum of the cubes of the various unsharpness factors. Some experimentalists use square roots and squares for the factors. In most practical applications, the difference between the two approaches is only a few percent. In either case, it indicates that the largest unsharpness factor will control, with the remaining factors contributing very little to the overall radiographic resolution. Thus, on the basis of resolution alone, if a single factor (such as film or x-ray energy) is the principal cause of the degree of unsharpness, improvements in the other factors (such as $\frac{d}{t}$ ratio) will have little effect on resolution. However, care must be taken in decisions to change factors for improved resolution because of the associated changes in such criteria as radiographic contrast, image distortion, beam coverage, or exposure time. It may be observed that many of the factors leading toward better contrast and sharpness also require longer exposure times. Optimum radiography, then, must be a compromise between economic considerations (frequently including the availability of equipment) and the radiographic quality essential to the successful evaluation. Despite the advances of other physical phenomena for nondestructive testing, through proper selection of the optimum conditions radiography has been and will continue to be a work horse in inspection technology.

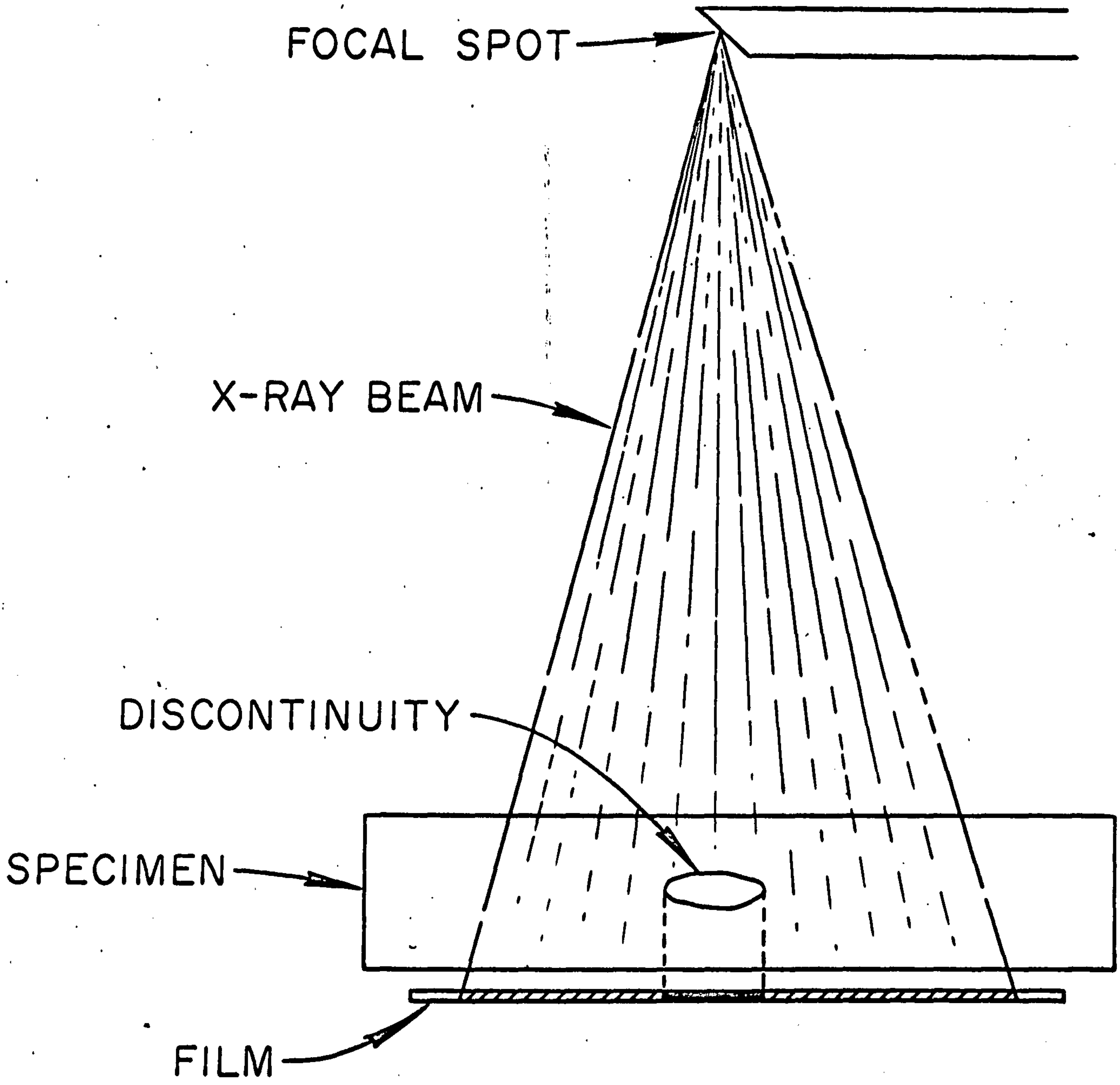
REFERENCES

1. Robert C. McMaster (ed.), Nondestructive Testing Handbook, Vol. I, Sections 14, 16, 20, and 21, 1959, Ronald Press Company, New York.
2. Herbert R. Isenburger, Addenda and Supplements to Industrial Radiology, John Wiley and Sons, New York; copyright by St. John X-Ray Laboratory, Califon, New Jersey.
3. R. W. McClung, "Techniques for Low-Voltage Radiography," Nondestructive Testing, Vol. 20, No. 4, July–August 1962, pp. 248–53.

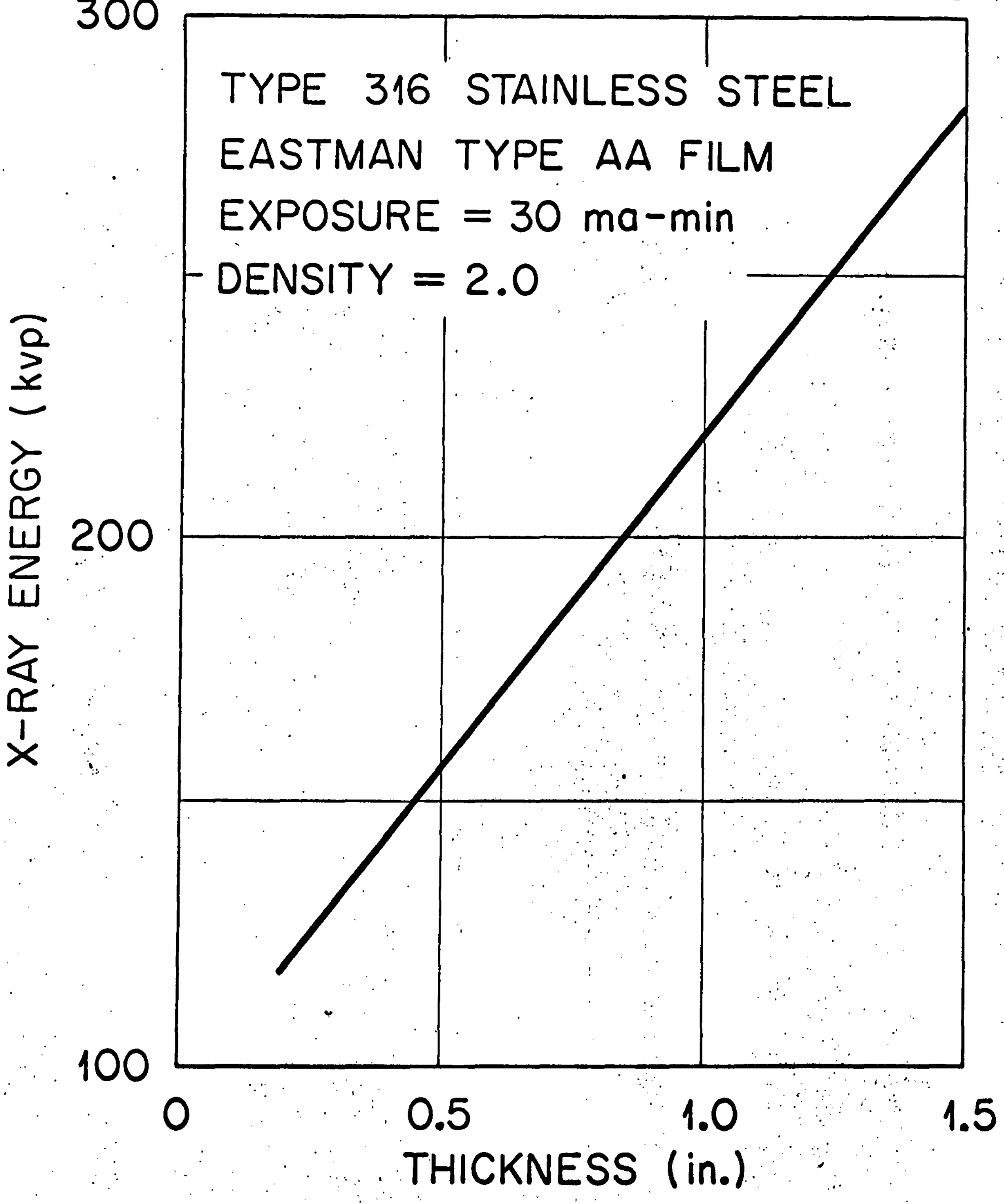
FIGURE CAPTIONS

Figure No.	
1	(ORNL-DWG 63-5429). Relative Arrangement of Factors for Radiography.
2	(ORNL-DWG 63-5428). X-Ray Energy Requirements as Steel Thickness Changes.
3	(ORNL-DWG 63-5427). Exposure Curves for Type 316 Stainless Steel.
4	(ORNL-DWG 63-5426). Effect of Changes in Relative Spacing Between Source, Specimen, and Film.
5	(ORNL-DWG 63-5425). Characteristic Curve for Typical Radiographic Film.
6	(ORNL-DWG 63-5655). Relative Response of Film as Function of X-Ray Energy. [Robert C. McMaster (ed.), Nondestructive Testing Handbook, p. 16.25, footnote 14, The Ronald Press Company, New York, Copyright © 1959.]
7	(ORNL-DWG 63-5653). Detectable Hole Sizes for Comparable Conditions Using Fine-Grain and Very Fine-Grain Film.
8	(ORNL-DWG 63-5654). Relative Film Densities With and Without Lead Intensifying Screens.
9	(ORNL-DWG 63-5424). Scattered Radiation in Radiography.
10	(ORNL-LR-DWG 43721R). Radiographic Mask for Inspection of Fuel Rod Closure Welds.

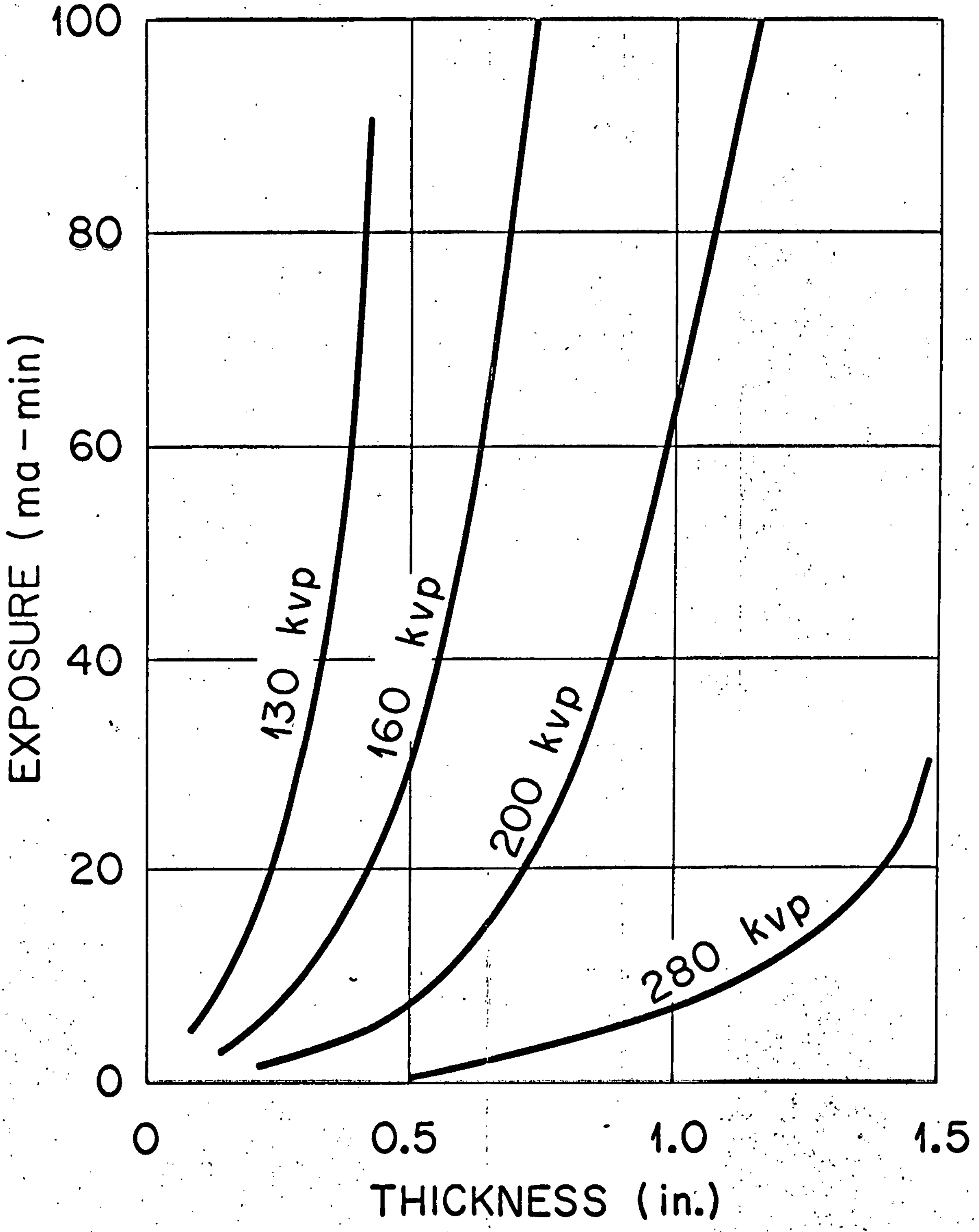
UNCLASSIFIED
ORNL-DWG 63-5429



UNCLASSIFIED
ORNL-DWG 63-5428

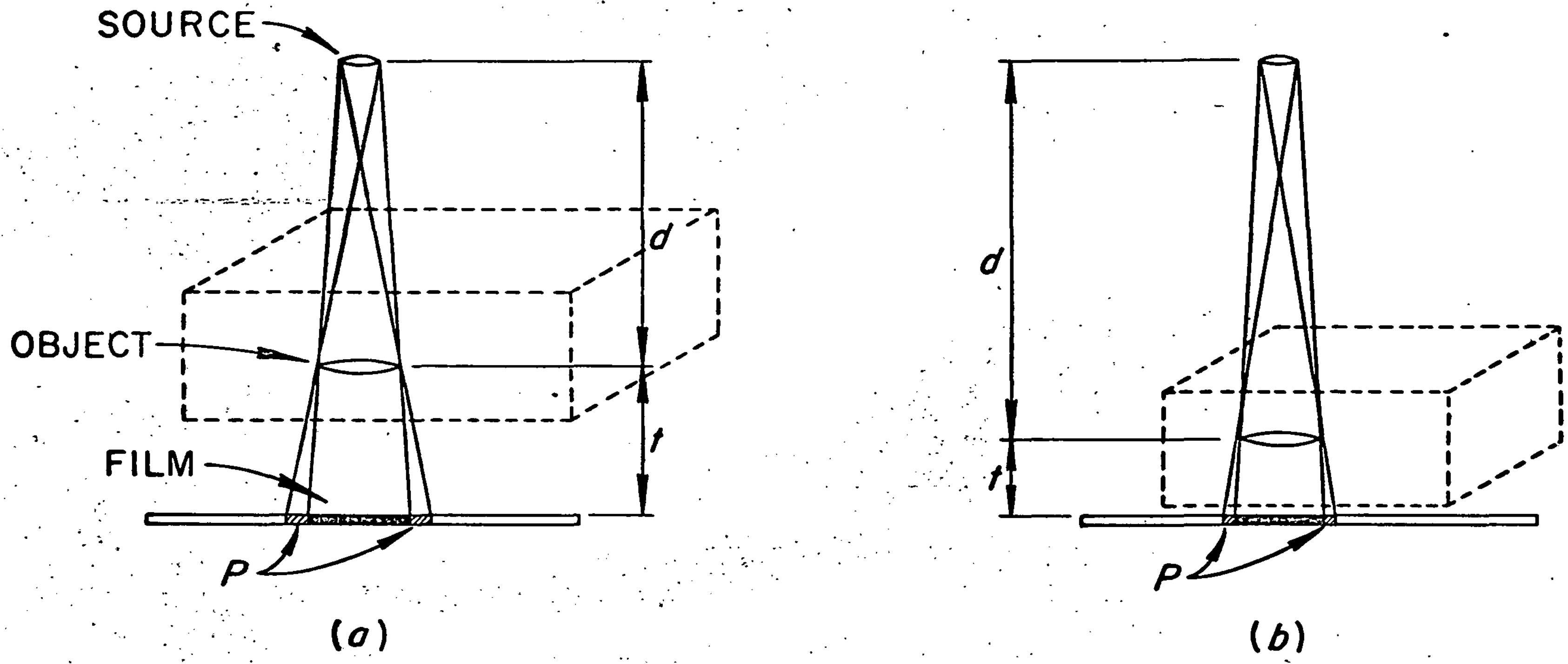


UNCLASSIFIED
ORNL-DWG 63-5427

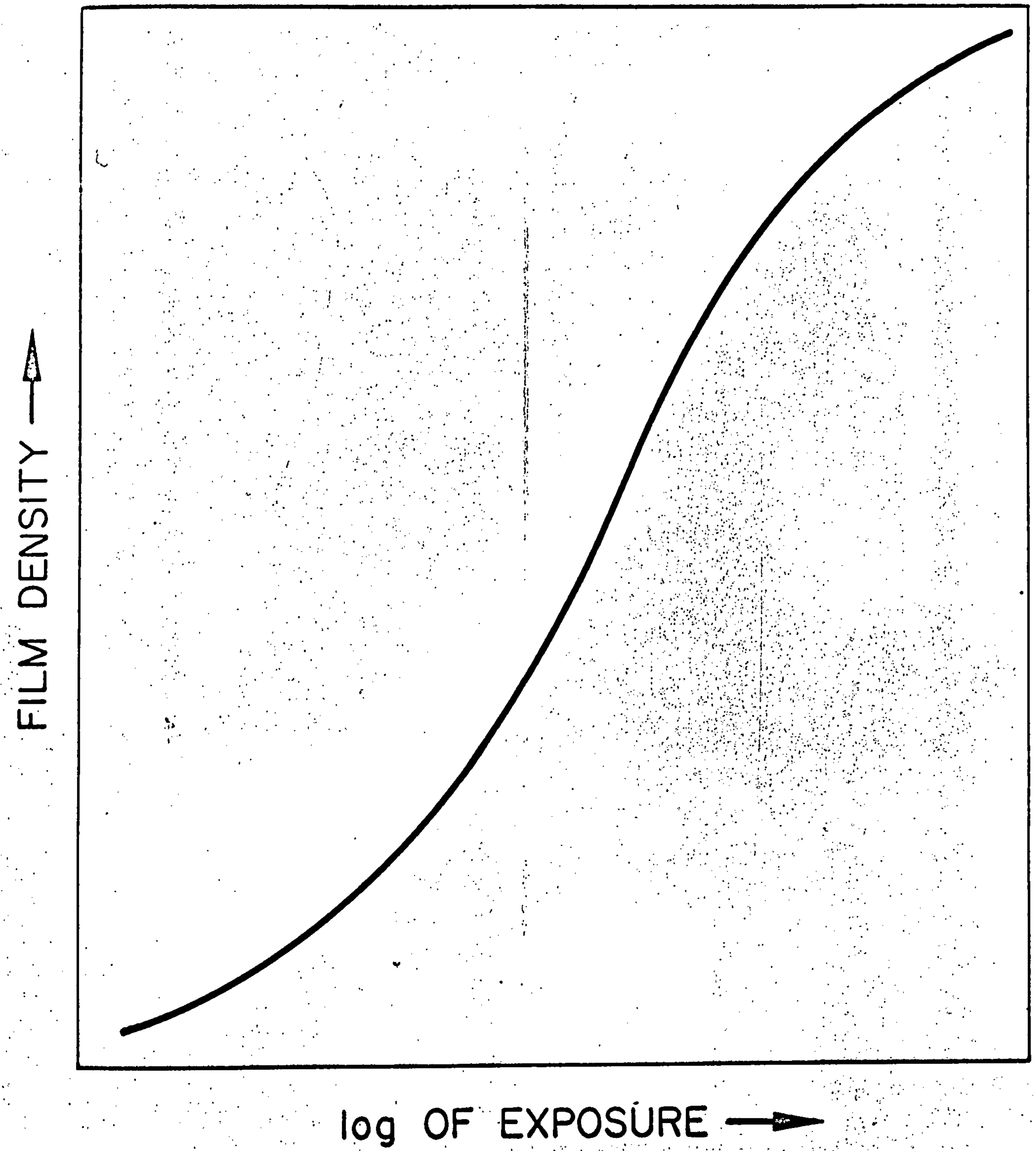


TYPE 316 STAINLESS STEEL
EASTMAN TYPE AA FILM
FILM DENSITY = 2

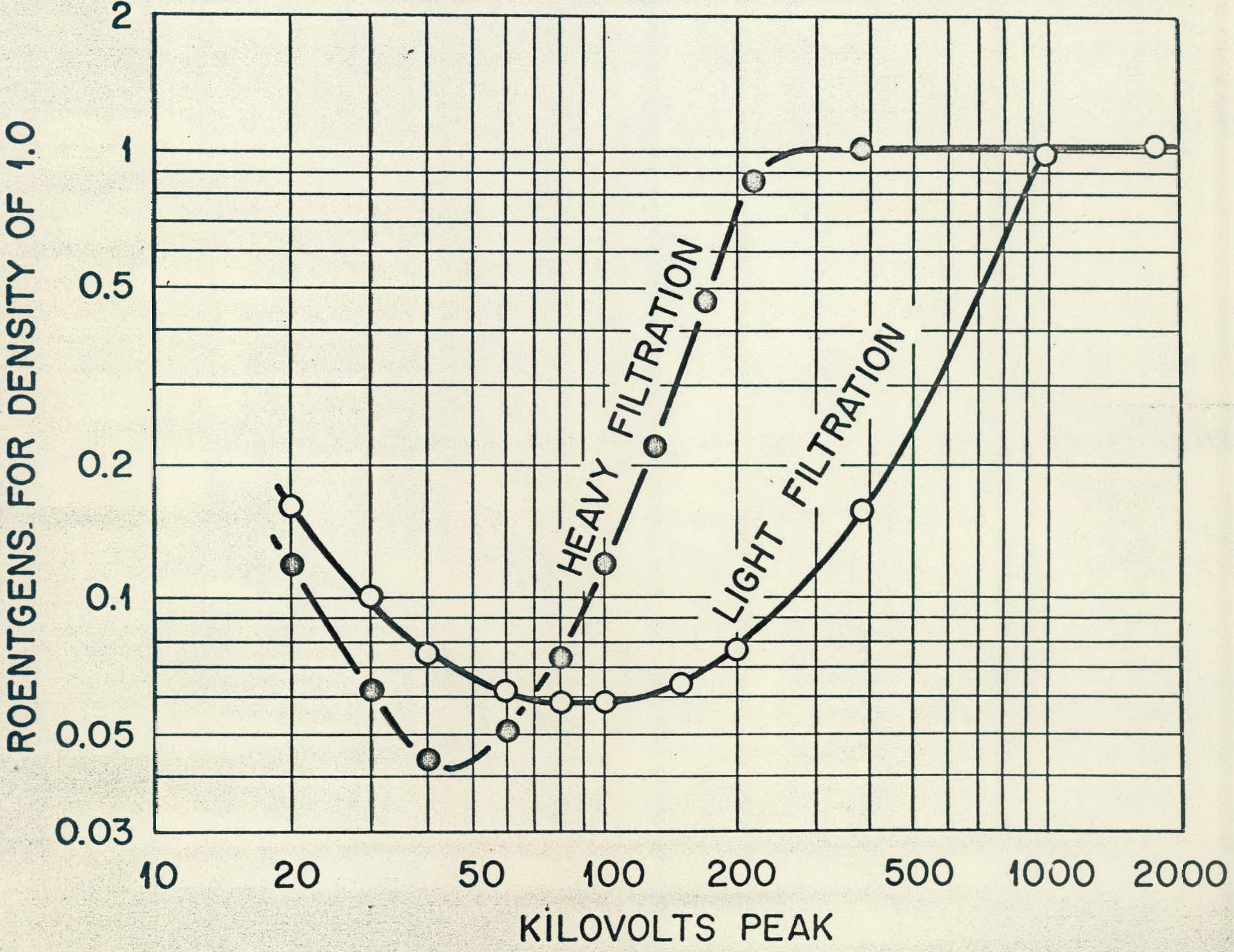
UNCLASSIFIED
ORNL-DWG 63-5426



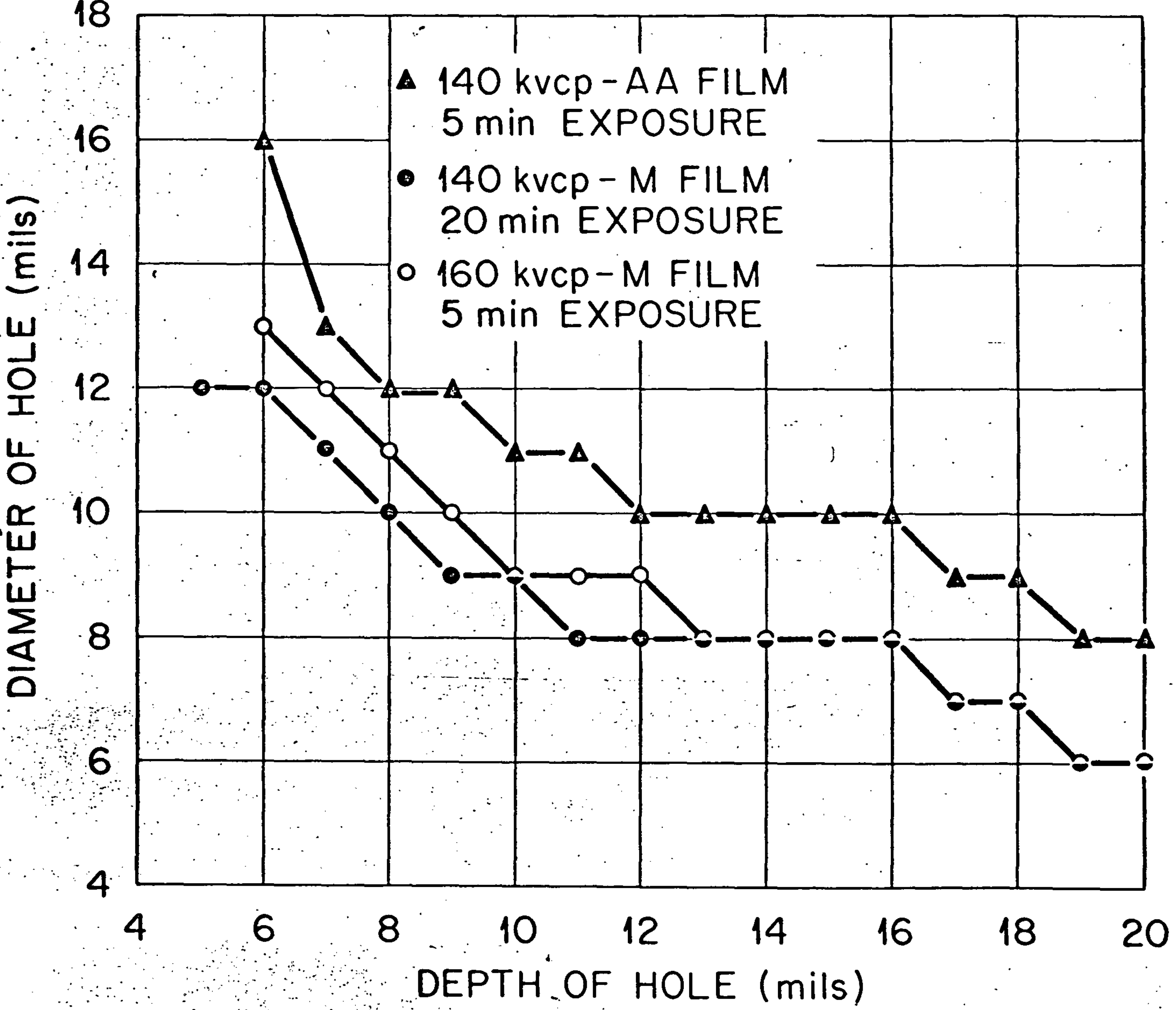
UNCLASSIFIED
ORNL-DWG 63-5425



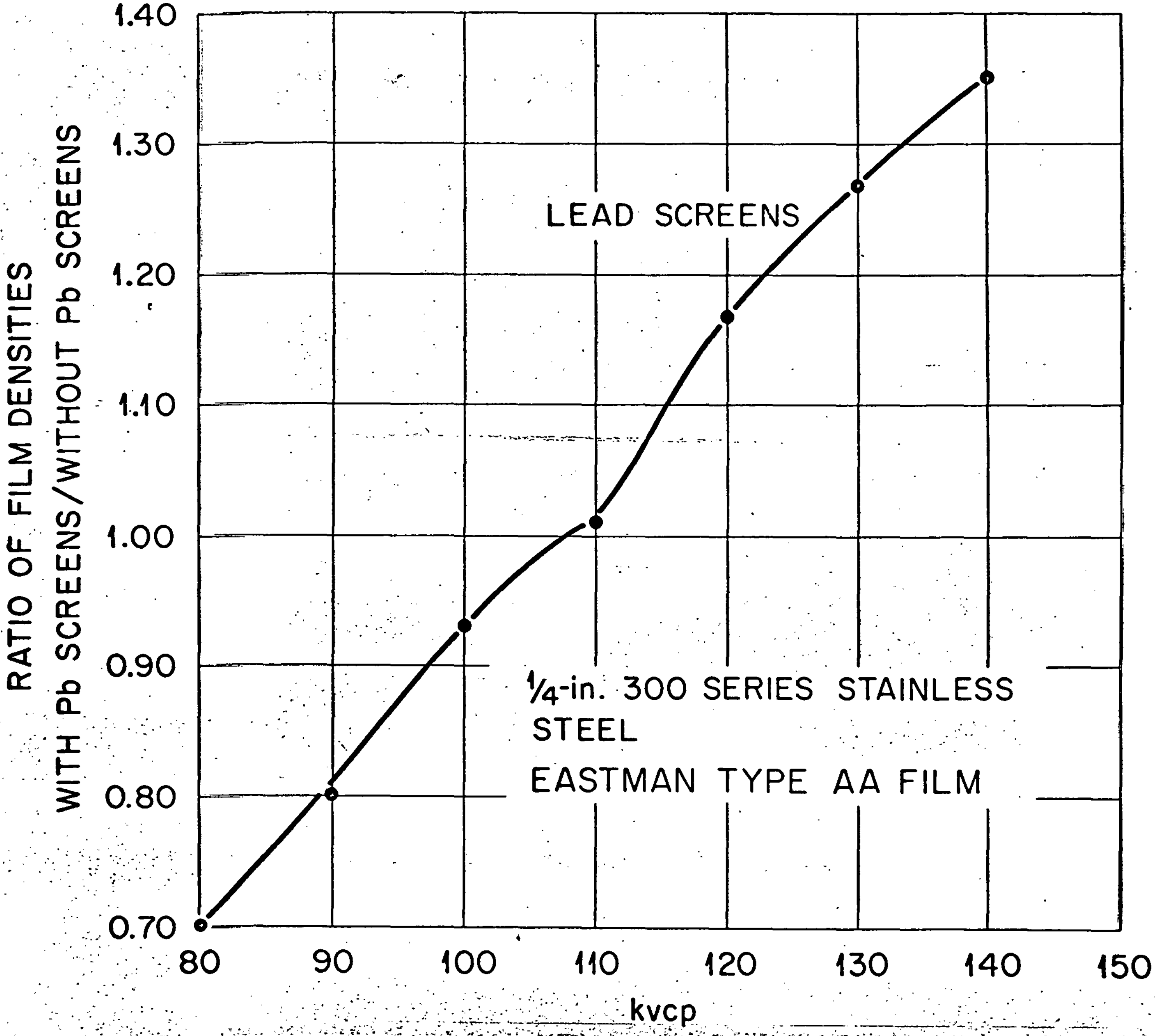
UNCLASSIFIED
ORNL-DWG 63-5655



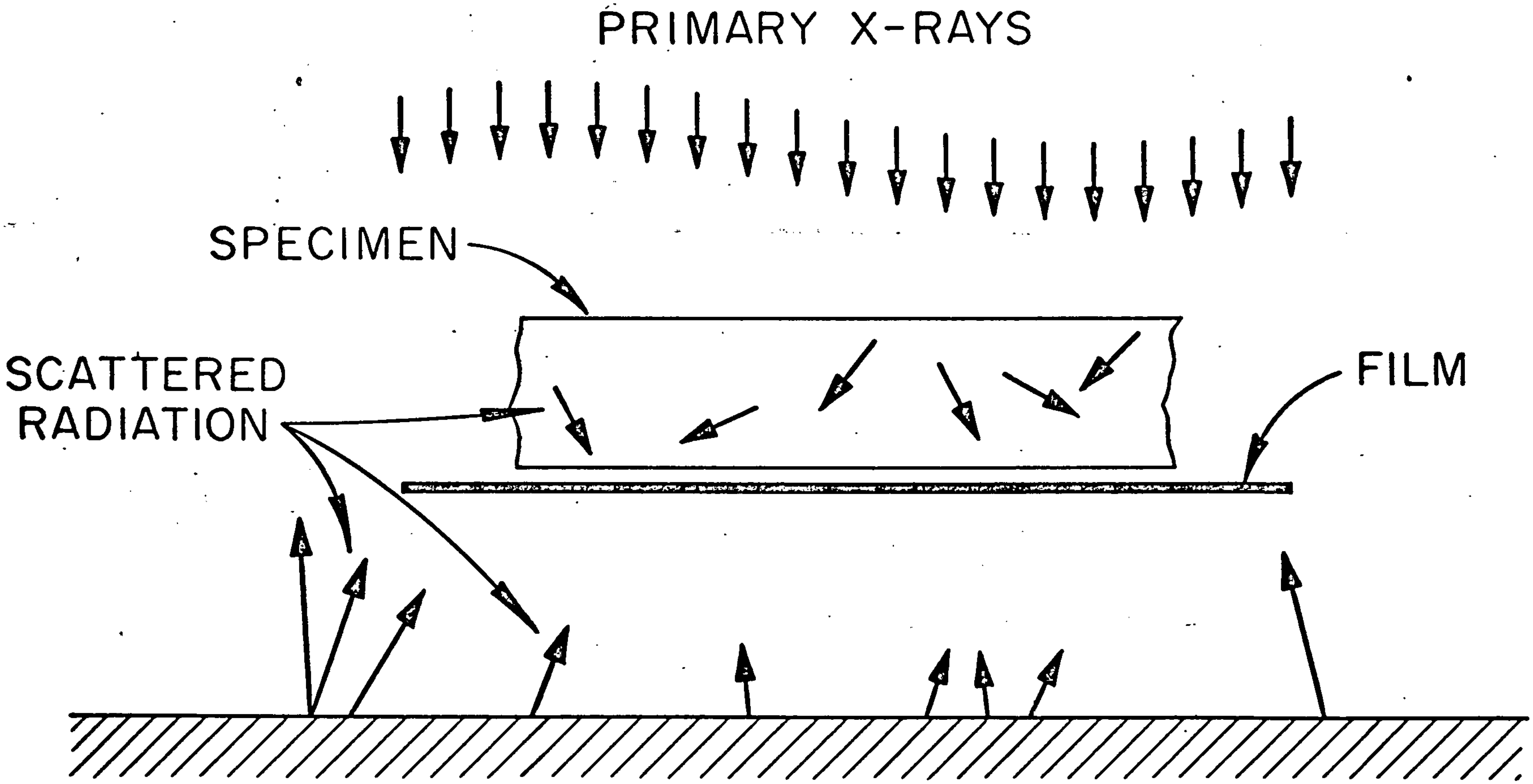
UNCLASSIFIED
ORNL-DWG 63-5653



UNCLASSIFIED
ORNL-DWG 63-5654



UNCLASSIFIED
ORNL-DWG 63-5424



UNCLASSIFIED
ORNL-LR-DWG 43721R