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TECHNIQUES FOR LOW-VOLTAGE RADIOGRAPHY

R. W. McClung

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TECHNIQUES FOR LOW-VOLTAGE RADIOGRAPHY

INTRODUCTION

The nuclear and aerospace industries have charted somewhat parallel courses in their need for high-temperature materials, thinner metallic sections, and such lightweight materials as beryllium. The utilization of such materials for critical applications demands the use of high-confidence inspection techniques to assure the material integrity. This has required improvements on existing methods and techniques, and, for some problems, development of new testing concepts. This report discusses some developments in technique which have been performed to improve the radiographic quality for relatively thin sections of such materials as aluminum, stainless steel, and beryllium.

THEORY

As is well-known, the radiographic method consists of transmitting a beam of x or gamma radiation through a test specimen and recording the transmitted radiation intensity on a medium such as film. Variations in the transmission properties of the specimen will cause associated variations on the recording medium. This may be seen from Lambert's law as expressed in the equation

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

where

I = radiation transmitted through specimen,

I_o = incident radiation,

μ = absorption coefficient,

ρ = density, and

x = specimen thickness.

The ability to detect a change in transmitted radiation intensity will depend, in part, upon the changes in the exponential terms, μ, ρ, and x across the projected area of the specimen. It is evident that the larger the exponent, the greater the radiation attenuation and, consequently, the greater the change in intensity. For useful radiography, there must be sufficient variation in the radiation absorption of the specimen for an interpretable contrast of density to be achieved on the

film or other detector. The quantity, μ, is energy dependent with generally increasing values occurring at decreasing energy levels. Therefore, for the thin sections and light materials, it has been necessary to use low-energy (low-kilovoltage) irradiation. This provides a large enough absorption coefficient to permit the detection of the minute thickness changes associated with the discontinuities of interest.

EQUIPMENT

Instrumentation

Commercial radiographic instrumentation[1] was used throughout this program. However, to gain better control over the various conditions of operation, several modifications were made. The changes were important for the attainment of precision for reproducible results in the determination of sensitivities, equivalence factors, etc. They were of less concern for actual applied radiographic inspection. Among the changes were the addition of a continuously variable power rheostat to allow complete control of the x-ray energy from 0–50 kvp. A high-precision timer was used which allowed reproduction of exposure times to the nearest 0.1 sec.

Reduction of Absorbers

The attainment of useful radiographs on very thin sections of aluminum and steel and thin sections of beryllium has required the use of very low-kilovoltage x rays. The use of these soft, easily absorbed x rays has made it necessary to eliminate all extraneous material between the irradiation source and the inspection specimen. These materials not only reduce the intensity of the x-ray beam, but also preferentially absorb the softer components of the spectrum which are so important in producing high-contrast, good-sensitivity radiographs.

The first step taken toward eliminating absorbing material was in the x-ray tube head. Because of the relative transparency of beryllium to x rays, it is normally used as the window in x-ray tubes requiring minimum filtration or absorption of the primary beam. The more common

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[1]Picker 50 PKV Industrial Unit, Picker X-Ray Corporation, Cleveland, Ohio.

commercial tube with a rating of 0–50 kvp contains a beryllium window which is approx 0.040 in. thick. For most radiographic practice, this is an insignificant amount of filtration. However, for very thin specimens which may be of the same material as the window, this becomes a more serious obstacle in obtaining the best sensitivity. Accordingly, a tube, containing a beryllium window only 0.008 in. thick, was obtained and used throughout the program.

Even air is a very effective attenuator or absorber of these soft rays. For example, in the 34-in. source-to-film distance which was used, an air medium would have the equivalent absorption of approx 0.140 in. of beryllium at 7 kvp. Therefore, to achieve the desired sensitivity, helium has been substituted as the intermediate atmosphere. The use of helium, of course, requires a relatively leak-tight container. This could be accomplished by dry-box techniques with both specimen and film being contained in the helium atmosphere. For convenience, a chamber has been constructed which will allow a helium atmosphere to exist between the source and specimen, but will prevent complete loss of helium as the specimen and film are removed. This chamber is shown in Fig. 1. It extends from the x-ray tube head to within approx 2 in. of the working surface. The lower end of the chamber is covered with an 0.0005-in.-thick sheet of polyethylene film which does a very good job of retaining the helium, yet is almost transparent to the soft x rays being used. Thus, both the specimen and film are in the normal room atmosphere and are completely accessible. Vacuum techniques could be utilized rather than helium, but this would demand the use of dry-box techniques as the very thin membrane could not withstand the pressure differential between the room atmosphere and the vacuum. A rather interesting by-product of the helium-chamber technique during the radiography of thin beryllium specimens is the fact that the 2 in. of air is an effective masking material for the very low-energy rays. Thus, there is essentially no scattered irradiation reaching the film to reduce image quality. The only exposure is that due to the primary beam.

Another important step in reducing unnecessary absorption has been the elimination of the cassette or film holder since this, too, will

Fig. 1. X-Ray Tube Head and Helium Chamber.

attenuate and change the character of the radiation. Bare film has been used thus necessitating the use of darkroom exposure techniques.

Each of the above precautions is of more importance in the lower end of the energy range and becomes of lesser importance for thicker specimens and higher energies. More will be said concerning the usefulness of these precautions during presentation of technique details and results.

EXPERIMENTAL PROCEDURES

Radiographic Control

An extensive program has been in progress to study the radiographic effects of variations in x-ray energy, specimen thickness, and the use of intermediate atmospheres of both helium and air. These studies have been made on beryllium, type 1100 aluminum, and type 304 stainless steel. Step wedges of each of these materials have been used in the following thickness ranges: for stainless steel, 0.001–0.006 in. and 0.006–0.040 in.; for aluminum, 0.003–0.024 in. and 0.020–0.445 in.; and for beryllium, 0.020–0.250 in. and 0.250–2.00 in. Each step wedge was radiographed in helium and air atmospheres at discrete energy levels from approx 5 to 50 kvp. At each energy level, a sufficient number of radiographs was taken with different exposure times to provide a complete span of readable densities for each thickness. Thus, for each thickness of every material, curves of film density vs exposure time could be plotted as a function of energy level and atmosphere. Maximum exposure times were generally held to 10 min or less with the greater portion of the exposures being 5 min or less.

Eastman type "M" film was used throughout the project. No cassettes were used, the specimens being placed directly on the bare film and the entire setup and exposure operation conducted under darkroom conditions.

Film-Processing Control

Control of the film-processing variables was mandatory for the attainment of reproducible results and to allow cross referencing and correlation between different radiographic conditions. This control was accomplished in two ways. A special aluminum step wedge was radiographed under very carefully controlled conditions to produce uniform high-contrast

films. These were cut into strips and developed at periodic intervals prior to processing of experimental film. A secondary check was made by reproducing an experimental exposure and developing the film. Film densities were measured and compared with results which had been obtained previously. If there were density or contrast changes, the concentration of the developing solution was altered and a recalibration made before the experimental film was processed.

Film Density Measurement

All film densities were measured on dry processed film with a Macbeth-Ansco Model 12A Densitometer[2] which is capable of making measurements over a density range from 0 to 8.0 with an accuracy of ± 0.02. Thus far in the study of radiographic variables, approx 1500 different film exposures have been made and about 7500 density measurements have been taken.

RESULTS

All of the data was transferred to basic graphs to display the milliampere – second exposures vs the attained film density for each specimen thickness. For each chart, the specimen material, the x-ray energy, and the intermediate atmosphere were held constant. Figure 2 is an example of a portion of such a chart which was produced from data for the radiography of thin beryllium sections in a helium atmosphere at an energy level of 24.5 kvp. As may be expected, a large number of these graphs was drawn. These then served as the basis for the subsequent data evaluation. Appropriate utilization of these curves provided the necessary information for the preparation of useful exposure charts for each of the examined materials as a function of energy. The relative value of intermediate atmospheres (helium vs air) could also be properly assessed. Calculations for attainable contrast sensitivities were made as a function of the varying conditions. Radiographic equivalence factors for each of the materials were calculated. Each of these considerations will be discussed and illustrated in some detail.

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[2]Macbeth Instrument Corporation, Newburgh, New York.

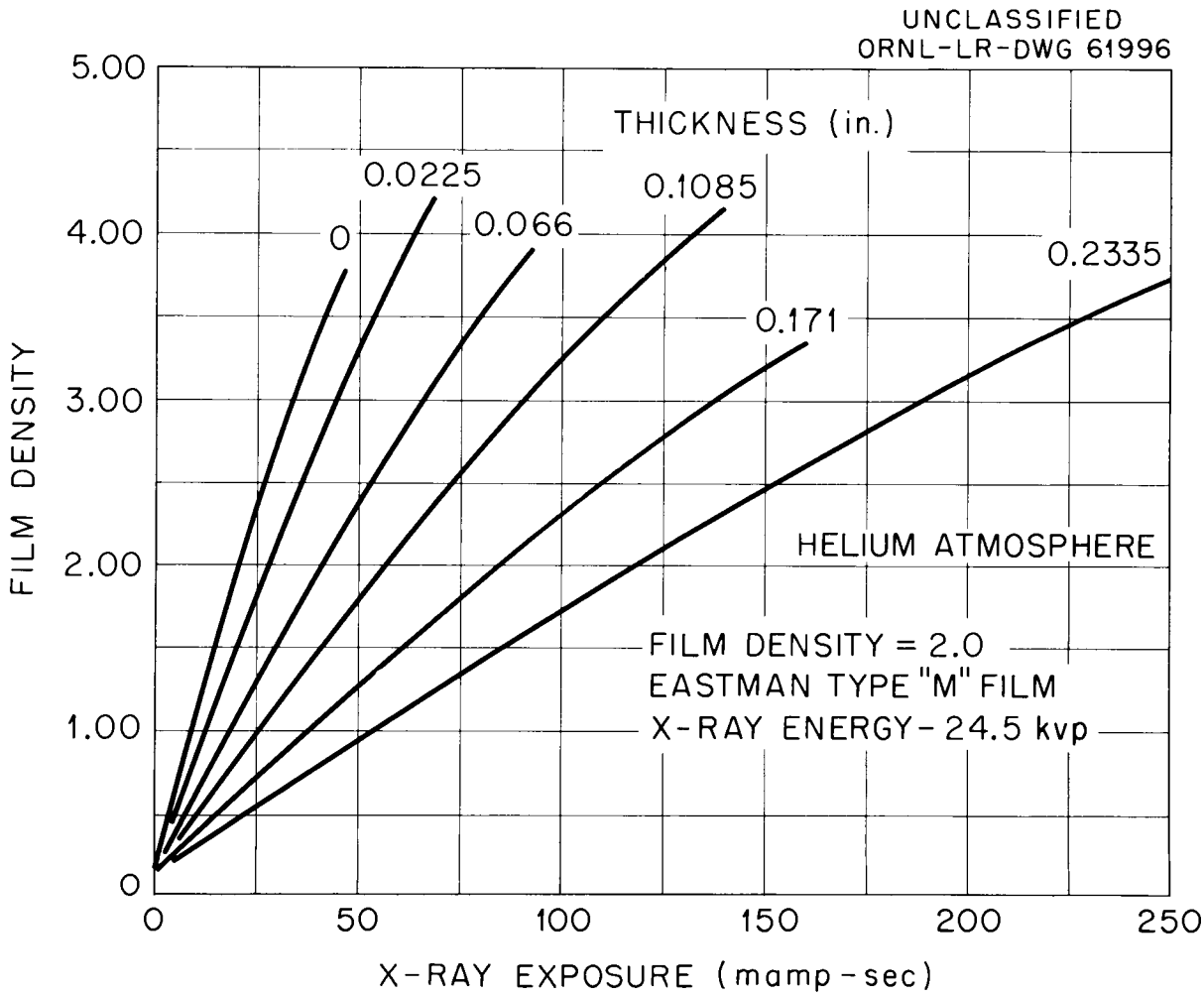

Fig. 2. X-Ray Exposure vs Density Chart for Radiography of Beryllium in Helium at 24.5 kvp.

Exposure Requirements

A film density of 2.0 was selected as standard for most of the data evaluation. Therefore, the composite exposure charts for various thicknesses and x-ray energies have been compiled from the exposure/density charts which display smooth curves through a density of 2.0. Figures 3 through 8 are the graphs which were determined for each of the examined materials using both helium and air atmospheres.

Helium vs Air Atmosphere

A helium intermediate atmosphere to reduce the radiation absorption and filtration was of benefit in the thinner sections of aluminum and steel, particularly in the lower energy ranges. It was particularly significant in the radiography of beryllium. Figure 9 is a comparison of several exposure vs density curves using both air and helium atmospheres for the radiography of thin sections of beryllium at 24.5 kvp. It is evident that there is a significant difference in the exposure requirements and this is even more pronounced at lower energies. The curve in Fig. 10 summarizes the data comparison for beryllium as a function of the ratio of the relative exposures in helium and air vs the kilovolt-peak energies. Similar curves were plotted for the different thicknesses of each of the materials studied. A portion of this data is included in the figures discussed relative to other absorbers. There is a difference in the contrast sensitivity which can be attained with each atmosphere. This will be noted in the discussion of sensitivity.

Other Absorbers

All absorbing material between the specimen and the x-ray target was removed or reduced. This included, in addition to the intermediate atmosphere, utilization of a thinner x-ray tube window and the removal of the film holder. As with the different atmospheres, the benefits were most pronounced at the lower energies and for the least absorbent materials. Calculations have been made to determine the conditions at which there is little advantage in the special precautions. Several assumptions were made for this determination. It was arbitrarily decided that any decrease in exposure time of 10% or less would offer little advantage. The film holder which was selected for comparison was a flexible plastic

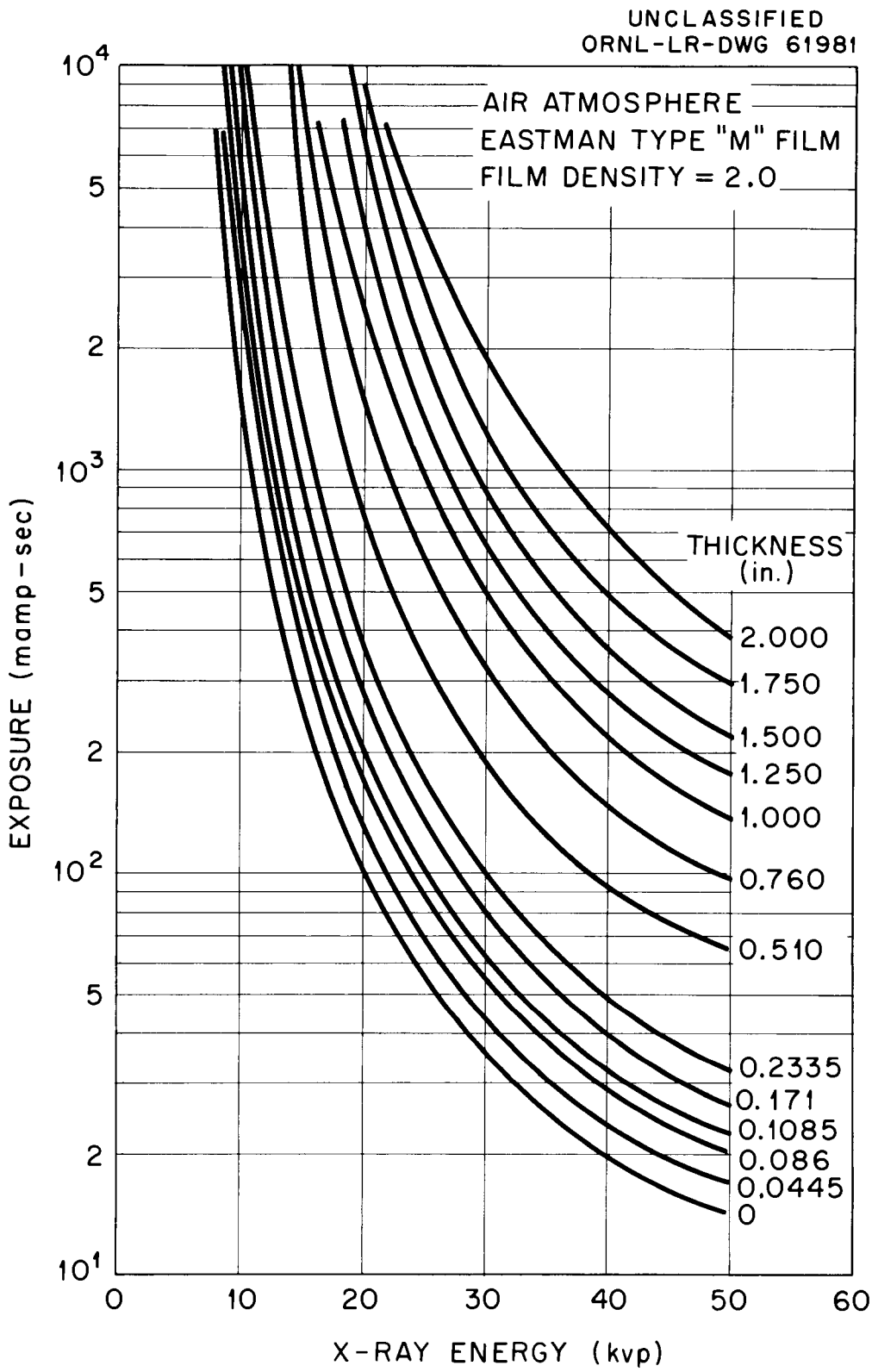

Fig. 3. Exposure Chart for Various Thicknesses of Beryllium with an Air Atmosphere.

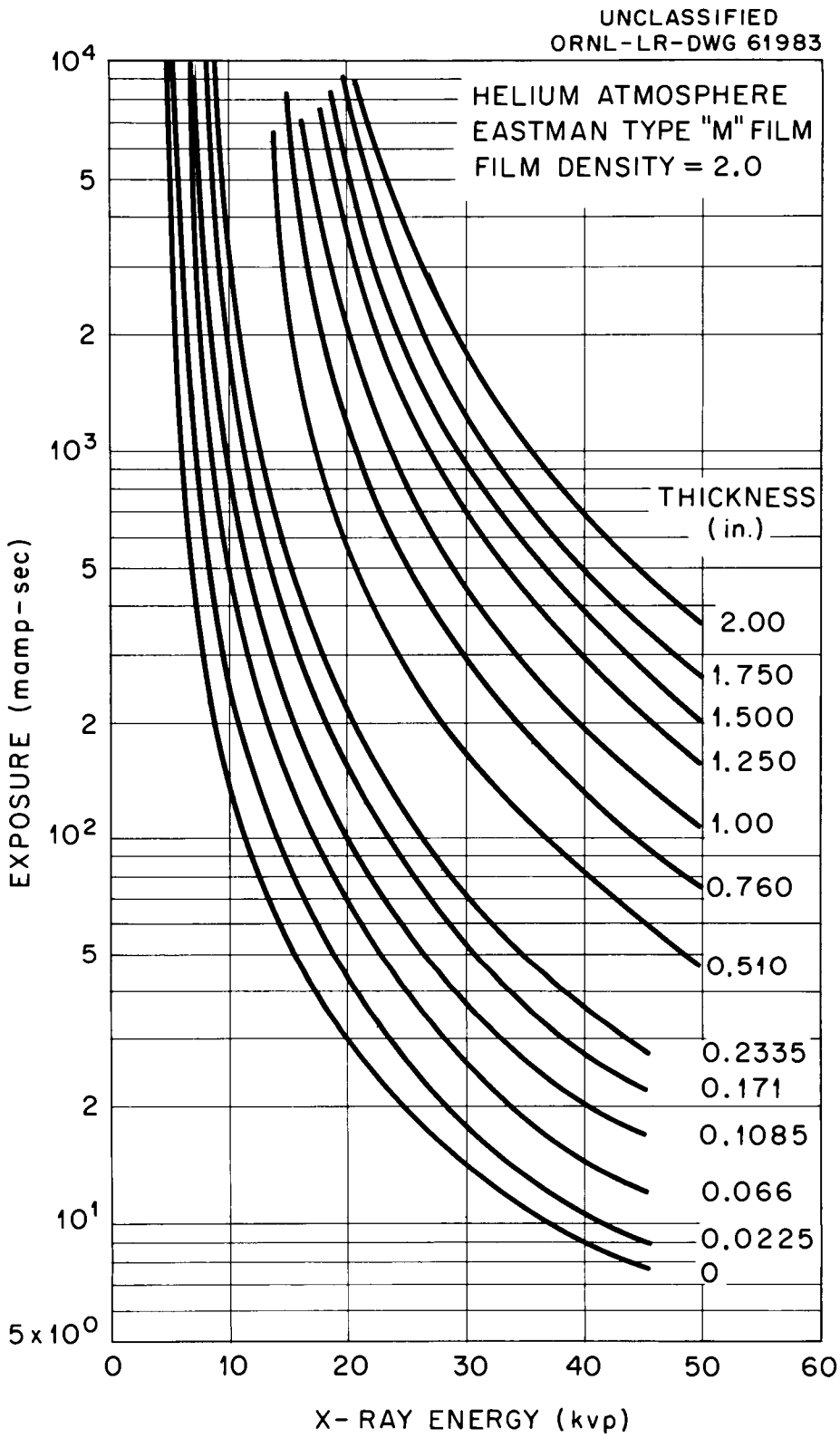

Fig. 4. Exposure Chart for Various Thicknesses of Beryllium with a Helium Atmosphere.

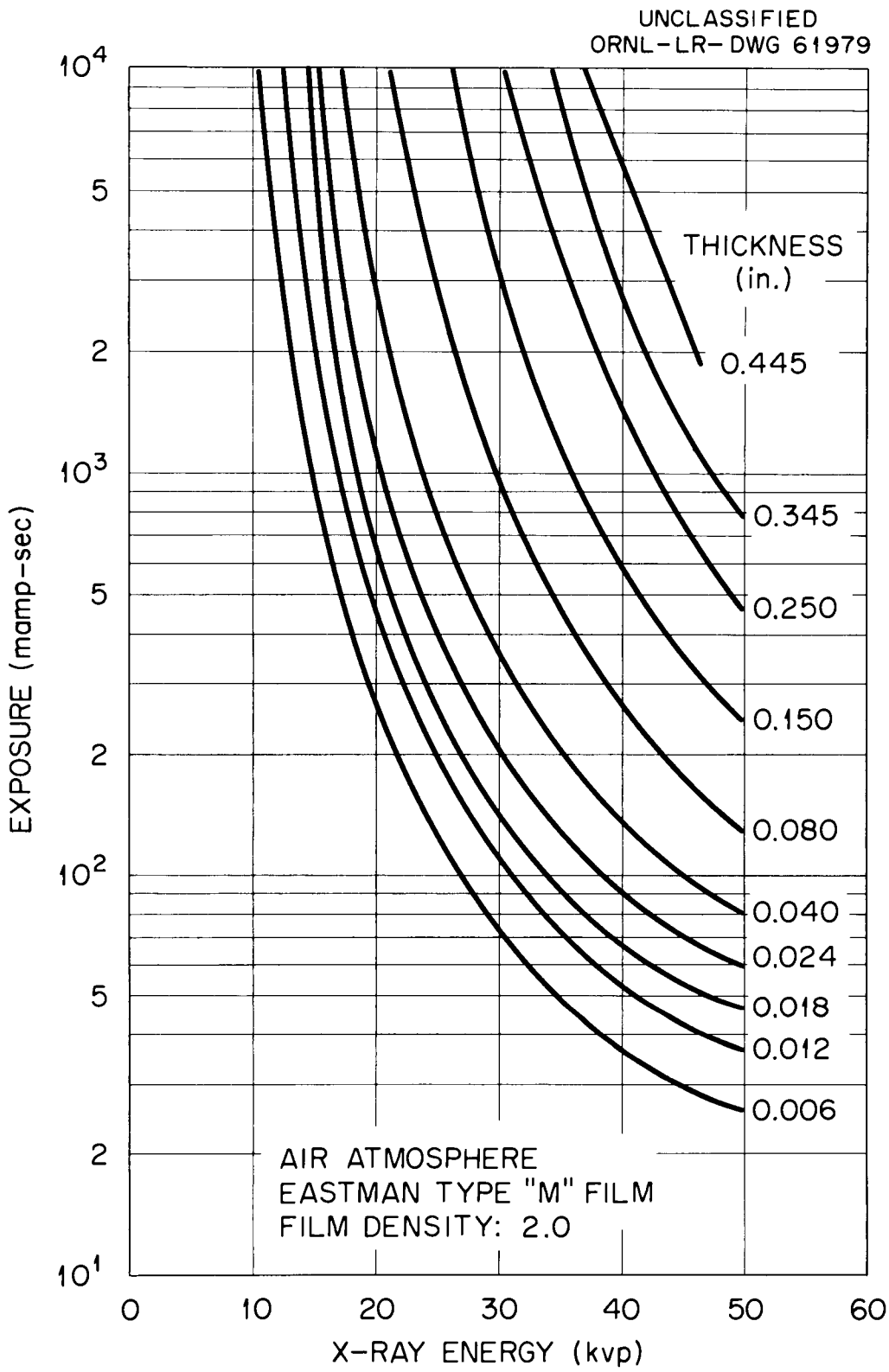

Fig. 5. Exposure Chart for Various Thicknesses of Aluminum with an Air Atmosphere.

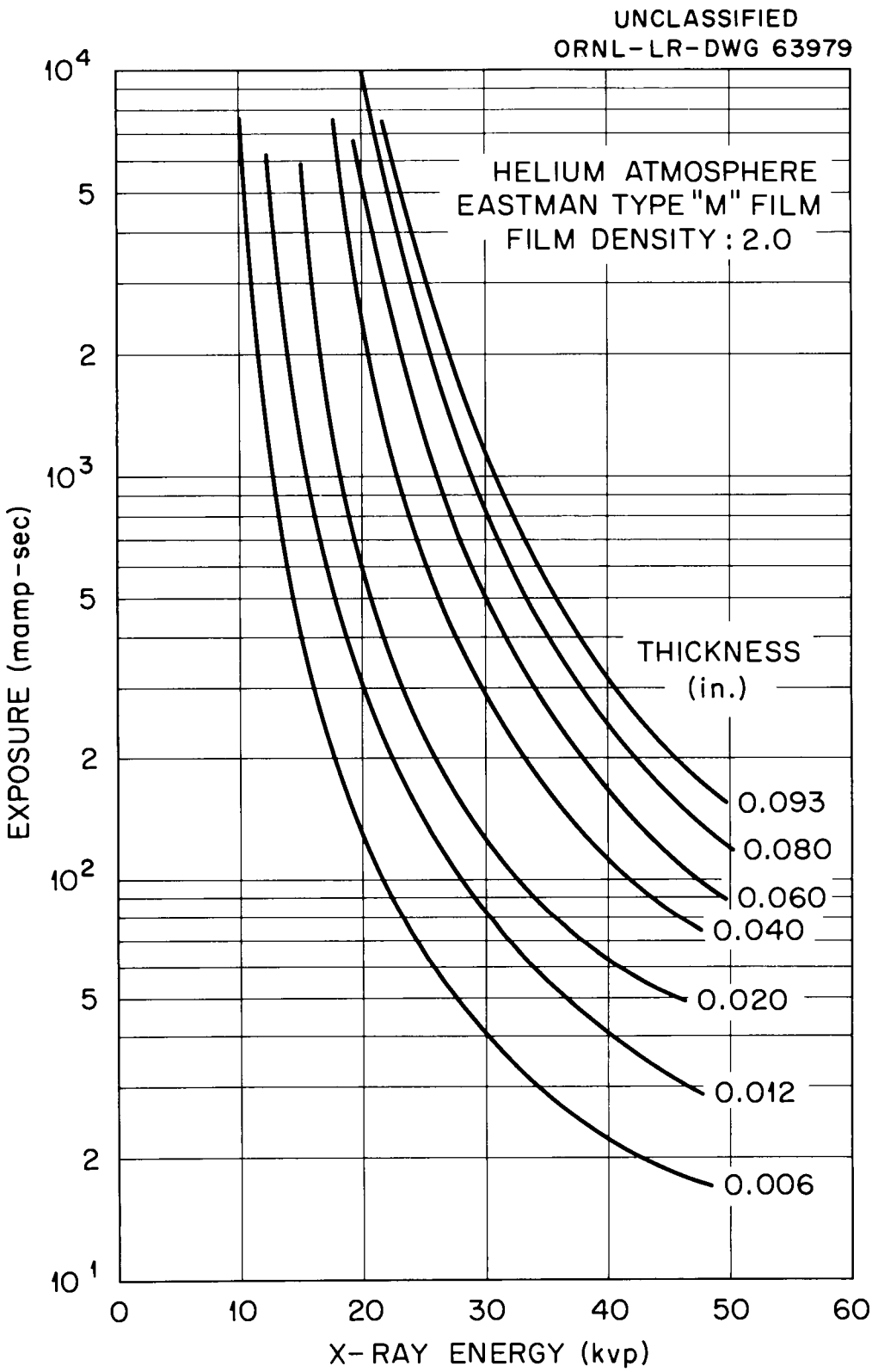

Fig. 6. Exposure Chart for Various Thicknesses of Aluminum with a Helium Atmosphere.

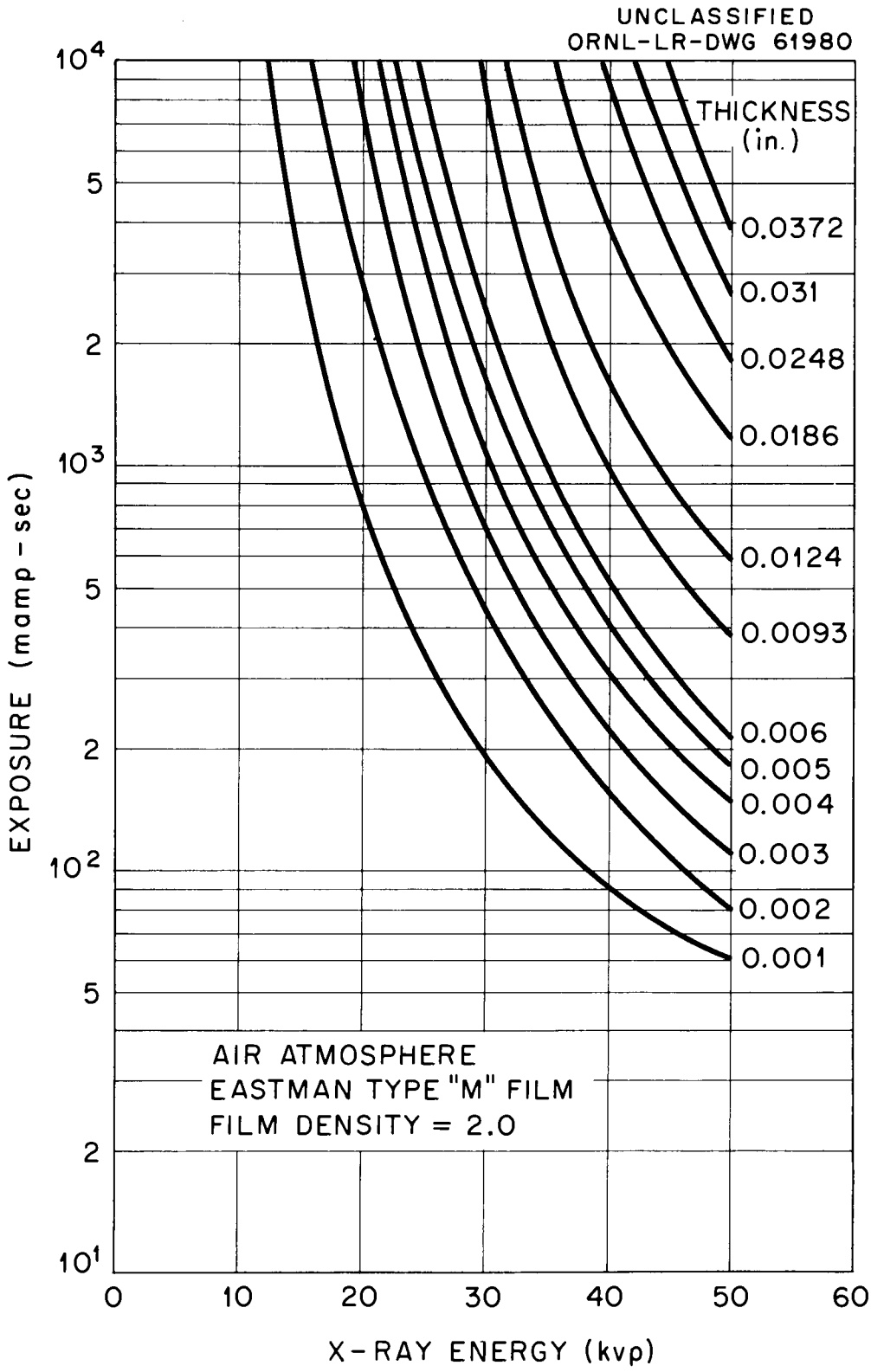

Fig. 7. Exposure Chart for Various Thicknesses of Stainless Steel with an Air Atmosphere.

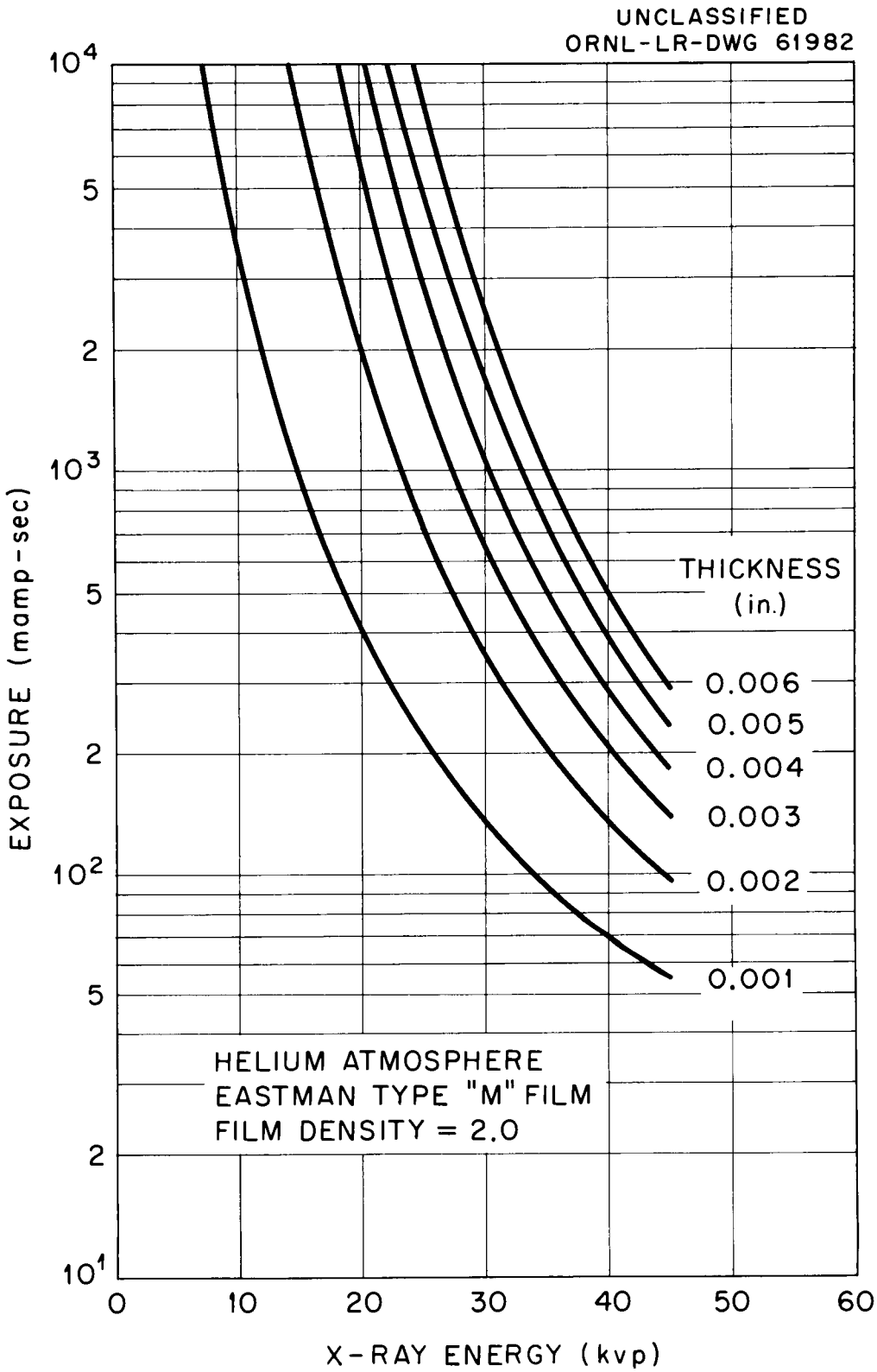

Fig. 8. Exposure Chart for Various Thicknesses of Stainless Steel with a Helium Atmosphere

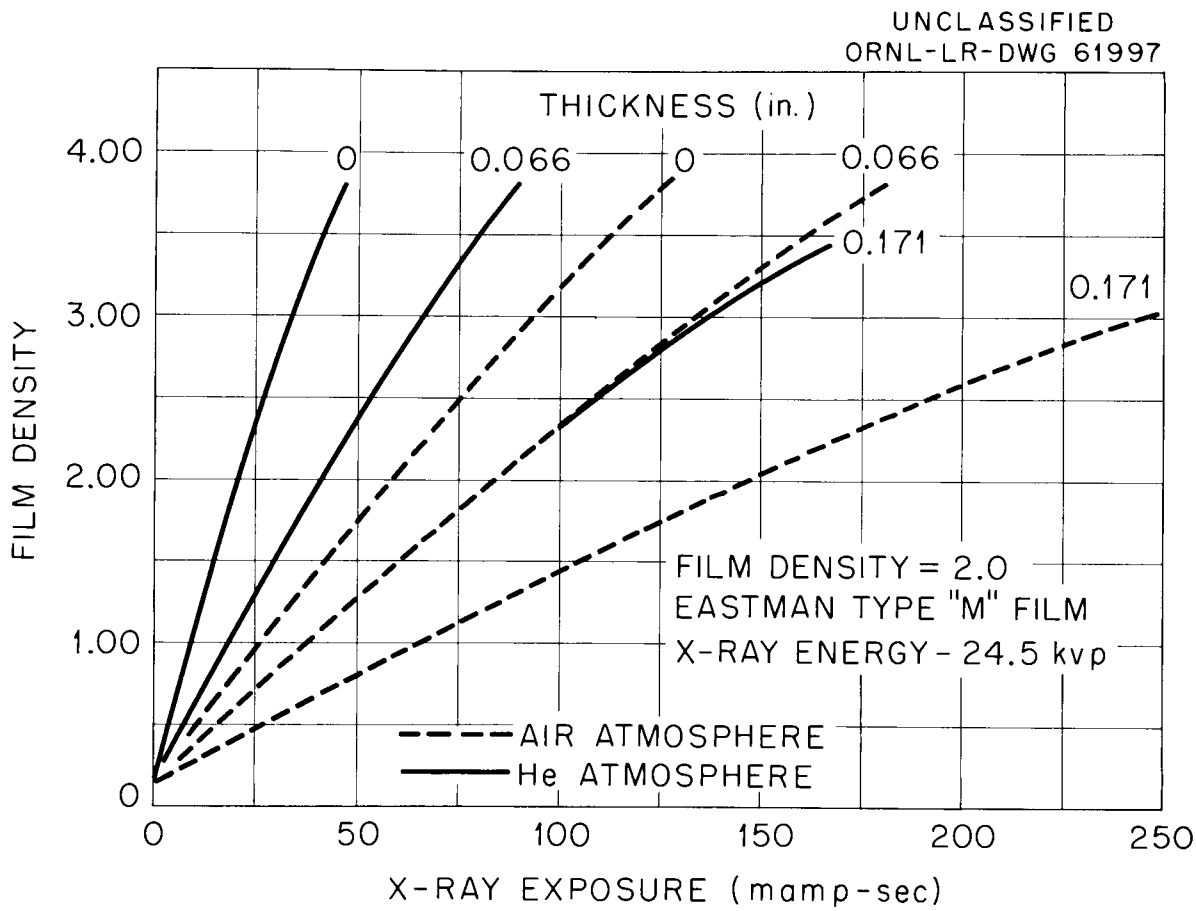

Fig. 9. Comparison of Exposure vs Density Curves for Helium and Air Atmospheres.

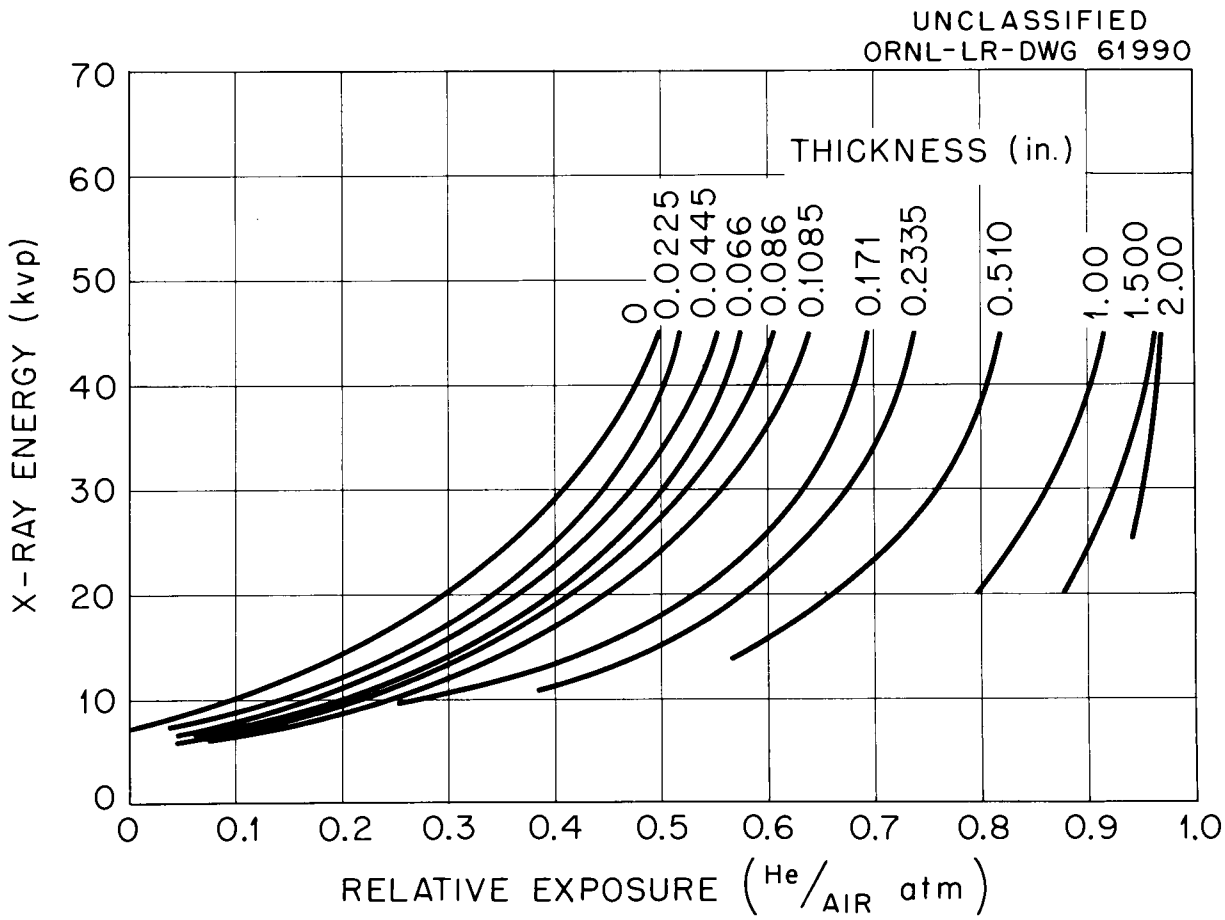

Fig. 10. Relative Exposure Requirements for Helium and Air Atmospheres During Beryllium Radiography.

cassette which interposed a single layer of plastic between the film and specimen. The results would be different for other cassette materials and designs. The calculations were made by determining the radiographic equivalent thickness of the air atmosphere, the cassette material, and the tube window thickness difference in terms of each of the inspected materials at various energy levels. The exposure curves were then evaluated to determine the conditions at which that thickness increase would require 10% change in exposure rate to maintain the same density. Figures 11 through 13 are the resultant curves which illustrate the conditions in which significant benefit may be obtained for the removal of absorbing material. These data can, of course, be superimposed on the composite curves to achieve overall technique charts. The advantage of using these precautions is not only decreased exposure time, but also improved sensitivity. There is little advantage in using the thin window tube for stainless steel or for aluminum sections thicker than about 0.025 in. The helium atmospheres are not needed for stainless steel thicknesses greater than approx 0.006 in., aluminum sections more than about 0.050 in., and beryllium thicker than 2.0 in. Similar values for the advantages of the cassette removal may be noted from these graphs. Of course, each of these benefits is energy dependent.

Contrast Sensitivity

Data were extracted from the exposure/density curves for the determination of contrast sensitivity. This was accomplished as follows. The exposure requirement to achieve a density of 2.0 on a given thickness of material was observed for a set of conditions of atmosphere and energy. The densities attained for adjacent thicknesses of material under the same exposure were measured. The values of thickness vs density were plotted as shown in Fig. 14. By measuring the slope of the line tangent to the curve at a density of 2.0 and using a value of 0.006 (ref 3) as

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[3]R. Meakin, "Scattered Radiation," pp. 44–63 in A Further Handbook of Industrial Radiology, ed. by W. J. Wiltshire, Edward Arnold, Ltd., London, 1957.

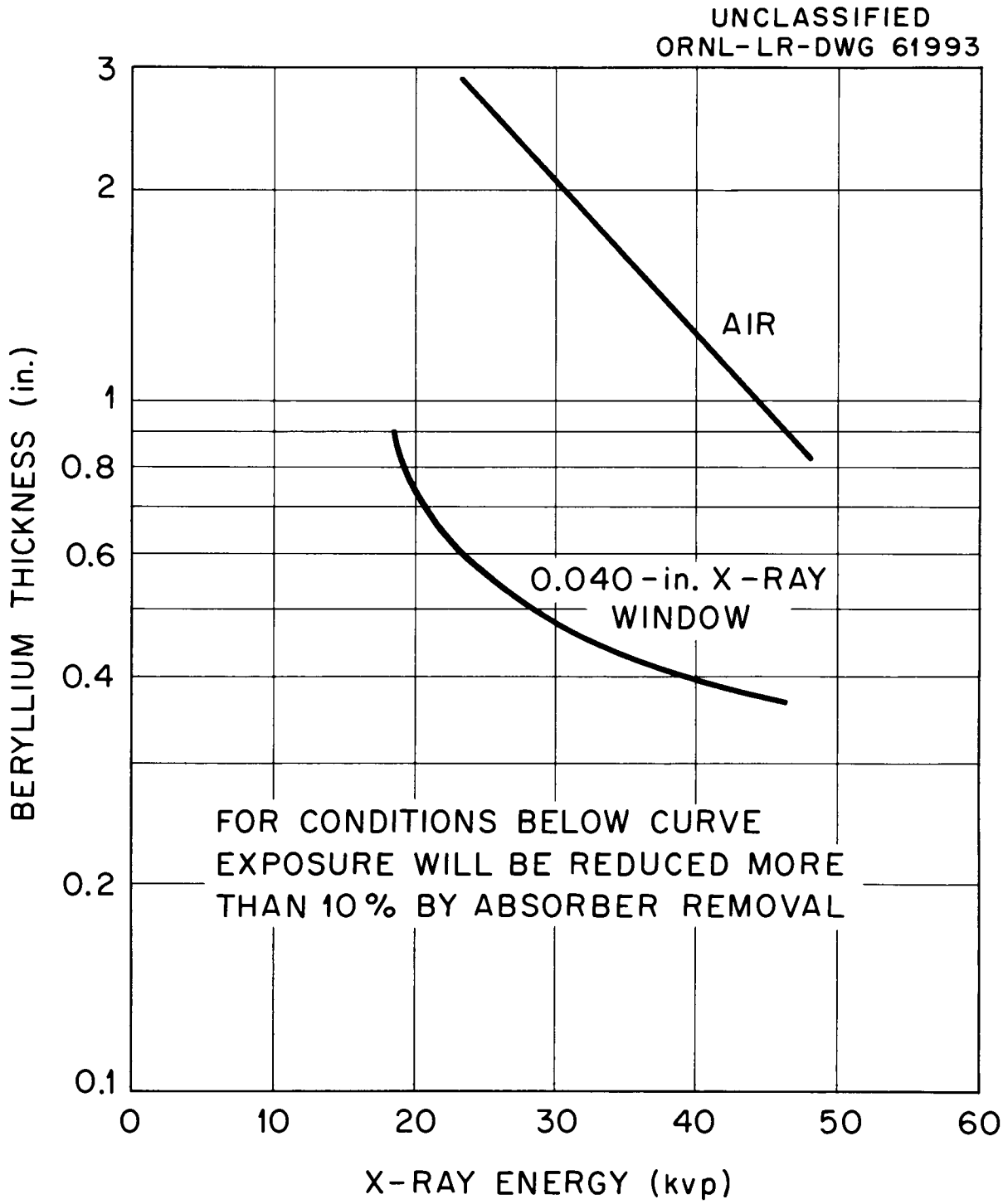

Fig. 11. Conditions Under Which Absorber Removal Will Effect 10% Change in Exposure Requirement for Radiography of Beryllium.

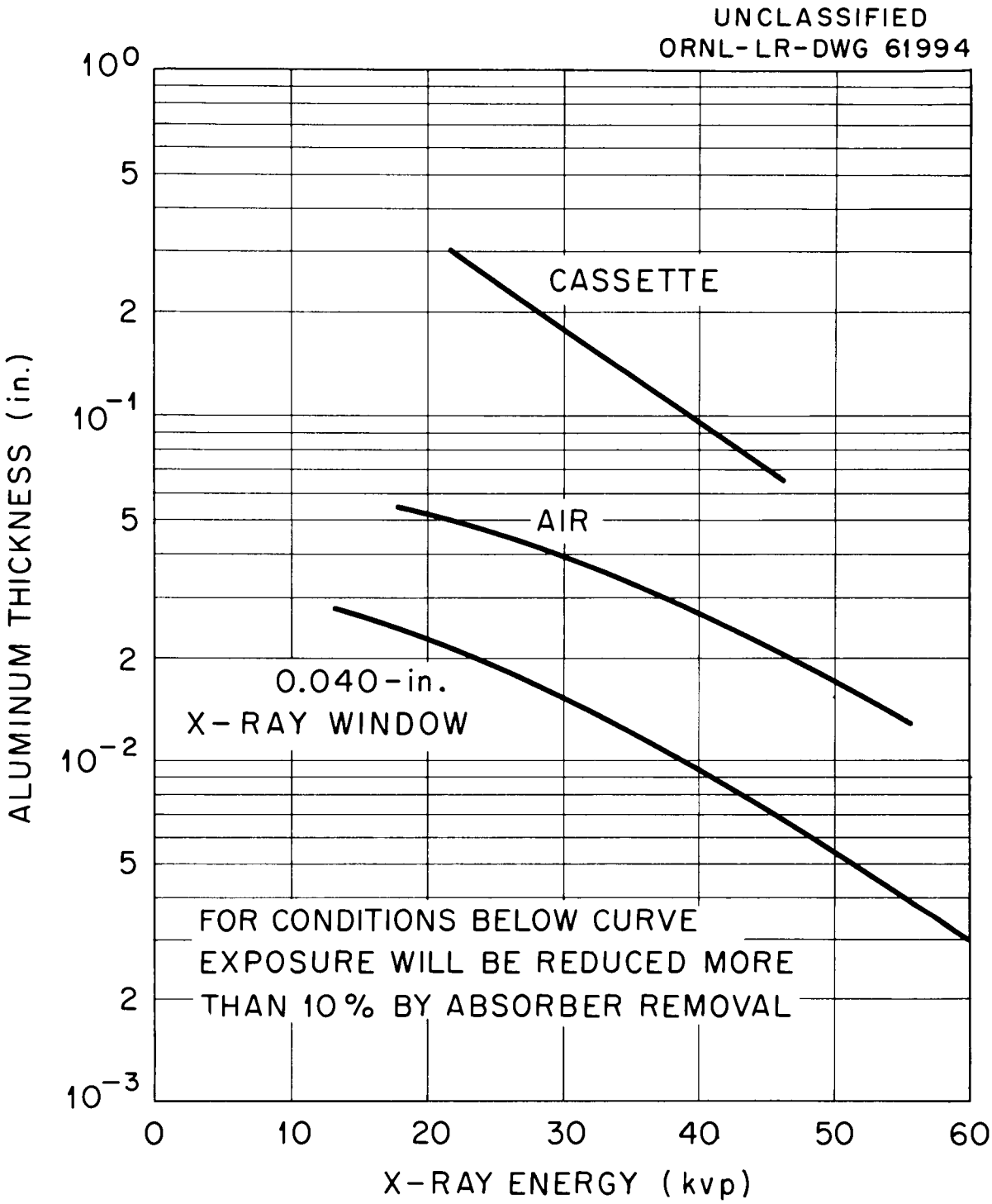

Fig. 12. Conditions Under Which Absorber Removal Will Effect 10% Change in Exposure Requirement for Radiography of Aluminum.

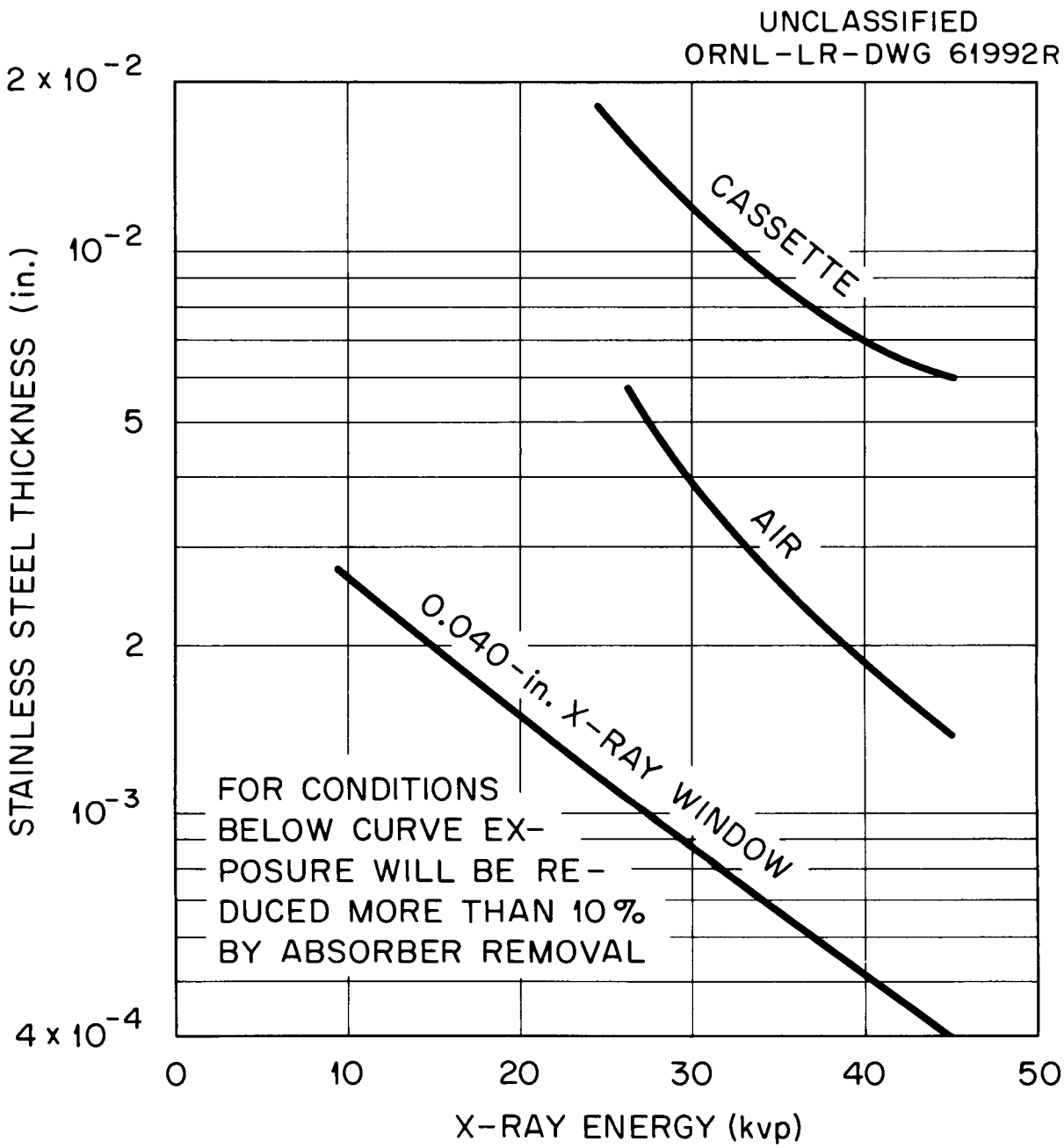

Fig. 13. Conditions Under Which Absorber Removal Will Effect 10% Change in Exposure Requirement for Radiography of Stainless Steel.

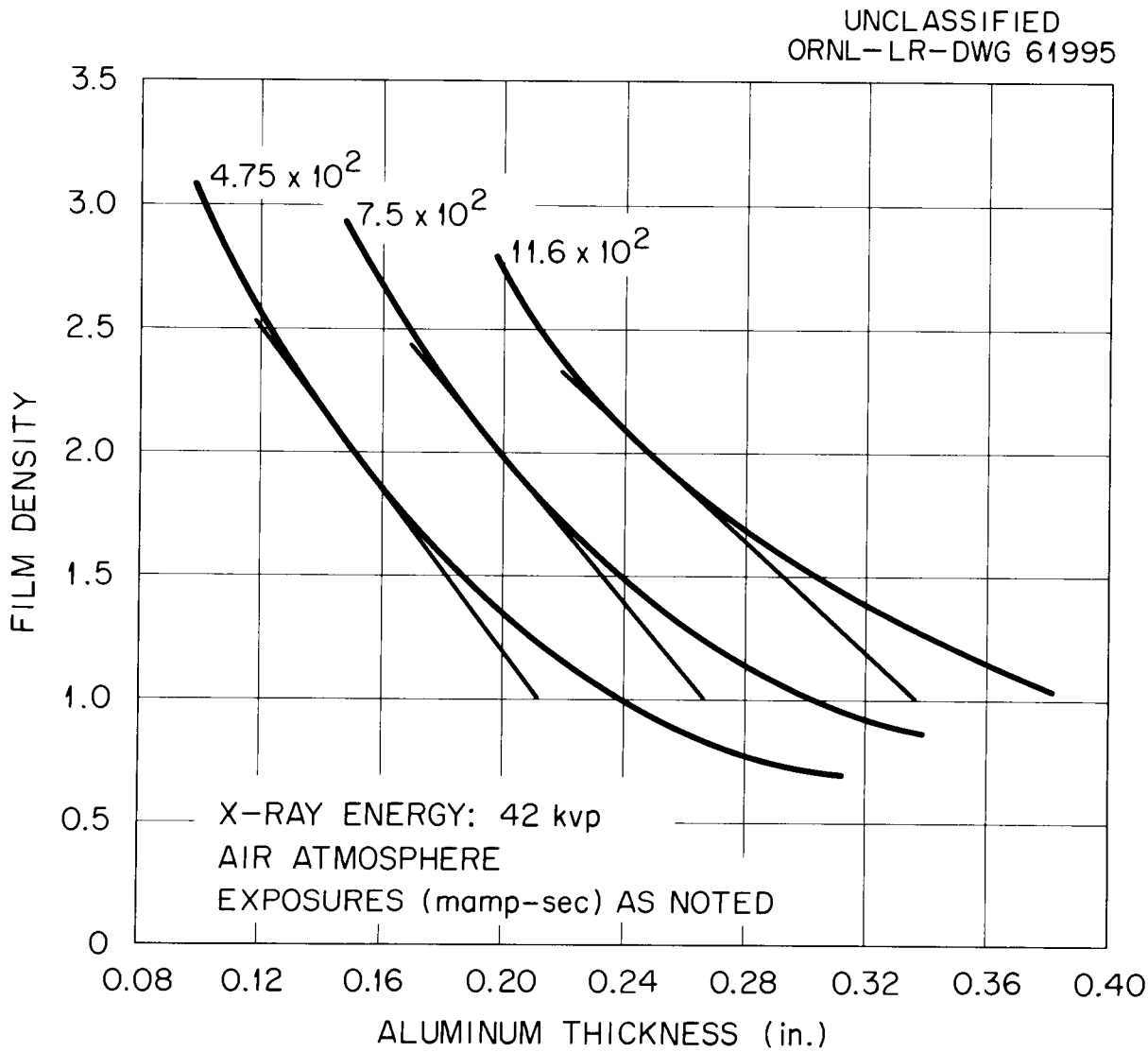

Fig. 14. Typical Thickness vs Density Curves for the Calculation of Contrast Sensitivity.

the minimum detectable change in density, the minimum detectable thickness change can be determined. From this, the sensitivity can be readily calculated. Figures 15 through 20 represent the calculated values of contrast sensitivity for the various conditions. It is evident that there is a decided improvement in contrast sensitivity when using the helium atmosphere. This advantage is slightly less than that noted for relative exposures. Spot checks with actual specimen and penetrameter thicknesses have been made with very good agreement between the calculated and observed sensitivities. The observed sensitivity has been frequently better than that which was calculated. It must be recognized that these contrast sensitivities of 0.2% and better were achieved on flat plates. The attainable sensitivities for complex shapes may be slightly reduced because of decreased image sharpness.

Resolution

For thin sections, the principal limitation on resolution or the minimum detectable defect size is the unsharpness factor of the film itself. Using round penetrameter holes as a basis for discussion, the minimum detectable size has been slightly less than 0.004 in. if no visual aids have been employed. By using low-power magnification, a hole 0.0022 in. in diameter has been seen. Of course, this achievement is dependent on the contrast and the background variation of the specimen. For the thicker section in which there is more radiation scattering to reduce image sharpness, the minimum detectable size may increase. However, confident detection of 0.0036-in.-diam holes has been made through 0.4 in. of aluminum and 0.010-in.-diam holes in 1.00 in. of beryllium.

Equivalence Factors

Radiographic equivalence factors have been determined for each of the energies and materials. All materials were related to steel and were calculated on the basis of the thickness of material necessary to have the equivalent absorption of 0.001 in. of the type 304 stainless steel. The equivalence factors varied slightly as a function of the x-ray energy for both beryllium and aluminum. Figures 21 and 22 relate the equivalence factor to the x-ray energy. In addition to the energy dependence, there was a slight change in the equivalence factor as a function of the total thickness because of the filtering effect of the specimens on the x-ray

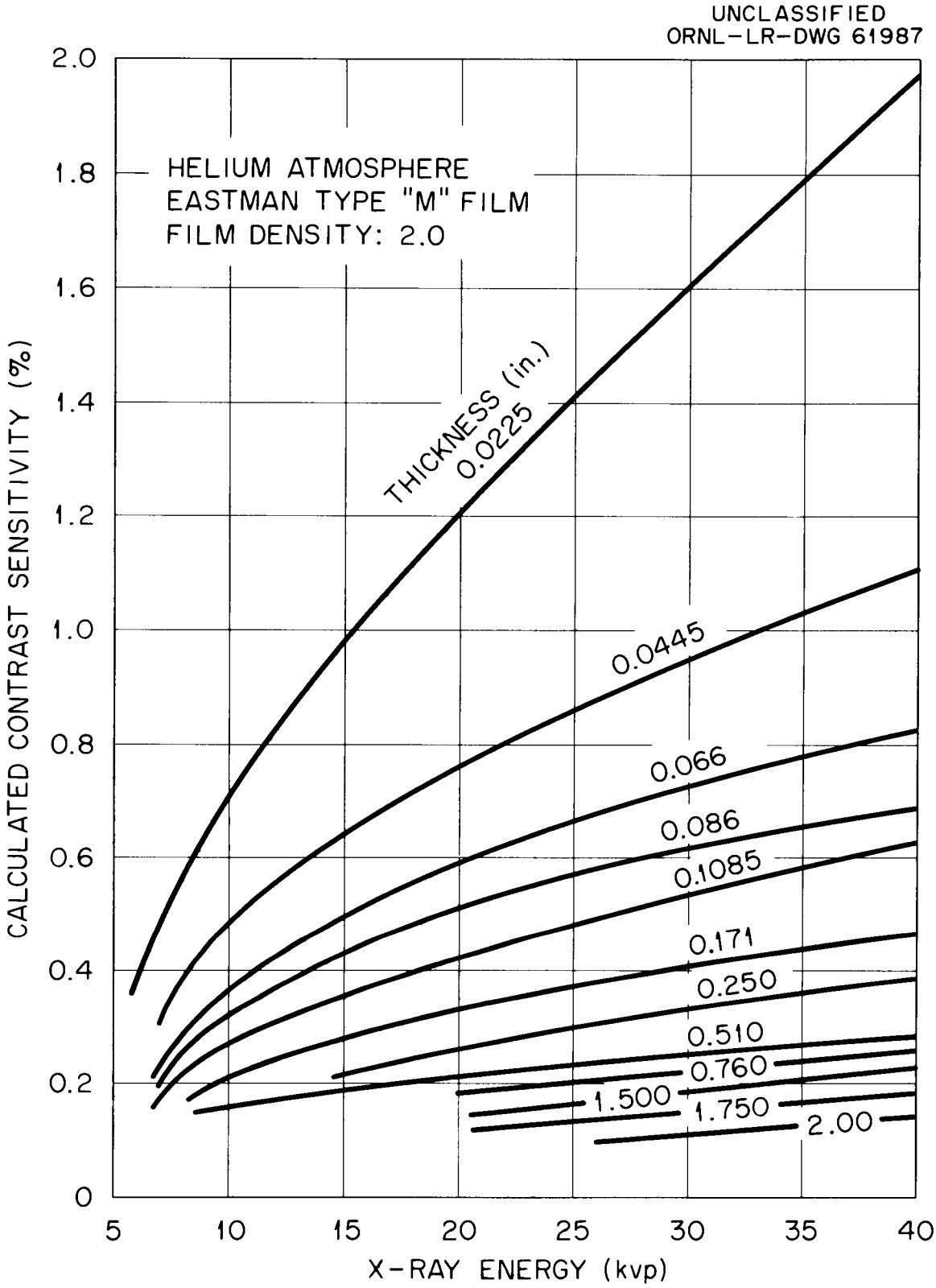

Fig. 15. Calculated Contrast Sensitivities for the Radiography of Beryllium in a Helium Atmosphere.

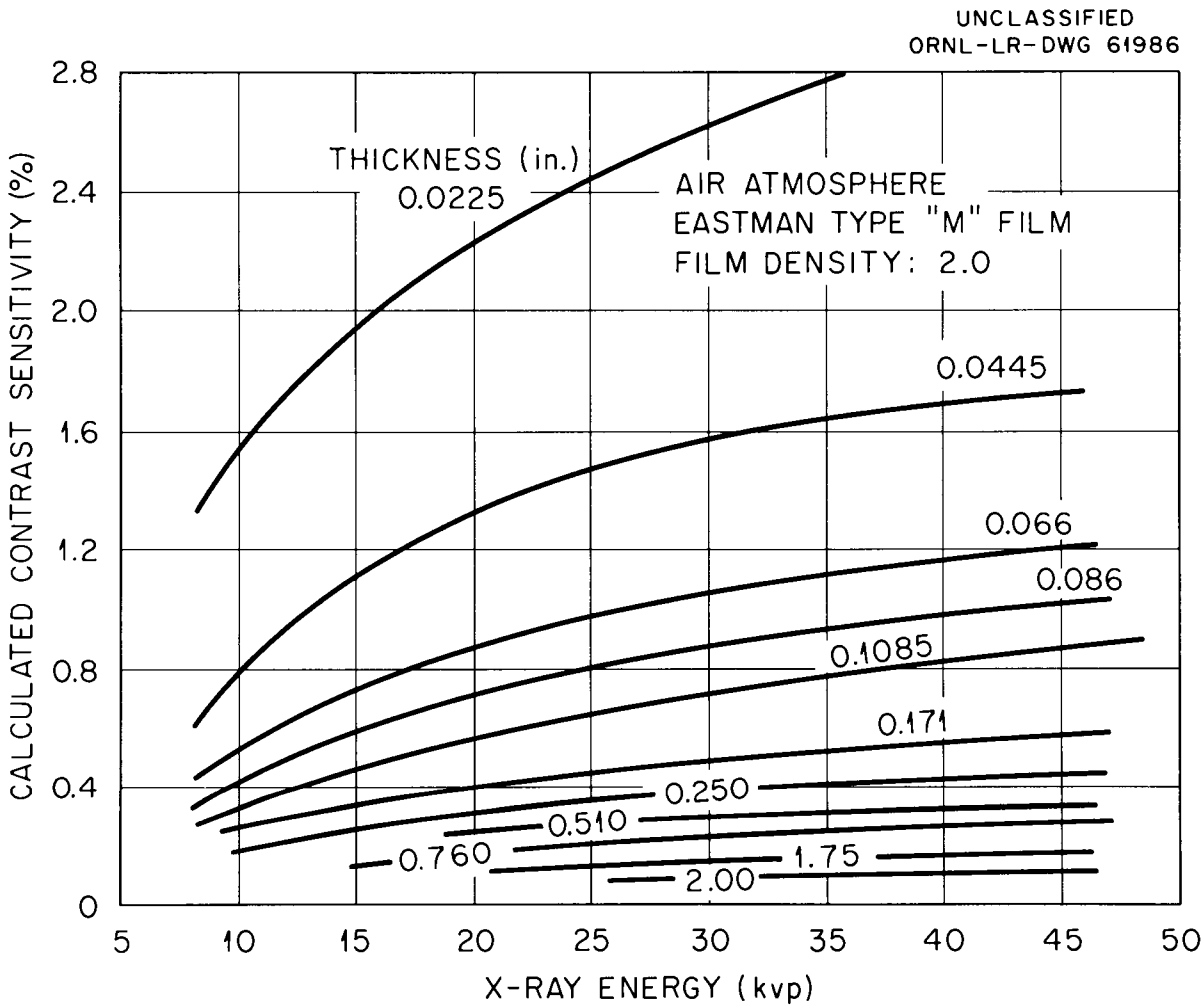

Fig. 16. Calculated Contrast Sensitivities for the Radiography of Beryllium in an Air Atmosphere.

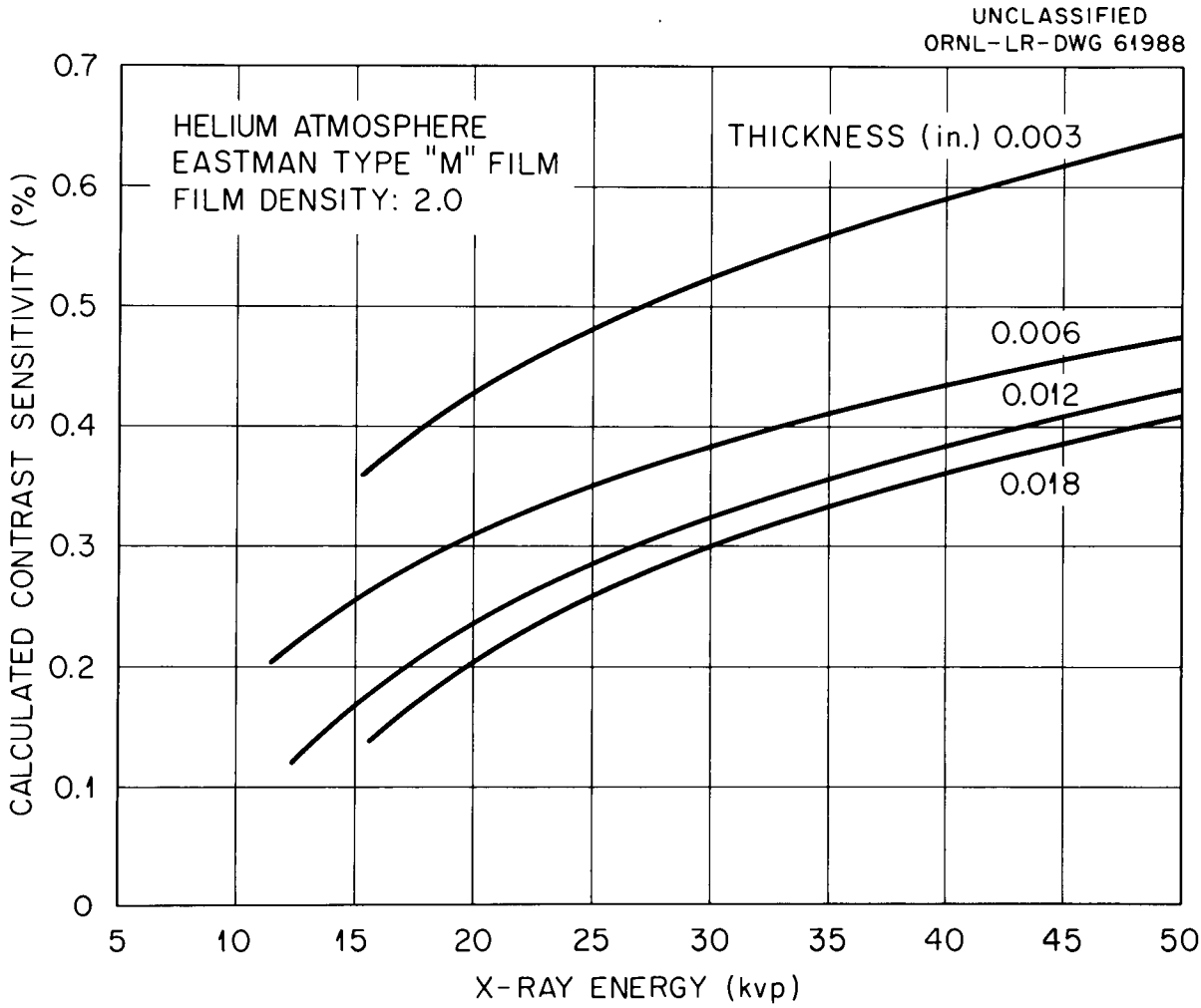

Fig. 17. Calculated Contrast Sensitivities for the Radiography of Aluminum in a Helium Atmosphere.

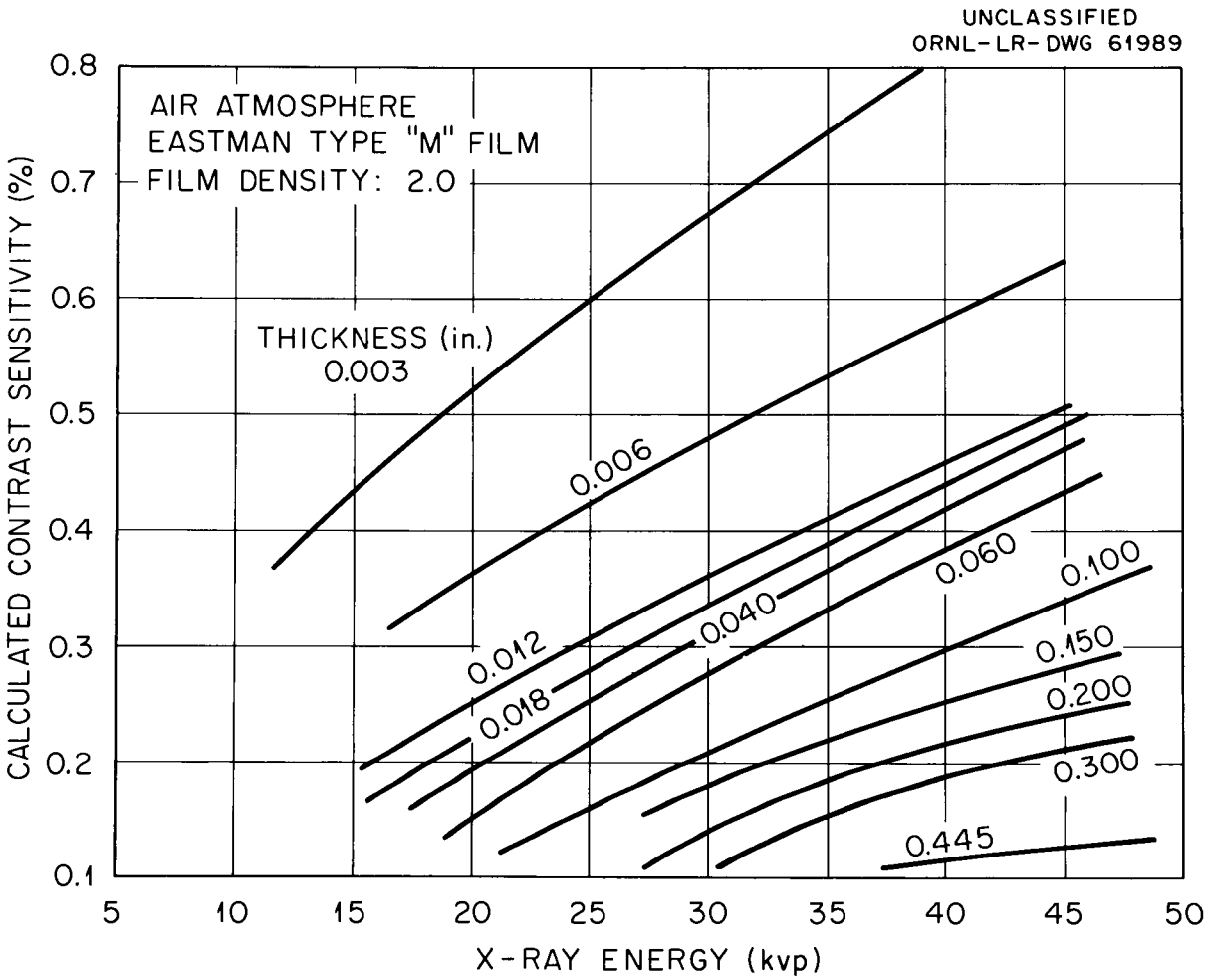

Fig. 18. Calculated Contrast Sensitivities for the Radiography of Aluminum in an Air Atmosphere.

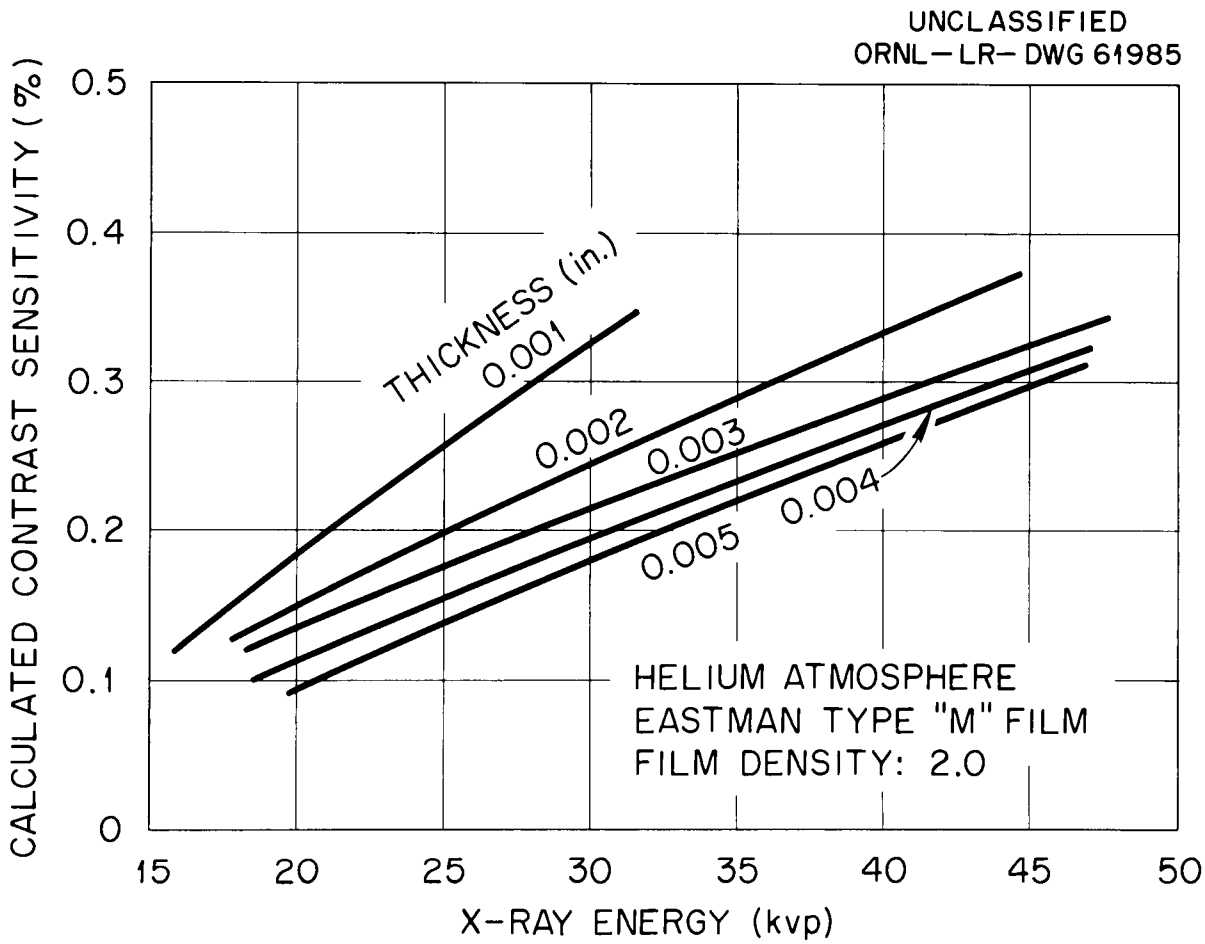

Fig. 19. Calculated Contrast Sensitivities for the Radiography of Stainless Steel in a Helium Atmosphere.

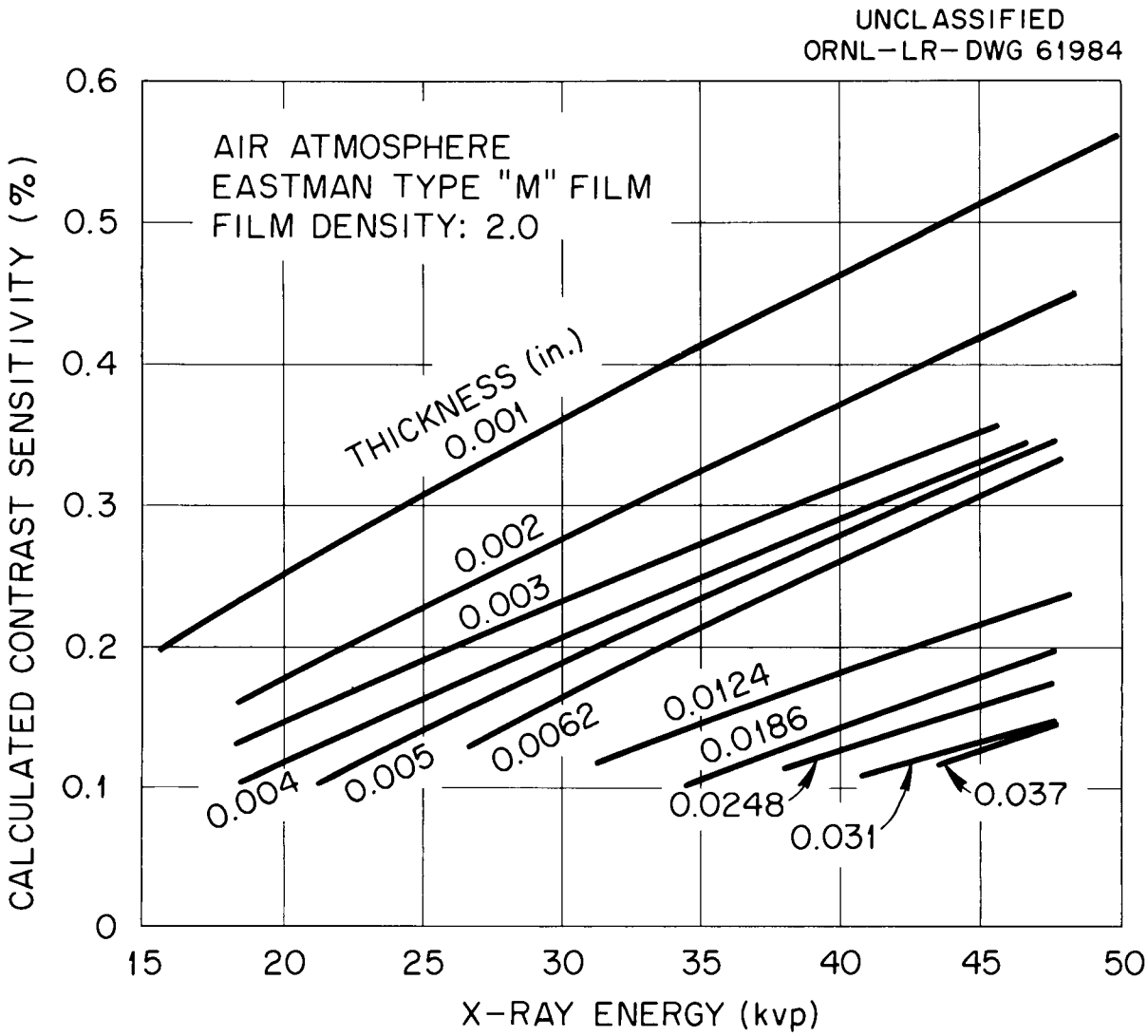

Fig. 20. Calculated Contrast Sensitivities for the Radiography of Stainless Steel in an Air Atmosphere.

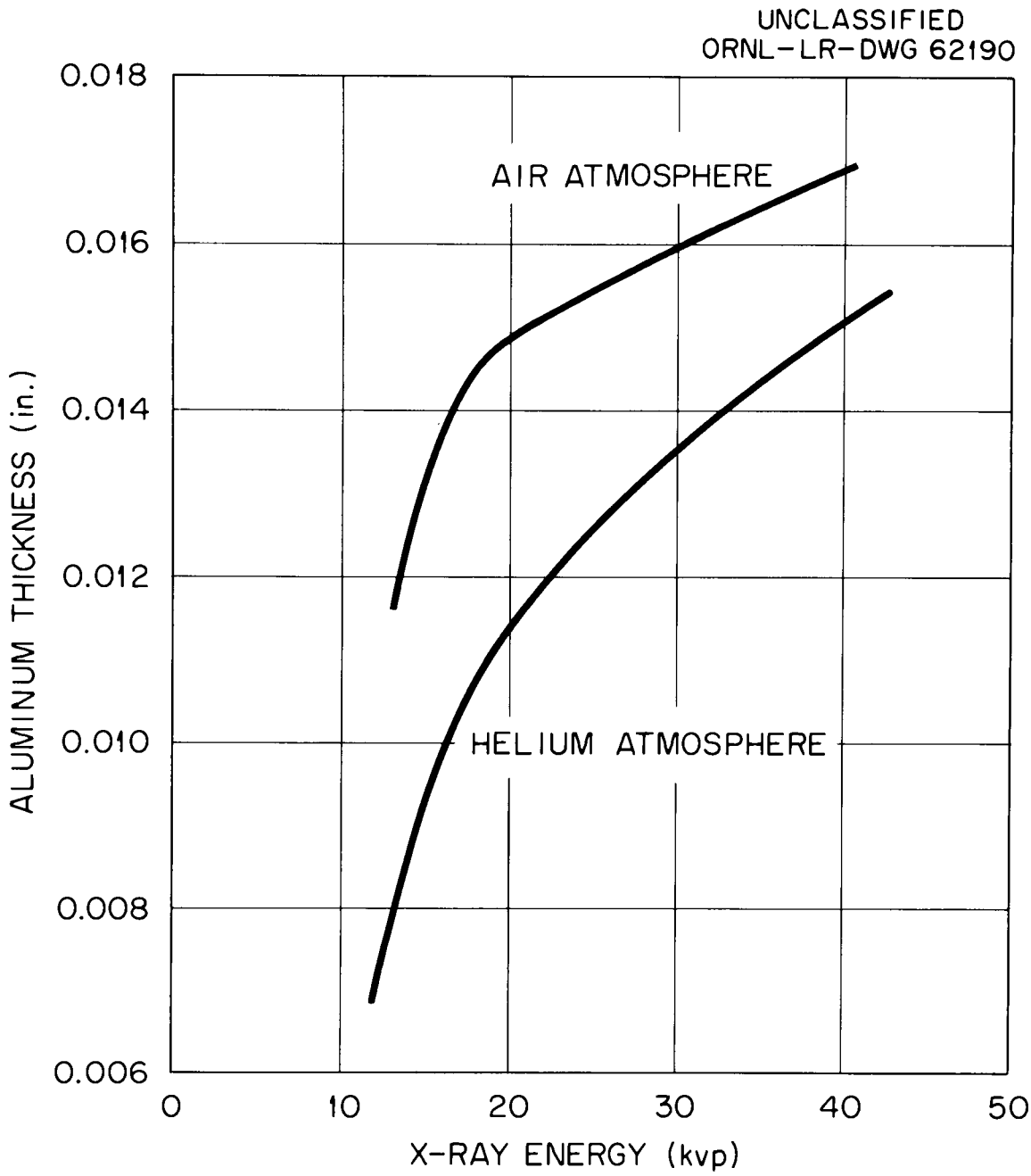

Fig. 21. Thickness of Aluminum with Equivalent Absorption to 0.001 in. of Stainless Steel.

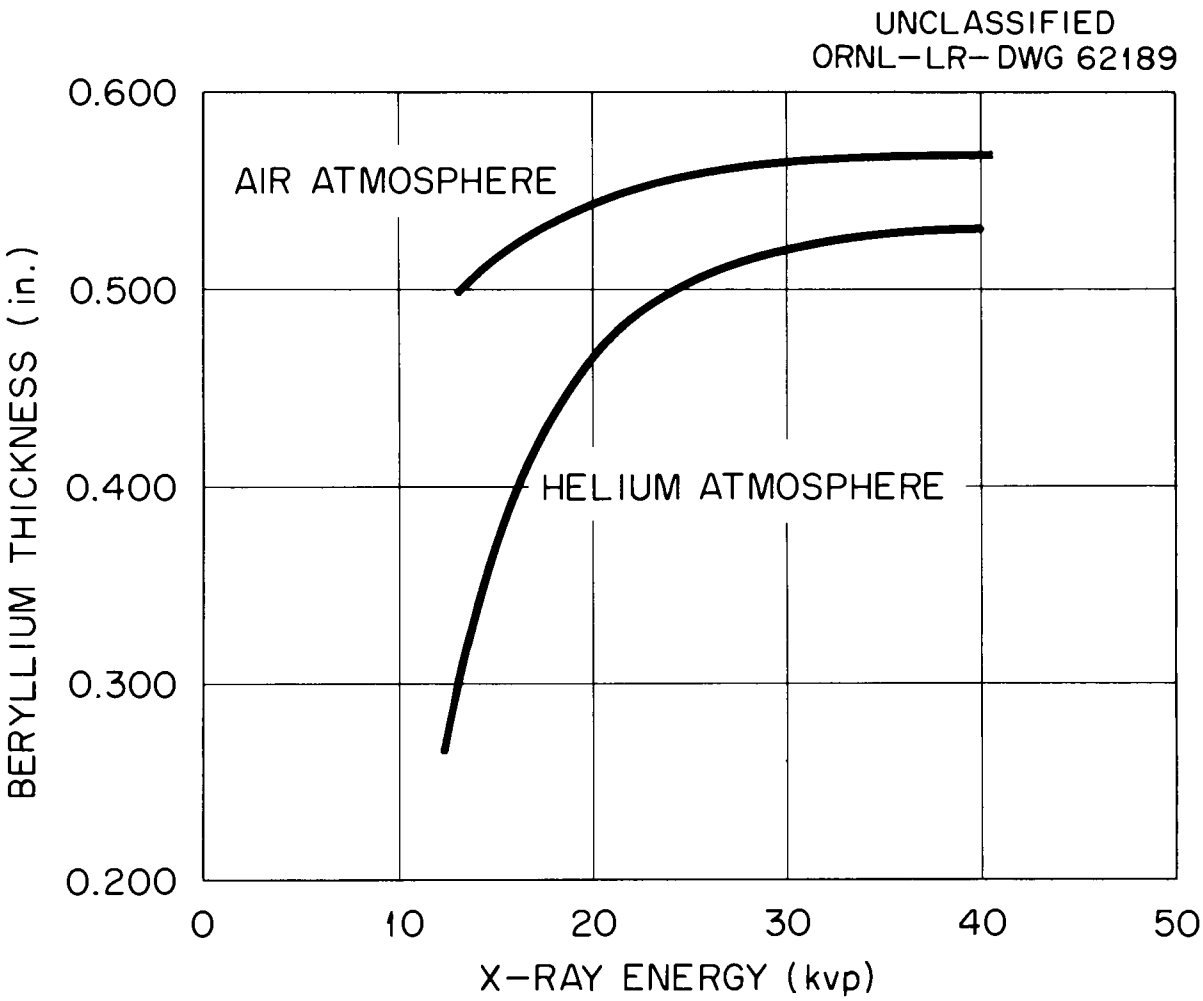

Fig. 22. Thickness of Beryllium with Equivalent Absorption to 0.001 in. of Stainless Steel.

spectrum. Thus, the thickness of beryllium equivalent to 0.002 in. of stainless steel would not be exactly twice that which was equal to 0.001 in. of stainless steel.

APPLICATIONS

A very ornamental demonstration of the capabilities of this test system is shown in Fig. 23 which is a radiograph of two American Beauty roses. The exposure was taken at approx 8 kvp with a helium atmosphere. Although our interest is not botanical in nature, this exhibit does display the extreme sensitivity which can be obtained. Note the image contrast between a single petal and two which overlap. The fine detail of the vein system is readily apparent.

Among the more mundane objects which have been subjects for low-voltage radiography are a host of material such as stainless steel, aluminum, beryllium, graphite, ceramics, epoxy compacts, and combinations of these and other materials. The configurations have included tubing, fuel capsules, plates, rods, cylinders, pellets, welds, and other more complex shapes.

As an example of some of the applications, Fig. 24 shows high-density material detected in an 0.300-in.-ID x 0.040-in. beryllium tube. The contamination, which is suspected to be iron, was a common fault in much of the beryllium tubing which has been examined to date. Figure 25 is a radiograph of beryllium tubing containing pits which are 0.002–0.003 in. deep. A very thin-wall (0.004 in.) stainless steel tube was radiographed with the results shown in Fig. 26. The wall-thickness variations which show so strongly were less than 0.0005 in. Among the inspection problems has been the radiography of beryllium tubing with helical fins such as shown in Fig. 27. The interesting geometrical pattern of Fig. 28 is the result of superimposition of fins as the radiation passes through both walls of the tube. Of particular concern is the thin-wall section at the root of the fin.

CONCLUSIONS

The low-voltage radiographic method has been demonstrated to be a very useful tool for the radiographic inspection of a number of components

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Fig. 23. Radiograph of Two American Beauty Roses.

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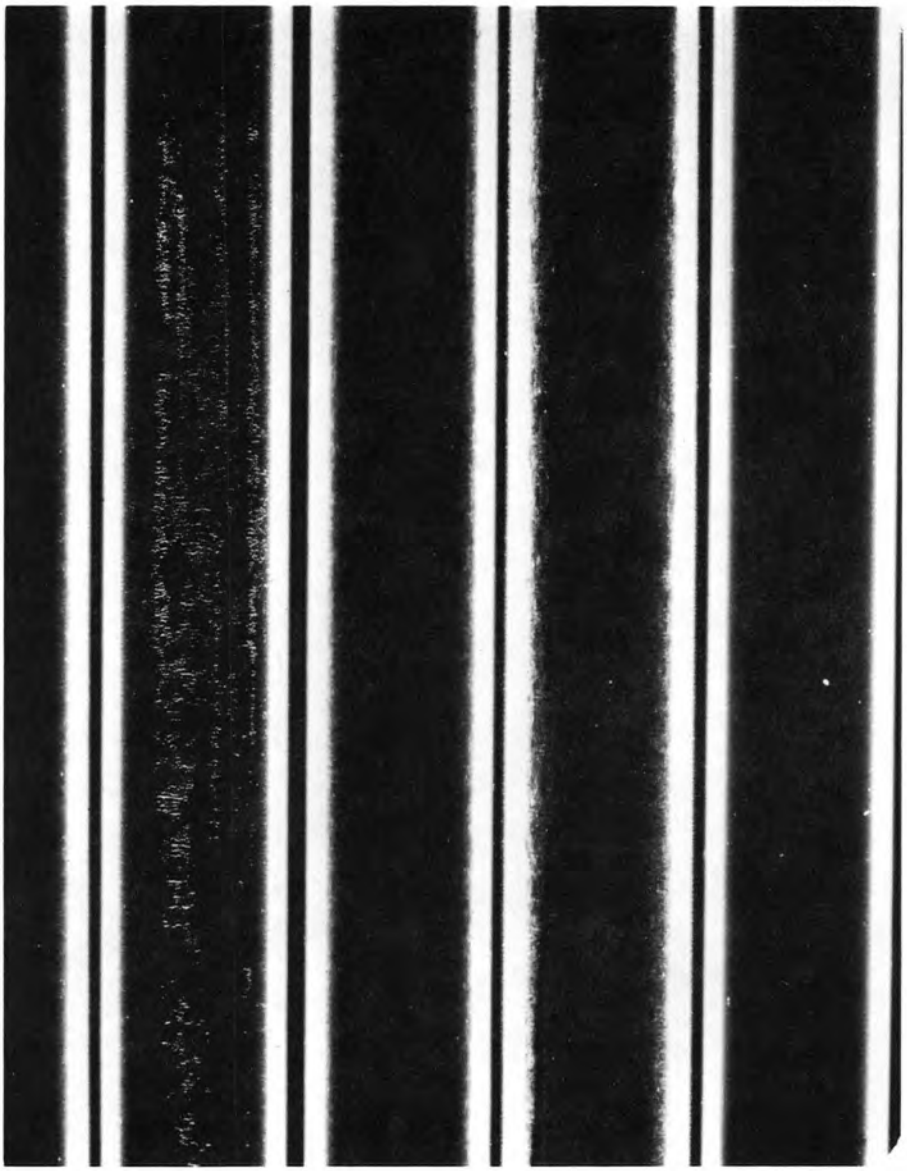

Fig. 24. Radiograph of High-Density Material in Beryllium Tubing.

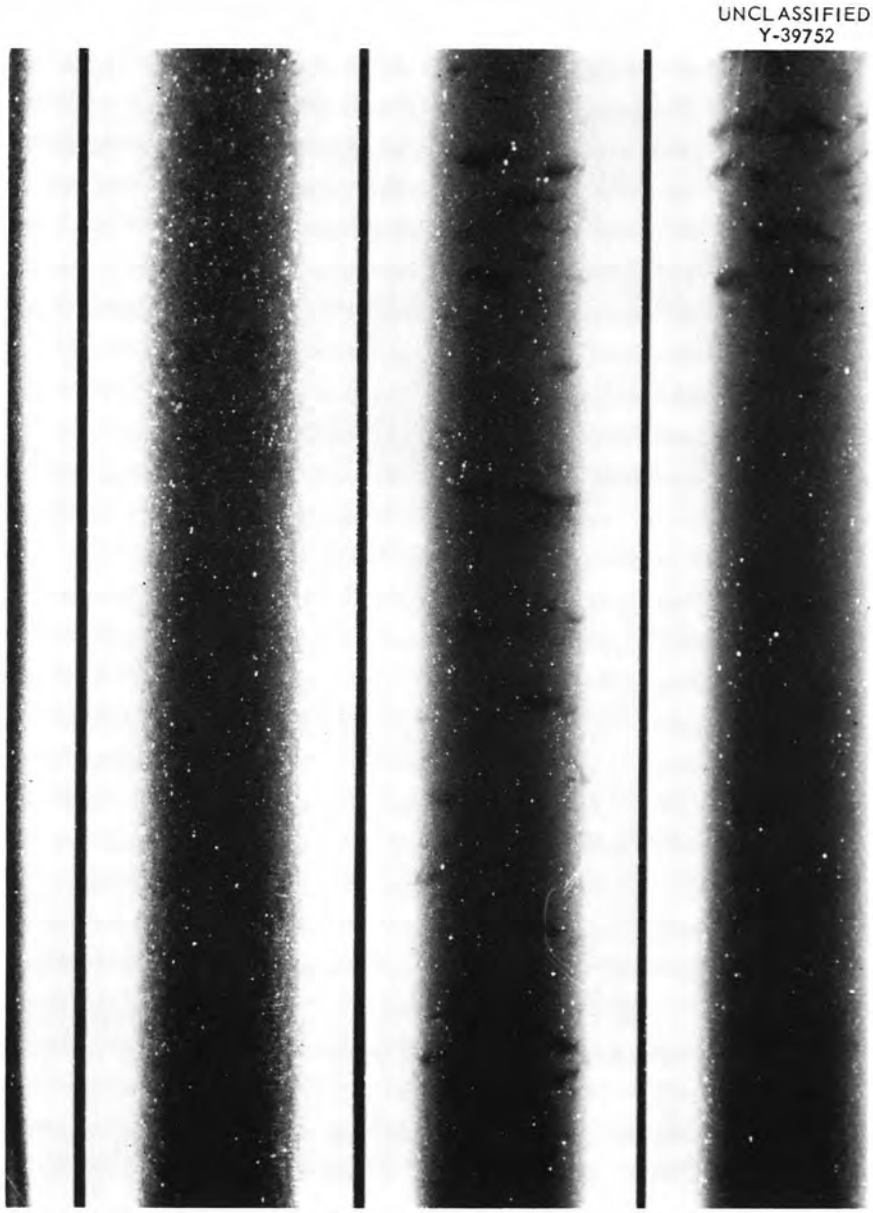

Fig. 25. Radiograph of Pits in Beryllium Tubing.

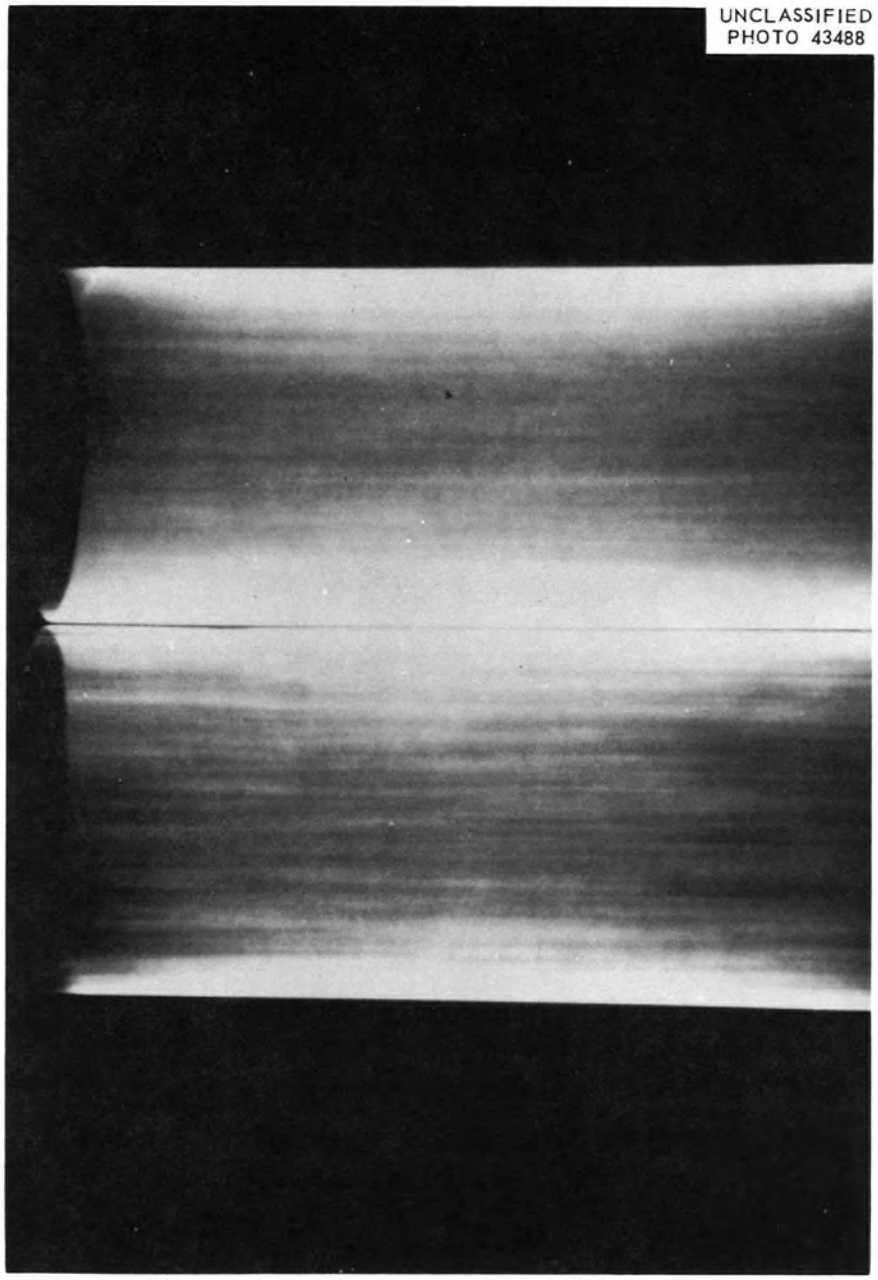

Fig. 26. Radiograph of 0.004-in.-Wall Stainless Steel Tubing.

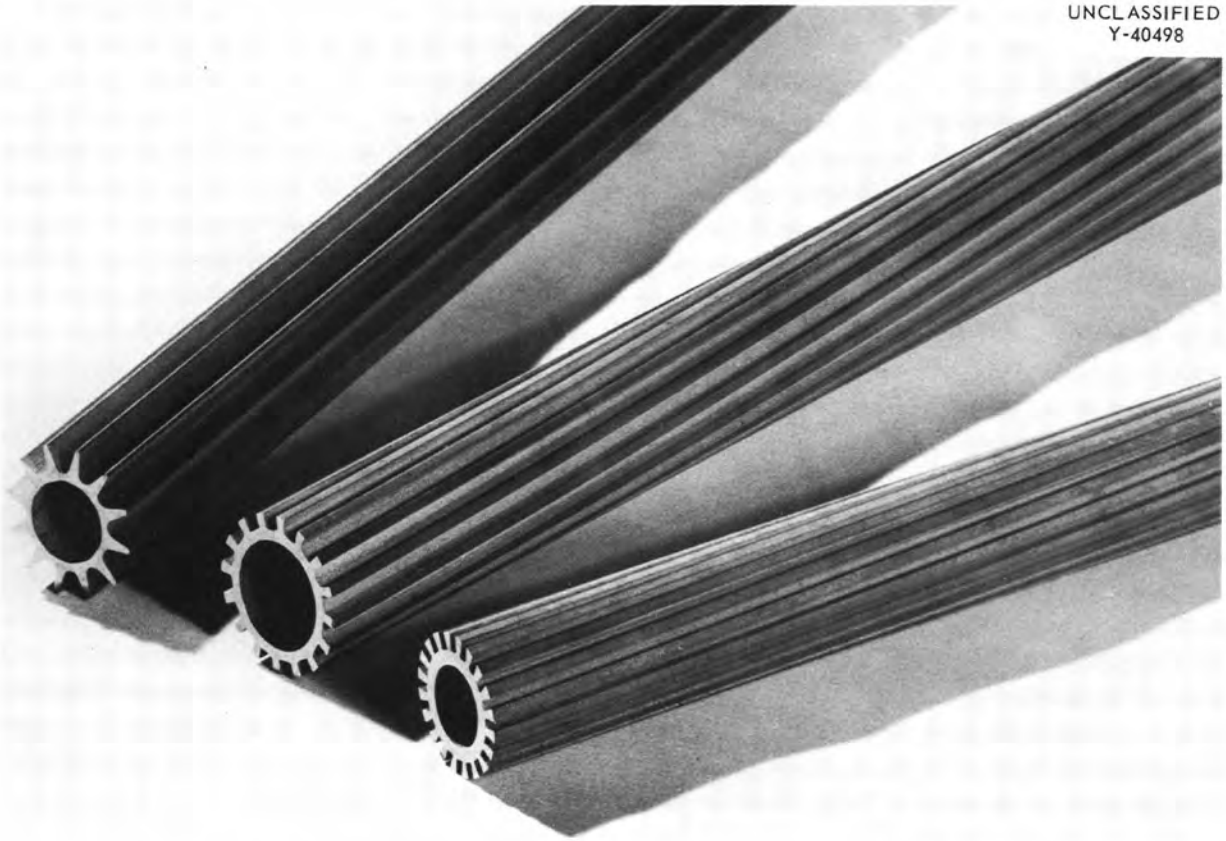

Fig. 27. Photograph of Beryllium Tubing with Helical Fins.

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Fig. 28. Radiograph of Beryllium Tubing with Helical Fins.

and materials such as beryllium and thin sections of aluminum and stainless steel. The applicable thickness ranges for the 0–50 kvp energy and reasonable exposure times (< 10 min) seem to be up to approx 0.037 in. of stainless steel, 0.750 in. of aluminum, and much more than 2.0 in. of beryllium. Considerable advantage can be realized for both sensitivity and exposure times by the use of intermediate helium atmospheres and darkroom bare-film exposure techniques. This is particularly true for the lower energies, thinner sections, or lighter materials. A number of exposure technique charts has been constructed as aids to the attainment of optimum radiographs. Variations in equipment and materials will probably prevent exact reproduction of these values, but these data should be of considerable benefit in establishing individual techniques. The contrast sensitivities which can be attained are excellent and this can be used to advantage for the detection and measurement of thickness, density, and flaws. Proper utilization of low-voltage radiography can provide and has provided a vital tool in the arsenal of inspection.

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