

NEUTRON RADIOGRAPHIC METHODS

by

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## I. INTRODUCTION

Practically all branches of engineering have a need for material testing. However, many of the techniques employed damage the test specimen. In some cases this is of no consequence, but there are other instances where it is important that as little damage as possible be imparted to the test piece. Several mechanical and electrical devices have been developed which provide a means for nondestructive testing. For example, the Brinell Hardness Test, which does not inflict serious damage to the test piece can often yield valid indications of the mechanical properties of the specimen. The electric strain gage which is being used extensively in industry today is another device in use for nondestructive testing. If it is desired to obtain information about the physical nature of the interior of the specimen without destroying it, X-ray radiography will often provide useful information.

Methods of X-ray radiography have been highly developed and are very useful in many aspects of material testing. However there are limitations to what can be done with X-rays. Fortunately, neutron radiography which has only been developed within the last twenty years, almost completely complements the use of X-rays. That is, (1) X-rays, though fairly penetrating at high energies, tend to be attenuated rapidly for the low energies usually available. On the other

hand, a neutron beam often may penetrate much more deeply into a substance and thus may be a better tool to study a very thick specimen; (2) X-rays are relatively ineffective when elements of low atomic weight are contained in the specimens (such as hydrogen, boron, carbon, etc.). This is because X-rays interact with the shell electrons of the atom and thus low atomic weight materials, having relatively few electrons, will cause very little attenuation of the X-ray beam. Neutrons, however, are scattered about equally well independently of the mass of the target atom and in addition are strongly absorbed by some elements throughout the periodic table. Taking advantage of the differences between neutrons and X-rays, Berger obtained an excellent neutron radiograph of a boral rod.<sup>1</sup> The exceptionally clear image obtained of the boral rod was due to the very high absorption cross section of one of the boron isotopes ( $B^{10}$ ) in the boral rod rather than any variation in the scattering cross section of any of the constituents of the rod.

In conclusion, neutron radiography supplements and complements the more common X-ray methods especially in permitting studies or tests which could not otherwise be made on low atomic weight elements. This thesis describes a successful experiment demonstrating neutron radiography with the V.P.I. UTR (10) reactor as a neutron source.

## II. REVIEW OF LITERATURE

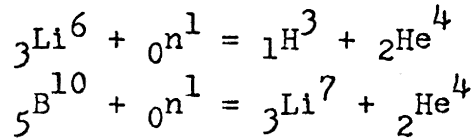
The development of the nuclear reactor has made available intense sources of high and low energy neutrons. However, even before nuclear reactors were in existence, the effects of neutron beams on different materials were being studied. As far back as 1938, investigations were underway studying the ability of irradiated metals to blacken X-ray film.<sup>12</sup> In that same year, the first neutron radiographs were made by Kallman and Kuhn in Germany.<sup>13</sup> The publication of these photographs was suppressed until 1946-7.

Using a weak neutron source derived from "a small discharge of 300 kilovolts constructed in the laboratory", and having a neutron flux "intensity of approximately 2-3 grams Ra-Be equivalent", Kallman initiated the attempts to make neutron radiographs.<sup>13</sup> From the results of his experiments, he set forth four requirements that he found necessary for an adequate source. They were:

- a. radiation must be sufficiently effective for photographic detection.
- b. radiation must be penetrative in order to study the interior of objects but must be absorbed selectively to produce contrast.
- c. the neutron beam should emanate from a point source so that it will be specular.

d. X-rays and fast neutrons should not accompany the slow neutrons.

Kallman also experimented with various types of converter screens for darkening photographic emulsions. For example, he considered using the following nuclear reactions:



The reaction products in these two interactions share an energy of about  $10^6$  electron volts and are very effective when used to darken film. Kallman also suggested that fluorescent screens could be used to increase the efficiency, but warned of considerable loss of resolution. He further investigated the use of converter screens which, upon absorption of neutrons, decayed with beta emissions. His early results showed that of all these latter types of screens, gadolinium caused the greatest darkening of the photographic plate. Kallman's experimentation also led him to make some constructive comments on the best physical arrangement of the source, test piece, screens and films. However, when a nuclear reactor is available, few of these comments are germane since they were mostly based on the premise of a point source.

Further significant advances in the field of neutron radiography were not made until several years later when Harold Berger, at the Argonne National Laboratory carried

out an extensive series of experiments in neutron radiography. 1,10

Berger investigated two main approaches to neutron radiography, the direct exposure method and the transfer method. In the direct exposure method, the photographic film is sandwiched by back and/or front screens of a suitable neutron detecting foil. With the test specimen attached to the front of, or placed just in front of this sandwich, the entire assembly is then placed in the neutron beam, with the beam passing through the specimen before reaching the film. Exposure of the film occurs only while the assembly remains in the beam. Once the photographic sandwich is removed, exposure is essentially stopped. In the transfer method, a suitable foil is placed in the neutron beam behind the test specimen. After a sufficient period of time, the foil is removed and the resulting induced radioactivity then used to darken a film. A few examples of materials used for the direct exposure method are cadmium, gadolinium, and silver. Examples of materials used for the transfer method are gold, indium, and dysprosium. The former group of detection foils is characterized by a very high thermal absorption cross section with the product nuclides stable, while irradiation of the latter group results in radioactive nuclides with half lives sufficiently long to allow transfer.



Berger found the direct exposure method, using a front and back screen sandwich, to give the fastest exposures. Using a sandwich with only a back screen provided the next most rapid exposure method, then followed by the front screen sandwich exposure method. Although the back screen technique was not as fast as the use of both front and back screens, the resolution was superior to either of the other two arrangements of the detection foils in the direct exposure techniques. This effect is probably due to scattering within the front detector foil since most of the induced activity is on the front surface of the foils. Unless the front screen detector is very thin, this will be a problem resulting in a loss of resolution.

Berger found that the transfer method required the longest amount of time before the finally exposed negative was available. However, he hastened to point out that this method did yield adequate results and in many respects could be more versatile than the direct exposure method. For example, it may be impractical to place the film sandwich in a suitable location due to lack of room or perhaps due to a hostile environment. In addition, if the neutron beam contains a strong gamma radiation background, exposure of the film in the direct method may come from the gamma radiation rather than from the neutrons. The transfer method may provide a way to overcome these problems.

Of the materials studied, gadolinium proved to give the most rapid results and also yielded the highest resolution. For these reasons, gadolinium as a back screen was used in the present investigation. Berger's techniques have been applied to several experimental applications in order to demonstrate the general features of the neutron radiographic technique and to illustrate its capability with the Virginia Polytechnic Institute UTR (10) reactor as a neutron source. We feel that this has been successfully done as will be illustrated by the results of this thesis. ✓

## III. INVESTIGATION

## A. NEUTRON MONOCHROMETER

It is important that a reasonably monoenergetic beam of neutrons be used when making a radiograph. The reason for this lies in the fact that the neutron cross section of a given material may vary strongly with the energy of the neutrons. If a broad spectrum of neutron energies were used in a beam, the high transmission of one group of neutrons could wash out or obscure the attenuation of another group of neutrons in the specimen. The contrast of the resulting radiograph would then be reduced. Gamma rays from the reactor also prove a serious problem if the apparatus is placed in the direct path from the beam port. The gamma rays would interact with the test specimen differently than do the neutrons and could obscure the neutron image. The gamma flux might even be sufficiently large to completely fog the film. Both of the above problems may be eliminated by using a neutron crystal spectrometer to obtain a reasonably monoenergetic diffracted neutron beam.

At the north beam port of the V.P.I. reactor, a broad spectrum of thermal and epithermal neutrons are present in a well collimated beam. As already mentioned, there is also present a relatively large gamma ray flux.

The neutron flux in the beam is approximately  $4 \times 10^5$  n/cm<sup>2</sup>sec. <sup>20</sup> At the time the experiment was performed no accurate measurements of the gamma level were available.

If a copper crystal is placed in the beam with the (111) plane parallel to the front of the crystal, neutrons will be preferentially scattered at any angle equal to the angle of incidence. The gamma rays are, for the most part, transmitted through the crystal into a lead catcher or are scattered relatively uniformly in space. Thus we have a neutron beam of reasonably high intensity which is relatively free of gamma radiation. The intensity of the neutron flux will depend on the scattering angle since different energy neutrons are scattered at different angles and the number of neutrons in the beam incident on the copper crystal is a strong function of energy.

The neutron spectrometer shown in Figures 1 and 2 has a high efficiency BF<sub>3</sub> counter located on the detector arm approximately six feet from the crystal table. As the counter rotates through an angle  $\Theta$ , the crystal table turns through an angle of  $\frac{\Theta}{2}$ . Thus, once the scattering maximum is located for a given crystal angle, the spectrometer can be engaged so that for any rotation of the detector arm, the crystal always remains aligned. The Bragg condition relating the scattering angle with the neutron energies is

$$E = \frac{n^2 h^2}{8 m d^2 \sin^2(\theta/2)}$$

where

n = order number

d = interlattice spacing of the 1,1,1 plane

$\theta$  = counter angle

h = Plank's constant

m = mass of the neutron

With the  $\text{BF}_3$  counter in place, the maximum count rate was found to be approximately 60,000 counts/0.10 minutes. It can be shown that the detector efficiency for thermal neutrons is approximately 100%. If this figure is used, it is possible to obtain a rough estimate of the neutron flux at the counter position. If the neutrons are assumed to be uniformly distributed over the 1.75 inch diameter face of the neutron detector, then we can make the following flux calculations.

$$\phi = (6 \times 10^4 \text{ NTS}) \left( \frac{1}{(3.14)(7/8)^2 \text{ IN}^2} \right) \left( \frac{1 \text{ m}^2}{(2.54)^2 \text{ CM}^2} \right) \left( \frac{1}{0.1 \text{ MIN}} \right) \left( \frac{0.1 \text{ MIN}}{6 \text{ SEC}} \right)$$

$$\phi \approx 650 \frac{\text{NEUTRONS}}{\text{CM}^2 \text{ SEC}}$$

Actually, the peak intensity is concentrated over a rectangular area approximately 1 inch by  $1\frac{1}{2}$  inches. However, later experiments showed that there was a reasonably high intensity of neutrons in the general vicinity of the screen. These features are visible in some of the photographs which are included here although they are

partially obscured by the reproduction process.

Rough estimates of the necessary exposure time were next made. For a cadmium screen placed behind the film, Berger needed an exposure time of approximately 15 minutes with a neutron flux of  $3 \times 10^5$  neutrons/cm<sup>2</sup>sec using type AA X-ray film. By substituting No Screen X-ray film, a gain of film speed of approximately 5 times can be obtained.<sup>16</sup> Thus we estimated our exposure time to be:

$$T = \left( \frac{1}{4} \text{ HOUR} \right) \left( \frac{3 \times 10^5}{6.45 \times 10^2} \right) \left( \frac{1}{5} \right)$$

$$T = 23.3 \text{ HOURS}$$

This is an extremely long period of time for a single run. However if the area of greatest intensity of the neutron beam actually observed is compared to the area of the detector, an actual flux in the central region of about 10 times that used in the above calculation would appear reasonable. This would allow an exposure time of the order of a few hours. In an effort to decrease the needed exposure time the film plate was moved closer to the crystal. Also, the thickness of the film holder front plate was reduced in order to reduce the scattering of the neutrons. This also served to reduce the loss in image contrast caused by scattering close to the film plane. Several tests were made but an exposure time of 4 hours proved long enough to obtain reasonable results as will

be seen in the pictures which were obtained.

#### B. THE BACK SCREENS

Neutrons have a relatively small capability for causing the direct activation of photographic film since the likelihood of a neutron interaction in the thin emulsion is slight. To facilitate a shorter exposure time, back and/or front converter screens are used. A necessary characteristic of all screen materials is that upon neutron bombardment, the neutrons will be captured and cause the emission of some other type of particle or gamma ray. Electrons would be very effective in darkening film although gamma rays emitted by the converter foil would also be reasonably effective.

Two different types of detector foils were to be tested, cadmium and gadolinium. The best resolution would be obtained from very thin foils and although the gadolinium produces a faster exposure, thin cadmium screens were more easily made. Also, the cadmium is much less expensive. Starting with a piece of 2 inch by 2 inch by 0.032 inch cadmium, several passes were made through a rolling mill, each pass reducing the thickness of the cadmium slightly. The results of several runs produced a few good pieces of cadmium foils varying in thickness from 0.001 inches to 0.004 inches.

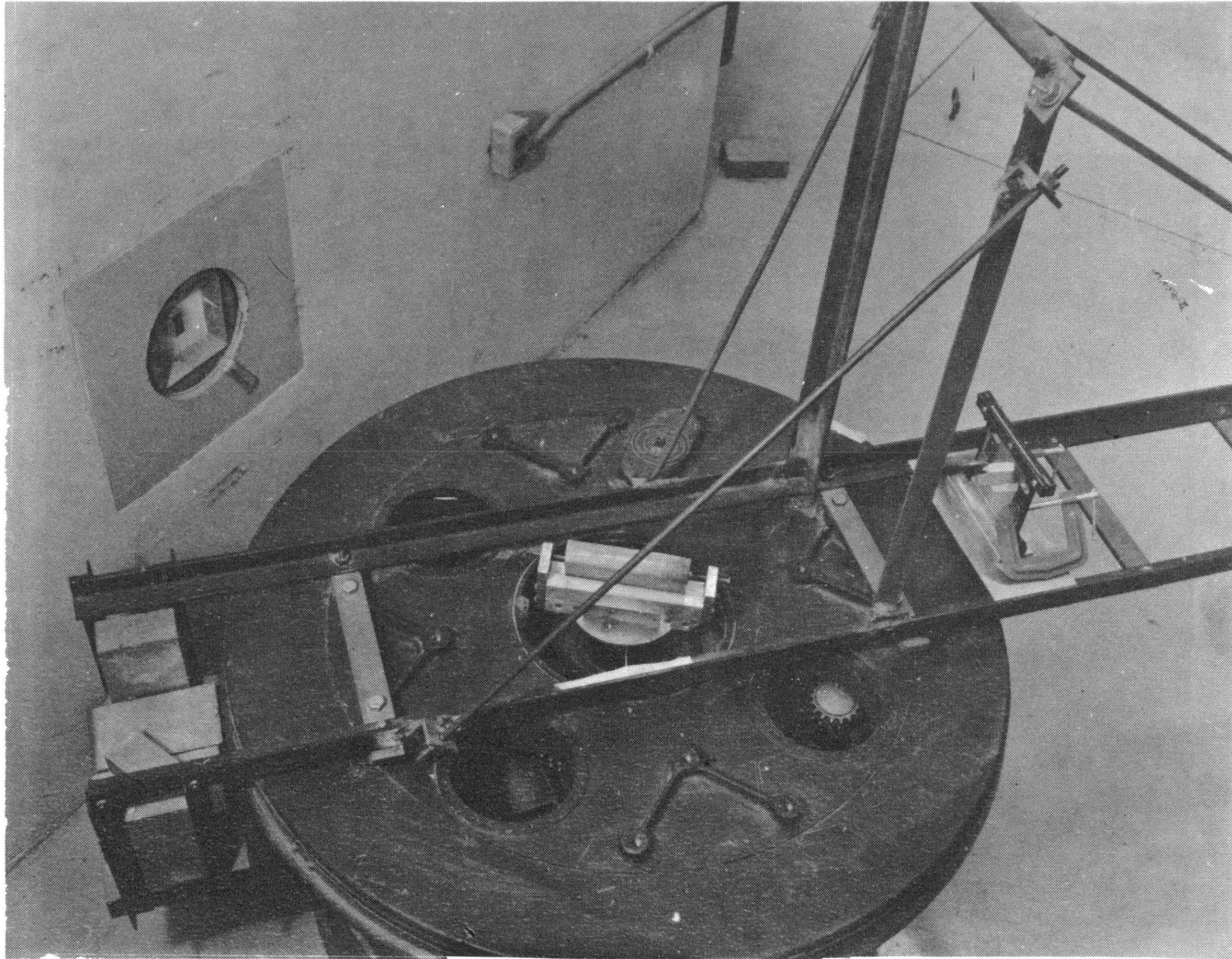
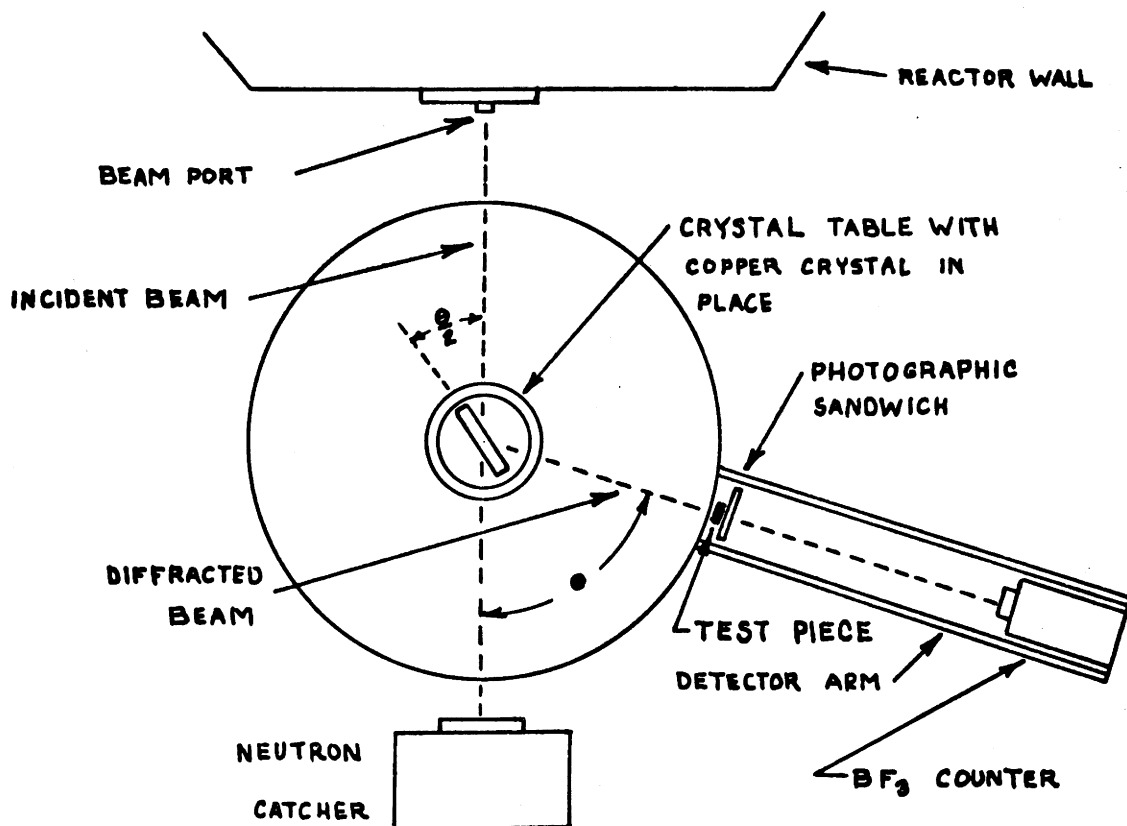


Figure 1 Reactor wall and neutron spectrometer with photographic sandwich in place



# CRYSTAL SPECTROMETER



## PHOTOGRAPHIC SANDWICH

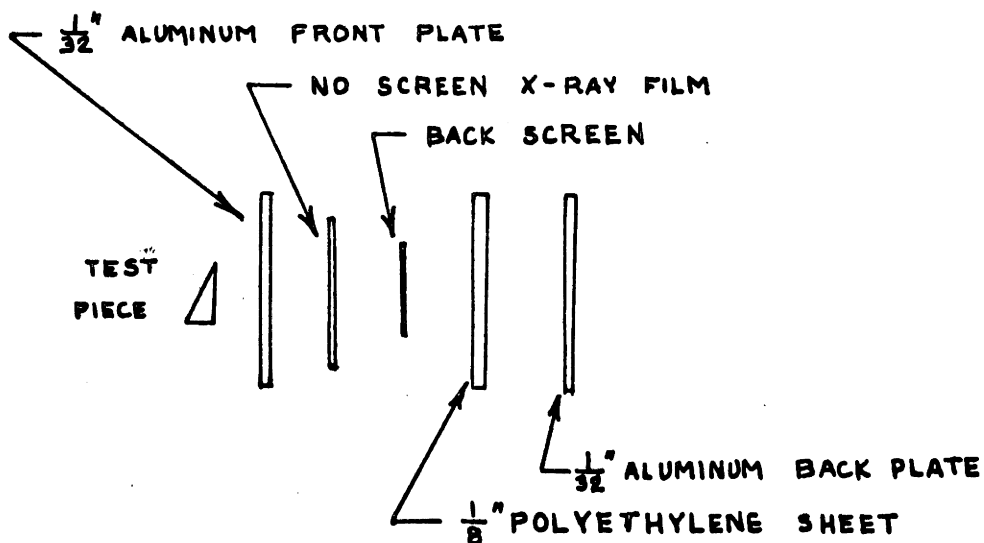


Figure 2

From these foils, a  $3\frac{1}{2}$  inch by 5 inch sheet with a thickness of 0.002 inches was chosen for the experiment.

As stated above the reduction in thickness is necessary to obtain satisfactory resolution. Berger has conducted extensive investigations in the optimum thickness for various detector foils producing the best resolution.<sup>5</sup> In general, it was concluded that the resolution improved as the thickness of the foil was decreased. This would be expected since most of the neutron capture events would occur very near the surface of the foils due to the high capture cross section, and the remaining bulk of the material would essentially serve only to scatter the emitted radiation.

Three, one inch squares, 0.005 inches thick, of gadolinium were obtained from A.D. MacKay. This thickness of gadolinium foils was somewhat greater than that suggested by Berger for best resolution, i. e. about 0.0005 inches.<sup>14</sup> However gadolinium is not easily rolled, so preliminary runs were made with the three 5 mil gadolinium foils taped end to end. The results of these preliminary radiographs were far superior to any of the radiographs obtained using the cadmium back screen and were quite usable. Since the results were satisfactory it was decided to use the foils as obtained rather than attempt to reduce the thickness and perhaps damage the foils.

### C. PHOTOGRAPHIC ALIGNMENT

Initial attempts incorporated a photographic frame which held the No Screen X-ray film against the back screen by means of spring loaded armatures at the four corners of the frame. This did not prove satisfactory in holding the film and screen in contact. A more crude and awkward frame was then constructed which did succeed in holding the X-ray film firmly against the detector foils. Simple C clamps were used to hold the sandwich together and in addition the sandwich was modified slightly. Behind the back screen foils, but inside the outer sheet of the aluminum sandwich, a 1/8 inch sheet of polyethylene was inserted. The effect was to hold the foils tightly in place and to prevent an apparent buckling which occurred with the metal back plate. The film was developed by following the standard procedures specified by Eastman Kodak for No Screen X-ray film.

In Figure 2 (bottom) there is a sketch of the general purpose photographic sandwich. Figure 3 shows the photographic sandwich with the three gadolinium foils taped in place.

### D. MATERIAL INVESTIGATION

The principle object of the experiment was to demonstrate the capability of the V.P.I. UTR (10) reactor

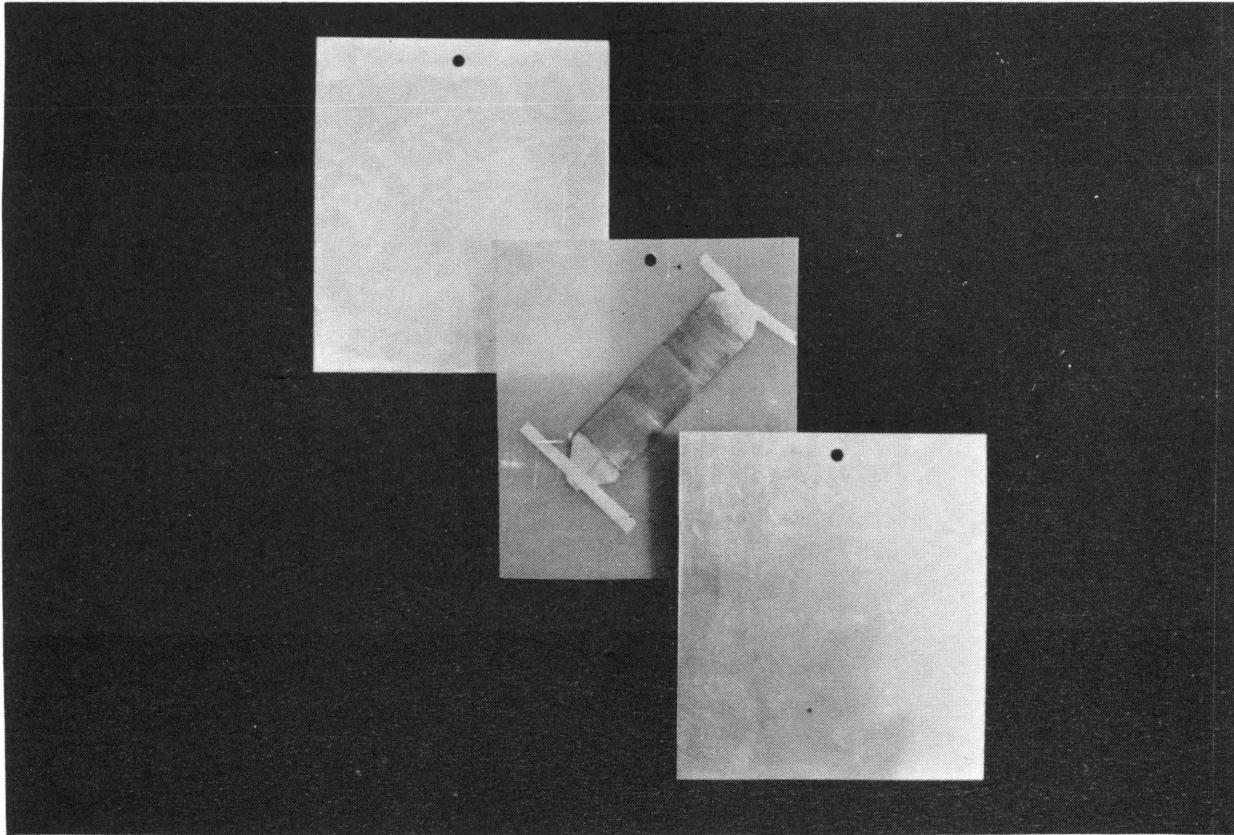


Figure 3 Photographic sandwich with gadolinium foils

to make neutron radiographs. As is implied in the previous section, many of the procedures employed in the experiment were based on the recent work of Berger at the Argonne National Laboratory. However, more emphasis has been placed on specimens composed of low atomic number elements than in Berger's original work, and on the effect of voids or imperfections within a solid.

The initial test piece was a small sheet of cadmium approximately 1/16 inch thick in which were drilled holes of various sizes. Cadmium was selected as a suitable test piece because it strongly absorbed neutrons. The purpose of the different size holes was to help in determining the sharpness, or resolution, of the image made on the film.. Several initial runs were made employing the cadmium back screen and the original spring loaded photographic frame. The results of these first runs permitted a determination of the exposure time needed to obtain an adequate radiograph. Before further experiments were made, the detector assembly was modified as previously discussed.

Using the C clamp frame with the cadmium back screen still in place, improved results were obtained. Still, the quality of the results was not up to expectations. The image was clearly discernible, but it was far from being sharp enough to ever be used in an exacting investigation.

The one inch squares of gadolinium were then substituted for the cadmium to make one sheet of gadolinium, 1 inch by 3 inches by 5 mils. A number of very successful runs were obtained with the combination of the C clamp frame and the gadolinium back screen.

Several objects were selected for investigating the resolution of the radiographs and for testing the penetrating ability of the neutron beam offered by the V.P.I. reactor facilities. Most of these objects yielded only visual results. That is to say, the radiographs of most of the objects were best evaluated by merely observing the radiographic negatives after development. Several of these objects were reproduced in Figure 4. The initial test piece is among those labeled cadmium.

Three test pieces were especially prepared in order to obtain quantitative results. Each of these three test pieces, made in the form of wedges, were constructed in essentially the same size and configuration, the only difference being their material content. Each wedge was  $2\frac{1}{2}$  inches long, 1 inch high at the broad end, and approximately  $\frac{3}{4}$  inches to 1 inch in width. On the sloping face of each wedge, three grooves were milled, one  $\frac{1}{32}$  inch, another  $\frac{1}{16}$  inch and a third one  $\frac{1}{8}$  inch in depth. The three wedges were made of reactor grade graphite, plexiglas and fibrous bakelite, respectively. A drawing of a typical

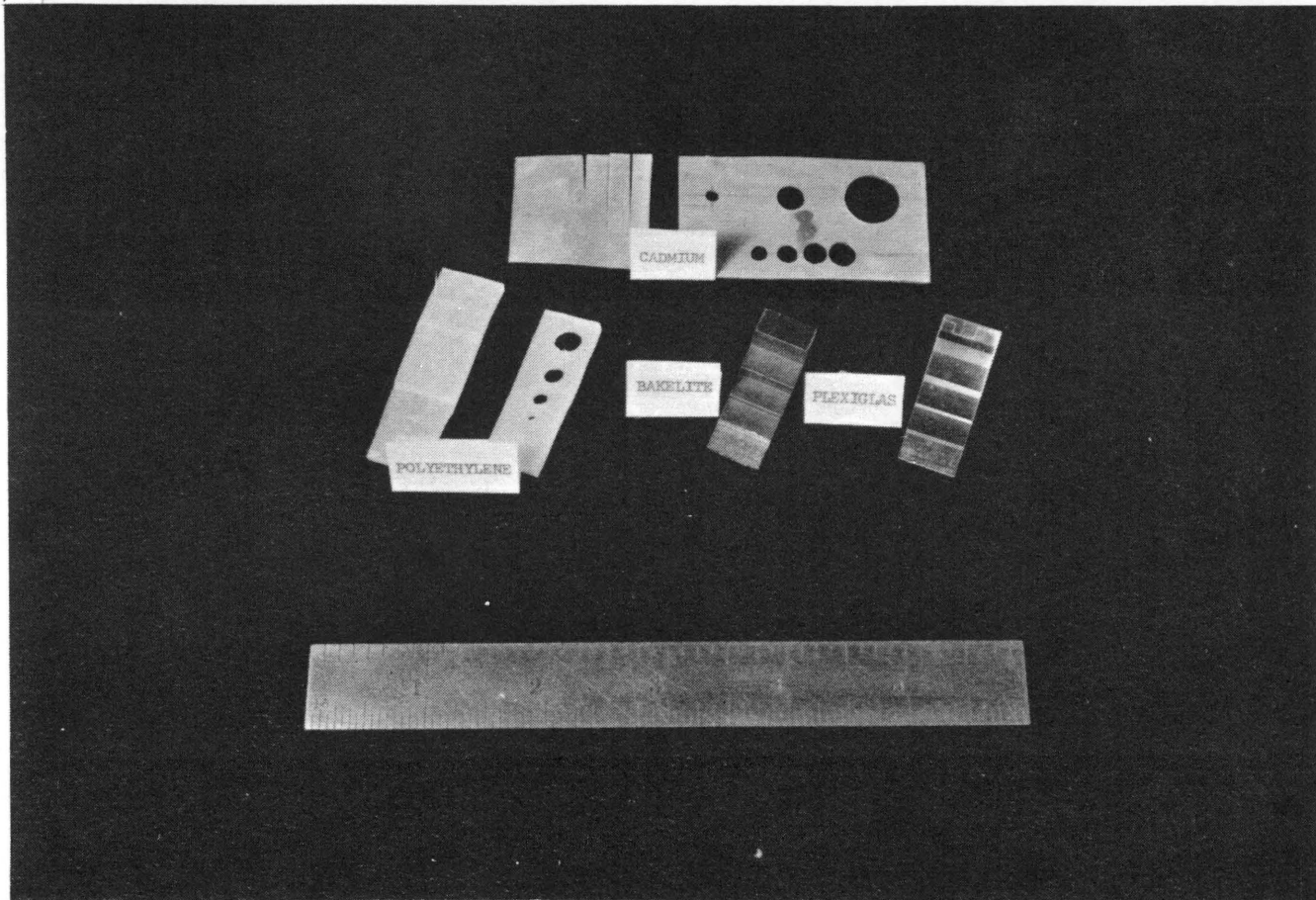


Figure 4 Other Test pieces

# TYPICAL WEDGE

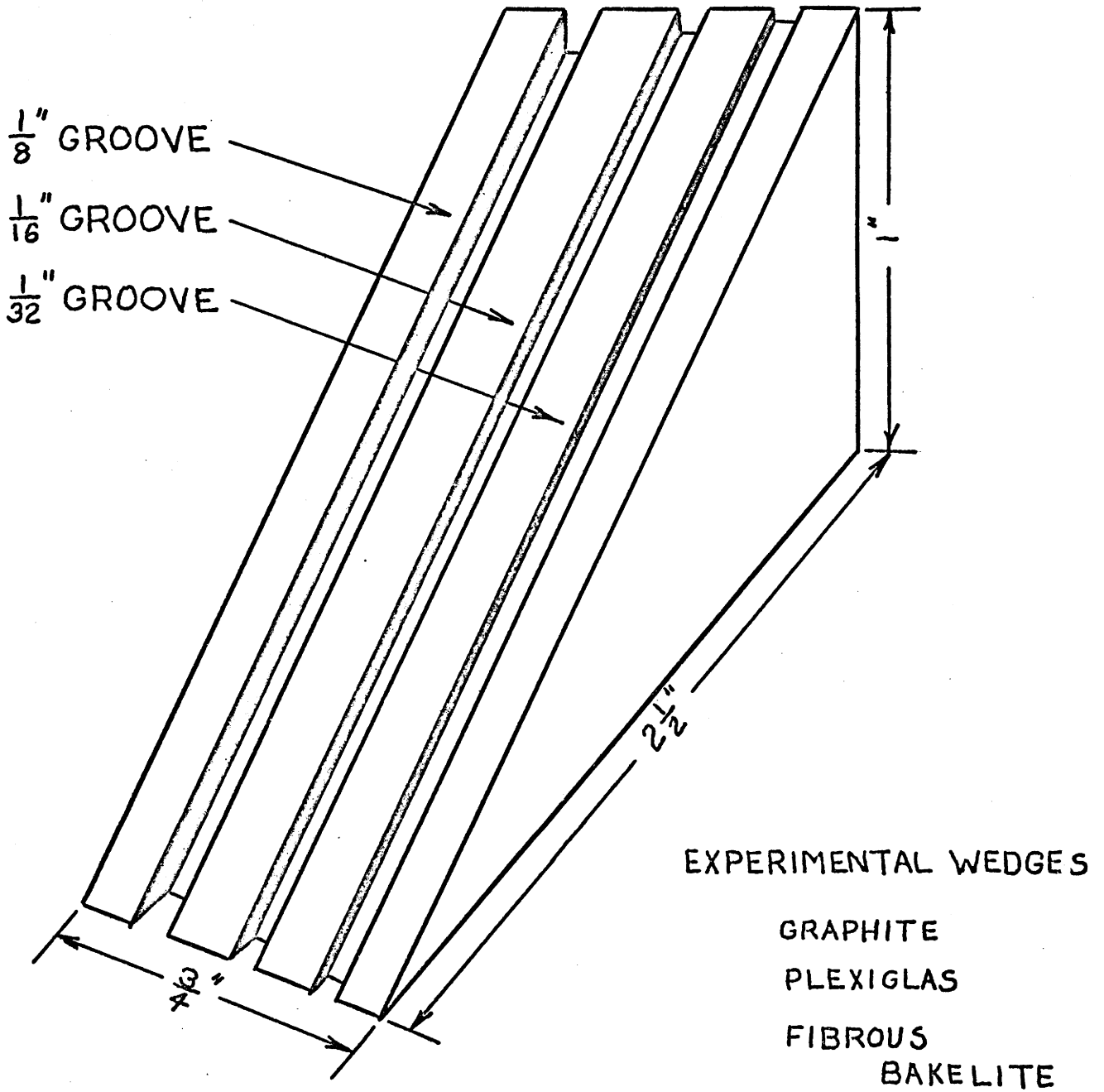


Figure 5



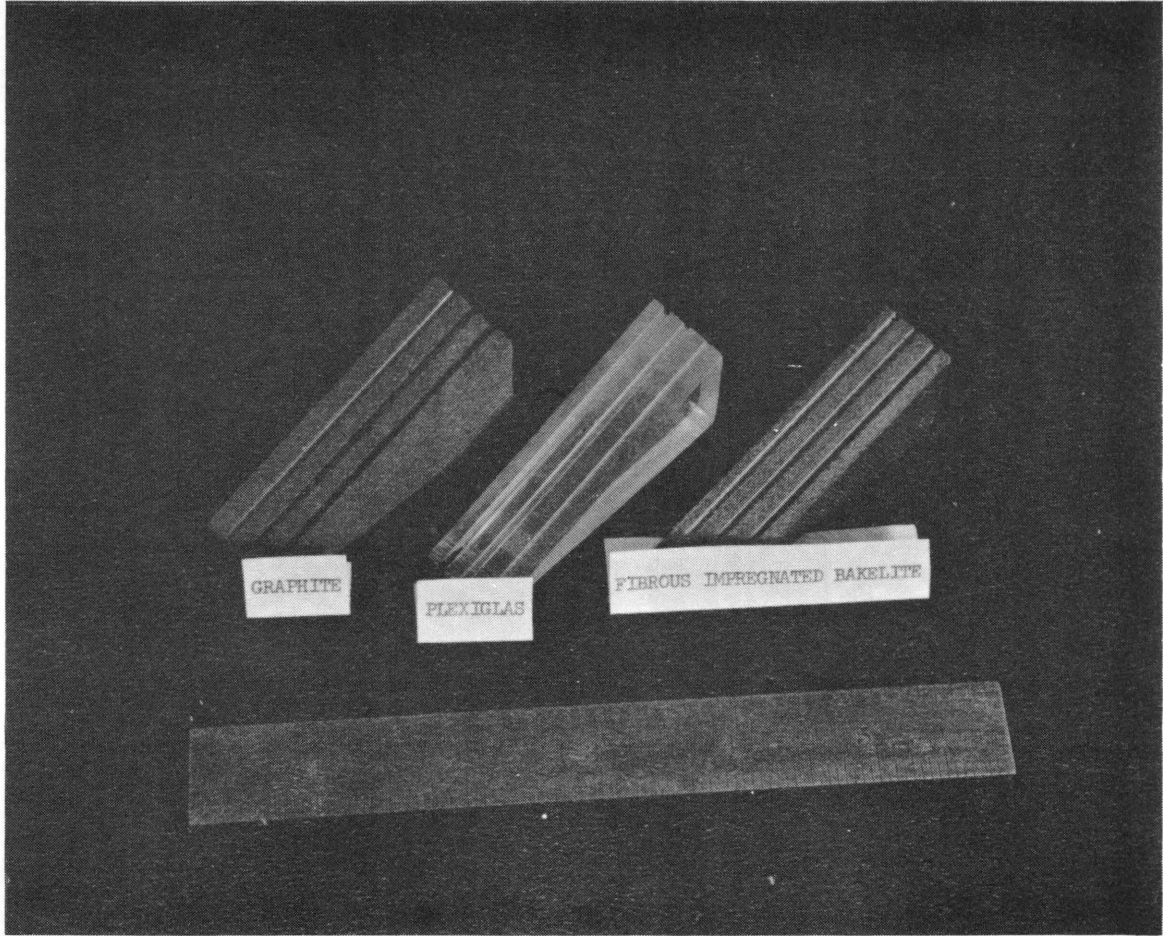


Figure 6 Three wedge test pieces

wedge is presented in Figure 5. Figure 6 is a photograph of all three test wedges.

All of the test pieces were attached with masking tape to the front of the C clamp frame when the respective radiographs were made. The usual running period for each exposure was four hours. One of the wedges, the plexiglas piece, was also used in an extended run of eight hours. This was done in order to estimate the increase in quality of the radiograph, if any, as a result of the additional exposure time. No significant improvement was observed which would justify additional running time.

#### E. DENSITOMETER

A densitometer used in optical spectrometry was employed in the investigation of the radiographic negatives which were made with the three wedge test pieces. It was decided, however, that the original selenium cell incorporated in the densitometer was not capable of distinguishing the very small differences in tone in the various portions of the negatives obtained in the experiment. The difficulty lay in the average high density of the negative so that the over-all output of the selenium cell was quite low. A cadmium sulfide photocell was substituted and the electrical circuit rearranged as shown in Figure 7. The cell was covered with black tape, except for a thin slit which was used

# THE DENSITOMETER

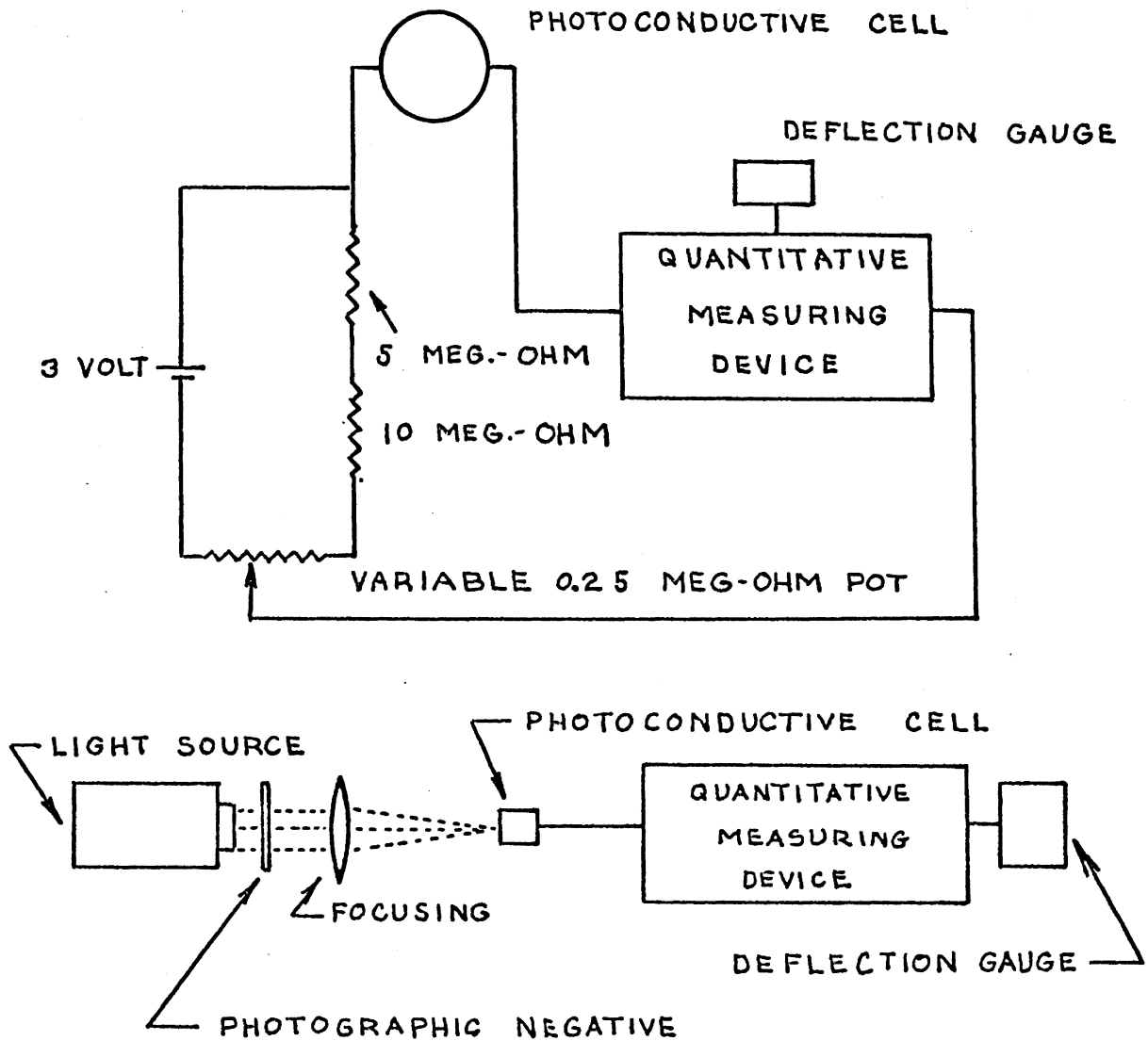


Figure 7

to scan the film. The area of the negative viewed by the slit was approximately 0.01 inch by 0.02 inch.

The 4 inch by 5 inch negatives were trimmed into the same shape as the usual glass spectrographic plates and then taped to blank specimens of these plates. This permitted the densitometer to be operated in a normal manner although the light sensor had been changed as discussed in the previous paragraph. Lateral readings were taken across the negatives where the images of the grooves on the wedges were expected to be.

#### IV. RESULTS

##### A. QUANTITATIVE RESULTS FROM THE WEDGE RADIOGRAPHS

Generally speaking, the three wedges, each of a different material, produced quite similar results. Of the three specimens, the graphite tended to produce the least sharp picture. The difference must lie in the nuclear properties of carbon and plastic materials since the densities of the wedges were nearly the same. Both the plexiglas and fibrous plastic wedges contain a fair proportion of hydrogen which does not tend to scatter neutrons forward into the detector assembly, while the graphite scatters neutrons approximately uniformly in all directions. In all cases, the gadolinium back screen was used.

In Figure 8, the wedge radiographs have been reproduced. The first three pictures, proceeding from the top to the bottom of the page, are (A) the graphite wedge, (B) the fibrous bakelite wedge, and (C) the plexiglas wedge, all taken using a four hour running time. The last picture (D) is of the plexiglas wedge taken with an eight hour exposure.

Using these radiographic negatives, measurements of the optical density at various points on the negatives were made for a large number of lateral scans as described in the previous section. Approximately 40 readings were

taken on each scan across the width of the wedges. From the relatively large number of scans which were made for each wedge, at varying wedge depths, two typical sets of densitometer readings were plotted. These graphical plots are shown in Figures 9, 10, and 11. For each of these graphs, the data were taken at distances of (A)  $7/8$  inch and (B)  $2\ 1/8$  inches from the broad end of the wedge. The respective wedge thicknesses corresponding to these points were approximately 0.65 inches and 0.15 inches. One can easily discern the three grooves on all the (B) graphs. On the (A) graphs, which illustrate a radiograph of a thicker portion of the wedges, most of the grooves are not clear. However, one can discern with the eye alone, (in the original negatives) the presence of the deepest groove essentially the entire length of the wedge as can be seen from a careful examination of the actual radiographs of the wedges in Figure 7. This can be attributed to the ability of the eye to group faint images together while the narrow slit scanning the negatives saw only a limited area of the negatives.

Four graphs illustrating lateral readings taken from the negative made from the eight hour run using the plexiglas wedge are shown in Figure 12. For this graph, the data were taken upon scanning (A)  $7/8$  inches, (B)  $1\ 1/4$  inches, (C)  $1\ 3/4$  inches and (D)  $2\ 1/8$  inches from the broad end of

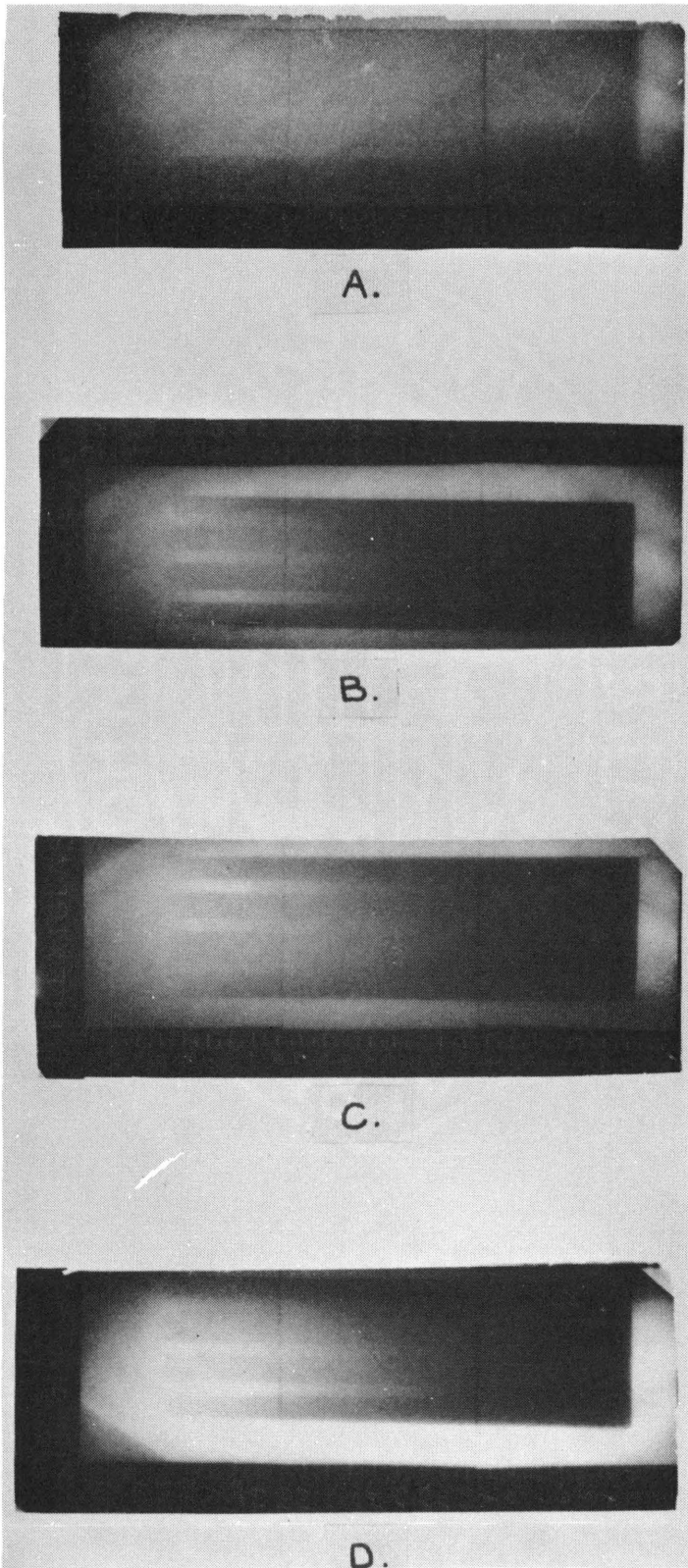
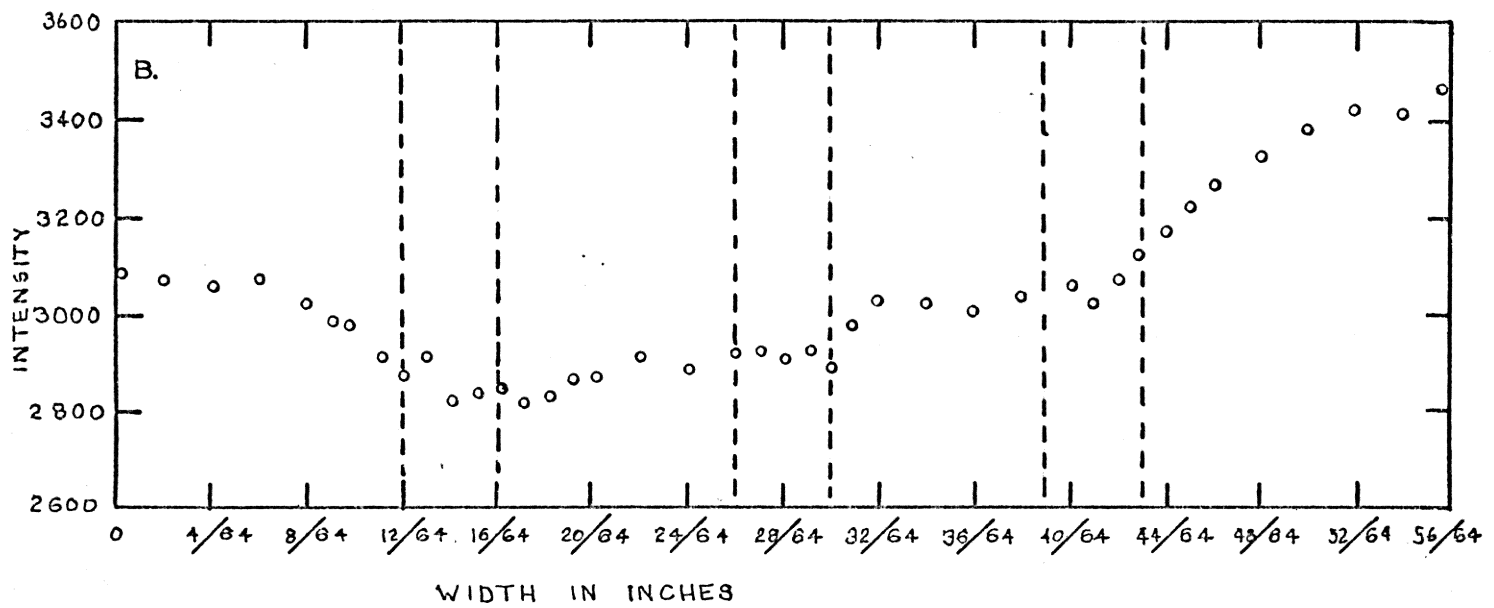
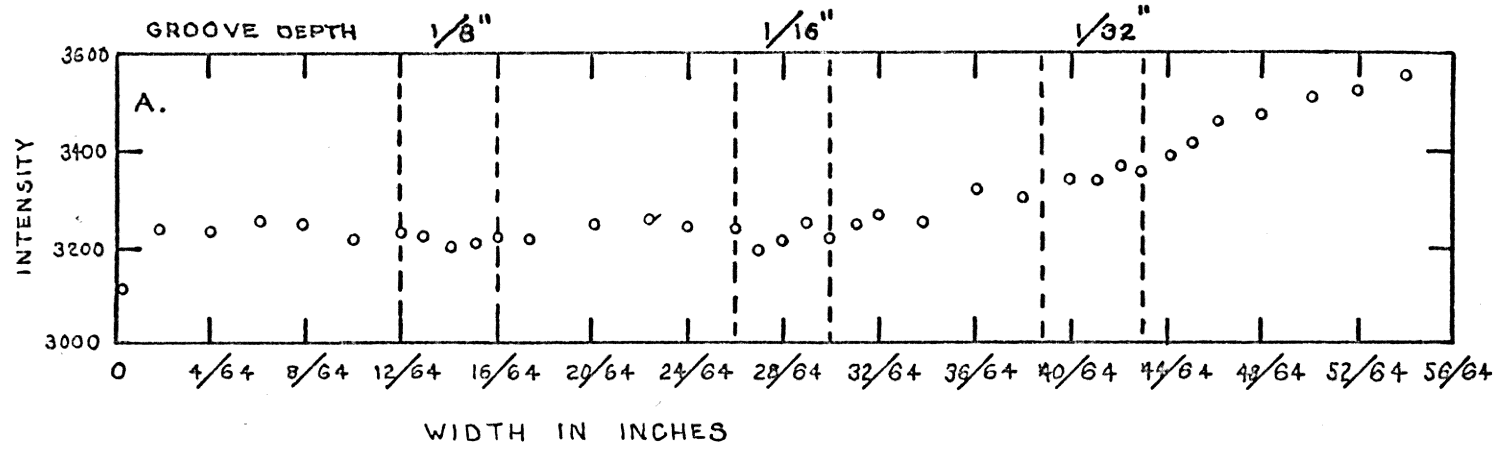


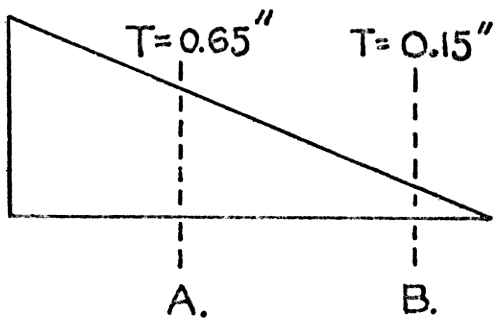
Figure 8 Radiographs of test wedges

# GRAPHITE WEDGE

FOUR HOUR RUN



LOCATION OF LATERAL SCAN



FOR EACH GRAPH

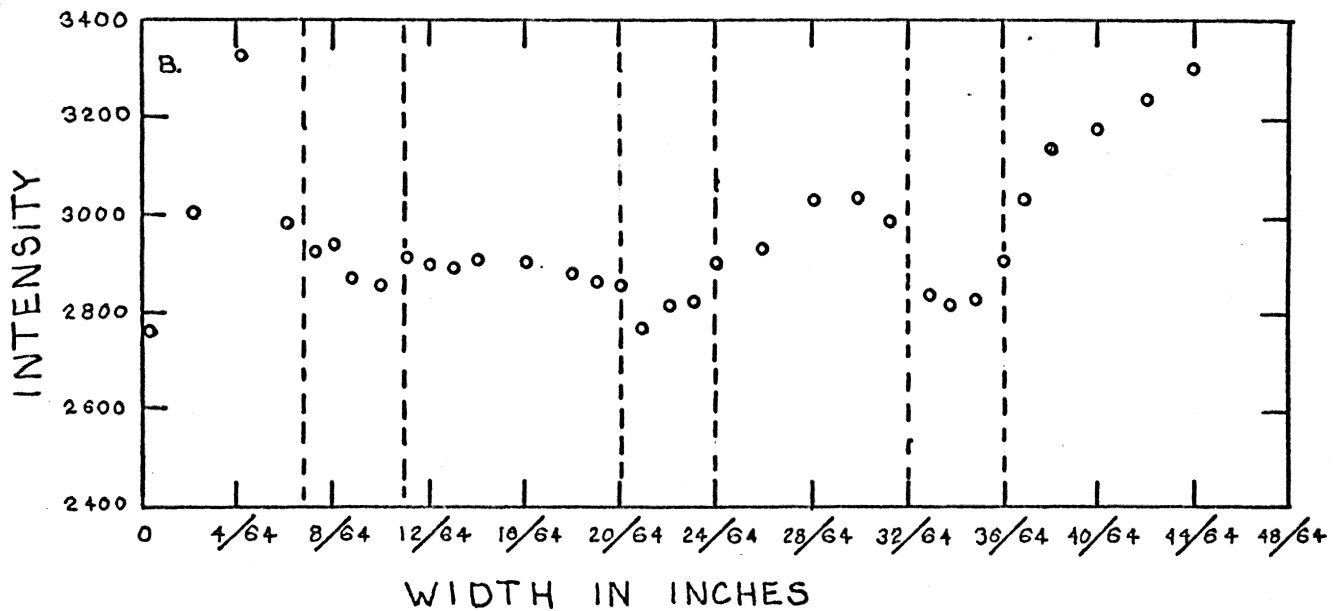
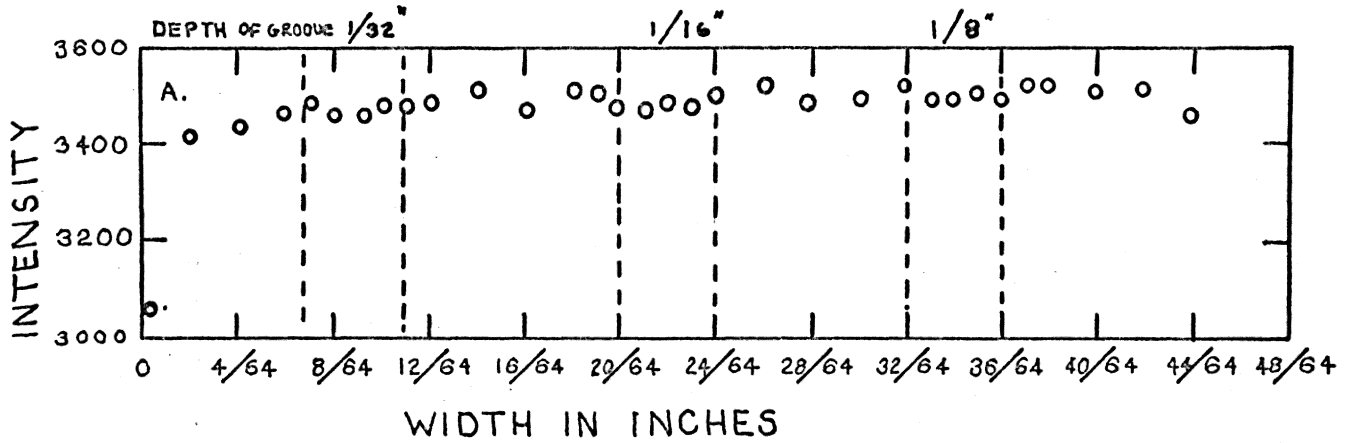
T = THICKNESS

Figure 9

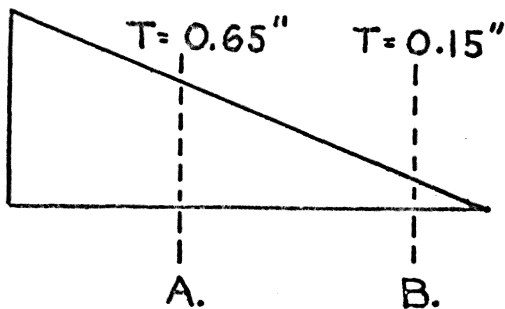


# FIBROUS BAKELITE WEDGE

FOUR HOUR RUN



LOCATION OF LATERAL SCAN FOR EACH GRAPH

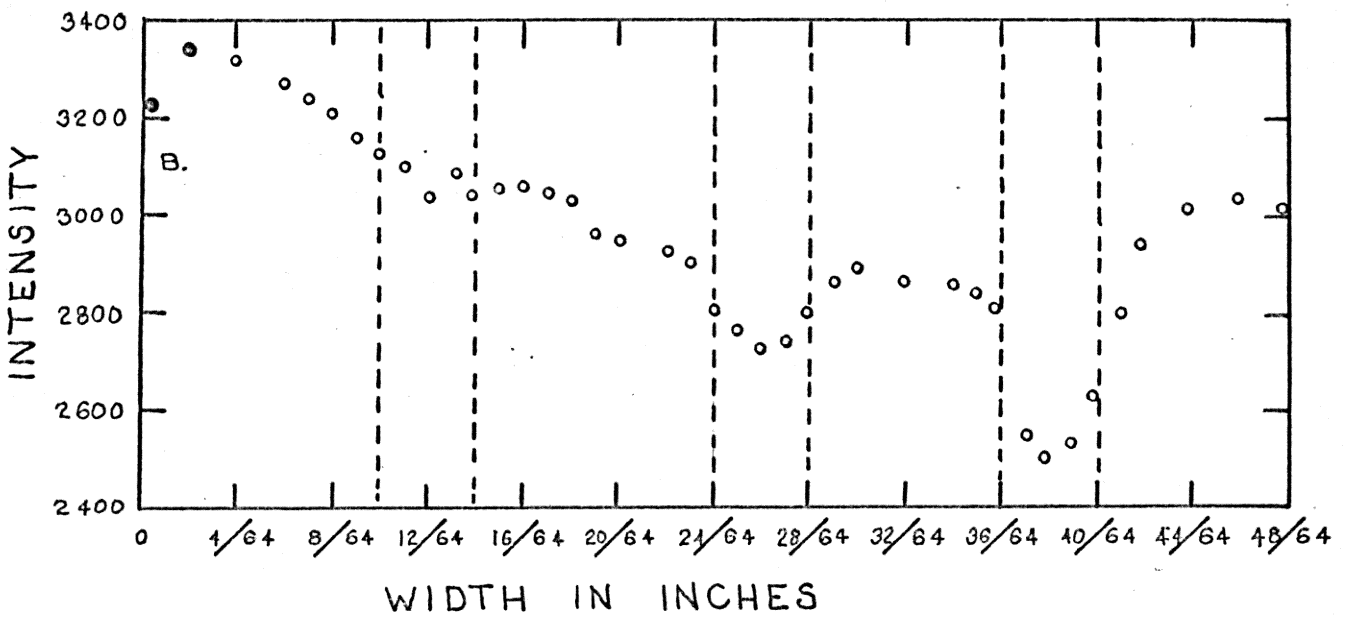
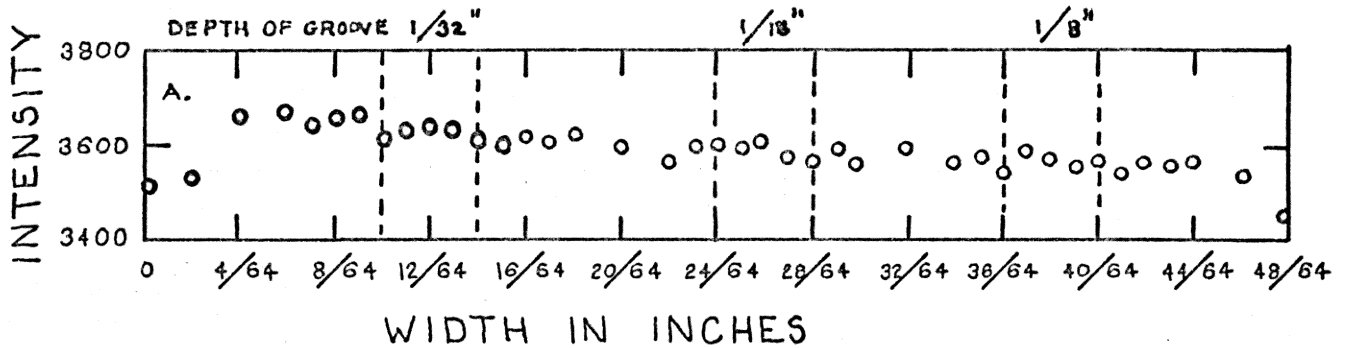


$T =$  THICKNESS

Figure 10

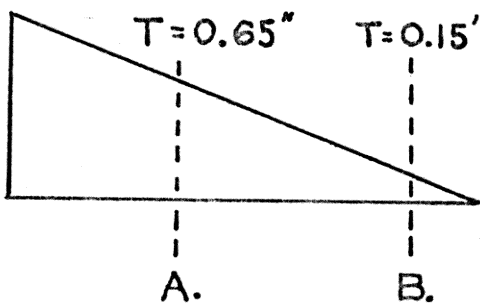
# PLEXIGLAS WEDGE

FOUR HOUR RUN



LOCATION OF LATERAL SCAN

FOR EACH GRAPH



$T =$  THICKNESS

Figure 11

# PLEXIGLAS WEDGE

EIGHT HOUR RUN

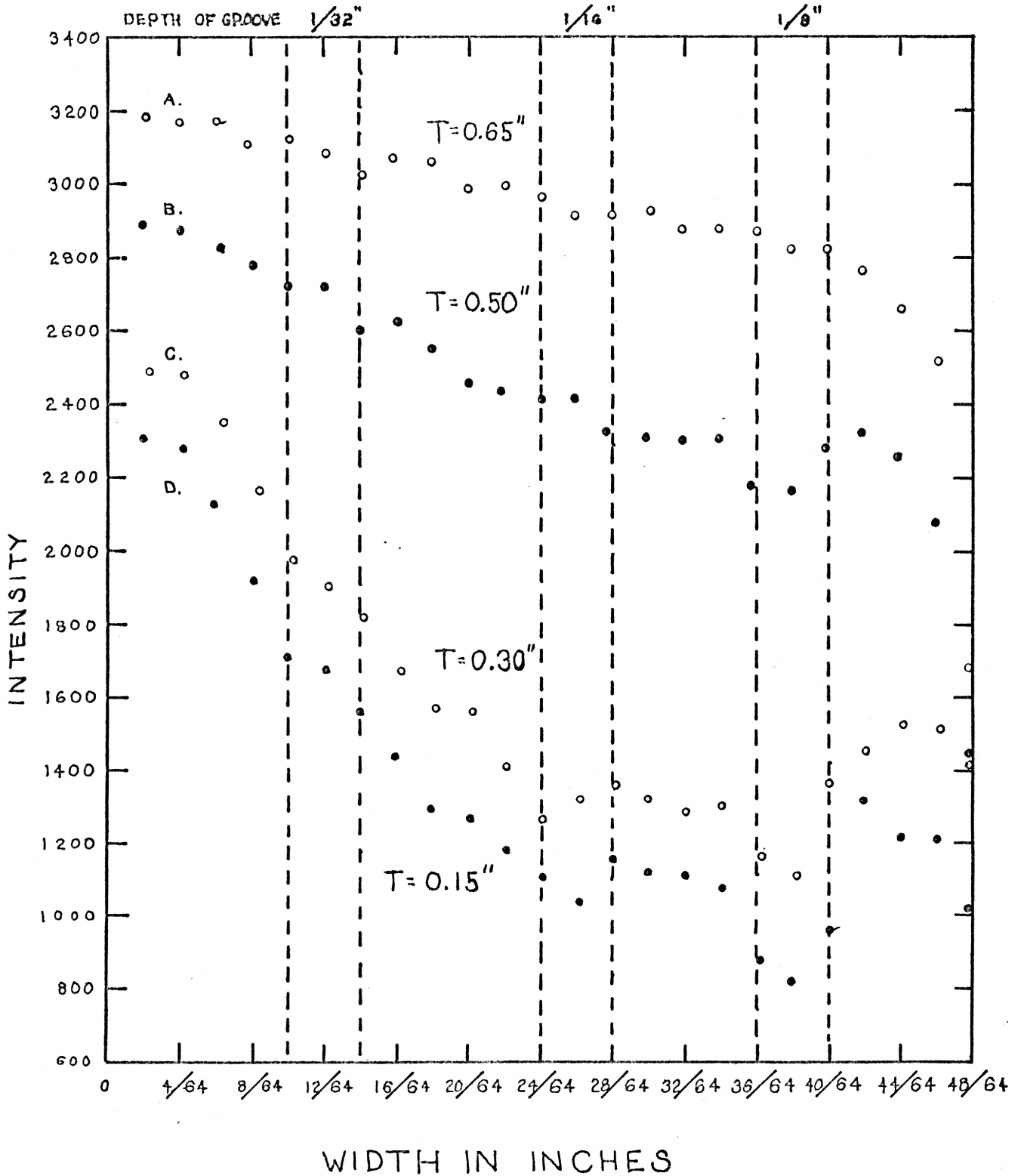


Figure 12

the wedge. The wedge thickness at these distances is respectively, 0.65 inches, 0.50 inches, 0.30 inches and 0.15 inches. It can be seen by comparing the intensity reading that due to the extended exposure, a much darker negative was obtained. Also, one can see a more intense background which tends to obscure the wedge-groove image. We must conclude, then, that no significant improvement was observed which would justify the additional four hour running time.

On all the densitometer graphs, the intensity scale offers a purely relative indication of the lightness or darkness of a given area on the film. Since the darkening of the film is directly proportional to the extent of exposure, we are necessarily only interested in the incremental changes in the intensity readings as we scan laterally across the film. Thus the intensity values which appear on the ordinate axis of each graph should be considered only as an indication of the change in lightness or darkness of the film.

The dotted lines superposed on each graph locate the actual grooves on the wedges.

#### B. OTHER RADIOGRAPHS

Several other radiographs of the various test specimens shown in Figure 4 have been reproduced in

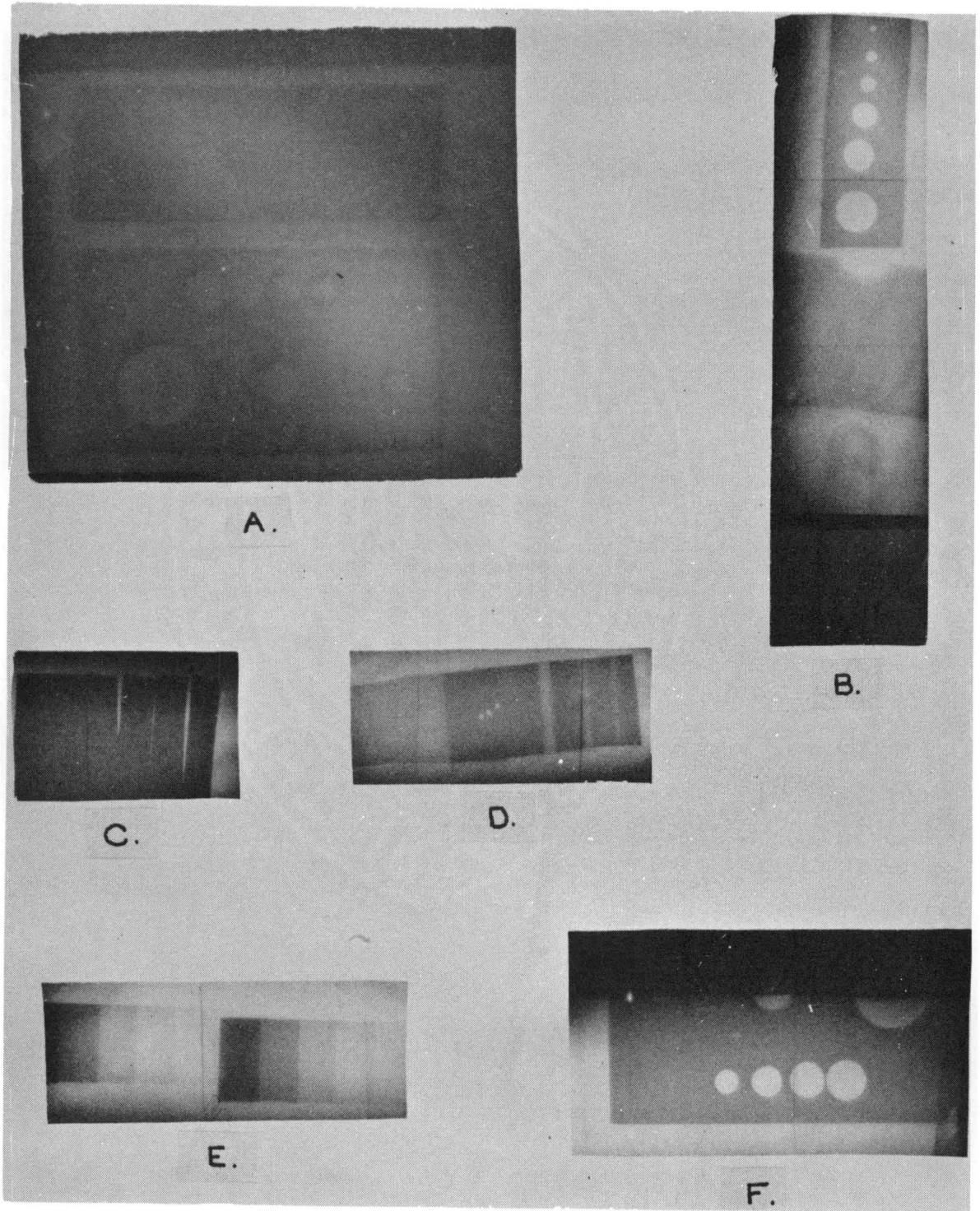


Figure 13 Radiographs of other test pieces

Figure 13. Very little quantitative information, however, has been derived from these pictures. Only picture (A) of Figure 13 was obtained by using the cadmium back screen. The test specimen used here was a 1/16 inch sheet of cadmium containing several holes of various sizes. Generally poor resolution was obtained in this radiograph, especially when it is compared to picture (F) of Figure 13. For this latter picture, as well as for all other pictures in Figure 13, the gadolinium back screen was used. It is of interest to note, further, in picture (A), the superposed light area running from the upper left corner to the lower right corner. This is the location of the most intense neutron flux.

The other pictures in Figure 13 are the following: (B) a piece of polyethylene with several drilled holes, a welded piece of iron and a safety pin; (D) a 1/8 inch piece of polyethylene with several holes drilled side-ways through it; (E) two step wedges, one of plexiglas and one of fibrous bakelite; and (F) a piece of 1/16 inch cadmium containing several holes of various sizes (the same piece as in picture (A)).

#### C. BACK SCREEN

It is obvious from the photographs obtained that superior results can be achieved if gadolinium is used

instead of cadmium as a detector foil. There is relatively little discussion in literature as to why this one element is better than the other which would afford an explanation for these results. However, two factors may be put forward as probably being the primary cause of this disparity. Both of these factors involve the absorption properties of the two substances.

First, the thermal absorption cross section for gadolinium is significantly higher than for cadmium (approximately  $2 \times 10^5$  barns versus  $2 \times 10^4$  barns). This would physically produce a thinner effective absorption layer on the gadolinium foil than on the cadmium foil. That is to say, a more significant number of absorptions would occur very close to the surface of the gadolinium, while deeper absorptions would occur in the cadmium. As was discussed earlier, this would result in reduced scattering of the emitted radiation after detection in the gadolinium, and thus serve to improve the resolution.

Secondly, the "cut off" energies for the absorption cross sections are different, that for gadolinium being higher than for cadmium. This would serve to utilize more of the higher energy neutrons which are present to some extent in the incident beam. Even though the presence of a broad spectrum tends to reduce contrast as described before, a small spread of energies is not too injurious to

the results and, in fact, must be expected. Since the cadmium cross section spectrum drops off so sharply for energies even slightly above its resonant peak, many of the more energetic neutrons may be lost, or at least not utilized near the foil surface. Gadolinium, maintaining a high absorption cross section for these more energetic neutrons, can utilize these captures near the foil surface and thus provide a more efficient converter screen.

#### D. DISCUSSION

It is important to note that due to the relatively weak intensity of the monoenergetic neutrons available from the V.P.I. UTR (10) reactor, a long period of time was needed to make each radiograph. The exposure time alone was usually four hours. This does not include bringing the reactor up to power and shutting it down. Thus it was very difficult to make more than one run a day. If the power of the reactor is increased by a factor of 10 as is being planned, then an adequate exposure could be obtained using the same configuration in about half an hour of actual reactor running time. Obviously, the usefulness of the technique could be significantly increased.

As mentioned earlier, the size of the neutron beam was quite small. This places a severe restriction on those



objects which may be investigated. This may or may not be important since the test piece may be small anyway. In any event, a dimensionally larger beam would enhance the radiographic method. Since the beam which was used was very well collimated, it should be a simple matter to reduce the collimation and obtain a larger usable beam for this application. However, the use of the crystal monochrometer would eventually limit the size of the beam due to the finite size of the crystal.

## V. CONCLUSIONS

It is clear that this technique can be very useful in physics and engineering. The applications to reactor engineering alone can be of great importance. For instance, this method has already been employed in the investigation of boral rods. It is also clear that further development is needed, both in general, and in the application of this technique with the V.P.I. reactor.

The work reported in this thesis does demonstrate that sufficient neutron intensities can be obtained from the V.P.I. UTR (10) reactor to make the technique feasible. With an increase in beam intensity and area, it should be possible to satisfactorily apply this method to any number of problems arising in material testing.

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# NEUTRON RADIOGRAPHIC METHODS

by

Charles Barry Hogge

## ABSTRACT

An experiment has been performed which establishes the capability of the reactor at V.P.I. to provide a satisfactory neutron supply for neutron radiography. Several different specimens including low Z materials and heavier materials such as iron have been used as test objects. The effects of alternate methods of obtaining the radiographs and of the different experimental parameters have been studied.

Quantitative investigations were made of the effects of voids of different depths in varying thicknesses of three test specimens which consisted of graphite, bakelite, and plexiglas. The results of these studies showed that it would be practical to detect voids of as little as  $1/32$  of an inch at depths of up to one inch in the test specimens.

It is felt that the research performed in this experiment adequately demonstrated the usefulness of neutron radiographic methods in non-destructive testing and the capability of the V.P.I. reactor facility for this technique.