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NEUTRON RADIOGRAPHY: A 1962 PROGRESS REPORT*

by

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INTRODUCTION

Since the relative absorption in materials for thermal neutrons and X-rays is very different,[1-3] the use of neutron radiography as a complimentary inspection method to X-radiography has many potential advantages.[1-6] The possibility of improved detection discrimination between selected materials, the high absorption of several light materials such as hydrogen, lithium and boron, and the relatively low absorption of many heavy materials are some characteristics which make neutron radiographic inspection attractive as a complimentary technique to X-radiography.

In the current study of neutron radiography which is being conducted at Argonne National Laboratory, the emphasis has been placed upon determining many of the characteristics of various techniques for detecting neutron images. This approach to an investigation of neutron radiography was taken in order that neutron radiography might be evaluated using detection methods which had desirable characteristics for the particular application under study. Many of the characteristics of photographic detectors for thermal neutron images have now been determined and reported. This report will outline some recent extensions of such data.

EXPERIMENTAL PROCEDURES

Before getting into the details of the data, however, it may be appropriate to discuss in general terms the methods which have been used in this study to detect thermal neutron images photographically. This limitation to photographic detection methods will apply to the work reported here. Readers desiring further information about nonphotographic techniques for detecting neutron images are referred to a review of that subject by Watts.[6] A second limitation is that the discussion will be concerned with neutrons in the thermal energy region. One reason for this last limitation is that neutrons of thermal energy yield widely varying absorption coefficients in different materials.[1-3] These absorption differences are much reduced for fast neutrons. Therefore, thermal neutrons appear capable of providing better radiographic discrimination between different materials than do fast neutrons. Although the resonance neutron region may provide even better discrimination capabilities than thermal neutrons, for a few selected materials in a particular neutron energy region, the use of thermal neutrons appears to have more general radiographic application.

In spite of the fact that thermal neutrons do influence photographic film itself, it has usually been found advantageous to employ with the film some converter material which converts the neutron image into one formed by some more readily detectable radiation. These converter materials include prompt emission materials such as cadmium, gadolinium, boron and lithium, and potentially radioactive materials such as rhodium, indium, silver, gold, and dysprosium. The characteristics of many of these materials for photographic neutron detection applications have been reported previously.[7,8]

The image detection methods used include both direct exposure techniques in which the film and converter screen are exposed to the neutron beam together, and transfer methods in which only the screen is exposed to the imaging beam. The screen is then transferred to a film loaded cassette and the photographic exposure is made by the radioactive decay of the image-carrying, radioactive screen. Materials which become radioactive easily, and which have convenient half-lives are used for this transfer technique. In this work, gold, indium and dysprosium have been used extensively. All the converter materials can be used for direct exposure techniques.

The neutron source used for most of this work has been described in several reports.[3,7,8] Use has been made of the monochromatic neutron beam (1.05 Å) used for neutron diffraction studies,[9] at Argonne's CP-5 reactor. This beam has an intensity of 3×10^5 thermal neutrons/cm^2-sec over an oval shaped area about 1/2 x 1 in., and covers about a 3 in. diameter circle for radiographic use. There is relatively little gamma radiation in the beam.[7,10]

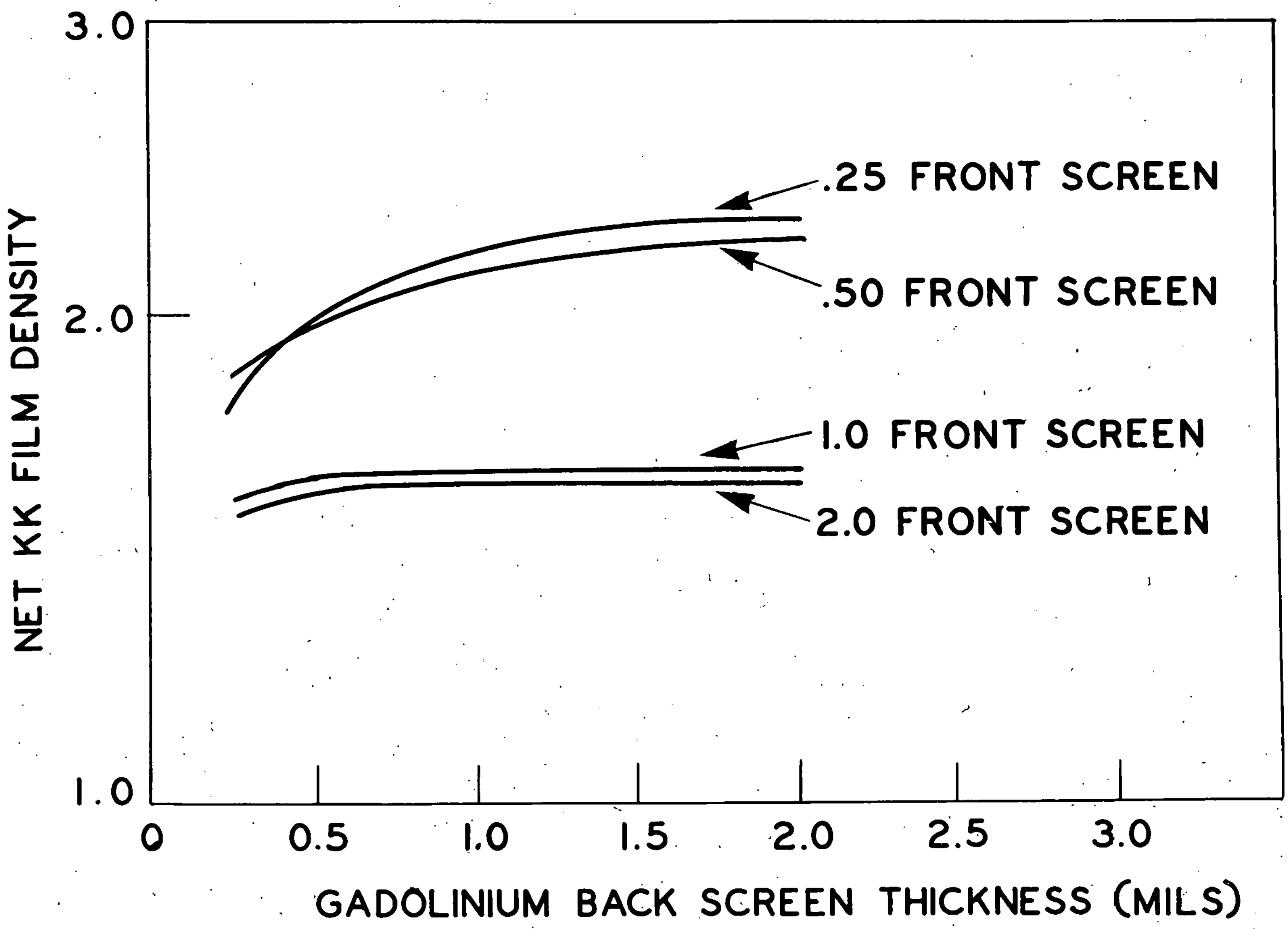
EXPERIMENTAL RESULTS

A. Metal Screen Data

In the progress report which was made last year,[8] the relative speeds of different thickness single gadolinium screens were presented in a preliminary manner. That information has now been confirmed, and the relative speeds of double screen gadolinium direct exposure methods have been determined. This is presented in Figure 1. The back screen (screen away from the neutron source) thickness is plotted against film density for each of several front screen thicknesses. Each neutron exposure for the various combinations was identical and films were processed together as much as possible. The film density therefore, represents speed and it can be seen that a 0.00025 in. front screen and a 0.002 in. back screen technique yields the best speed. The notation we have used for such an exposure technique is 0.25-2 Gd. The first number represents the thickness of the front screen in mils; the second number is the back screen thickness in mils and the chemical symbol identifies the material.

The resolution characteristics of various gadolinium screen combinations have also been studied in more detail during the past year.[11] For single screen work, best resolution results have been obtained for a 0.00025 in. screen with either a front or back film and for a 0.0005 in. screen with a front film. From the speed standpoint the 1/2 mil screen with a front film would be the best of these three good resolution techniques and would, therefore be preferred.

FIGURE 1



The film density obtained for equal neutron exposures of several double screen gadolinium direct exposure methods is plotted against back screen thickness, for each of several front screen thicknesses. Best film density, and therefore best speed, is shown by the 0.25 - 2 Gd technique.

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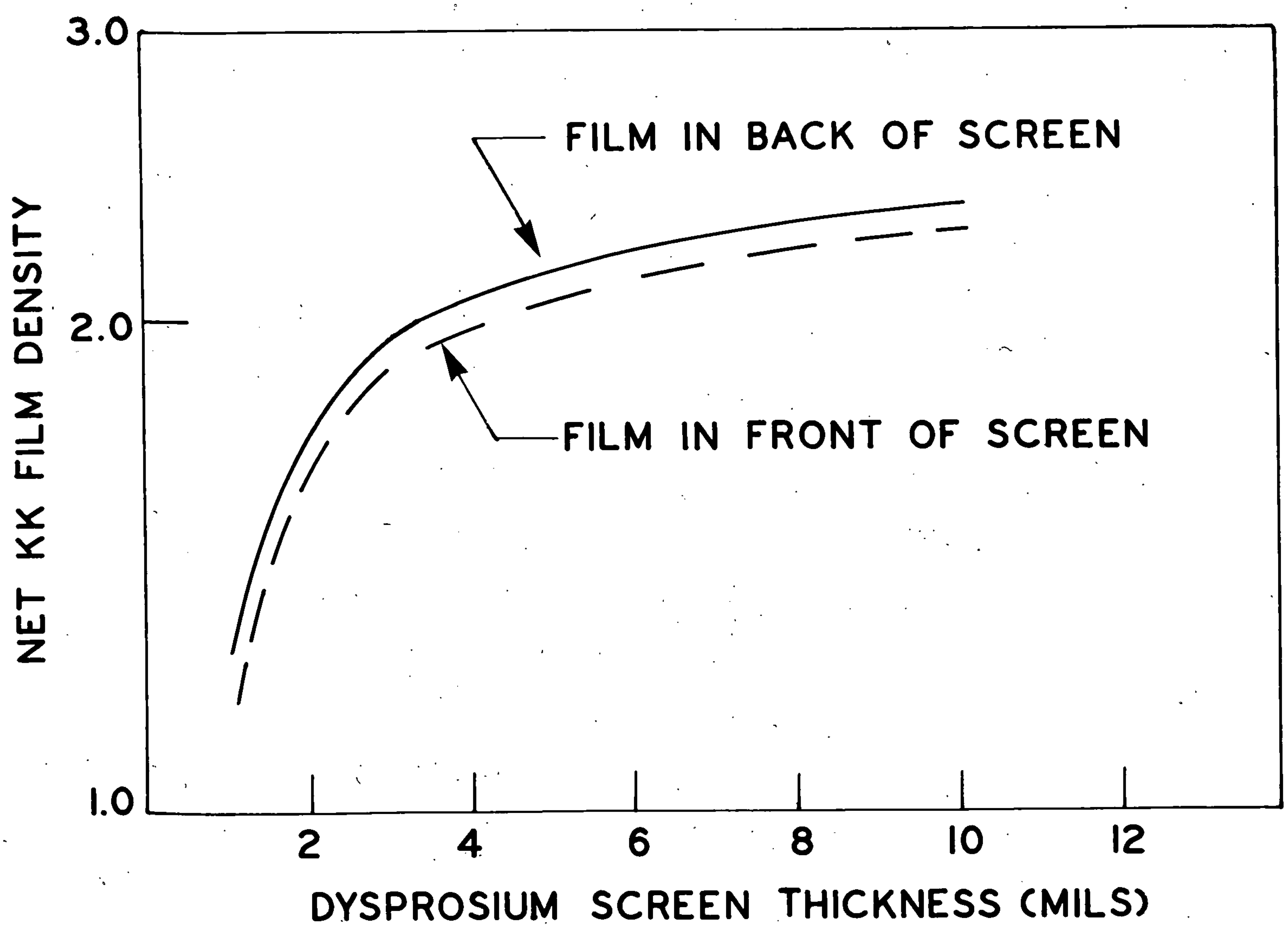
Almost as good resolution can be obtained with a double screen technique employing 0.25 - 2 Gd screens. The lead-gadolinium screen combination discussed previously[8] offers no advantage over this technique either in speed or resolution. Using a 0.005 in. lead front screen with a gadolinium back screen yields about the same speed as the 0.25 - 2 Gd technique, and does not yield as good resolution characteristics.

A better metal screen technique for speed takes advantage of the fact that, for single screen work, front films yield best speed when used with gadolinium while back films yield best speed for most of the other metal screens. Therefore a combination of a gadolinium back screen and a front screen which yields fast results should produce a fast method. A 0.010 in. rhodium front screen and a 0.002 in. gadolinium back screen direct exposure combination, for example, has yielded a speed number which is faster than the double rhodium screen technique (the fastest response metal screen method from previous data[7]) by a factor of about 15 per cent.[12] Similar high speed results may be obtained for a dysprosium-gadolinium screen combination. All these techniques appear to have good resolution qualities.[11]

The other metal screen material which has received appreciable attention during the past year is dysprosium. This rare earth metal has 1.3 minute and 2.3 hour activities having activation cross sections of about 500 and 2000 barns respectively. Although the practical useful cross sections are not actually so large because they both involve Dy-164 which is only 28.1% of naturally occurring material, the convenient half-lives and high cross sections combine to make this material very useful for transfer techniques, in particular.[8]

Single screen speed data for various thicknesses of dysprosium are shown in Figures 2 and 3. For both transfer and direct exposure techniques a screen

FIGURE 2



Film density for equal neutron exposure of several different thickness dysprosium single screen direct exposure methods is plotted against screen thickness for both front films (on the same side of the screen as the neutron source), and back films. The curves level in the order of 0.010 in., indicating that this is about the optimum speed thickness. Back films show slightly better speed than do front films.

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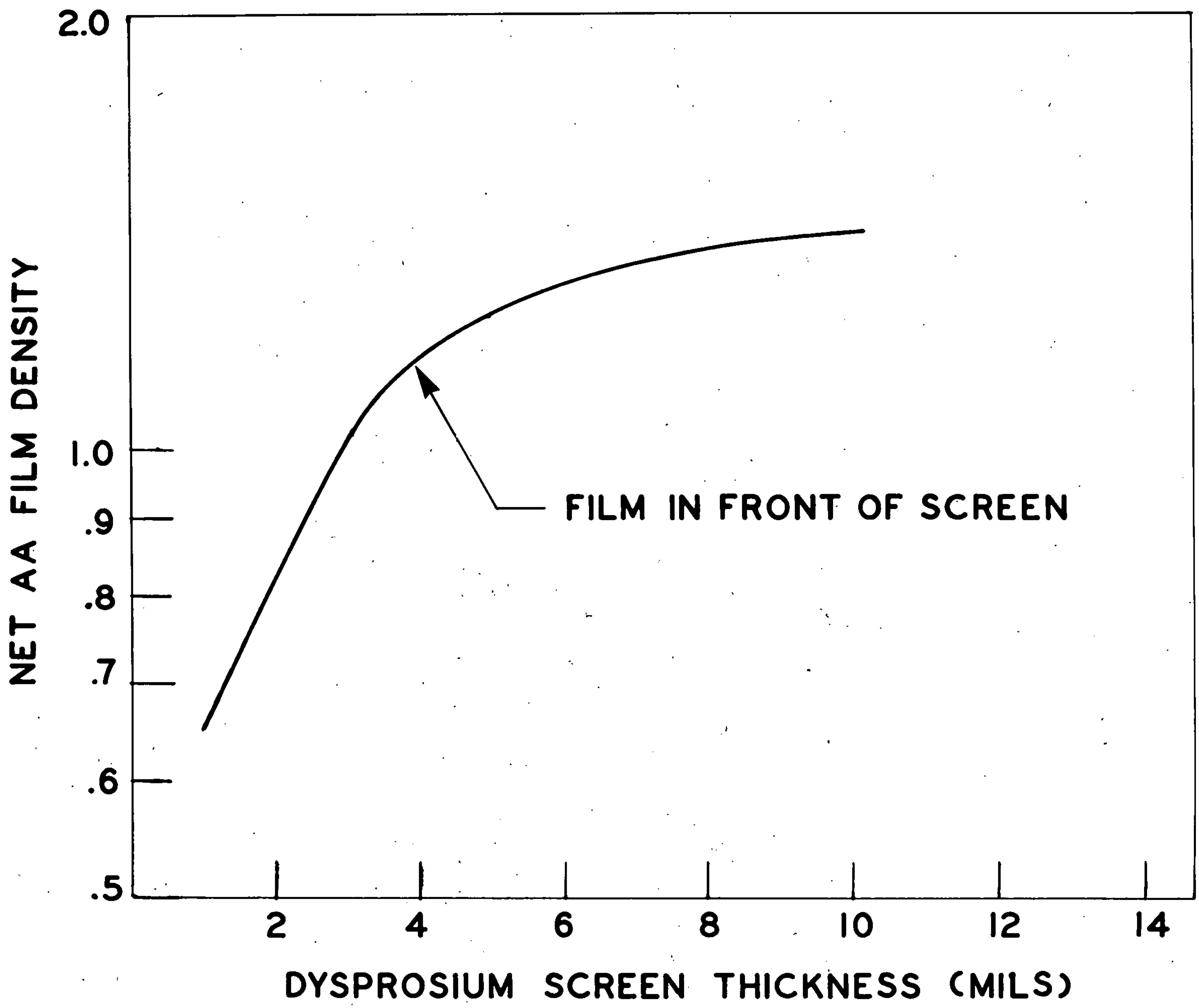
FIGURE 3

Th curve is similar to those of Figure 2, except this is for a dysprosium transfer exposure technique. thickness of about 0.010 in. is again optimum for speed. The curve shown is for a front film. The curve for a back film is similar except that it begins to show a decrease in speed at 5 to 10 mils because of absorption of the neutron beam in the screen material.



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thickness in the order of 0.010 in. appears about optimum for speed considerations. The relative speed rating of a 0.010 in. dysprosium single screen direct exposure method using a back film is about 0.9 (based on response of 10 - 20 Cd = 1.0) on the same basis as previously published speed comparisons.[7,8,10] This is a fast single screen technique. Double screen data is not yet available, but a high speed rating for that technique would also be anticipated. A double screen method employing a dysprosium front screen and a gadolinium back screen also puts forth the promise of a high speed metal screen technique, with reasonably good resolution qualities. These methods are expected to be more fully studied in the near future.

From the resolution standpoint dysprosium yields average results, about equal to rhodium for direct exposures and to indium for transfer work.[13] The high speed of dysprosium transfer techniques, however, makes this an extremely useful exposure method. A number of exposure curves for heavy metals have been obtained and are being reported for this exposure method.[14,15]

A third rare earth metal which also appears useful is samarium.[16] Samarium metal screens are expected to be available for detailed study at Argonne in the near future.

To summarize these results on metal converter screens, it can be pointed out that, of the materials evaluated to date, gadolinium screens appear to provide the best image quality for direct exposure techniques. Used as single screens to yield the best resolution qualities, as double screens for better speed, or in combination with some material such as rhodium or dysprosium to yield even better speed, the resolution qualities of gadolinium direct exposure neutron radiographs are better than any of those obtained with the other converter materials studied in this program.[11]

For transfer work the results found in this work indicate the superiority of dysprosium for speed and of gold for resolution.

B. Scintillators

Additional efforts with boron and lithium based scintillators[4] during the past year have yielded further information on speed comparisons, contrast capabilities, resolution qualities and reciprocity-law failure responses. Speedwise the 4:1 ZnS(Ag) and Li-6F scintillator mixture described by Wang et al[17] is the fastest photographic thermal neutron image converter material presently known to the author. Using fast films such as 3000 speed Polaroid film or Type F or similar X-ray film, a useful image can be obtained with total exposures[17,18] of much less than 10^5 thermal neutrons/cm^2.

The actual value will depend upon the neutron intensity because of the influence of the reciprocity-law failure response of the film used.[19,20] Observed reciprocity-law failure responses for a B-10 polyester type scintillator and Type F X-ray film have involved speed differences in the order of 5 times for a neutron intensity change of 100 times.[12] Somewhat less change in speed has been observed for the Li-6 scintillators and Polaroid film.[18] In practice the reciprocity-law failure response need not limit the use of these materials for neutron radiography. Once this type of response is recognized it is a simple matter to adjust exposure times for different conditions.[14,15] For a speed comparison, however, this type of response presents difficulties.

The resolution capabilities of the scintillator-film detectors were generally good. Although the resolution observed on neutron radiographs taken with scintillator techniques was not as good as that obtained with the best imaging methods (gadolinium screens, for example), the values observed were generally comparable to those which could be obtained with metal screen methods.[11] Excellent resolution was observed on radiographs made with a specially prepared thin scintillator employing a vapor deposited phosphor layer[21] on a thin B-10 deposit, but this technique was extremely slow,[11] and therefore of less practical value.

The contrast sensitivities generally observed with the scintillator detectors have been in the order of 6 to 15 per cent. The best values (6 to 10 per cent) were observed on radiographs of several inches of uranium using the B-10 scintillator and Type F X-ray film.[14,15] The poorer values were observed on similar test samples using a Li-6 scintillator and Polaroid film.[18] The limitation in this latter case appeared to be the film, however, rather than the scintillator. Using Type F film instead of the Polaroid, a contrast sensitivity in the order of 10 per cent was obtained.

In summary, the scintillator techniques as detectors for neutron radiography offer excellent speed of response. This advantage, along with good resolution properties and relative neutron-gamma response (to be discussed in more detail later in this report) should make such imaging methods very useful. Problems such as reciprocity-law failure response, relatively poor ability to display small changes in neutron intensity and nonuniformities[7,8,10] should, however, be recognized. This latter problem involving graininess and nonuniform distribution of components within the scintillator can be largely eliminated by taking advantage of scintillating glasses.[22] Recent work by Watts[23] with such materials has indicated that uniformity problems are much reduced and that good speed of response has been maintained. The additional property that the glasses are more chemically stable than many of the other scintillator forms is another advantage.

C. Relative Neutron-Gamma Response

The relative response of direct exposure detection methods to neutrons and to gamma radiation is of importance in many radiographic situations. If the inspection object is radioactive or emits large amounts of radiation upon neutron bombardment, or if the neutron beam itself contains high intensity components of gamma radiation, a direct exposure neutron radiograph may not yield the desired information.[3,7,10] In extreme cases, of course, transfer methods can be used to eliminate such interferring radiation.

Nevertheless, a knowledge of the relative neutron-gamma response of direct exposure detection methods can be useful in helping to decide whether or not the slower speed transfer methods[10] appear necessary. It is difficult to generalize such information because the gamma energies involved in one situation may be different from those of another one. However, for the specific comparison between thermal neutrons and cobalt-60 gamma radiation it was found that a total exposure of about 10^5 thermal neutrons/cm^2 yielded about the same film response as 1 milliroentgen of gamma radiation. That information was for double metal screen techniques used with Type KK film.[3] More recent data[24] indicate that this ratio is reasonably accurate for single metal screen methods and for Type AA film. Similar results have been reported by Watts.[25] Some agreement is also found in the data of Ehrlich[26] which indicated a ratio in the order of 5×10^6 for each of several different speed films exposed without converter screens. The addition of the converter screen increases the speed of the detector to neutrons by a factor in the order of 20 to 100 times,[8] and yields little change in the gamma response.[3] The ratio of 5×10^6, as indicated by Ehrlich, therefore, approaches a value of 10^5 when the detector consists of converter screens and film.

Because of the high speed of the scintillator techniques for neutron detection, a somewhat better ratio of neutron-gamma response is found. The B-10 scintillator with Type F film requires only about 10^4 thermal neutrons/cm^2 for the same response as 1 mr of gamma radiation and the Li-6 scintillator presents an even better relative response ratio.

Therefore, for a given exposure situation, a knowledge of the total neutron and gamma exposures that the film will receive can be used to determine the correct exposure technique. If the ratio of neutrons/cm^2 to milliroentgens of gamma radiation is appreciably greater than 10^5, no difficulty with direct exposure methods should be encountered. If this ratio is in the order of 10^5, scintillator direct exposure methods may prove useful. For neutron/cm^2 to gamma mr ratios less than 10^5 however, transfer methods may be required.

This last statement employed the word "may" rather than "must" because the gamma image of the object under study will be detrimental to the neutron radiograph primarily if the object contains light materials and in cases in which the interferring radiation originates in the object itself. The neutron image of a plastic component, for example, might be obliterated if the high transmission of a large gamma intensity were also recorded on the neutron radiograph. Neutron radiography of a radioactive object would also present problems since the radioactive decay radiation would tend to fog the film. In neutron radiography of some material such as lead, however, gamma radiation in the neutron beam would not necessarily be a problem since a gamma image of the lead objects would contribute to a further reduction in exposure time. Each problem therefore, must be considered individually as far as the influence of interferring radiation on the final image is concerned.

D. The Influence of Scatter on Image Quality

The influence of scattered radiation on image quality is a problem encountered in any imaging technique. Watts has studied this problem in regard to neutron imaging.[6,25] In one report by Watts,[25] neutron radiographs of some cadmium strips of various sizes were shown, as graphite was placed between object and detector. The influence of the scattering medium, as represented by the graphite was quite apparent.

The test strips used by Watts, however, did not permit him to place a number on the degradation of image quality as a function of scatter thickness. Since a test piece designed at Argonne for resolution studies[11] was available, it was decided that Watts' work might be profitably repeated in order to numerically define the influence of the scattering medium on image resolution.

The test piece designed for resolution studies consisted of a 0.020 in. thick cadmium sheet containing a number of 0.020 in. diameter holes whose spacing continually decreased. The spacing between holes was 0.00012, 0.002, 0.0036, 0.0048, 0.0096, 0.019 and 0.0304 in. Resolution was determined by a number of observers deciding what holes were resolved on the neutron radiograph of the test piece. The smallest separation between holes which could be resolved by the majority of the observers was said to be the resolution.

To study the influence of scatter, an imaging method having good resolution properties in itself was used.[11] The single screen gadolinium direct exposure technique employing a 0.0005 in. screen and a front film was used throughout.

Figure 4 shows the influence of spacing the test object away from the film cassette, both as a function of air spacing and graphite spacing. The additional influence of the scattering medium is apparent from this plot. The resolution of the test object, described above, through 4 in. of graphite was so poor that none of the 0.020 in. diameter holes could be resolved. Another cadmium test piece, containing drilled holes varying in diameter from 0.013 in. to 0.040 in. was used to obtain that last point. The smallest hole size observed on the radiograph was 0.030 in. (0.020 in. hole could not be resolved).

Although the influence of scattering material on image quality is appreciable, in practical situations an even greater influence on such factors may be contributed by the divergence of the neutron beam itself. This study at Argonne has benefited from the fact that a well defined, parallel neutron beam was available.[7,10,11] Other investigators have had neutron beams containing appreciable amounts of diverging radiation to contend with. The neutron beam used in Watts' study, for example, was barely capable of resolving the neutron image of a 0.051 in. wide cadmium strip which was separated from the detector by an air path of 3 in. From the data presented in Figure 4, this beam divergence causes as much, or more, degradation in image resolution with a 3 in. air path as does 4 in. of graphite. The characteristics of the neutron beam therefore, may be a greater influence on image quality than that produced by scattering media.

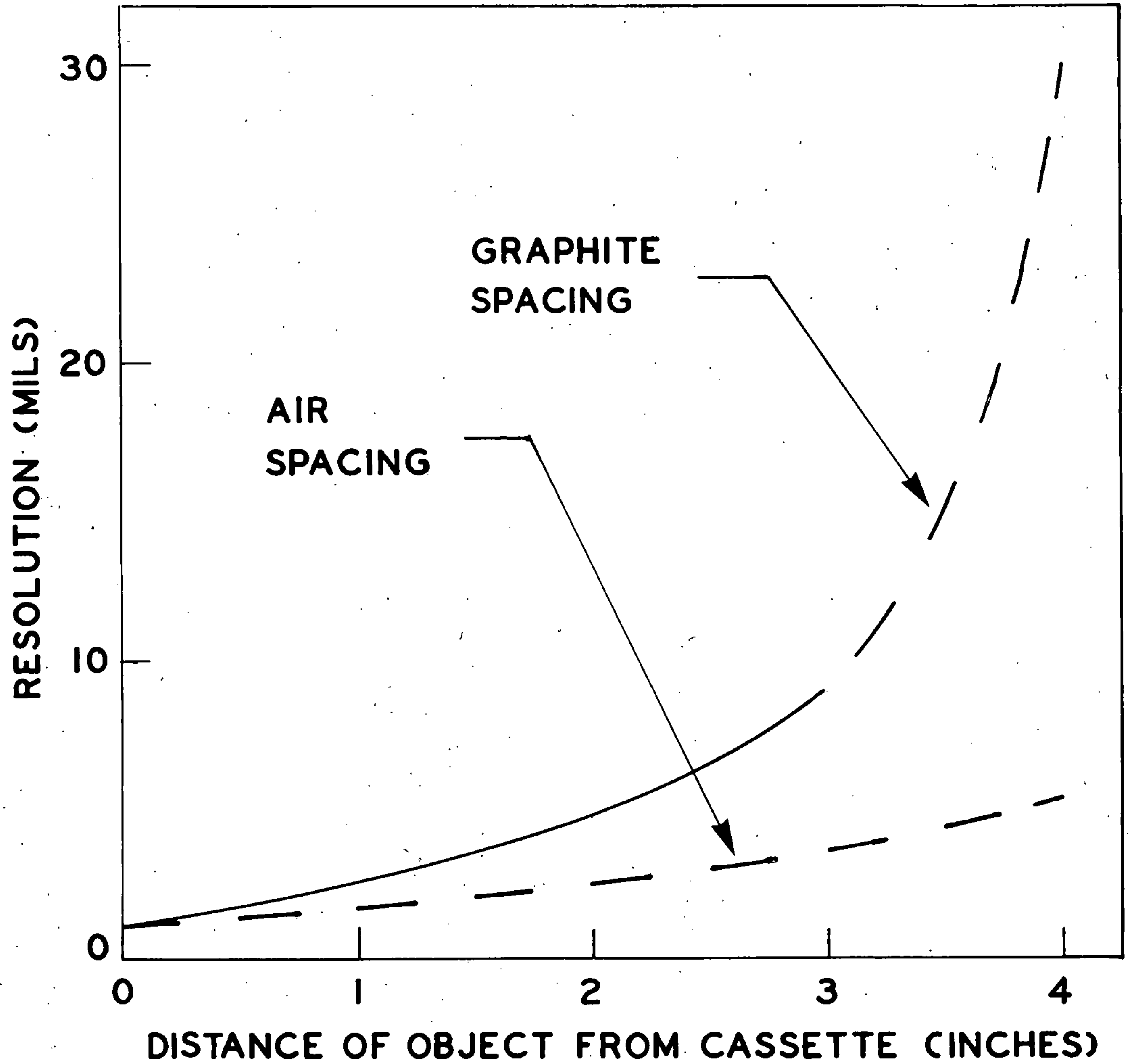
This is a problem which is just beginning to receive attention in this study at Argonne, because such problems have been encountered at a second neutron radiographic facility recently made available. This beam facility is located at Argonne's Juggernaut reactor. The beam presently available has a thermal neutron intensity of about 10^7 neutrons/cm^2-sec and uniformly covers a 2 1/2 x 4 in. area. Beam divergence is such that spacing the test object a distance of 1 in. from the cassette results in a resolution in the order of 0.010 to 0.020 in. A Soller slit collimating arrangement[27] is now being prepared to make this neutron beam more useful for inspecting large thickness samples.

DISCUSSION AND CONCLUSIONS

Many of the characteristics of methods for detecting thermal neutron images are now known. As far as photographic detection techniques are concerned, methods covering a wide range in properties such as speed, contrast, resolution and relative neutron-gamma response are available. Some general comparisons between different classes of photographic detection methods are

FIGURE 4

The sm est hole separation in a cadmium test object (see text) which could be resolved on neutron radiogra is plotte against the distance the object was spaced in front of the film cassette, for both air spacing and g ite spacing. The additional influence of the scattering medium, as represented by the graphite, is shown by the upper curve. The resolution obtained when 4 in. of graphite was used was so poor that none of the 0.020 in. holes in the test piece could be resolved. An additional test piece, containing hole sizes up to 0.040 in. was used for that final resolution determination. The mean free scattering path for graphite is about 1 in.



summarized in Table I. Of these photographic detection techniques, the most promising appear to be scintillator direct exposure methods, particularly for problems requiring high speed, gadolinium screen direct exposure methods for high resolution, and dysprosium and gold transfer methods for situations requiring respectively high speed or high resolution techniques. Most of these detection methods are capable of yielding images having qualities good enough for many inspection problems.

As far as applications of neutron radiography are concerned, studies are under way at a number of laboratories,[6,28-31] and, from the number of inquiries about these methods which have been received, it would appear that many additional organizations are presently considering neutron radiographic inspection. At Argonne, some limited inspections of heavy metals,[14,15] and reactor control components,[10,15] have been made. In each case neutron radiography offered a definite advantage over other inspection methods.

This application work is expected to be appreciably expanded with the present availability of the Juggernaut reactor neutron beam facility. That facility has a greater neutron intensity, a much improved uniform beam area and a better means of handling large inspection samples than was available at the small beam facility at CP-5 reactor. Inspections presently being considered with this facility include reactor control assemblies, reactor fuel components and the inspection of highly radioactive materials. Preliminary work in this latter category involving irradiated reactor fuel elements has recently been completed.[15] Neutron radiographic inspections of such samples, which emit radiation levels of several thousand R/hr at one foot distance, have shown excellent image quality. Deformation of the fuel due to radiation effects is easily shown by neutron radiography transfer methods.

TABLE 1

SUMMARY OF PROPERTIES OF PHOTOGRAPHIC DETECTORS FOR NEUTRON RADIOGRAPHY

Method	Converter	Contrast[a]	Approximate Neutron Exposure Time for Medium Film Density[b]	Resolution[c]	Approximate Total Neutron Exposure to Equal Film Response to 1 mr of Co-60 Gamma Exposure	Comments
Direct Exposure	scintillator	Fair	1 sec or less	2 to 5 mils	10^3 to 10^4	Direct exposure techniques are fast but are subject to interferring radiation. Scintillator methods have additional disadvantages of nonuniformities and reciprocity law failure responses.
	double metal screen technique[d]	Good	1 to 1 1/2 min	< 1	10^5	
	single metal screen technique[e]	Good	2 to 3 min	< 1	10^5	
Transfer Exposure[f]	Dysprosium	Excellent	4 min	2	-	Transfer techniques offer high contrast and ultimate discrimination against interferring radiation at the expense of speed.
	Indium	Excellent	15 min	2	-	
	Gold	Excellent	60 min	1	-	

[a]Contrast comparisons were made by determining contrast sensitivities on neutron radiographs of several inches of uranium. Fair covers a range of 6 to 15%; good 2 to 3% and excellent 1 to 2%.

[b]Thermal neutron intensity for this comparison was 3×10^5 n/cm^2-sec. Films used were fast films, equivalent to Type F or high speed Polaroid for the scintillators and Type KK for the metal screens. The transfer exposures required a three half-life decay period on the film for these exposures.

[c]Resolution listed is the minimum separation between images of 0.020 in. holes in a cadmium test piece which could be resolved on neutron radiographs made by each technique.

[d]Double metal screen combinations which offer best results include 10 Rh - 2 Gd for high speed and 0.25 - 2 Gd for best resolution. The resolution listed is for the latter technique.

[e]Single metal screen techniques which offer best resolution employ 0.25 or 0.5 mil gadolinium screen as back screens.

[f]Thicknesses of transfer screens which have yielded best resolution results are 0.010 in. dysprosium, 0.002 in. indium and 0.003 in. gold. See reference 11.

Some examples of neutron radiographs taken at the Juggernaut beam facility are shown in Figures 5 and 6. Figure 5 is a neutron radiograph of an interval timer. This is shown, not as an example of an application, but because it is an easily recognized object which contains a variety of components. For a progress comparison this radiograph can be judged against a similar neutron radiograph taken early in this investigation.[32]

Figure 6 shows a neutron radiograph of some uranium rods which contain holes drilled part way into one end. Neutron radiographic inspection of such material presents a distinct advantage over conventional radiography, both in terms of exposure time and reduction of scatter problems.[14]

Another area in which some progress can be reported is in the photographic detection of neutron diffraction patterns. Appreciable interest in such applications of photographic neutron image detection methods has been expressed in the literature of the past year.[12,17,33] The diffraction pattern reproduced in Figure 7 was obtained using a rhodium-gadolinium double screen technique and using a curved film holder. The exposure time was competitive with electronic detection methods and the resolution was sufficient so that the 311 and 222 reflections from nickel could be easily distinguished. The use of metal screen detectors for such applications permits intensity comparisons between different diffracted lines since the response of these metal screen-photographic film detectors is relatively independent of neutron intensity (at least for neutron intensities of 10^5 n/cm^2-sec and less, as are normally encountered in diffraction work). Such an intensity comparison is shown in Table 2. Although this diffraction pattern could have been obtained in much less time using scintillator techniques, the intensity comparison would have been difficult because of the reciprocity-law failure response.

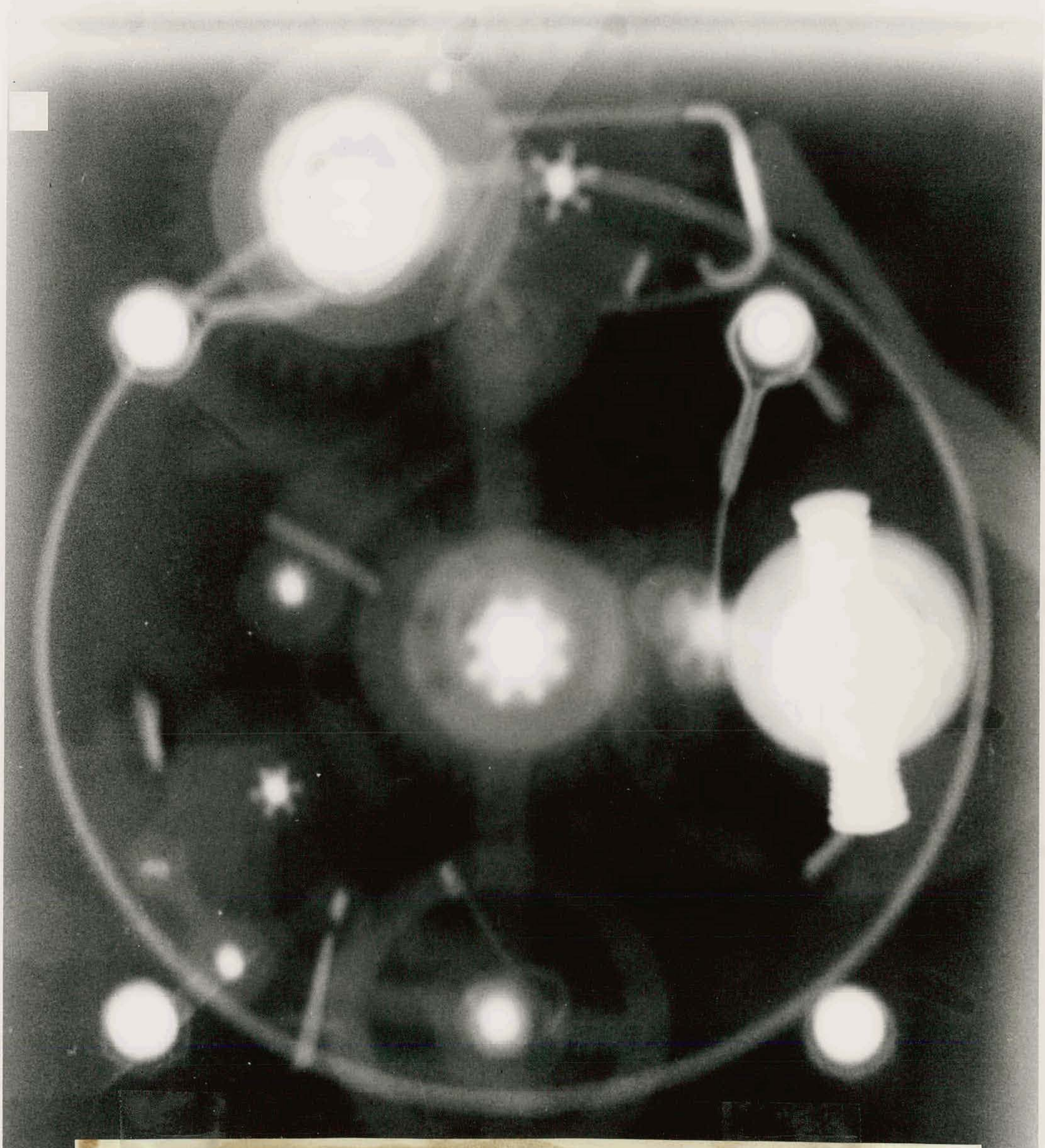


FIGURE 5

This is a reproduction of a neutron radiograph of an interval timer. The exposure technique was a 0.5 mil gadolinium screen and a front film in a direct exposure. This radiograph, taken with AA film, required an exposure of 1 3/4 minutes at the Juggernaut reactor beam facility. The overall size of the timer is about 3 3/4 x 4 inches.

FIGURE 6

Two depleted uranium rods, 0.435 in. in diameter and containing 1/32 in. diameter holes in one end are shown. Masking tape around the rods also shows neutron absorption. This radiograph, taken under the same conditions as that of Figure 5, required an exposure of 1 1/2 minutes.

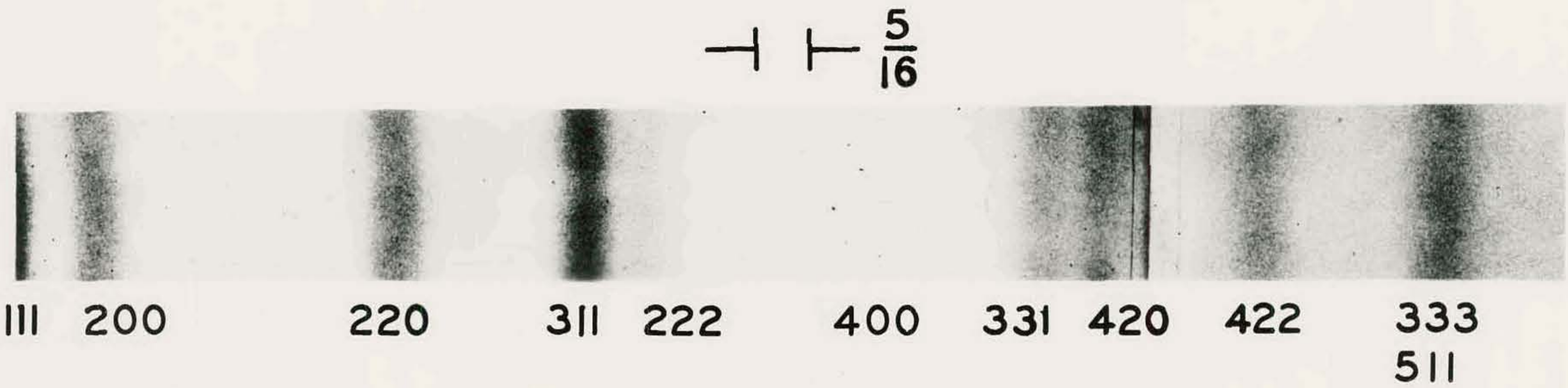


FIGURE 7

A neutron diffraction pattern of a 5/16 in. diameter powdered nickel sample is shown. The camera radius was 6 inches. The detector was a rhodium-gadolinium screen combination with Type KK film, in an overnight exposure. At the 6 in. distance, and width of the diffracted lines is about equal to the sample size. The neutron wavelength was 1.16 A.

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TABLE 2

NEUTRON DIFFRACTION DATA FROM
A POWDERED NICKEL SAMPLE DIFFRACTION FILM[a]

d(A) (Literature[b])	d(A) (Determined from Film)	Estimated Relative Intensity[c]	Miller Indices
2.03	2.03[d]	VS	111
1.76	1.758	S	200
1.244	1.257	S	220
1.061	1.073	S	311
1.017	1.022	W	222
0.881	0.888	W	400
0.808	0.816	M	331
0.788	0.788	M	420
0.719	0.727	M	422
0.678	0.678	M	333 511

[a] Sample size was 5/16 in. Camera radius was 6 in. Detector used was a rhodium-gadolinium screen combination with KK film. The neutron wavelength was 1.16 A.

[b] Hannawalt, J. D., H. W. Rinn and L. K. Frevel, Industrial and Analytical Chemistry, Analytical Edition, 10, No. 9 (1938).

[c] VS = very strong; S = strong; M = medium; and W = weak.

[d] The test camera used covered a 150° arc. Therefore the first arc distance needed to determine the first reflection d was not known accurately. This distance was set to yield 2.03 and the same distance was then used for the rest of the d spacing determinations.

In conclusion, it is hoped that the efforts of the past year, at the several laboratories in which neutron radiographic and associated studies are underway, has brought neutron radiography that much closer to being a useful inspection method. The work presently forseen for the next year should also make some significant contributions toward that goal. At Argonne it is hoped that appreciable application experience will be gained with the Juggernaut reactor beam facility. This application work, along with that at other laboratories using reactor,[6,30] accelerator,[28] and radioactive[29,31] neutron sources, should help provide the type of information needed by potential users of neutron radiography.

ACKNOWLEDGMENTS

The continued cooperation of S. S. Sidhu, M. H. Mueller and L. Heaton in making the CP-5 reactor neutron diffraction facility available to us is sincerely appreciated. Their assistance in setting up the Juggernaut reactor beam facility and their cooperation in many helpful discussions is also gratefully acknowledged. The technical assistance of I. R. Kraska and R. E. Dickens, the preparation of metal screens by F. J. Karasek and the cooperation of the Juggernaut reactor crew have also contributed significantly to this program.

FOOTNOTES

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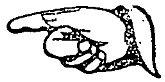
1 - 5. Dr. H. D. Young 
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