NEUTRON RADIOGRAPHY - UTILIZATION OF NEUTRONS
FROM A COCKCROFT-WALTON ACCELERATOR

A Thesis

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ABSTRACT

The results of an investigation of the direct exposure technique of neutron radiography are presented. A workable system for making neutron radiographs was obtained using the existing facilities and equipment of the Louisiana State University Nuclear Science Center.

The neutron source available for this study was Texas Nuclear Corporation 150Kv Cockcroft-Walton type accelerator. The maximum neutron output which could be obtained utilizing the $T(d,n)He^4$ reaction was about 1.3×10^{10} neutrons/second. This is one order of magnitude less than the full rated capability of the generator.

A thermal neutron beam was obtained by using a four inch thick paraffin moderator. With a target to film distance of 27 inches the maximum total neutron flux at the imaging plane was 2.0×10^5 neutrons/ cm^2-second. The cadmium ratio of the neutron beam was 1.50.

The most efficient image detecting method, of those evaluated, was 0.010 inch thick indium foils sandwiched around Kodak KK industrial x-ray film.

The factor limiting the usefulness of the present facility was lack of collimation of the neutron beam. Only thin specimens could be radiographed with any suitable amount of resolution. Several examples of these neutron radiographs are presented.

With improved collimation of the neutron beam and use of more efficient neutron image detection methods the present facility should be capable of making more desirable neutron radiographs.

CHAPTER I

INTRODUCTION

The Problem

Neutron radiography, in the last few years, has emerged from being considered a potentially valuable supplement for x-ray and gamma ray radiographic techniques to one which has shown definite usefulness in many inspection problems.

Unfortunately almost all previous neutron radiography has been done utilizing a nuclear reactor as a neutron source. Reactors are very intense sources of neutrons and can easily produce a useful neutron beam. The reactor's high cost, large size, and lack of mobility made it impractical for most inspection problems. This has limited the use of neutron radiography to a few laboratories which have nuclear reactors available.

In A Summary Report on Neutron Radiography, Berger states, "The problem of obtaining useful radiographic neutron beams from neutron sources other than nuclear reactors is the key to broadening the usefulness of neutron radiography."[1] In addition to nuclear reactors, accelerator and radioactive sources of neutrons are available. The neutron outputs of these sources are several orders of magnitude lower than from a reactor. It should be possible, however, to utilize some of the more

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[1] Harold Berger, A Summary Report on Neutron Radiography, ANL-6846, (A.E.C. Research and Development Report, Argonne National Laboratory, Argonne, Ill., July, 1964), p. 22.

intense accelerator and radioactive sources for neutron radiography. These sources have the advantages of much lower cost and small size in comparison to a reactor; they are also relatively easy to move and install.

This investigation was conducted to show the usefulness of a Cockcroft-Walton type accelerator as a source for neutron radiography. A workable system was devised for making neutron radiographs using the existing facilities and equipment of the Louisiana State University Nuclear Science Center.

Neutron Absorption

The absorption of neutrons in a material, follows an exponential absorption law similar to that for x-rays and gamma rays.

For x-rays and gamma rays the absorption equation is commonly written as:

$$I = I_0 \, e^{-(\frac{\mu}{\rho})\rho x} \tag{1-1}$$

in which,

I_0 = initial intensity of x-rays or gamma rays.

I = intensity of radiation transmitted through the absorber.

ρ = density of the absorber (gm/cm^3).

x = thickness of the absorber (cm).

μ = linear absorption coefficient (cm^{-1}).

μ/ρ = mass absorption coefficient (cm^2/gm).

For the absorption of neutrons the equation usually is given in the form,

$$I = I_o \, e^{-N\sigma x} \qquad (1-2)$$

in which,

I_o = initial intensity of neutron beam.

I = intensity of neutron beam transmitted through the absorber.

N = number of atoms in the absorber (atoms/cm^3).

x = thickness of absorber (cm).

σ = total atomic cross section of absorber (cm^2, 1 barn = $10^{-24} cm^2$).

This equation can also be rewitten in the form of Equation 1-1,

$$I = I_o \, e^{-(\frac{\mu}{\rho})\rho x} \qquad (1-3)$$

in this case $\mu = N\sigma$.

The similarities in absorption behavior of neutrons and x-rays, shown in Equations 1-1 and 1-3 suggest that neutrons could be used for radiographic inspection work in the same manner as x-rays. This concept was first investigated by Kallman.[2] In recent years several other investigators have shown that neutron radiography is a useful inspection technique.[3]

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[2]H. Kallman, "Neutron Radiography," Research, 1:254-260, March, 1948.

[3]See Chapter II for history of neutron radiography.

The absorption of neutrons in a material, as given in Equation 1-2, is dependent on the cross section (σ) of the material. The neutron cross section is a measure of the probability of interaction of a neutron with the nucleus of an atom. It is a specific property of a nucleus for a particular reaction with an incident neutron of a given energy. Although the units are cm^2, the cross section is not a geometrical cross sectional area of the nucleus.

The total absorption of neutrons is a result of the combination of two processes. First, there is true absorption, or capture, in which a neutron enters the nucleus followed by emission of particles or gamma rays. Second is scattering, in which a neutron interacts with a nucleus and transfers some, or all, of its energy to the nucleus, but the neutron remains free after the process. Both processes remove neutrons from the incident neutron beam and therefore contribute to the total cross section of an atom.

Various types of absorption or scattering interactions will have an associated cross section. For instance, if a neutron is captured and gamma rays are emitted, the reaction abbreviated (n,γ), will have a definite cross section value for a neutron of given energy. Other common absorption reactions are: (n,p) neutron captured, proton emitted, and (n,α) neutron captured and alpha particle emitted. One or more of these reactions make up the absorption cross section of an atom, and, hence, its total cross section.

The variation of neutron cross sections is extremely complex. It is dependent on the energy of the incident neutron as well as the

absorber material. The cross section will also vary from one isotope to another of the same element as well as change for different types of reactions.

Before proceeding any further it is best to define some of the terms used in referring to neutron energies. Neutron energies are usually expressed in electron volts (ev).[4] Neutrons have a wave length and velocity associated with them. The relationship between wave length and energy is,

$$\lambda = \frac{0.2860}{E^{1/2}} \qquad (1-4)$$

The velocity can be found from the relationship,

$$v = 1.4 \times 10^6 \, E^{1/2} \qquad (1-5)$$

In these equations,

λ = wave length in angstroms.

E = neutron energy in electron volts.

v = neutron velocity in cm/sec.

Neutrons with energies in excess of about one million electron volts (Mev) are referred to as fast neutrons. Intermediate neutrons have energies from 1 Mev down to about 1 ev. Slow neutrons are those having energies below about 1 ev. Neutrons which are in thermal equalibrium

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[4]One electron volt is the energy acquired by a charged particle carrying a unit charge when it passes through a one volt potential difference.

with their surroundings are referred to as <u>thermal</u> <u>neutrons</u>. The average energy of a thermal neutron distribution is approximately 0.025 ev at a temperature of 72°F. The upper limit of the thermal neutron energy region, for the purpose of this investigation, will be about 0.4 ev. Neutrons having energies above thermal energies are referred to as <u>epithermal</u> <u>neutrons</u>. The relationship among these various terms is shown in Figure 1-1.

```
        Thermal  |  Epithermal
             |   |
  _____|___|_____|_____
                      1 ev               1 Mev

  0.025ev    0.4ev
                           |                  |
         Slow         |    Intermediate   |   Fast
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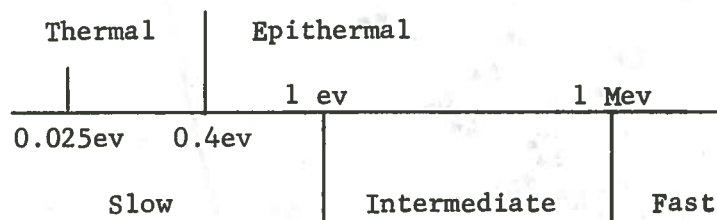
Figure 1-1. Neutron Energies

As pointed out previously, Equations 1-1 and 1-3 show the similarities in the absorption behavior of neutrons and x-rays (or gamma rays). The most important feature of neutron radiography arises from the fact that the mass absorption coefficients of the elements for neutrons are very different than that for x-rays. These differences are particularly well illustrated in Figure 1-2.[5] The total mass absorption coefficients of the elements for 0.05ev neutrons and 130 Kev

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[5]Data for Figure 1-2 from, J. Thewlis, "Neutron Radiography," <u>Progress</u> <u>in</u> <u>Nondestructive</u> <u>Testing</u>, 1:111-126, (Heywood and Co., Ltd., London, 1958).
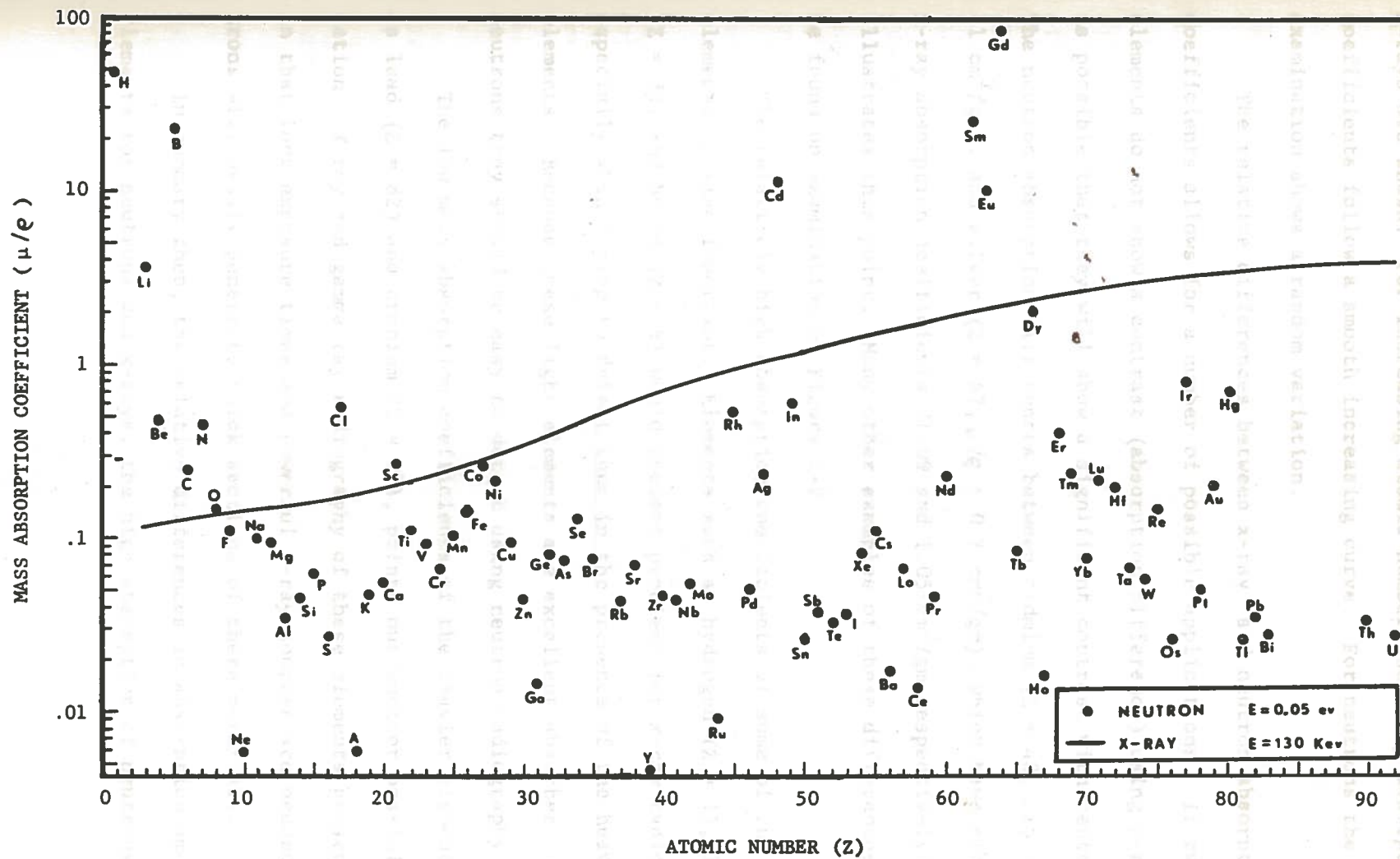
Figure 1-2. Mass Absorption Coefficients of the Elements for Neutrons and X-rays.

x-rays are shown. For increasing atomic number the x-ray absorption coefficients follow a smooth increasing curve. For neutrons the same examination shows a random variation.

The relative differences between x-ray and neutron absorption coefficients allows for a number of possible applications. If two elements do not show a contrast (absorption difference) using x-rays it is possible that they will show a significant contrast with neutrons. The neutron absorption differences between cadmium ($Z = 48$, $\mu/\varrho = $ 11 cm^2/gm), and silver ($Z = 47$, $\mu/\varrho = 0.2$ cm^2/gm), which have similar x-ray absorption coefficients (1.09 and 1.05 cm^2/gm respectively), illustrates this point. Many other examples of these differences can be found on examination of Figure 1-2.

The relatively high absorption coefficients of some of the light elements is also important. Elements such as hydrogen ($Z = 1$), lithium ($Z = 3$), and boron ($Z = 5$) would present problems for x-ray radiography especially when trying to detect them in the presence of the heavier elements. Because these light elements are excellent absorbers of neutrons they should be easy to detect using neutron radiography.

The low mass absorption coefficients of the heavier elements, such as lead ($Z = 82$) and uranium ($Z = 92$), points out another possible application. X-ray and gamma ray radiography of these elements present problems in that long exposure times and powerful x-ray sources are needed. Neutrons will easily penetrate thick sections of these materials.

In summary then, the relative differences in absorption among the elements for neutrons and x-rays, the high absorption of neutrons of some

light elements, and the low absorption of many heavy elements offer
useful areas of application for neutron radiography.

Thermal Neutron Beam

The neutron source available for this investigation produces an
approximately isotropic yield of 14 Mev neutrons. It is possible to
obtain a beam of neutrons from 14 Mev down to thermal energies by use
of a suitable moderator and experimental arrangement. The neutron
energy which is most useful for radiography must therefore be determined.
The three most important considerations for selecting a suitable neutron
energy are, (1) differential absorption of neutrons in the object being
inspected, (2) efficiency of detection of the neutrons and, (3) ease of
producing a beam of the desired energy. Generally, a thermal neutron
beam best satisfies these considerations.

The large neutron absorption differences among the elements exist
primarily for neutrons in the thermal energy region. As neutron energies
increase, through the intermediate energy region, the absorption differ-
ences generally decrease. In the fast neutron energy range the total
cross section of the elements is low, and there is little variation from
element to element.[6]

For many elements, the absorption differences which make thermal
neutrons useful, continue into the low epithermal energy region. The

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[6]Donald Hughes, et al., Neutron Cross Sections, BNL-325, (2nd. ed.,
July, 1958; supp. No. 1, January, 1960; and supp. No. 2, May, 1964, Brook-
haven National Laboratory, Upton, New York).

epithermal region from 0.1 ev to 1000 ev is referred to as the reso-
nance energy region. This region is characterized by peaks where
neutron absorption cross sections rise sharply to very high values,
for a specific energy, and then fall again. Some elements, such as
cadmium, will only have one peak. Other materials, such as indium,
silver and gold, will have more than one resonance peak. Cadmium has
a resonance peak for neutrons of 0.18 ev energy. The main resonance
peak of indium is for neutrons of 1.44 ev energy; there are also lower
peaks at neutron energies of 4 ev and 10 ev.[7]

For certain applications of neutron radiography resonance neutron
absorption might be useful. If there is not a great contrast in
absorption between an object and its surroundings in the thermal energy
range, then it may be possible to find a large absorption difference by
going to the resonance energy of either the object or its surroundings.
The chief drawback to the use of resonance neutrons is that to take full
advantage of the discrimination available, an essentially monochromatic
neutron beam should be used. It would be very unlikely that a mono-
chromatic beam of sufficient intensity could be extracted from a small
accelerator source. The available neutrons would first have to be
slowed down to the resonance energy region with a suitable moderator.
Next, some device for obtaining a monochromatic neutron beam, such as a
crystal, would have to be used to select neutrons of the desired reso-
nance peak. The loss of neutron intensity of such an arrangement would
be quite high.

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[7] Ibid.

Another problem involved with resonance neutrons is that of detection. After the neutrons have been differentially absorbed in the inspection object some method of converting them to a photographically detectable radiation must be found. A material which has a large cross section for some useful reaction at the selected resonance energy must be available. An examination of neutron cross sections in BNL-325 will show that it is not always possible to find such a reaction.[8]

In comparison to a resonance energy neutron beam, a thermal neutron beam will be much easier to produce and detect. To obtain a beam with neutrons in the thermal energy region, it should only be necessary to slow down the fast neutrons with a moderator several inches thick. While several orders of magnitude of neutron flux will be lost by this process the remaining thermal neutron intensity should be sufficient for radiography.[9] Materials which have useful reactions for detecting neutrons, generally, have very large cross sections in the thermal energy range.

Because of the large differences in neutron absorption, the efficiency of detection and, the ease of production, a thermal neutron beam is, generally, the most useful for radiography.

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[8] Ibid.

[9] Berger, _A Summary Report on Neutron Radiography_, ANL-6846, _op. cit._, p. 21.

CHAPTER II

REVIEW OF RELATED RESEARCH

History

1935-1960. Successful neutron radiographs were made about thirty

years ago by Kallman.[1] The pioneering work of Kallman established many

of the basic factors which have since been the primary concern of investi-

gations of neutron radiography. The source of neutrons for his investi-

gation utilized ion bombardment of a suitable target to produce fast

neutrons. The fast neutrons were moderated to obtain a thermal neutron

beam. The detector which Kallman found most useful was a photographic

film sandwiched between two fluorescent layers. The fluorescent layers

were coated with boron or lithium. Boron or lithium when bombarded by

neutrons will emit alpha particles. The alpha particles in turn cause

light emission from the fluorescent layers. The light emission produces

the film darkening. Kallman also investigated the use of several other

converter materials. He mentioned, specifically, cadmium which produces

film darkening from capture gamma rays and gadolinium, silver and indium,

which cause film darkening from the emission of beta particles.

One of the most important problems that Kallman pointed out was

the film blackening effect of gamma radiation which is almost always

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[1] H. Kallman, "Neutron Radiography," Research, 1:254-260, March,
1948.

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present in the incident neutron beam. The advantages of neutron radiography result from the fact that the absorption of neutrons is different from that of gamma rays. Any image produced by gamma rays would tend to mask the desired neutron image. Kallman pointed out that neutron pictures which were free of this distrubing gamma radiation could be obtained by irradiating, in the neutron beam, foils which become radioactive. The radioactive image carrying foil would then be moved out of the neutron beam and placed in contact with a photographic film. The decay radiation, primarily beta particles from materials such as indium and silver, would expose the film. This technique has been termed the transfer method by other investigators. The direct exposure method is used to describe the technique in which both the film and converter material are placed together in the neutron beam.

Kallman made neutron and x-ray radiographs of several small test objects to show the contrast difference which could be obtained. The objects included cadmium, lead and boron sheets one millimeter thick; an iron screw in a paraffin block and a coin. With his best experimental setup, and using the direct exposure method, Kallman was able to obtain radiographs with exposures of about four hours.

Peter extended the work of Kallman employing a neutron source of much higher intensity.[2] He was able to obtain neutron radiographs with one to three minute exposures. Peter's detection method was x-ray film

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[2] O. Peter, "Neutron-Durchleuchtung," Naturforsh, 1:557-559, 1946, reviewed by Harold Berger, "Neutron Radiography," Symposium on Physics and Nondestructive Testing, pp. 12-37, ANL-6346, (A.E.C. Research and Development Report, Argonne National Laboratory, Argonne, Ill., October, 1960).

sandwiched between 0.004 inch thick silver foils and backed by a 0.020 inch thick cadmium foil. Peter also obtained radiographs utilizing the transfer method with silver foils. The objects which he radiographed included a pressure gauge; a small valve, a test tube filled with heavy water (D_2O), and a test tube filled with natural water.[3]

In the late 1950's Thewlis published the results of an investigation of neutron radiography which had been conducted at the Atomic Energy Research Establishment, Harwell, England.[4] The BEPO nuclear reactor was used as a source of thermal neutrons. The detection method used most by Thewlis was indium foils and x-ray film. The foil and film were exposed together to the neutron beam; they were then removed from the beam and the radioactive foil was allowed to decay in contact with the film. This combined use of the direct and transfer method helped to improve the neutron image. The radiographs published by Thewlis were of comparable resolution quality to many gamma ray radiographs.

Thewlis also attempted to illustrate some of the possible applications of neutron radiography. Among the applications which he pointed out were, inspection of neutron shielding materials, heavy metals and biological studies. The high neutron cross section of hydrogen is what makes biological studies attractive. The biggest advantages, however, would be in the inspection of objects made of materials which are not

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[3] Kallman, loc. cit.

[4] J. Thewlis, "Neutron Radiography," Progress in Nondestructive Testing, 1:111-126, (Heywood and Co., Ltd., London, 1958).

able to be inspected by other methods. A neutron radiograph of a piece
of waxed string in a two-inch lead block was used by Thewlis to illus-
trate this point.

1960-1965. Since 1960 many reports on neutron radiography have
been published by various investigators. A review of the research
closely related to the present study is given in this section.[5]

The most extensive amount of reported work has been conducted by
Berger at the Argonne National Laboratory. A summary of the major
portion of this work was given in 1964.[6] The Argonne CP-5 and Jugger-
naut reactors were used as sources of thermal neutrons. The investi-
gation was primarily concerned with the photographic detection of
thermal neutron images. The detection methods investigated included
the use of loaded (boron or lithium) film emulsions and normal x-ray
films, both alone and in conjunction with various converter materials.
The converter material technique was found to be best. Exposures
could be made in the shortest times and very good resolution capabili-
ties were obtained. A thorough evaluation of many direct and transfer
method converter materials was carried out. The characteristics of
many of these converter material and x-ray film combinations were re-
ported. The relative speeds, optimum thickness, resolution properties,

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[5] A more complete list of articles and publications can be found
by referring to the Selected Bibliography.

[6] Harold Berger, A Summary Report on Neutron Radiography, ANL-6846,
(A.E.C. Research and Development Report, Argonne National Laboratory,
Argonne, Ill., July, 1964).

radiographic contrast capabilities, and relative neutron-gamma ray response were evaluated.

The detection methods which Berger found most useful are as follows.[7] For the direct exposure technique, the use of a single gadolinium (0.001 inch thick) metal back foil and the use of a rhodium (0.010 inch) front foil with a gadolinium (0.002 inch) back foil.[8] The single gadolinium foil method was used because of its excellent resolution. The double foil technique yielded almost as good resolution results as the single gadolinium foil along with improved speed. For the transfer exposure method, indium foils 0.010 inch thick were used extensively because of its availability and reasonable cost. Indium was not as fast as dysprosium, nor did it give as good resolution as did gold foils, but it did give useful results for the majority of inspection problems.

Berger has recently reported the successful use of a vacuum tube type image detector.[9] While this detector has shown great promise it is still quite new. It is also relatively complex and expensive in comparison to photographic detection methods.

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[7]Ibid., pp. 14, 18.

[8]A front foil refers to a foil placed between the neutron source and x-ray film. A back foil is placed on the side of the film which faces away from the neutron source.

[9]Harold Berger, Wilfrid F. Niklas, and Adolph Schmidt, "An Operational Thermal Neutron Image Intensifier," J. Appl. Phys., 36:2093-2094, June, 1965, and Berger, On the Possibilities for Thermal Neutron Image Intensification, ANL-6917, (A.E.C. Research and Development Report, Argonne National Laboratory, Argonne, Ill., November, 1964).

Throughout the extensive series of reports and articles which were published as a result of the Argonne National Laboratory investigations, many uses of neutron radiography were illustrated. Discussions are also presented indicating other useful applications that might be found.[10] The entire study clearly demonstrated that neutron radiography is applicable to a wide variety of inspection problems.

In 1962, Watts published a report summarizing the neutron radiographic work which had been conducted at the Armour Research Foundation.[11] For his neutron source, Watts utilized a thermal neutron beam produced by the Armour Research Reactor. The investigation covered several methods of neutron detection. The use of several converter material - x-ray film combinations were studied. Watts also evaluated the use of a multi-wire spark counter and an array of semiconductor particle detectors. Neither of the methods proved as useful as the converter-film combinations.

The study evaluated the effects on the final image quality of the neutron image detector resolution, the neutron scattering in the inspection object, and the effective source, or focal spot, size of the neutron beam. All of these effects were illustrated in the report.

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[10]A summary of some of these applications are present in the Applications section of this chapter.

[11]H. V. Watts, Research on Neutron Interactions in Matter as Related to Image Formation, ARF-1164-27, (Division of Isotope Development, U. S. Atomic Energy Commission, Armour Research Foundation of Illinois Institute of Technology, Chicago, Ill., August, 1962).

Several examples of practical neutron radiographic applications were presented as well as a comprehensive list of other areas of possible use.[12]

Schultz and Leavitt have published the results of neutron radiographic inspection work with thick sections of uranium and lead.[13] Thermal neutron beams obtained from nuclear reactors were used as the neutron source. Because of the very high gamma ray content of the neutron beams the transfer method was used. Indium foils (0.015 inch thick) were evaluated in conjunction with several types of x-ray films. It was pointed out in these studies that the maximum thickness of uranium capable of being examined with two million volt x-rays is about two and three-quarter inches. These investigations showed that two to four inches of uranium and two to six inches of lead could be inspected with good results using a thermal neutron beam.

All of the research reviewed thus far has been concerned with the utilization of thermal neutrons for radiography. As mentioned previously, thermal neutrons are the most practical for general radiographic applications. At this point, though, some mention should be made of the investigations which have utilized fast neutrons.

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[12]This list is presented in the Applications section of this chapter.

[13]Arnold W. Schultz, and William Z. Leavitt, The Feasibility of Using Neutron Radiography as a Nondestructive Testing Technique, WAL TR 142/67, (Watertown Arsenal Laboratories, Watertown, Mass., December, 1961); and Schultz and Leavitt, The Neutron Radiography of Uranium and Lead, (U. S. Army Materials Research Agency. Presented at, American Society for Metals/Materials Congress and Exposition, Philadelphia, Penn., October, 1964).

In 1961, Criscuolo and Polansky reported the results of a study of fast neutron radiography.[14] The neutron source was a 400 Kv positive ion accelerator which produced 14 Mev neutrons. The report was primarily concerned with utilizing these neutrons for the inspection of thick sections of material. Best results were obtained by using x-ray film and fluorescent screens at a target to film distance of two feet. With this detection method it was possible to resolve an 0-ring through two inches of lead, although the resolution was poor.

Another study on the use of fast neutron radiography was reported by Tochilin.[15] Fast neutrons of different energies were obtained using the University of California 60-inch cyclotron. Tochilin found that the best film responses were obtained with organic phosphor materials in contact with x-ray film. Test samples of lead, aluminum, copper and plastic were radiographed. The study showed that the use of fast neutrons did not produce discriminating capabilities among these different materials. This indicated that applications would be limited to inspection of large thickness of homogenous materials.

Tochilin pointed out that most of the results he found were rather disappointing. He concluded that, "Because of these limitations one is forced to conclude that fast neutron radiography, with currently available

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[14] E. L. Criscuolo and Daniel Polansky, "Fast Neutron Radiography," Missiles and Rockets Symposium, Concord, Calif., 1961, pp. 112-115, (Bureau of Naval Weapons, U. S. Naval Ammunition Depot, Concord, Calif.).

[15] E. Tochilin, Photographic Detection of Fast Neutrons: Application to Neutron Radiography, USNRDL-TR-766, (U.S. Naval Radiological Defense Laboratory, San Francisco, Calif., July, 1964).

photographic detection techniques, offers no improvement over conventional radiographic methods. It further appears that there is no physical basis for expecting to find unique radiographic conditions where the supplemental use of fast neutrons could in any way improve existing techniques."[16]

Applications of Neutron Radiography

Up to the present time relatively little use has been made of neutron radiography as a practical inspection technique. The main reasons for this have been the limited availability of adequate neutron sources and the lack of information on neutron imaging techniques and processes. Of the three categories of neutron sources available, (radioactive, reactor, and accelerator) only reactors have been used with any success. As a result of these limitations only a very few facilities capable of making useful neutron radiographs have been available.

Only one inspection problem which is handled on a relatively routine basis has been described in the literature. At the Argonne National Laboratory neutron radiography is used to inspect irradiated reactor fuel specimens. The transfer method is used since the high gamma ray activity of the specimens would fog a photographic film.[17]

While no other routine use of neutron radiography has been described, many promising areas of application have been demonstrated.

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[16]Ibid., p. 13.

[17]Berger, A Summary Report on Neutron Radiography, ANL-6846, op. cit., p. 22.

A very comprehensive list of potential uses has been given by Watts.[18]
The list is as follows,

Reactor Technology

1. Inspection of control rods or plates for homogeneity, continuity, and content of poison elements.

2. Inspection of neutron shielding material for voids.

3. Location of organic residues in metal tubes or lines.

4. Inspection of thick fuel elements.

5. Study of inclusions in metals, such as hydrides or boron in zirconium.

Rocket and Missile Technology

6. Examination of large thicknesses of cast solid fuels for cracks or fissures.

7. Inspection of plastic or rubber tubing components in air frames.

8. Inspection of rubber or organic gaskets for correct position and seating in assembled metal units.

General

9. Study of thin biological specimens such as plant tissues, animal tissues, and insects, with much greater contrast.

10. Inspection of plastic materials such as electrical insulation for flaws and defects.

11. Inspection of cadmium plating for homogeniety and continuity.

12. Diffusion of materials, such as boron in silicon or germanium.

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[18] Watts, Research on Neutron Interactions in Matter as Related to Image Formation, ARF-1164-27, op. cit., p. 8.

General (continued)

13. Inspection of indium metal gaskets in pressure or vacuum systems.

14. Inspection of radioactive specimens or of items which are in a high ambient gamma ray field.

In the last few years several areas of application have been given a a comparatively detailed evaluation by various investigators. Some studies are more complete than others but all have shown promise for neutron radiography.

1. The determination of cadmium burnup in reactor control rods.[19]

2. The nondestructive testing of brazed joints.[20]

3. Crystal orientation in thin metallic specimens.[21]

4. Inspection of thick sections of materials.[22]

5. Inspection of heavy elements such as uranium and lead.[23]

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[19] Berger, J. H. Talboy, and J. P. Tylka, "Determination of Cadmium Burnup in Reactor Control Rods by Neutron Radiography," Nucl. Sci. Eng., 18:236-241, February, 1964.

[20] Akira Kanno, The Nondestructive Testing of Brazed Joints, ANL-6924, (A.E.C. Research and Development Report, Argonne National Laboratory, Argonne, Ill., November, 1964).

[21] Berger, "Visualization of Internal Structure in Metals Using Neutron Radiography," Trans. Am. Soc. Metals, 55:251-254, 1962.

[22] Berger and I. R. Kraska, "Neutron Radiographic Inspection of Heavy Metals and Hydrogenous Materials," Materials Evaluation, 22:305-309, July, 1964; and Schultz and Leavitt, The Neutron Radiography of Uranium and Lead, (U. S. Army Materials Research Agency. Presented at, American Society for Metals/Materials Congress and Exposition, Philadelphia, Penn., October, 1964).

[23] Ibid.

6. Neutron microradiography.[24]

7. Medical applications.[25]

As neutron radiography becomes more widely available, undoubtedly many new areas of application will be suggested and evaluated.

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[24]D. S. Eppelsheimer and Maynard Armet, "Neutron Microradiography of a Cadmium-Tin Alloy," Nature, 207:69-70, July 3, 1965.

[25]J. P. Barton, "Some Possibilities of Neutron Radiography," Physics in Medicine and Biology, 9:33-42, January, 1964.

CHAPTER III

IMAGE DETECTION

Converter Materials

Almost all investigations of neutron radiography have utilized a combination of a converter material and x-ray film as the image detection system. This method is the only one which has given any practical results. A converter material is used since a standard photographic film, by itself, is relatively insensitive to neutrons. The converter material changes a neutron into some more photographically effective particle or radiation, such as alpha particle, beta particle, proton, gamma ray or visable light.

In the thermal neutron energy region there are three reactions which might be useful for a converter material. These reactions involve capture of a neutron followed by either, (1) the emission of gamma radiation (n, γ), (2) the ejection of an alpha particle (n, α), or (3) the ejection of a proton (n, p).

The radiative capture reaction (n, γ) is the most common and occurs with a wide variety of materials. There are two related radiative capture processes which are of importance for neutron radiography. In the first type of reaction the nucleus captures the neutron and forms a compound nucleus in a high energy, or excited, state. The excess energy is then emitted as one or more gamma rays.

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The gamma ray emission takes place almost instantaneously upon the capture of the neutron. These are referred to as capture, or prompt, gamma rays. The compound nucleus is left in the ground state and is not radioactive. In the second type of radiative capture reaction capture gamma rays are also emitted, but the compound nucleus produced is radioactive. A radioactive nucleus undergoes spontaneous change at a definite exponential rate into another type of nucleus and at the same time emits characteristic particles. The particles emitted by the neutron enriched nucleus are generally beta particles (negatrons). The betas are often followed by the emission of gamma rays.

The important characteristics of several materials which have been used as thermal neutron converters are given in Table 3-1. Materials which cause film darkening primarily from prompt capture radiations are designated as (n,γ) reactions in this table. An example of this type of reaction is the neutron capture in cadmium-113.

$$_{48}Cd^{113} + {}_0n^1 \longrightarrow {}_{48}Cd^{114} + \gamma \tag{3-1}$$
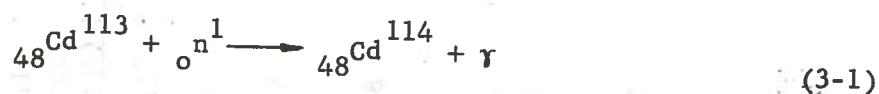
The cadmium-114 product is stable.

For materials which become radioactive after neutron capture most of the film darkening is usually caused by decay beta particles. These activation reactions are designated as (n) in Table 3-1. The activation of indium is an example of this type of reaction.
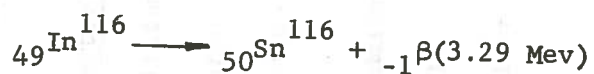
$$_{49}In^{115} + {}_0n^1 \longrightarrow {}_{49}In^{116} + \gamma \tag{3-2}$$

$$_{49}In^{116} \longrightarrow {}_{50}Sn^{116} + {}_{-1}\beta(3.29 \text{ Mev})$$

TABLE 3-1

CHARACTERISTICS OF SEVERAL NEUTRON CONVERTER MATERIALS[a]

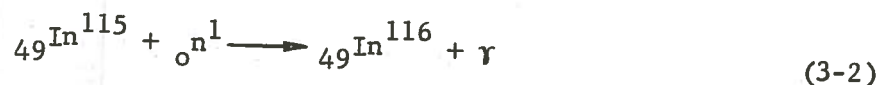| Material	Isotope Involved in Reaction	Natural Abundance (per cent)	Cross Section (Barns) [b]	Reaction and Product [c]	Half-life	Predominant Radiation (Mev) [d]
Lithium	Li-6	7.52	945	Li-6(nα)H-3	-	α+H-3=(4.78)
Boron	B-10	19.8	4017	B-10(nα)Li-7	-	α+Li-7=(2.3)
Indium	In-115	95.77	155	In-115(n)In-116m	54m	β(1.00,0.87,0.60)+γ
			52	In-115(n)In-116	13s	β(3.29)
Cadmium	Cd-113	12.26	20,000	Cd-113(n,γ)Cd-114	-	Capture Gammas
Gold	Au-197	100	96	Au-197(n)Au-198	2.7d	β(0.963)+γ
Silver	Ag-107	51.35	44	Ag-107(n)Ag-108	2.3m	β(1.77)+γ
	Ag-109	48.65	110	Ag-109(n)Ag-110	24.2s	β(2.24,2.82)+γ
			2.8	Ag-109(n)Ag-110m	253d	β(0.087,0.053)+γ
Tantalum	Ta-181	99.98	19	Ta-181(n)Ta-182	115d	β(0.51)+γ
Tungsten	W-186	28.4	34	W-186(n)W-187	24h	β(0.63,1.33)+γ
	W-182	26.4	20	W-182(n,γ)W-183	-	Capture Gammas
Titanium	Ti-48	73.95	8.3	Ti-48(n,γ)Ti-49	-	Capture Gammas
Aluminum	Al-27	100	0.21	Al-27(n)Al-28	2.27m	β(2.86)+γ
Dysprosium	Dy-164	28.18	2000	Dy-164(n)Dy-165m	1.25m	IT,Gamma
			800	Dy-164(n)Dy-165	140m	β(1.25,0.88,0.42)+γ

TABLE 3-1 (Continued)

CHARACTERISTICS OF SEVERAL NEUTRON CONVERTER MATERIALS[a]

Material	Isotope Involved in Reaction	Natural Abundance (per cent)	Cross Section (Barns)[b]	Reaction and Product[c]	Half-life	Predominant Radiation (Mev)[d]
Gadolinium	Gd-155	14.37	56,200	Gd-155(n,γ)Gd-156	-	Capture Gammas+β[e]
	Gd-157	15.68	242,000	Gd-157(n,γ)Gd-158	-	
Rhodium	Rh-103	100	12	Rh-103(n)Rh-104m	4.4m	IT,Gamma
			140	Rh-103(n)Rh-104	44s	β(2.6)+γ
Samarium	Sm-149	13.84	40,800	Sm-149(n,γ)Sm-150	-	Capture Gammas
	Sm-152	26.63	140	Sm-152(n)Sm-153	47h	β(0.69,0.80)+γ

[a] Data for this table taken from Donald J. Hughes, et al., Neutron Cross Sections, BNL-325, (2nd ed. July, 1958; supp. No. 1, January, 1960; and supp. No. 2, May, 1964; Brookhaven National Laboratory, Upton, New York); and D. Strominger; J. M. Hollander; and G. T. Seaborg, "Table of Isotopes," Reviews of Modern Physics, 30:585-904, April, 1958.

[b] Cross Sections are given for thermal neutrons (0.0253 ev). One barn = 10^{-24} cm^2

[c] Metastable excited states are indicated by the designation m. (n,γ) designation for prompt gamma ray emitters, product is a stable isotope. (n) reactions which produce radioactive isotopes.

[d] β-negative beta particle (negatron), α-alpha particle, γ-gamma radiation, IT - isomeric transition (transition from upper to lower energy of same nucleus).

[e] Internal conversion electrons accompany the prompt gamma emission from gadolinium, O. Sala; P. Apel, and M. Goldhober, "Internal Conversion Electrons Accompanying Slow Neutron Capture in Gd," Physical Review, 74:1249, 1948.

and

$$_{49}In^{115} + _{0}n^{1} \longrightarrow _{49}In^{116m} + \gamma \qquad (3-3)$$

$$_{49}In^{116m} \longrightarrow _{50}Sn^{116} + _{-1}\beta(1.00, 0.87, 0.60 \text{ Mev}) + \gamma$$
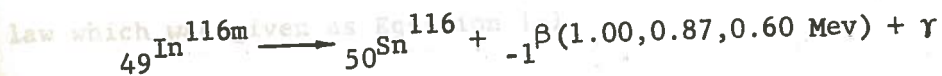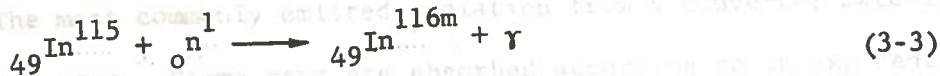
For neutrons of 0.025 ev energy the cross section for Equations 3-2 and 3-3 are 52 barns and 155 barns respectively.

The (n,α) and (n,p) reactions are relatively rare for neutrons in the thermal energy range. There are, however, two important exceptions. The (n,α) reactions of boron-10 and lithium-6 both have very large cross sections. The equations for these reactions are,
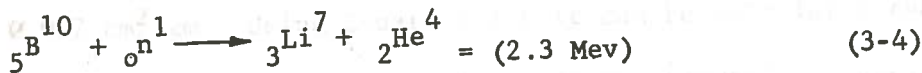
$$_{5}B^{10} + _{0}n^{1} \longrightarrow _{3}Li^{7} + _{2}He^{4} = (2.3 \text{ Mev}) \qquad (3-4)$$

and

$$_{3}Li^{6} + _{0}n^{1} \longrightarrow _{1}H^{3} + _{2}He^{4} = (4.78 \text{ Mev}) \qquad (3-5)$$
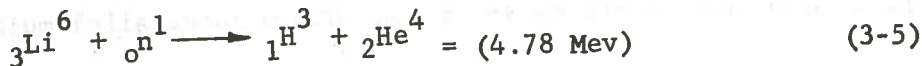
The cross sections for these reactions are, 4017 barns (Equation 3-4), and 945 barns (Equation 3-5) for neutrons of 0.025 ev energy.

To apply any of the previously described reactions it is necessary to understand some of the characteristics of the emitted radiation. In using a converter material it is first necessary to absorb the incident neutrons. This will depend on the absorption cross section of the converter. The emitted particle or radiation must then be able to reach the film. The penetrating power (or range) of the particle or radiation in the converter material will determine how much reaches the film.

The most commonly emitted radiation from a converter material are gamma rays. Gamma rays are absorbed according to an exponential law which was given as Equation 1-1.

$$I = I_o e^{-(\frac{\mu}{\rho})\rho x} \qquad (3-6)$$

If a material, such as cadmium, is used as a converter it is possible to absorb more than 99 per cent of an incident thermal neutron beam in a foil 0.020 inch thick. The predominant gamma rays emitted by thermal neutron capture in cadmium have emergies in the million electron volt range.[1] The mass absorption coefficient of cadmium for 1 Mev gamma rays is 0.057 cm^2/gm. Using Equation 3-6 it can be calculated that only about 2 per cent of gamma rays of 1 Mev will be absorbed in passing through a foil 0.020 inch thick. It is therefore reasonable to assume that cadium foils about 0.020 inch thick should be useful as neutron converters.

When trying to utilize the prompt gamma ray emission from materials such as titanium and tungsten, unreasonable foil thicknesses become necessary. For these materials the total cross is about 10 to 20 barns. It can be calculated that a foil thickness of about one-quarter inch is needed to absorb 50 per cent of a thermal neutron beam.

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[1] E. Troubetzkoy and H. Goldstein, A Compilation of Information on Gamma-Ray Spectra Resulting from Thermal-Neutron Capture, ORNL-2904, (Neutron Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tenn., January, 1961).

For materials which become radioactive a large portion of the film darkening is usually caused by beta particles, these particles are much more photographically effective than gamma rays. Beta particles are much less penetrating in the foil material and film than are gamm rays, and, therefore, will produce an image with better resolution. After a neutron interacts with a nucleus the resultant gamma rays or beta particles are emitted isotropically. Beta particles which leave at a small angle to the film will be absorbed in the foil before they reach the surface. The imaginary cone formed by the beta particles which do reach the film will have a much smaller angle than that of the cone formed by gamma rays. The resulting area which is covered by the base of the cone on the film is smaller for the beta particles than the gamma rays. The smaller area darkened by the beta particles is seen as better resolution.

The same effect described above also relates to the foil thickness. As the thickness of a foil is increased the area affected by a given cone of radiation will increase (provided the radiation can still reach the film). This indicates that foils should be kept as thin as possible to improve resolution.

Because of the advantages of having beta particles darken a film, the foil thickness which best utilizes these particles is

desired. Beta particles have been found to be absorbed approximately according to the relationship,[2]

$$R = 0.542 \ E - 0.133 \quad \text{for } E > 0.6 \text{ Mev} \tag{3-7}$$

in which,

$$R = \text{beta particle range (gm/cm}^2).$$

$$E = \text{beta particle energy (Mev)}.$$

This equation is known as Feather's Rule.

Using Equation 3-7 it is possible to make a rough estimate of the useful foil thickness of beta emitter materials such as indium, silver, gold, tantalum and tungsten. Table 3-2 shows the predominant beta energies which these materials emit. Also shown is the range of the beta particles, in mg/cm^2, and the corresponding thickness, in mils, for each material. The approximate percentage of a thermal neutron beam (0.025 ev energy) that each foil thickness will absorb is also given. The percentage of the beam absorbed is an indication of the effectiveness of each material. The materials which absorb more of the incident beam should darken a film in a shorter time.

Boron-10 and lithium-6 are two materials that have a useful cross section for an (n,α) reaction. When these converter materials are used in layer or sheet form, where it is necessary for the resultant alpha

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[2] Radiological Health Handbook (Revised ed., Division of Radiological Health, U. S. Dept. of Health, Education and Welfare, Wash., D. C., September, 1960), p. 46.

TABLE 3-2

ESTIMATED USEFUL FOIL THICKNESS FOR SOME
SELECTED CONVERTER MATERIALS
(BETA EMITTERS)

Material	Predominant Betas (Mev)	Beta Range (mg/cm^2)	Foil Thickness (mils)	Absorptions of 0.025 ev Neutrons (per cent)
Indium	0.60,0.87 1.00,3.29	0.19-1.65	10-90	17-80
Silver	1.77,2.24 2.82	0.83-1.40	30-50	25-40
Gold	0.96	0.39	8	12
Tantalum	0.50	0.15	4	1
Tungsten	0.63	0.21	4	1

particles to leave the surface, thicknesses are restricted to about 0.001

inch. The range of an alpha particle in air is given by the equation,[3]

$$R = 0.318E^{3/2} \tag{3-8}$$

in which,

R = alpha particle range in air (cm)

E = alpha particle energy (Mev)

The range of an alpha particle in boron or lithium is about 100 times

less than in air. With thickness of about 0.001 inch only a few per

cent of an incident thermal neutron beam will be converted to alpha

particles. These materials, however, have been used to great advantage

as a homogeneously mixed additive in a detector such as a scintillator.

With a scintillator light is the photographically effective radiation.

High conversion efficiencies have been obtained with reasonable thick-

nesses of these materials.

Several investigators have evaluated the usefulness of various

neutron converter materials. The work performed by Berger at the

Argonne National Laboratory is the most extensive. Table 3-3 is a

partial list of Berger's results for direct exposure converter

materials. These results are typical of those found by other investi-

gators. The numbers in parentheses in the table refer to the front and

back foil thickness, respectively in mils. This notation is used

throughout the remainder of the present investigation.

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[3]Ibid.

TABLE 3-3

RELATIVE PHOTOGRAPHIC SPEED FOR SEVERAL
DIRECT EXPOSURE NEUTRON CONVERTER
MATERIALS[a]

Converter Material and Configuration[b]	Film Type	Relative Photographic Speed[c]
Li-6 Enriched Scintillator[d]	F	50
B-10 Enriched Scintillator[e]	F	35
Rhodium(10)-Gadolinium(2)	KK	1.6
Rhodium(10-10)	KK	1.4
Gadolinium(0.5-2)	KK	1.1
Indium(20-30)	KK	1.1
Dysprosium(3-10)	KK	1.1
Cadmium(10-20)	KK	1.0
Silver (18-18)	KK	0.8
Gold(6-10)[f]	KK	0.3
Film Only - No Converter	KK	0.03

[a] Data for table from Harold Berger, "A Summary Report on Neutron Radiography," ANL-6846, (A.E.C. Research Development Report, Argonne National Laboratory, Argonne, Ill., July, 1964), p. 14.

[b] Numbers refer to front and back foil thicknesses respectively, in mils.

[c] Relative speeds were obtained by comparing film densities for similar neutron exposures for each detector. The thermal neutron intensity used was 3×10^5 n/cm^2-sec.

[d] The lithium scintillator was a 1:4 powder mixture of 96 per cent enriched Li^6F and ZnS(Ag). See S. P. Wang; C. G. Shull; and W. C. Phillips "Photography of Neutron Diffraction Patterns," Rev. Sci. Instr., 33:126-128; and Harold Berger, "Photographic Detectors for Neutron Diffraction," Rev. Sci. Instr., 33:844-846, August, 1962.

[e] The boron scintillator was the type described by, K. H. Sun; P. R. Malmberg; and F. A. Pecjak, "High Efficienty Slow Neutron Scintillation Counters," Nucleonics, 14:46-49, July, 1956.

[f] The gold foils were allowed a one half-life decay period (2.7 days) next to the film after neutron activation was completed. All other radioactive foils were allowed a three half-life decay.

The relative photographic speeds are obtained in the following manner. All converter material-film combinations are given similar neutron exposures. The densities obtained on the various films are then recorded. With the use of the characteristic curve for the film, the relative exposure corresponding to each film density can be found. The speeds of the various materials are inversely proportional to the relative exposures.[4] The characteristic curve for a film expresses the relation between exposure applied to the film and the resulting photographic density; it is a plot of the density against the logarithm of the relative exposure.[5] In Table 3-3 the cadmium foils were, arbitrarily given a speed rating of 1.0. The relative photographic speeds of the other converter materials are then obtained by comparing their relative exposures to that for cadmium.

The values of foil thickness which are given in Table 3-3 were those which were found to be optimum from the point of view of speed only. No consideration of the resolution capabilities of different thickness of these materials was taken into account. Single foil methods were also evaluated by Berger.[6] In general, the optimum single foil thickness gave a speed value of one-half that of the double foil method. Berger has pointed out that the results in Table 3-3 are strictly correct only for the particular neutron beam

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[4]Radiography in Modern Industry, (2nd. ed., Eastman Kodak Co., Rochester, New York, 1957), p. 100.

[5]Ibid., p. 42.

[6]Harold Berger, A Summary Report on Neutron Radiography, ANL-6846, (A.E.C. Research and Development Report, Argonne National Laboratory, Argonne, Ill., July, 1964), p. 14.

and exposure times used in his investigation. The results should, how-
ever, be a fairly good guide as to what speeds to expect from other
exposure conditions.

As can be seen in Table 3-3 the materials which give the fastest
results are materials which can only be used in the direct exposure
mehtod. These materials are the alpha emitters boron and lithium, the
prompt emitter gadolinium, and the activation converter rhodium. While
rhodium does become radioactive its principal product (rhodium-104) has
only a 44 second half-life. A half-life this short would be very diffi-
cult to use for the transfer method of radiography.

Although the transfer method does give a pure neutron picture
the direct exposure method has the decided advantage of much higher
speeds. For the same exposure conditions a direct method radiograph
can be completed in a much shorter time. In addition to utilizing the
fastest converter materials the direct method does not have to wait
for foil decay times after the activation is completed. Immediately
after exposure the film is ready to be processed. Also, with a
material such as indium which can be used in both the direct or trans-
fer method significant speed increases are obtained by the direct method.
This results from the film being present not only to record decay
products from the long half-life isotope (indium-116m, 54 minutes), but
also from the short lived isotope (indium-116, 13 seconds). The film
is also present to record the prompt gamma radiations which result from
neutron capture in the foil.

In practical applications of neutron radiography, a converter material and x-ray film combination will undoubtedly be the most widely used imaging technique. It is the most highly refined method and it has the advantage of leaving a permanent record of the object being inspected. X-ray film and its processing are commonly available and inexpensive.

In applying small accelerator sources to neutron radiography, the low neutron flux available will be a critical problem. The most efficient converter-film techniques will have to be utilized. The direct exposure method is, therefore, expected to be the most widely used method.

CHAPTER IV

EXPERIMENTAL

Apparatus

Neutron Generator. The neutron generator available for this
investigation was a Texas Nuclear Corporation, 150 Kv Cockcroft-Walton
type deuteron accelerator. The generator, as used in the Nuclear
Science Center, produces neutrons from the following reaction.[1]

$$_1H^2 + {_1}H^3 \longrightarrow (_2He^5) \longrightarrow {_0}n^1 + {_2}He^4 + 17.6 \text{ Mev}. \qquad (4\text{-}1)$$
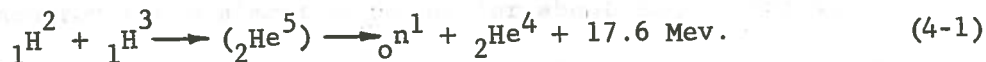
This reaction is frequently written in shorthand notation as
$T(d,n)He^4$. The neutron energy is approximately 14 Mev; the yield is
nearly isotropic.

In operation the generator accelerates deuterons $(_1H^2)$ through
a potential drop of 150 Kv. After acceleration the deuterons are
allowed to fall on a target to produce neutrons. The target consists
of tritium $(_1H^3)$ absorbed in a layer of titanium which is evaporated
onto a 0.010 inch thick copper backing. The normally used targets
contain three to five curies/inch^2 of tritium. The rated neutron
yield of the generator is 1.2×10^{11} n/sec at 1.0 milliampere of
deuteron beam current and 150 Kv bombarding voltage.

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[1]J. T. Prud'homme, Texas Nuclear Corporation Neutron Generators,
(2nd ed., Texas Nuclear Corp., Austin, Texas, 1964), pp. 3-8.

The neutron output from the $T(d,n)He^4$ reaction decreases during operation as the tritium in the target is used up. The rate of decline is approximately exponential.[2] The time required for the neutron output to drop by one-half (the target half-life) is two to three hours at 1.0 milliampere of deuteron beam current. At a beam current of 0.5 milliampere the half-life is about two times longer. Targets with concentrations of greater than three to five curies/inch[2] of tritium are available from which longer lifetimes and higher yields can be expected. Special assemblies for targets have also been described which maintain the neutron yield almost constant for about twenty hours.[3]

The main components of the generator are: an ion source, vacuum pump, accelerating tube, target assembly, high voltage power supply, and remote control console.[4] In operation all controls and settings were regulated to obtain the maximum neutron output available from the system. The maximum beam current which could be obtained during most of the experimental work was between 0.60 and 0.68 milliampere. With a fresh target, this corresponded to a maximum average output of 1.3×10^{10} n/sec.
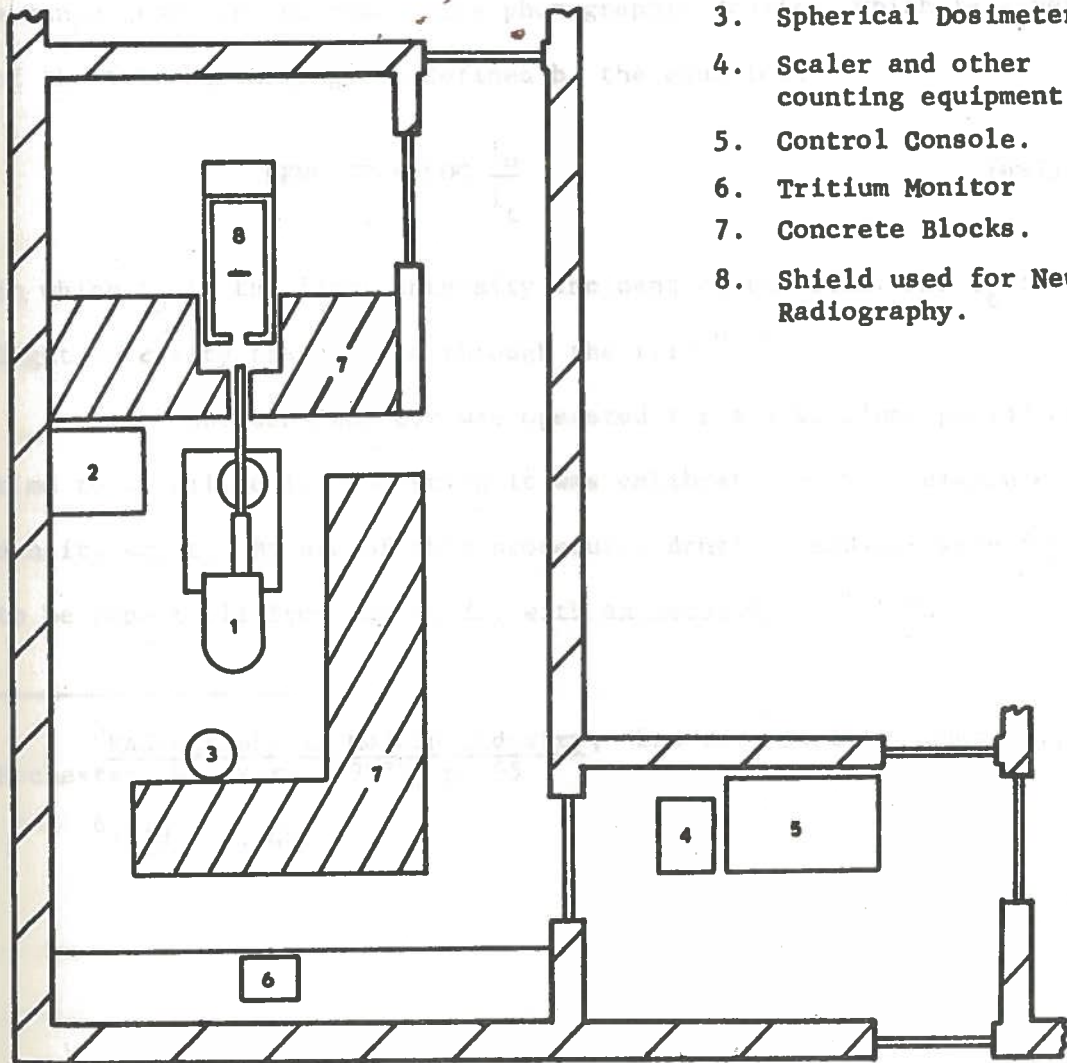
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[2] Ibid., pp. 55-56.

[3] Ibid.

[4] Ibid., pp. 13-54. No attempt will be made here to give a detail description of this equipment. A thorough description of the components, their operation and installation can be found in the reference cited.

Flux Monitor. A Radiation Instrument Development Laboratory Model 200 Scaler connected to a Texas Nuclear Corporation Spherical Dosimeter was used to monitor the production of the 14 Mev neutrons. The spherical dosimeter was located about ten feet from the target behind the generator. The scaler was located in a control panel beside the generator console. The arrangement is shown in Figure 4-1. When neutrons are being produced by the generator a constant fraction of them are automatically counted. The flux monitor was calibrated so that it was possible to calculate the average neutron output during any run. The equation is,

$$\text{OUTPUT(n/sec)} = 5.8 \times 10^6 \frac{\text{FLUX MONITOR COUNTS}}{\text{ACTIVATION TIME (SEC.)}} \qquad (4\text{-}2)$$

Film Processing. The film used throughout this investigation was Kodak Industrial X-ray Film, Type KK. Processing was done in the darkroom of the Nuclear Science Center. The darkroom is fully equipped for processing of x-ray film. The processing was as follows: the film was developed for eight minutes in Kodak Liquid X-ray Developer; placed in a circulating water stop bath for five minutes; fixed in Kodak Liquid X-ray Fixer for ten minutes; the final wash was in a second circulating water bath for twenty minutes. During all processing, developer, fixer and water temperatures were maintained at $68 \pm 1^\circ$F. When density readings among different films were to be compared, as often as was possible, these films were processed at the same time.

Eight minute developing was used to obtain maximum film density.
An eight minute developing time gives a speed increase of about twenty-five over using over time for a standard five minute development.

Neutron density readings were made on a densitometer.
Density readings were made directly on a photographic step wedge with a densitometer.

1. Neutron Generator.
2. High Voltage Power Supply.
3. Spherical Dosimeter.
4. Scaler and other counting equipment.
5. Control Console.
6. Tritium Monitor
7. Concrete Blocks.
8. Shield used for Neutron Radiography.

Figure 4-1. Neutron Generator Facility at the Louisiana State University Nuclear Science Center.

Eight minute developing was used to obtain maximum film density. An eight minute developing time gives a speed increase of about twenty-five per cent over that for a standard five minute development.[5]

Densitometer. All density readings were made on a Macbeth-Ansco Densitometer. The densitometer reads directly on a density scale with a range from zero to four. The photographic density, which is a measure of the film blackening, is defined by the equation,

$$\text{DENSITY} = \text{LOG} \frac{I_o}{I_t} \tag{4-3}$$

in which I_o is the light intensity incident on the film, and I_t is the light intensity transmitted through the film.[6]

After the densitometer was operated for a sufficient period of time to stabilize its operation it was calibrated with a reference density sheet. By use of this procedure, density readings were found to be repeatable from day to day with an accuracy of ± 0.02.

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[5] Radiography in Modern Industry, (2nd ed., Eastman Kodak Co., Rochester, New York, 1957), p. 55.

[6] Ibid., p. 40.

Moderator Thickness. In the discussion in Chapter III, a thermal
neutron beam was determined to be the most useful for neutron radiography.
The neutron generator, as used in this investigation, produces neutrons
of about 14 Mev. It is therefore necessary to use a moderator to slow
these fast neutrons down to thermal energies. Materials which make
good moderators include ordinary water, heavy water (D_2O), beryllium,
paraffin and carbon. Paraffin was selected for use in this investi-
gation because of its availability, low cost and ease of handling.

The optimum moderator thickness, for the purpose of this investi-
gation, is that which will produce the maximum number of thermal neutrons.
An experimental arrangement was designed so that it would be possible to
vary the moderator thickness and record the thermal flux produced at a
specified distance from the target. As the moderator thickness is
increased a greater portion of the initial fast neutron beam will be
reduced to thermal energies. However, as the moderator thickness is
increased beyond a certain limit the additional thermal neutrons
produced will be offset by the increased capture of neutrons in the
moderator material. It is, therefore, expected that at some moderator
thickness a maximum number of thermal neutrons will be obtained.

The neutron generator facility at the Nuclear Science Center is
normally used for activation analysis studies. The Activation Analysis
Laboratory consists of the neutron generator, a Technical Measurements
Corporation 400 channel analyzer, a pneumatic transfer system and a

control system.[7] This equipment was employed for the moderator thickness determination in the following way. Samples of aluminum powder (1.3900 grams) were loaded in polyethylene sample vials. The vials were placed in the transfer system and moved to a position six inches from the target. The generator was set for maximum neutron output and the samples were activated for two and one-half minutes. Immediately after activation the samples were transferred to a gamma ray spectrometer [NaI(Tl) crystal and 400 channel analyzer]. The decay gamma radiation was counted for four minutes. A readout of the gamma ray spectrum was then obtained. This process was repeated for various thicknesses of paraffin placed between the generator target and the aluminum sample.

Aluminum was chosen as the material to be activated because it has two very convenient neutron reactions.[8] At thermal neutron energies there is a Al-27(n,γ)Al-28 reaction with a cross section of

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[7]Robert F. Decell and Frank A. Iddings, Activation Analysis System at the Nuclear Science Center, Louisiana State University: Installation, Use, and Operating Procedures, (Nuclear Science Center, Louisiana State University, Baton Rouge, La., August, 1965).

[8]Neutron cross section and isotope decay data used in this chapter, unless otherwise noted, are from D. Strominger, J. M. Hollander, and G. T. Seaborg, "Table of Isotopes," Revs. Mod. Phys., 30:585-904, April, 1958; and Donald J. Hughes, et al., Neutron Cross Sections, BNL-325, (2nd ed., July, 1958; supp. No. 1, January, 1960, and supp. No. 2, May, 1964; Brookhaven National Laboratory, Upton, New York).

0.231 barn. The aluminum-28 product emits a 1.78 Mev decay gamma ray; the half-life is 2.3 minutes. In the fast neutron energy range aluminum undergoes a Al-27(n,p)Mg-27 reaction. The magnesium-27 product emits two gamma rays, 1.02 Mev and, 0.84 Mev; the half-life is 9.5 minutes. At 14 Mev the cross section for this reaction is 0.080 barn. A typical spectrum obtained from counting the decay gamma radiation from the aluminum sample is shown in Figure 4-2.

A survey of the literature no where indicated that the Al-27(n,γ)Al-28 reaction was limited to the thermal energy range. To be sure that the activation recorded was produced by thermal neutrons the aluminum samples were activated with and without a 0.020 inch thick cadmium cover in place. The cadmium was positioned so that it completely surrounded the aluminum sample. A 0.020 inch cadmium sheet will, for all practical purposes, absorb all thermal neutrons. The effective cadmium cutoff energy is about 0.4ev. Any activity induced with the cover in place would, therefore, be due to epithermal neutrons. It was found that about 75 per cent of the aluminum-28 activity was produced by thermal neutrons. This percentage remained approximately constant for all thicknesses of paraffin.

The results of this portion of the investigation are summarized in Figure 4-3. The 1.02 Mev and 0.84 Mev gamma ray energies, with or without the cadmium cover in place, are produced by fast neutrons as a result of the Al-27(n,p)Mg-27 reaction (curves 1 and 2). As the moderator thickness is increased the number of fast neutrons decreases.

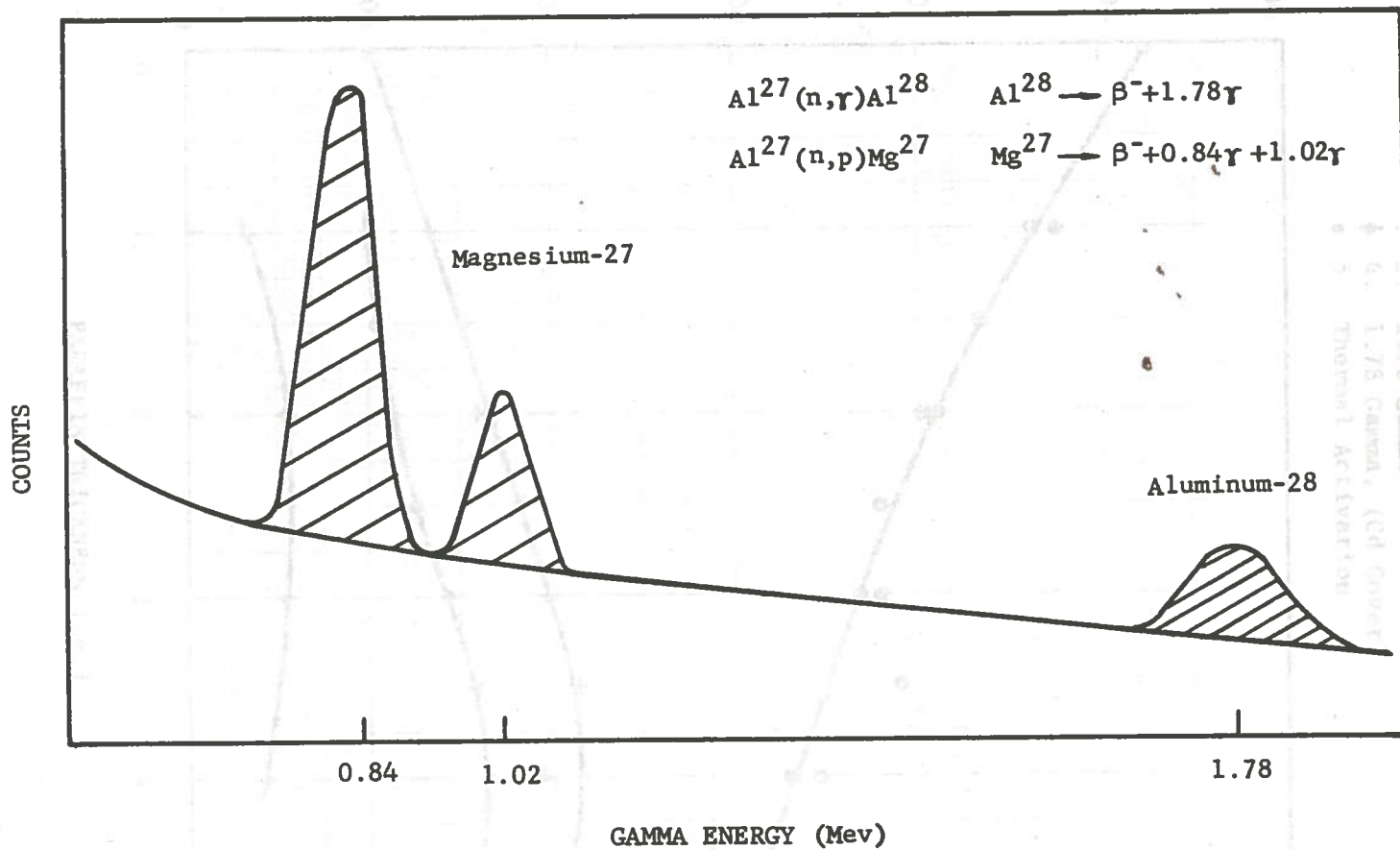Figure 4-2. Typical Gamma Ray Spectrum Obtained from Aluminum Samples.

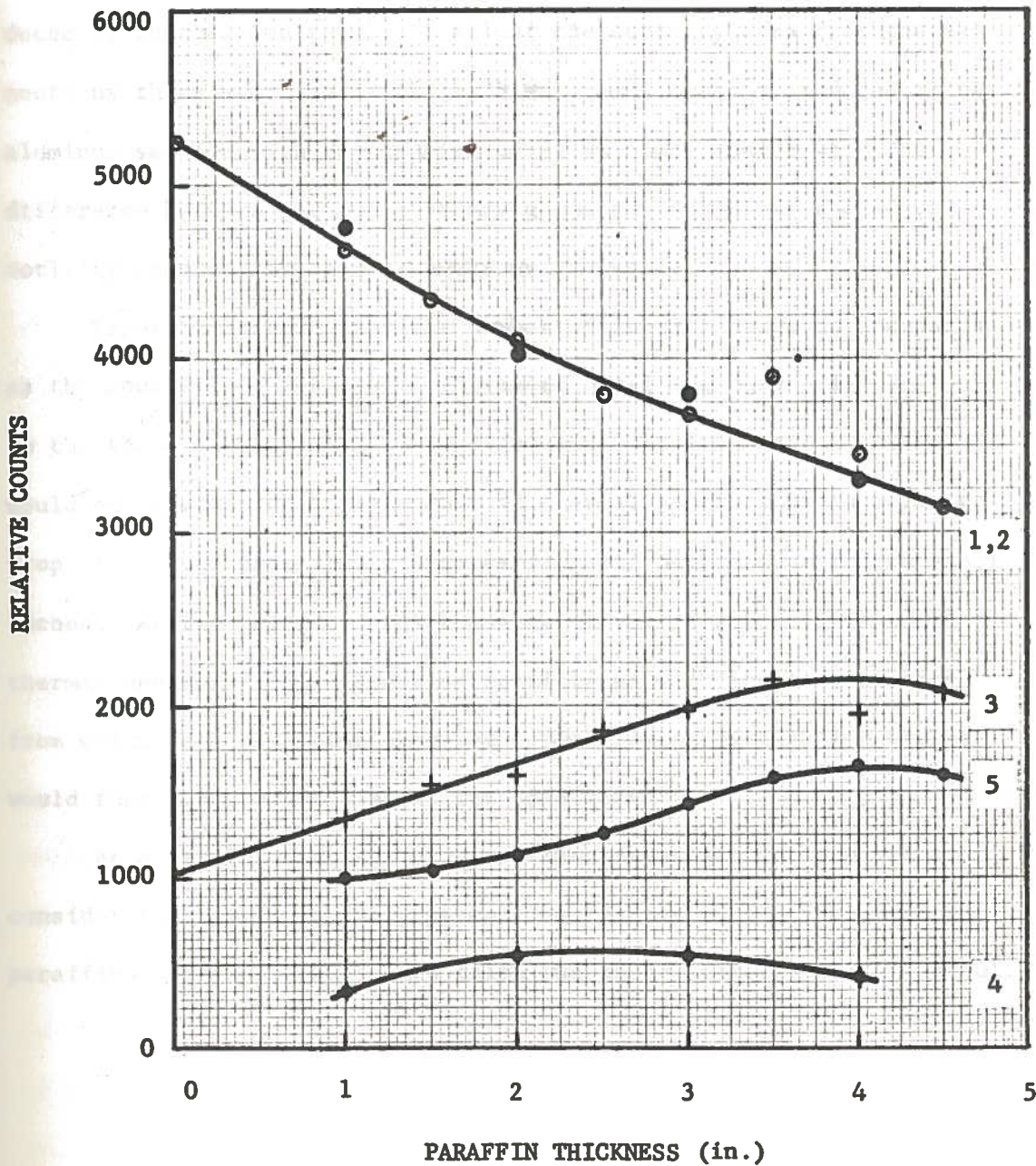| o | 1. | 1.02 + 0.84 Gamma |
•	2.	1.02 + 0.84 Gamma, (Cd Cover)
+	3.	1.78 Gamma
φ	4.	1.78 Gamma, (Cd Cover)
•	5.	Thermal Activation

Figure 4-3. Determination of Optimum Moderator Thickness.

The fast neutrons are being removed from the beam by thermalization and capture. The 1.78 Mev gamma ray energies result from the capture of neutrons in the Al-27(n,γ)Al-28 reaction. As shown by curves 3 and 4 for the 1.78 Mev gamma rays, not all of this activity is produced by thermal neutrons. If all of the activity were from thermal neutrons there would be little 1.78 Mev gamma activity induced in the aluminum samples with the cadmium cover in place (curve 4). The difference between the two 1.78 Mev gamma ray curves is the actual activity produced by thermal neutrons (curve 5).

Figure 4-3 shows that the number of thermal neutrons increases as the moderator thickness is increased until the curve flattens out in the three and one-half to four and one-half inch region. It would be expected that the number of thermal neutrons would begin to drop off if the experiments were carried out beyond four and one-half inches. As the moderator thickness is increased beyond this point the thermal neutrons should reach an equilibrium with the fast neutrons from which they are being produced. Both fast and thermal neutrons would then tend to decrease at the same rate.

As a result of this portion of the investigation, and with consideration given to the physical limitations of the work area, a paraffin moderator four inches thick was determined to be most useful.

Experimental Configuration. After the optimum moderator thickness was determined, it was necessary to obtain a suitable arrangement for making neutron radiographs. In order to compare various setups, trial radiographs were made. A test pattern was devised so that the resolution quality and gamma ray content of the neutron beam could be evaluated for each setup.

The test pattern consisted of two cadmium and two lead test pieces as shown in Figure 4-4. The cadmium test pieces were 1 inch x 1-1/2 inches and 0.10 inch thick. The lead test pieces had the same overall dimensions but were 0.20 inch thick. Each object had various size holes drilled through it; the hole dimensions are given in Figure 4-4. Cadmium is an excellent absorber of thermal neutrons and a relatively poor absorber of x-rays or gamma rays. The cadmium cross section for thermal neutrons is about 2,450 barns; the linear absorption coefficient for 150 Kv x-rays is 4.77 cm^{-1}. Lead on the other hand is a poor absorber of neutrons and an excellent absorber of x-rays. Lead has a total cross section for thermal neutrons of only 11 barns; the linear absorption coefficient for 150 Kv x-rays is 21.8 cm^{-1}. These materials should show very clearly if the radiographic images obtained are caused by gamma rays or thermal neutrons.

Kodak type KK x-ray film sandwiched between two 0.010 inch thick indium foils was used as the image detecting method during this part of the investigation. The KK film was selected for its high speed. Indium foils were used because of indium's high thermal cross section
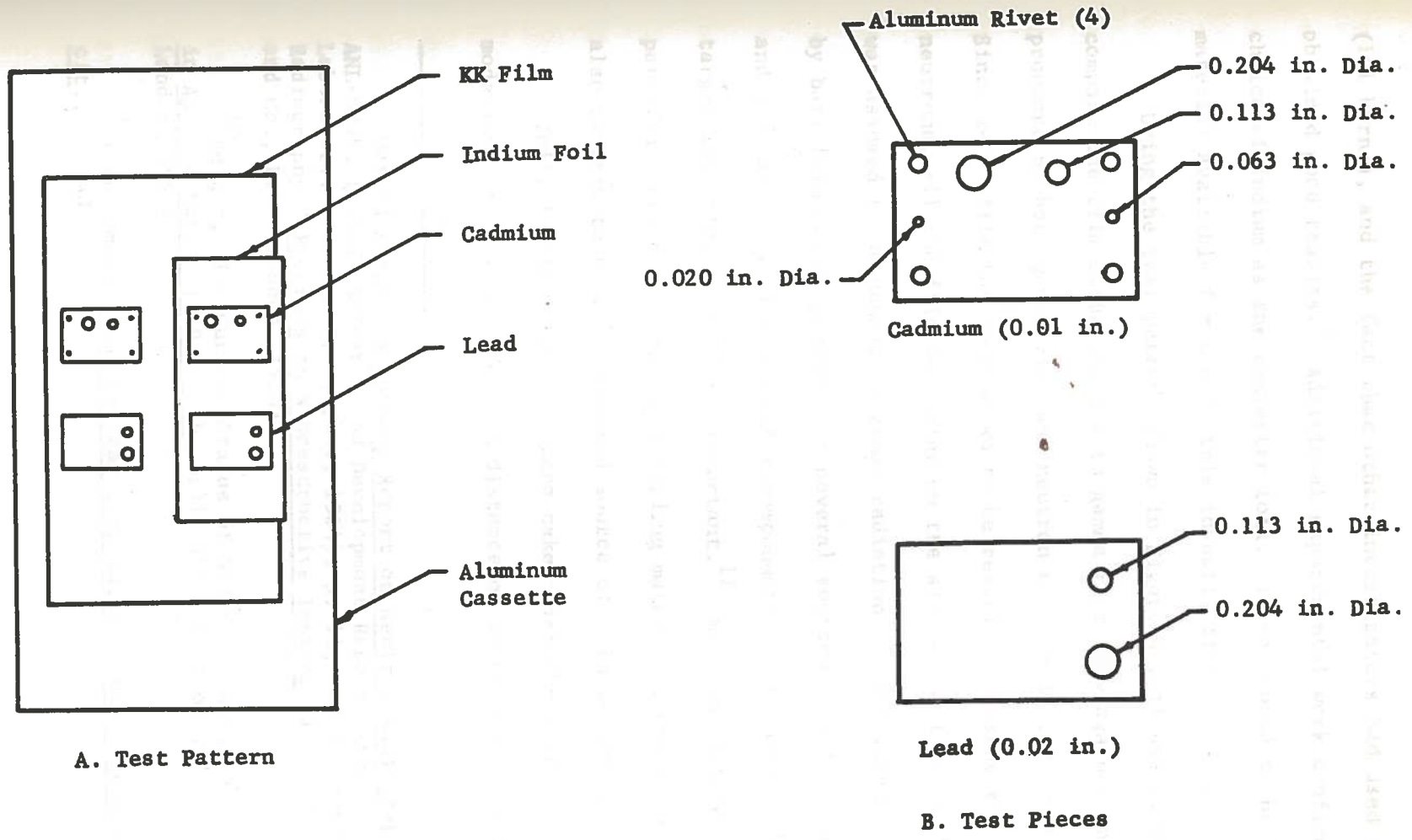
A. Test Pattern

KK Film
Indium Foil
Cadmium
Lead
Aluminum Cassette

Aluminum Rivet (4)
0.204 in. Dia.
0.113 in. Dia.
0.063 in. Dia.
0.020 in. Dia.

Cadmium (0.01 in.)

0.113 in. Dia.
0.204 in. Dia.

Lead (0.02 in.)

B. Test Pieces

Figure 4-4. Test Pattern; Lead and Cadmium Test Pieces.

(191 barns), and the fact that other investigators had used them and obtained good results.[9] Additional experimental work confirmed the choice of indium as the converter foil. It was found to be the best material available for use in this investigation.

Using the test pattern shown in Figure 4-3 it was possible to compare the film darkening due to gamma rays only against that produced by both gamma rays and neutron capture in the indium foil. Since x-ray film has been shown to be relatively insensitive to neutrons, all the film darkening on the side without the indium foils was assumed to be caused by gamma radiation.[10] The gamma rays detected by bare film can originate from several sources. Neutron capture in, and activation of, the generator components, particularly the aluminum target assembly, is the most important.[11] Neutron capture in the paraffin moderator, concrete shielding materials, and cassette will also contribute to this unwanted source of film darkening.

Initial trial exposures were taken with the four inch paraffin moderator and a target to film distance of seven and one-half inches,

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[9]Harold Berger, A Summary Report on Neutron Radiography, ANL-6846, (A.E.C. Research and Development Report, Argonne National Laboratory, Argonne, Ill., July, 1964), p. 14; and J. Thewlis, "Neutron Radiography," Progress in Nondestructive Testing, 1:111-126 (Heywood and Co., Ltd., London, 1958).

[10]Berger, "The Current Status of Neutron Radiograph," Progress in Applied Materials Research, 4:115-148, (Heywood and Co., Ltd., London, 1962).

[11]Prud'homme, Texas Nuclear Corporation Neutron Generators, op. cit., p. 143.

No shielding of any kind was provided. As would be expected, resolution was very poor, and film darkening due to gamma radiation was extremely high. Both lead test objects produced comparable images. The cadmium test pieces produced no more contrast than did the lead objects.

To reduce the amount of gamma radiation lead was placed between the target and the moderator. This position of the lead did not appreciably reduce the film darkening due to gamma rays. The two inch thick lead block was next placed between the moderator and the cassette. This placement reduced the amount of film darkening due to gamma radiation considerably. This indicated that a large amount of the gamma rays were orginating in the paraffin moderator and the surrounding concrete neutron shielding material. With the lead in the second position gamma rays were estimated to be responsible for 25 per cent of the film exposure. The resolution was still very poor. Only the largest holes (0.204 inch and 0.113 inch diameter) could be distinguished in the cadium test piece.

The poor resolution could be expected not only because of the small target to film distance, (thermal neutrons are essentially coming from the entire face of the paraffin moderator which is 5 inches x 5 inches, with a target to film distance of seven and one-half inches a beam with virtually no collimation is produced) but also from neutron scattering by the concrete shielding material and the walls of the generator room. Wigginton using the same facilities in his investigation of the transfer method of neutron radiography encountered the

same problem.[12] As a result of further investigation, he found that backscatter at the imaging plane was 30 per cent of the primary neutron beam. Sidescatter was found to be about 35 per cent of the direct flux. In order to eliminate this problem Wigginton built a scatter shield. The shield consisted of a rectangular plywood box 22 inches x 22 inches x 38 inches long. A two inch thick layer of a mixture of boric acid and paraffin lined the inside. Approximately 235 pounds of paraffin and 20 pounds of boric acid were used. An inner box 17 inches x 17 inches x 36 inches long was completely lined with a sheet of cadmium 0.020 inch thick. The rear face of the shield was hinged for access to the inner box as shown in Figure 4-5A. The front face of the shield had a 4 inch x 4 inch opening for the neutron beam to be admitted (Figure 4-5B). This shield reduced backscatter to 1 per cent and the sidescatter to 15 per cent of the direct neutron beam. The shield was mounted on casters so that it could be moved into position in front of the generator target. This neutron shield was used in all further parts of the present investigation.

The additional materials in the scatter shield could be expected to be a source of gamma radiation in addition to those previously mentioned. Paraffin and cadmium will emit gamma rays upon neutron capture. In order to reduce the film darkening from all sources of gamma radiation the inner box was lined with lead bricks. The bricks
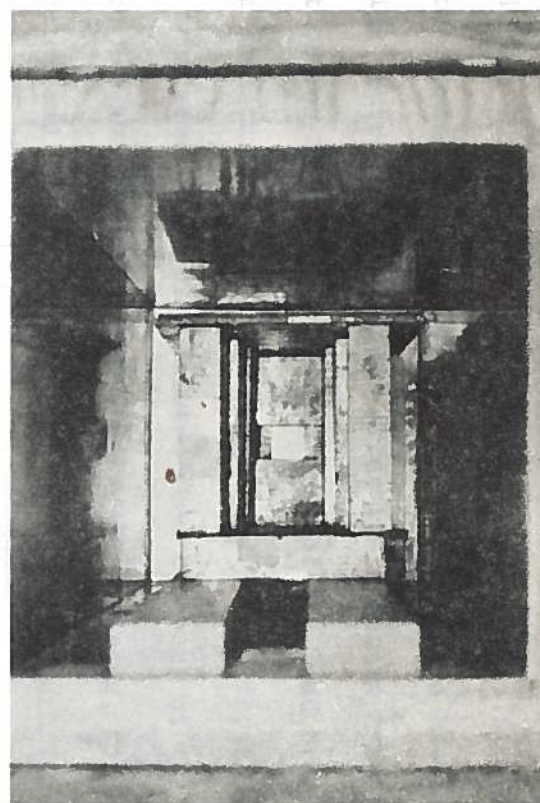
[12]David Wigginton, Neutron Radiography - Investigation of Experimental Parameters, (Masters Thesis, Louisiana State University, Baton Rouge, La., August, 1964), p. 39.
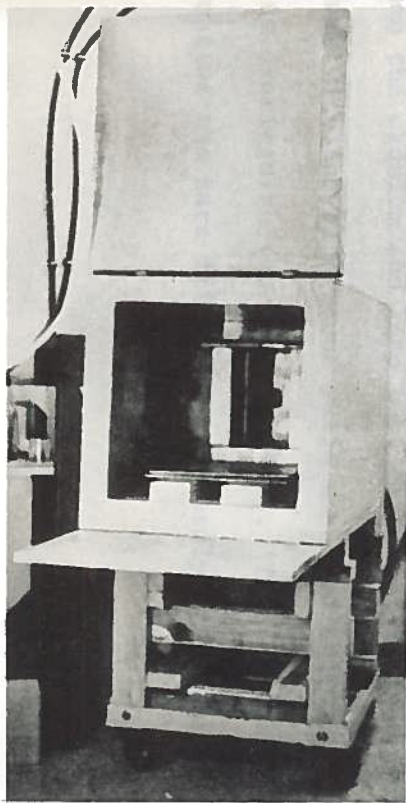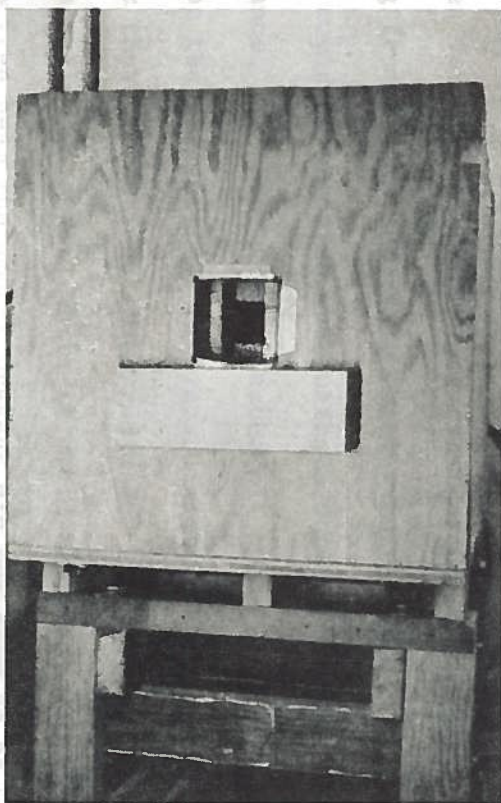
A. Rear of Shield   B. Front of Shield   C. Lead Lining

Figure 4-5. Neutron Shield and Lead Lining.

were 2 inches x 4 inches x 8 inches. Figure 4-5A shows the lead lining
in place. Figure 4-5C shows a close-up of the lining with a 2 inch x
2 inch opening in the front. It is through this opening that the
imaging neutron beam passes. After the cassette has been placed in
position for an exposure (at the rear of the lead bricks) two three-
eight inch thick lead plates are placed behind it; this protects the
film from gamma radiation emitted from the back of the scatter shield.
Figure 4-6 shows the scatter shield, lead lining, four inch paraffin
moderator and cassette in position for an exposure (see also Figure 4-1).

   To try to improve the resolution of the radiographs, target to
film distances of twelve inches, twenty-seven inches and thirty-nine
inches were tried. There was considerable resolution improvement in
going from twelve inches to twenty-seven inches. No noticeable improve-
ment could be observed when using a thirty-nine inch target to film
distance. At twenty-seven inches all holes in the cadmium test piece,
except the smallest, (0.020 inch diameter) could be distinguished.
Under these conditions gamma radiation was responsible for 32 per cent
of the film exposure. While it would be preferable to have a virtually
gamma free beam the amount present did not seem to be objectionable. The
distinguishing differential absorption of neutrons was clearly observable
between the cadmium and lead test objects. The cadmium test piece showed
contrast with the background while the lead object was much more diffi-
cult to distinguish (see Figure 4-18). The cadmium and lead test pieces
in front of the bare film produced hardly any image.

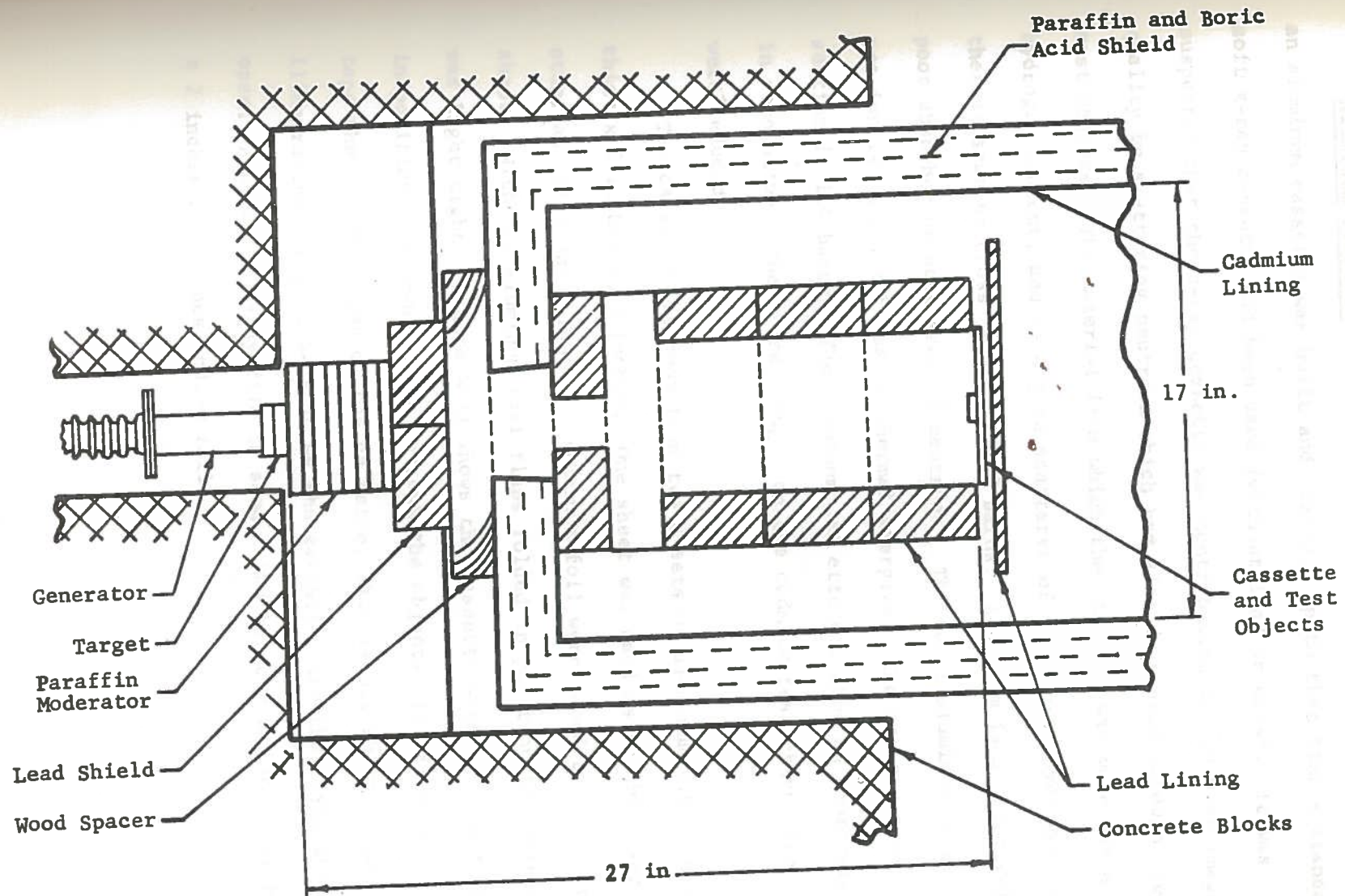Figure 4-6. Experimental Setup for Making Neutron Radiographs.

Paraffin and Boric Acid Shield

Cadmium Lining

17 in.

Cassette and Test Objects

Lead Lining

Concrete Blocks

Generator

Target

Paraffin Moderator

Lead Shield

Wood Spacer

27 in.

Aluminum Cassette. At a very early point in the experimental work an aluminum cassette was built and tested. Up to that time a standard soft x-ray cassette had been used (without lead screens). It was suspected that the x-ray cassette was contributing to the poor image quality by scattering neutrons which had already passed through the test objects. The material from which the cassette was made has a high hydrogen content, and is a good scatterer of neutrons. Hydrogen has a thermal scatter cross section of 38 barns. Aluminum is a relatively poor absorber or scatterer of neutrons. The total aluminum cross section is only 1.8 barns at thermal energies. The scatter cross section is 1.4 barns. The aluminum cassette did show an improvement in resolution. The "fuzzy" edges on the cadmium test object features were reduced.

The cassette was made from two sheets of aluminum 0.015 inch thick x 6 inches x 12 inches. One sheet was used as the back and the other as the front. Flaps of aluminum foil were taped to the front sheet. With the aluminum foil flaps folded in position the cassette was light tight. Figure 4-7A shows the cassette with some test objects in position. In order to radiograph the objects, it was necessary to tape them to the front of the cassette, this is not shown in the illustration. Figure 4-7B shows the cassette with the flaps and back open. A piece of x-ray film is sandwiched between two 0.010 inch thick x 2 inches x 5 inches indium foils.
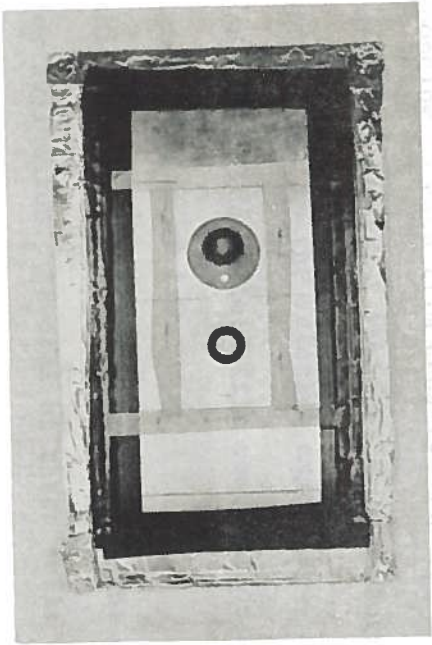
A. Cassette with Test Objects
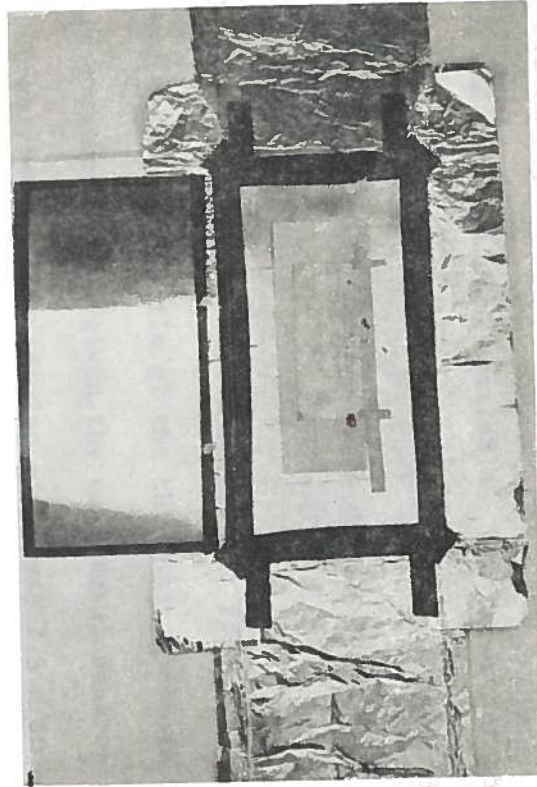
B. Back of Cassette.

Figure 4-7. Aluminum Cassette.

Evaluation of Several Converter Materials.

After a suitable exposure setup and cassette had been developed it was possible to evaluate several converter materials. Foils of indium, cadmium, gold, silver, tantalum, tungsten, dysprosium(5.24%)-aluminum, and titanium were available. The important thermal neutron properties of these materials have been given in Table 3-1. The relative photographic speed, and an indication of the resolution properties of each foil was obtained.

In order to evaluate the photographic speed, KK film was sandwiched between two foils of the thickness shown in Table 4-1. Each foil-film combination was given the same total neutron exposure. The total neutron yield at the imaging plane was 7.5×10^7 n/cm^2. Exposure times were between eleven and eighteen minutes. All foils were allowed to decay in contact with the film for a period of two hours after the neutron exposure was completed.

The results of this evaluation are given in Table 4-1. The relative speeds were obtained by comparing film densities. The relative exposure, corresponding to each film density, was obtained from the characteristic curve for the film. The relative photographic speeds are inversely proportional to the relative exposures. All speed values have been compared to the indium foil-film combination which was arbitrarily assigned a value of 1.0.

The foil thicknesses listed in Table 4-1 are the only ones which were available for evaluation. Several of these foils were below the thicknesses which were estimated to be optimum (Chapter III). These

TABLE 4-1

EXPERIMENTAL DETERMINATION OF RELATIVE PHOTOGRAPHIC
SPEED FOR SEVERAL DIRECT EXPOSURE
CONVERTER MATERIALS

Converter Material[a]	Activation Time (Min.)	Relative Photographic Speed[b]
Indium (10-10), 185	18	1.00
Silver (5-5), 133	11	.83
Cadmium (20-20), 440	13	.66
Tungsten (5-5), 245	13	.55
Tantalum (5-5), 210	18	.51
Gold (2-2), 96	13	.51
Dysprosium (5.24%) -Aluminum (5-5), 34	11	.43
Titanium (10-10), 118	13	.42
KK Film Only	13	.42

[a] Numbers in the parenthesis refer to the front and back foil thickness, respectively, in mils. The front foil is the foil closest to the neutron source. The third number is the thickness density in mg/cm^2, for a single foil.

[b] The relative photographic speed was obtained by comparing film densities for the same total neutron exposure. The relative flux was 875,000 counts on the flux monitor. This is estimated to correspond to a total neutron yield of 7.5×10^7 n/cm^2 at the imaging plane. The cadmium ratio of the beam was 1.50. All speed values have been compared to the (10-10) indium combination which was assigned a value of 1.0. Exposures were made with KK film in the direct exposure method. All foils were allowed to decay two hours in contact with the film after activation was completed.

include the high neutron absorbers gold, silver and indium. The indium

foils are at the lower range of the estimated useful thickness (0.010

inch to 0.090 inch). It could, therefore, be expected that thicker foils

of silver, gold and indium would give increased speeds. This point was

confirmed in a later investigation of indium foils.

Longer decay times for materials which utilize a long half-life

decay product, such as gold (2.7 days), could be expected to increase

its relative speed. Most of the film darkening, however, in the direct

exposure method comes from prompt gamma radiation and short half-life

activities. Increases in speed of only 10 to 20 per cent could be

expected for longer decay times of these materials.[13]

Titanium and dysprosium(5.24%)-aluminum foils would probably not

show any significant results no matter what thickness or decay times

were used. These materials have no important thermal neutron reaction

cross section and showed no intensification effect in this experiment.

A pure dysprosium foil, however, would be expected to give good results.

Dysprosium has a total thermal neutron cross section of 950 barns.

The results obtained in Table 4-1 are strictly valid only for the

neutron beam and exposure conditions used. Neutron beams with different

ratios of thermal to fast neutrons and different gamma ray contents

could be expected to yield different results. The relative speeds,

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[13] Berger, "Neutron Radiography," Symposium on Physics and Non-
destructive Testing, pp. 12-37, ANL-6346, (A.E.C. Research and Develop-
ment Report, Argonne National Laboratory, Argonne, Ill., October, 1960).

though, should be a fairly good indication of what to expect from setups with similar conditions.

To obtain an indication of the resolution quality of the various materials each foil-film combination was exposed with the cadmium test piece in place. Only the indium, silver and cadmium foils produced enough film darkening so that the test piece could be observed. For these three foils indium gave the best results; silver was next and cadmium was the poorest. The observations to determine resolution were admittedly very rough. The only effort made was to see what holes could be distinguished on the test piece. If the same holes could be observed the relative clarity of the feature was evaluated. For the indium foil all but the smallest (0.020 inch diamter) hole could be observed. For the gold foil these same holes could be observed but the 0.063 inch diameter hole was not easy to distinguish. For the cadmium foil only the two largest holes (0.113 inch and 0.204 inch diameter) could be seen.

The relative resolution properties of these foils are approximately as would be expected. The resolution should be related to the foil thickness and the hardness of the radiation causing the photographic effect. A material such as cadmium, which emits gamma rays of from several electron volts up to about 9 Mev, from the Cd-113(n,γ)-Cd-114 reaction, would be expected to produce a less sharp image than a beta emitter such as indium or gold.

While the foils did follow the expected trends the wide variation from foil to foil was not expected. Berger in his study of the

resolution properties of various converter materials found that indium

and silver, in the direct exposure method, gave similar results.[14]

While his cadmium foils did give poorer results the difference between

indium and cadmium is not as great as was found in this investigation.

Two factors, in addition to the quality of the photographically

effective radiation, help to explain the wide variations in resolution

found in this investigation. The resolution capabilities of the foils

are in the same order as the relative photographic speeds. For the

slower foil materials a greater portion of the image will be produced

by the highly penetrating gamma radiation in the neutron beam. This

would tend to produce a less sharp image for these materials.

The second factor contributing to variation in resolution

capabilities is the stiffness of the various foils. It was found in

a later investigation of indium foils that the soft, relatively

flexible, aluminum cassette could not provide good foil film contact.

This condition will cause a "fuzzy" image and poor resolution. The

same effect is observed in x-ray radiography when the intensifying

screens are not in good contact with the film.[15] The 0.020 inch

cadmium foils are very rigid and would present a considerable

problem in this respect. Silver foils were the next most rigid, and

indium was the softest. The very flexible indium foils would have a

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[14] Berger, "Resolution Study of Photographic Thermal Neutron Image Detectors," J. Appl. Phys., 34:914-918, April, 1963.

[15] Radiography in Modern Industry, op. cit., p. 24.

relatively easy time in conforming to the contours of the film and cassette. On this basis the order of resolution capability should again be indium, silver and cadmium.

It is felt that the combination of all three factors, (1) hardness of the radiation emitted by the foil, (2) relative contribution to the exposure by gamma rays in the imaging neutron beam and (3) the ability to maintain good foil-film contact, helped to contribute to the large variation in resolution capabilities among the various materials.

This portion of investigation showed indium foils to be the most useful converter material available. Indium had a much greater speed than any of the other materials and its resolution capabilities were the best.

Indium Converter Foils

Speed and Resolution. Since indium foils were found to be the most useful converter material a further investigation of its characteristics was undertaken. In the initial theoretical discussion it was estimated that indium foils in the 0.010 inch to 0.090 inch thickness range might be useful. Four 0.010 inch thick indium foils were available. These foils were stacked in various front and back foil combinations around the film to see if any speed increases could be obtained.

The results of this evaluation are summarized in Figure 4-8. All foil-film combinations were activated by the same total number of neutrons. The total flux monitor reading was 700,000 counts. This corresponds to a total estimated neutron yield of 6.1×10^7 n/cm^2 at the imaging plane.
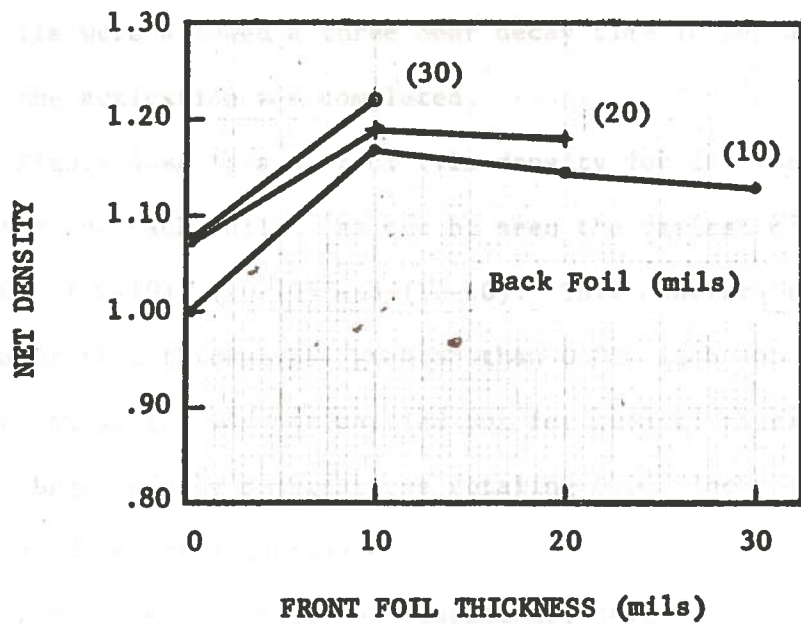
A. Combinations of Front and Back Foils
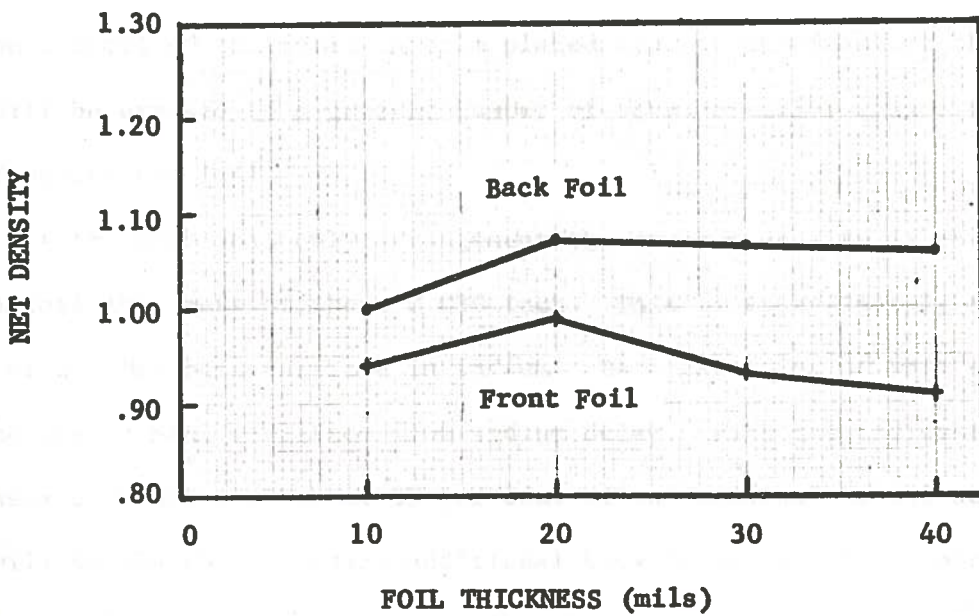
B. Front or Back Foil Only

Figure 4-8. Determination of Optimum Indium Foil Arrangement.

Exposure time varied from four and one-half to five and one-half minutes. The foils were allowed a three hour decay time in contact with the film after the activation was completed.

Figure 4-8A is a plot of film density for the various combinations of front and back foils. As can be seen the fastest combinations are (30-10), (20-10), (20-20) and (10-10). This confirms the previous estimates that thicknesses greater than 0.010 inch should improve speed. The investigation was not carried out for greater thicknesses than those shown, because only combinations totaling 0.040 inch could be obtained with the four foils available.

For the single foil configurations, (Figure 4-8B) back foils gave the best results. This is as expected since a greater portion of the neutron beam is absorbed in the front surface (the surface facing the neutron source) of the foil. A film placed against the front of the foil will be exposed to a greater number of beta particles than a film placed behind the foil.

For the back foil only arrangement the maximum density is obtained with a foil thickness of about 0.020 inch. This is approximately the range of a 1 Mev beta particle in indium. Beta particles of this energy are the predominant radiation from indium decay. With the indium foil thickness of 0.020 inch about 35 per cent of an incident thermal neutron beam will be absorbed. Adding additional back foils, to absorb more of the neutron beam, does not increase the photographic effectiveness (Figure 4-8B). The beta particles produced in the added foils are absorbed before they can reach the film.

For a front foil only, the maximum density is also obtained at a thickness of 0.020 inch. Adding more front foils decreases the density. The beta particles generated in the additional foils do not reach the film. The extra foils act as a neutron shield; they absorb a large portion of the neutron beam and do not allow the highest possible activation of the more effective foils close to the film.

The overall trends of this part of the investigation are similar to those which Berger has obtained.[16] Berger found the optimum indium foil-film combination was (20-30).[17] In the case of the front or back foil only arrangement there is disagreement. Berger found the best results using front foils.[18] Why his results should be different from those obtained in this investigation (Figure 4-8B) is not apparent. As discussed previously, it seems that back foils should give the best film density. Further investigation of this point was not conducted since it was not of primary importance for this study.

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[16]Berger, and W. J. McGonnagle, Progress Report on Neutron Radiography, ANL-6279, (A.E.C. Research and Development Report, Argonne National Laboratory, Argonne, Ill., February, 1962), p. 17.

[17]Berger used foils which were homogeneous, i.e. he did not stack foils to obtain a desired thickness, a single foil of the required thickness was used. See Table 3-3.

[18]Berger, "Neutron Radiography: A Second Progress Report," Second Symposium on Physics and Nondestructive Testing, ANL-6515, (A.E.C. Research and Development Report, Argonne National Laboratory, Argonne, Ill., October, 1961), p. 36.

Resolution properties of the various indium foil-film combinations were evaluated in a manner similar to that described in the last section. A 0.060 inch thick cadmium test piece with 0.063 inch and 0.111 inch diameter holes was used in this case. It was found that there were significant differences in the resolution capabilities of the various arrangements. Table 4-2 is a summary of the results of this evaluation. The resolution capabilities vary over a wide range, from fair (both holes visible), to extremely poor (no holes visible). Here, as in the evaluation of resolution capabilities of the indium, silver and cadmium foils, the faster arrangements tend to give better resolution. The large variation though is felt to be primarily caused by the cassette. As noted previously the cassette was made from 0.015 inch thick aluminum sheets which were very flexible. There was no means for providing positive contact among the various stacked foils and between the foils and the film. This condition will cause poor resolution.

From the evaluation the (10-10) indium foil combination was determined to be the most useful. Its speed was not significantly lower than the faster foil-film combinations, and its resolution capabilities were among the best obtained. Another advantage of the (10-10) arrangement is that there is only one front and one back foil. This reduces problems involved with thicker combinations where good contact must be maintained between the layers of foils, as well as the foil and film. The possibility for inconsistancies in resolution, from one radiograph to the next, is lessened.

TABLE 4-2

RESOLUTION CAPABILITY OF VARIOUS INDIUM
FOIL ARRANGEMENTS

Rating[a]	Foil Combination[b]	Rating	Foil Combination
1	(20-10)	3	(0-10)
1	(20-20)	3	(10-0)
1	(10-30)	4	(30-0)
1	(10-10)	4	(0-30)
2	(10-20)	4	(30-10)
2	(0-20)	4	(0-40)
		5	(20-0)
		5	(40-0)

[a]The test object was 0.060 inch thick cadmium with two holes (0.111 inch and 0.063 inch diameter) drilled through. All combinations were subject to the same total neutron exposure (700,000 counts on the flux monitor or about 6.1×10^7 n/cm^2 at the imaging plane). Activation time varied from 4-1/2 to 5-1/2 minutes, foil decay time was three hours.

The various ratings are as follows: 1, both holes in the test piece could be observed; 2, both holes could be observed although the small hole was very difficult to distinguish; 3, only the large hole could be distinguished; 4, the large hole was extremely vague; and 5, no hole could be seen.

[b]The numbers refer, respectively, to the front and back foil thickness in mils. The front foil is between the film and the neutron source.

Exposure Curve. During the investigation a number of exposures were made using the (10-10) indium foil-film combination. From the film densities obtained it was possible to plot an exposure curve. This curve is shown in Figure 4-9. The exposure scale is given as the relative flux, that is, the number of counts recorded on the flux monitor. All exposures were made using the previously described experimental configuration. Important features of the exposure and processing conditions were, target to film distance of twenty-seven inches, four inch paraffin moderator (with two inch lead shield), three hour foil decay, and eight minute film development.

A plot of the exposure curve for a bare film (gamma ray exposure only) is also shown. The density readings for this curve came from the same films which were used to plot the (10-10) indium foil curve. The readings were taken on a portion of the film which was not covered by the foils.

If the density is plotted against relative exposure, instead of the logarithm of relative exposure, it is found that a linear relationship exists (Figure 4-10). The equation approximating this relationship is,

$$R = 950 (D - 0.42) \qquad (4-4)$$

in which R is the relative exposure (flux monitor reading), and D is photographic density. The linear relationship, however, cannot be assumed to exist over more than a limited range. The film type and

A. Target to Film Distance 27 in.
B. Paraffin Moderator 4 in.
C. Lead Shield 2 in.
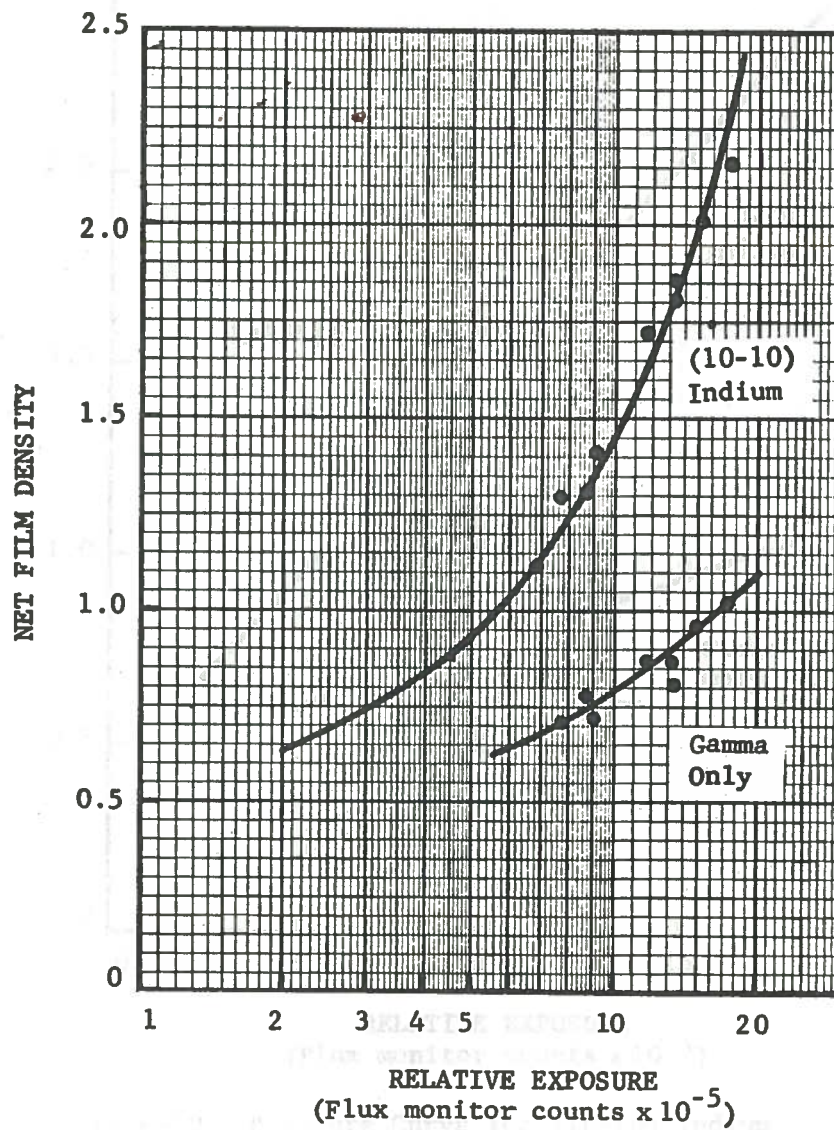D. Foil Decay 3 hrs.
E. Film Development 8 min.

Figure 4-9.   Exposure Curve for (10-10) Indium
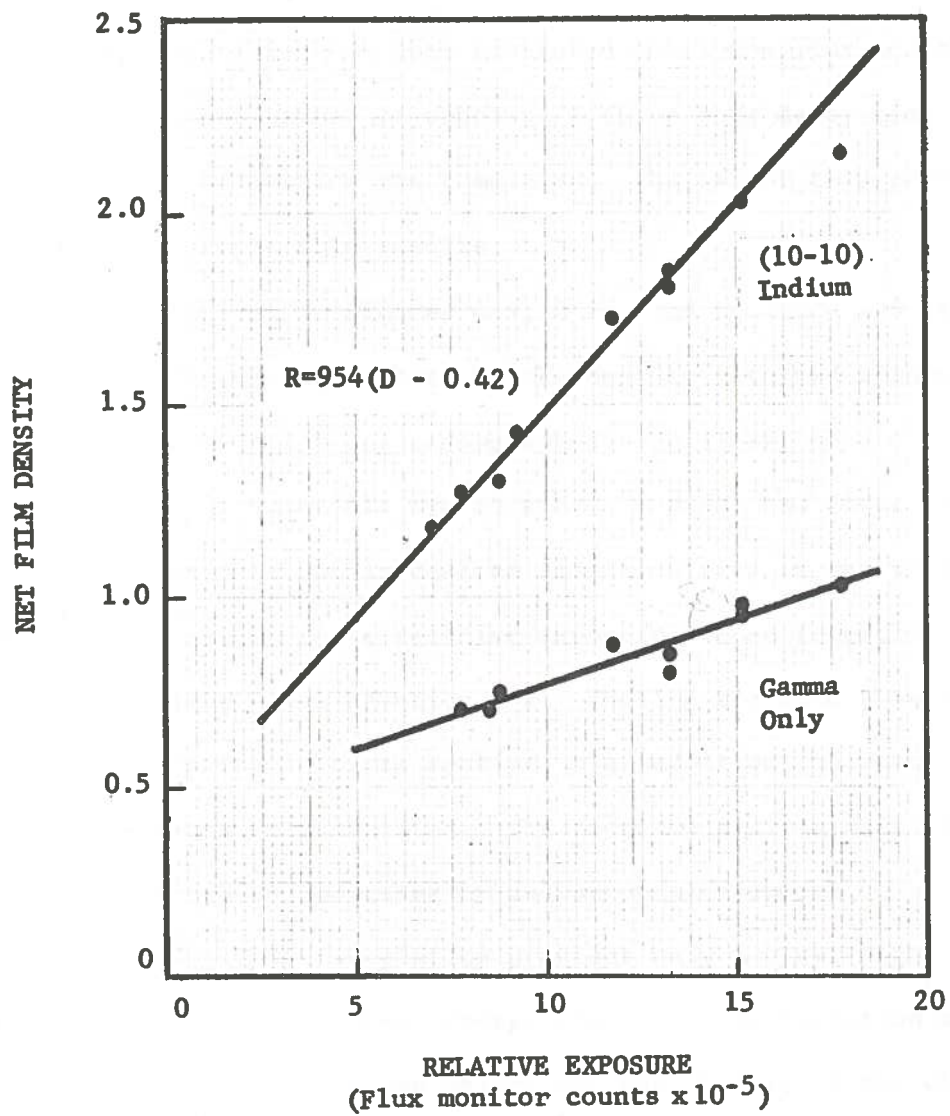Foil-KK Flim Combination.

Figure 4-10. Exposure Curve for (10-10) Indium
Foil-KK Film Combination, Linear Relation.

processing conditions will determine over what range the relationship will be valid.[19] Equation 4-4, therefore, cannot be assumed to be useful for densities greater than about 2.5.

To obtain a required density it was only necessary to calculate the required relative flux using Equation 4-4. The (10-10) indium foil, KK film combination was then activated until the flux monitor recorded the required number of counts. A three hour decay time was allowed after the activation was completed. The use of this procedure gave consistently repeatable results.

The density given in Figures 4-9, 4-10, and Equation 4-4 is the net background film density, that is the density obtained without any neutron absorbing object being radiographed. Until exposure curves for various absorbing materials are obtained, a trial and error method will have to be used to obtain desired film densities in the area of interest. An estimate of the relative exposure needed to pentrate an absorber can be made using Equation 1-2. Knowing the thickness of the object and its absorption cross section, the reduction in intensity of the neutron beam can be calculated. The relative neutron flux (R in Equation 4-4) should be increased by an appropriate amount, i.e. $R' = R/e^{-\sigma Nt}$. This calculation provides only a very rough approximation. The neutron beam energy spectrum; the variation of the neutron cross section of the object and the ability of the object to attenuate gamma rays will all influence the relation between relative exposure and the final film density.

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[19] Radiography in Modern Industry, op. cit., p. 101.

Film Darkening Due to Foil Decay. As mentioned previously, indium foils were allowed to decay in contact with the film for an additional period of time (usually three hours) after activation. This procedure was used to take advantage of the darkening from the indium-116m (54 minute half-life) decay products. This additional decay time was found to increase film density by 10 to 15 per cent. Figure 4-11 shows the increase in density as a function of decay time for one particular activation. Other activations showed similar results. The shape of the curve is exponential and exhibits a half-life of thirty minutes. It would be expected that this curve would match the decay of indium-116m. Slight variations in the net film density readings ($\pm$ 0.02) will shift the curve to a fifty-four minute half-life. The curve, therefore, is well within the limits of accuracy of the experimental work.

From the results of this evaluation it is doubtful if there is any real advantage in using the additional decay time. With a fresh target in the generator exposures of ten to fifteen minutes were needed to obtain densities of 2.0. Thus if the indium-116m decay was not utilized, an exposure increase of one or two minutes would give the same net film density. As exposure times are increased, the effect of additional decay time becomes even less important.

Film darkening due to the indium-116m decay does have one advantage. Additional density is obtained without any film darkening from the unwanted gamma rays in the neutron beam. But here again, under the exposure conditions of this investigation, the advantage was

Gamma radiation was found to be comparable for the film exposure when a three hour foil decay time was used.
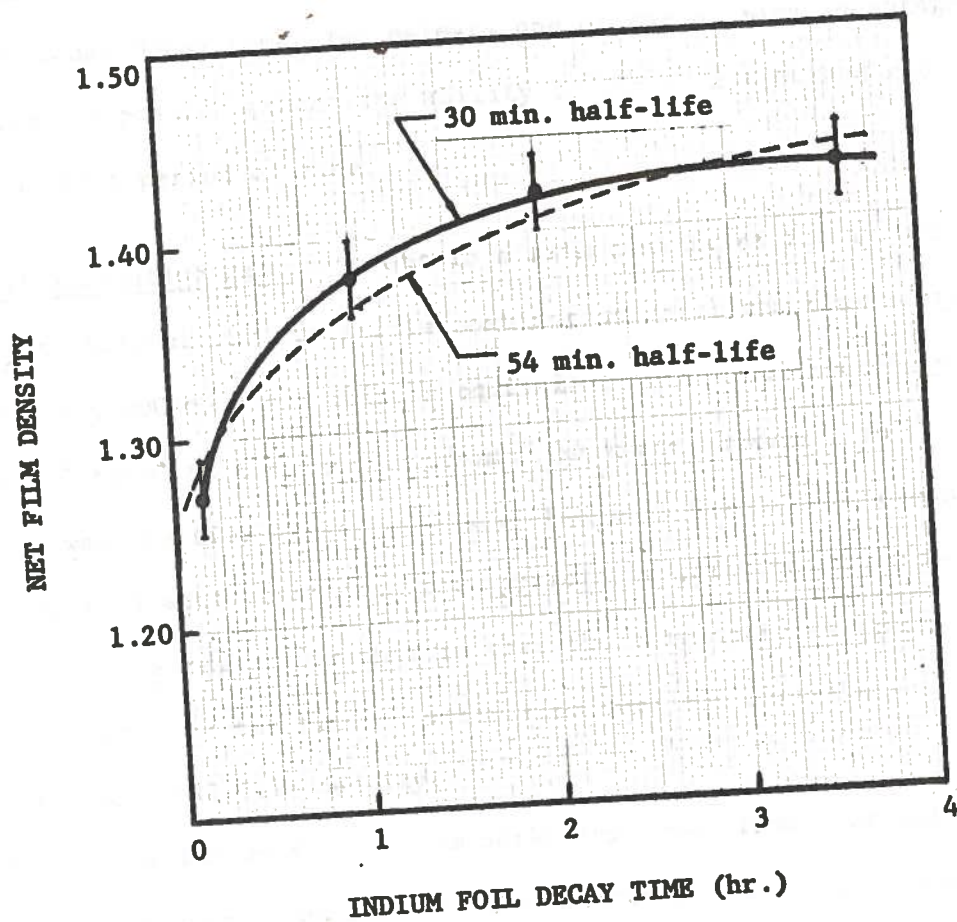

Figure 4-11. Net Film Density Increase as a Result
of (10-10) Indium Foil Decay.

not significant. Gamma radiation was found to be responsible for 32 per cent of the film exposure when a three hour foil decay time was used. If no decay time were allowed this would increase to only about 37 per cent. This difference was not important. Actual radiographs obtained with and without decay times were found comparable in contrast and resolution.

Additional decay time also defeats one of the primary advantages of the direct exposure method, the ability to obtain a finished radio-graph in a short period of time.

Foil Activation Rate. To obtain a film density of 2.0 it was necessary to activate the foil-film combination until the flux monitor recorded 1,500,000 counts. This is equivalent to a total neutron yield of 1.3×10^8 n/cm^2 at the imaging plane. No where, however, in Equation 4 was the time of activation of the foil taken into account. The rate of foil activation does not appreciably influence the final net density. The reason for this is that the only activity (indium-116m) which is effected by the time of activation does not contribute a large portion of the total film density.

When using indium foils, film darkening comes from four main sources, (1) the gamma radiation in the neutron beam, (2) the prompt gamma rays from neutron capture in the foils, (3) beta particle (2.95 Mev) from the decay of indium-116 (13 second half-life), and (4) beta particles (1.00, 0.87 and 0.60 Mev) from the decay of indium-116m (54 minute half-life). The film darkening caused by items (2) and (3), is for all practical purposes, completed within one minute after each neutron is

captured. Item (1) is assumed to be directly proportional to the total number of neutrons in the beam and hence, to the total number of neutron captures in the foil. The first three sources, therefore, are dependent only on the total neutron captures in the foil and not on time. The indium-116m isotope, with its 54 minute half-life is the only factor which is effected by activation or decay time.

The total number of atoms of indium-116m formed during a bombardment time t of the foil is given by,[20]

$$N_t = \sigma \ P \ N_n \ t \ \frac{ML}{W} \qquad\qquad (4\text{-}5)$$

The total number of neutrons per cm^2 which reach the imaging plane $(N_n t)$, is a constant for any particular film density. Therefore, for a required density, the total number of nuclei to be activated (N_t) is not dependent on the foil activation time.

The number of radioactive nuclei which are left at the end of any activation time (the total number formed (N_t) less those which have decayed) can be found from the equation,[21]

$$N = 1.44 \ \sigma \ P \ N_n \ \frac{ML}{W} \ T \ (1 - e^{-\lambda t}) \qquad\qquad (4\text{-}6)$$

The number of radioactive nuclei which exists at some time t_1 after activation has stopped (i.e. the activation time t plus a decay time t_1) is,

$$N_{t_1} = N \ e^{-\lambda t_1} \qquad\qquad (4\text{-}7)$$

---

[20] See Appendix A for definition of symbols.

[21] Ibid.

During this investigation, activation times to obtain a net density of 2.0 varied from eleven to sixty minutes. With these activation times and a three half-life decay time, the results obtained from Equations 4-5, 4-6, and 4-7 for indium-116m nuclei are given in Table 4-3.

The difference between N_{t_1} for the eleven and sixty minute activation times is 1.8×10^5 activated nuclei. This is the difference in the number of indium-116m nuclei which were used in exposing the film and corresponds to 3 per cent of the total number of these nuclei activated (N_t). This small difference does not appreciably effect the final film density. If no decay time were used the difference in the number of nuclei which helped expose the film would be 1.4×10^6. This corresponds to 22 per cent of the total number of activated indium-116m nuclei. This difference will cause a variation in the net film density of only about 2 to 3 per cent. This is well within the limits of accuracy of the film processing or flux monitoring equipment.

The rate of activation of the foils, therefore, is not an important factor in determining the final film density. This applies to the direct exposure method within the limits of this investigation. If exposure times of a few minutes were being compared to some of several hours observable differences could be expected.

It was previously stated that the amount of film darkening resulting from additional decay times becomes less important as activation times increase. This can be seen by referring to Table 4-3. For the sixty minute activation 31 per cent of the available indium-116m nuclei have decayed by the time the activation has been completed. For the

eleven minute activation only 8 per cent has decayed. Thus, when longer activation times are needed the advantages to be gained from additional less decay are decreased.

<div align="center">TABLE 4-3</div>

<div align="center">INDIUM-116m NUCLEI PER CM^2 FOR AN ACTIVATED
INDIUM FOIL (10 MILS THICK)</div>

| | Activation Time | | |
	11 Minute	60 Minute	Difference
N_t	6.2×10^6	6.2×10^6	
N	5.7×10^6	4.3×10^6	1.4×10^6
N_{t_1}	7.1×10^5	5.3×10^5	1.8×10^5

N_t, N and N_{t_1} are the number of nuclei/cm^2 which can be photographically effective. For a (10-10) indium foil arrangement this assumes that 50 per cent of the decay products from each foil reach the film. The calculations were therefore based on an equivalent 10 mil foil. The thermal neutron flux was approximately 6.5×10^4 n/cm^2-sec, and 1.2×10^4 n/cm^2-sec, respectively, for the eleven and sixty minute activations.

N_t = Total number of nuclei produced.

N = Number of nuclei which exist at the end of activation.

N_{t_1} = Number of nuclei which exist at time t_1 after activation.

The half-life for copper-62 is 9.73 minutes. The cross section of the Cu-63(n,2n)Cu-62 reaction is 0.5 barn for 14 Mev neutrons.[23]

After the gamma radiation has been counted the neutron flux can be calculated using the relation,[24]

$$N_n = \frac{N_r W}{EB\ 1.44\ \sigma\ PMLT\ (1-e^{-\lambda t})\ (e^{-\lambda t_1} - e^{-\lambda t_2})} \qquad (4\text{-}9)$$

The flux was determined to be 8.4×10^7 n/cm^2 - sec at one-half inch from the target for a generator beam current of 0.10 milliampere. This flux was correlated with a flux monitor reading of 294 counts/sec.[25] With this information it was possible to find the average neutron (14 Mev) output during any activation using the relationship,

$$OUTPUT(n/sec) = 5.8 \times 10^6\ \frac{FLUX\ MONITOR\ COUNTS}{ACTIVATION\ TIME\ (SEC.)} \qquad (4\text{-}10)$$

This was previously given as Equation 4-2.

The relationship between generator output and the neutron flux available at the imaging plane was then established. From Figure 4-3 it can be found that the total neutron flux (curve 1,2 plus curve 3) is reduced 12 per cent by the four inch paraffin moderator. Using the relationship,

$$FLUX(n/cm^2\text{-}sec) = \frac{OUTPUT(n/sec)}{4\pi r^2} \qquad (4\text{-}11)$$

---

[23] A. S. Gillespie, and W. W. Hill, "Sensitivities for Activation Analysis with 14-Mev Neutron," _Nucleonics_, 19:170-173, Nov., 1961.

[24] See Appendix A for definition of symbols.

[25] Neutron generator flux was determined by Dr. Frank A. Iddings, Nuclear Science Center, Louisiana State University, Baton Rouge, La.

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[23] A. S. Gillespie, and W. W. Hill, "Sensitivities for Activation Analysis with 14-Mev Neutron," Nucleonics, 19:170-173, Nov., 1961.

[24] See Appendix A for definition of symbols.

[25] Neutron generator flux was determined by Dr. Frank A. Iddings, Nuclear Science Center, Louisiana State University, Baton Rouge, La.

in which r is the target to film distance in centimeters, and assuming that the two inch lead shield does not absorb an appreciable amount of neutrons, the following expression can be derived for the average total flux at the imaging plane.[26]

$$\text{Total flux (n/cm}^2\text{-sec)} = 86.5 \ \frac{\text{FLUX MONITOR COUNTS}}{\text{ACTIVATION TIME (SEC.)}} \qquad (4\text{-}12)$$

The cadmium ratio of the beam was determined to be 1.50. The following relationships can therefore be written for the thermal and epithermal components of the total flux.

$$\text{Thermal flux (n/cm}^2\text{-sec)} = 28.8 \ \frac{\text{FLUX MONITOR COUNTS}}{\text{ACTIVATION TIME (SEC.)}} \qquad (4\text{-}13)$$

$$\text{Epithermal flux (n/cm}^2\text{-sec)} = 57.7 \ \frac{\text{FLUX MONITOR COUNTS}}{\text{ACTIVATION TIME (SEC.)}} \qquad (4\text{-}14)$$

To check the flux values found in these equations a second method of estimating the flux available at the imaging plane was used. Film densities which were obtained in this investigation were compared to those obtained by Watts using a thermal neutron beam of known flux. Watts found the following response for (10-10) indium foils and Kodak type AA x-ray film in the direct exposure method.[27]

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[26] The absorption cross section for lead at thermal energies is only 0.170 barn.

[27] H. V. Watts, Research on Neutron Interactions in Matter as Related to Image Formation, ARF 1164-27, (Division of Isotopes Development, U. S. Atomic Energy Commission, Armour Research Foundation of Illinois Institute of Technology, Chicago, Ill., August, 1962), p. 44.

Indium (10-10) Direct-AA film	Thermal Neutrons $6.0 \times 10^8 n/cm^2$	Gamma Rays 3000 mr

The exposures given are those needed to obtain a net film density of 1.0. The gamma ray response data was obtained with a cobalt-60 source at an intensity of 2 R/hr. The thermal neutron data was determined with a neutron beam having the following characteristics.[28]

Thermal Neutrons	7.9×10^6 n/cm^2-sec	$\pm 10\%$
Fast Neutrons (greater than 1.8 Mev)	2.3×10^4 n/cm^2-sec	$\pm 10\%$
Gamma dose rate	25 R/hr	$\pm 15\%$

Kodak type KK x-ray film is approximately six times faster than type AA. Using this information and the known gamma ray and neutron content of the beam in this investigation a total neutron flux could be calculated. The total neutron flux found by this method was,

$$\text{Total flux (n/cm}^2\text{-sec)} = 152 \frac{\text{FLUX MONITOR COUNTS}}{\text{ACTIVATION TIME (SEC.)}} \qquad (4-15)$$

The constant, 152, is higher than the value of 86.5 found in Equation 4-12. Since both estimates were necessarily very rough, the agreement was considered to be good. The fluxes found using Equations 4-12, 4-13 and 4-14 were, therefore, used with some degree of confidence.

The average total neutron flux, available at the imaging plane, varied from a high of 2.0×10^5 n/cm^2-sec to a low of about 2.0×10^4 n/cm^2-sec.

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[28] Ibid., p. 53.

Cadmium Ratio. Cadmium covers are used to shield a foil from neutrons with energies less than the effective cadmium cutoff energy (about 0.4 ev.). They are used to determine the thermal and epithermal flux components. Thermal and epithermal fluxes refer to the flux below and above the cadmium cutoff energy.

The cadmium ratio is defined as,[29]

$$C.R. = \frac{\text{UNCOVERED ACTIVITY}}{\text{Cd COVERED ACTIVITY}} = \frac{\text{(THERMAL + EPITHERMAL) ACTIVITY}}{\text{EPITHERMAL ACTIVITY}} \tag{4-16}$$

The cadmium ratio was determined using cadmium covers and indium foils. The foils were from a Nuclear Chicago foil holder kit Model FHK-1. The indium foils were 1.062 inches in diameter and five mils thick. The cadmium covers were 1.125 inches in diameter and twenty mils thick.

The method of determining the cadmium ratio was as follows: one uncovered and one cadmium covered indium foil were placed in individual foil holders. The foil holders were taped to the front of a thin (.015 inch thick) aluminum sheet and placed at the imaging plane of the experimental setup. The foil holders were positioned so that they were as close as possible to the same location in the neutron beam. The foils were then activated for fifteen minutes. After activation the foils were allowed to decay for at least five minutes before counting

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[29]Reactor Physics Constants, ANL-5800, (2nd ed., Reactor Physics Constants Center, Argonne National Laboratory, Argonne, Ill., Division of Technical Information, U. S. Atomic Energy Commission, Washington, D. C., July, 1963), p. 674.

was begun. This allowed the interferring indium-116 (13 second half-life) and indium-114 (72 second half-life) isotope activities time to decay. The activity which was counted was that of indium-116m (54 minute half-life).

After the indium foils were removed from the holders they were placed on suitable trays. Counting was done with a Geiger-Muller counter. The foils were placed in the same counter, alternating every two minutes for a counting time of 100 seconds. The number of counts were recorded for each 100 seconds. By plotting this data on semi-log paper the 54 minute half-life of indium-116m could easily be varified. The ratio of activities, at any particular time, is the cadmium ratio. For two different experimental runs this value was found to be 1.50. Figure 4-12 is a plot of the results of one of these determinations.

Gamma Ray Content of the Beam. The gamma ray content of the beam was found to be fairly high. The exposure curve obtained for KK film due to gamma radiation in the neutron beam is shown in Figures 4-9 and 4-10. From Figure 4-9 or 4-10 it is possible to calculate that the gamma radiation is responsible for about 32 per cent of the film exposure.

Resolution Capability. The resolution capability of the neutron beam was poor. Although no effort was made to assign a specific numerical value to resolution it was found that the smallest hole, 0.020 inch in diameter, in the cadmium test piece could not be observed (Figure 4-18). This poor quality was further emphasized when an attempt was made
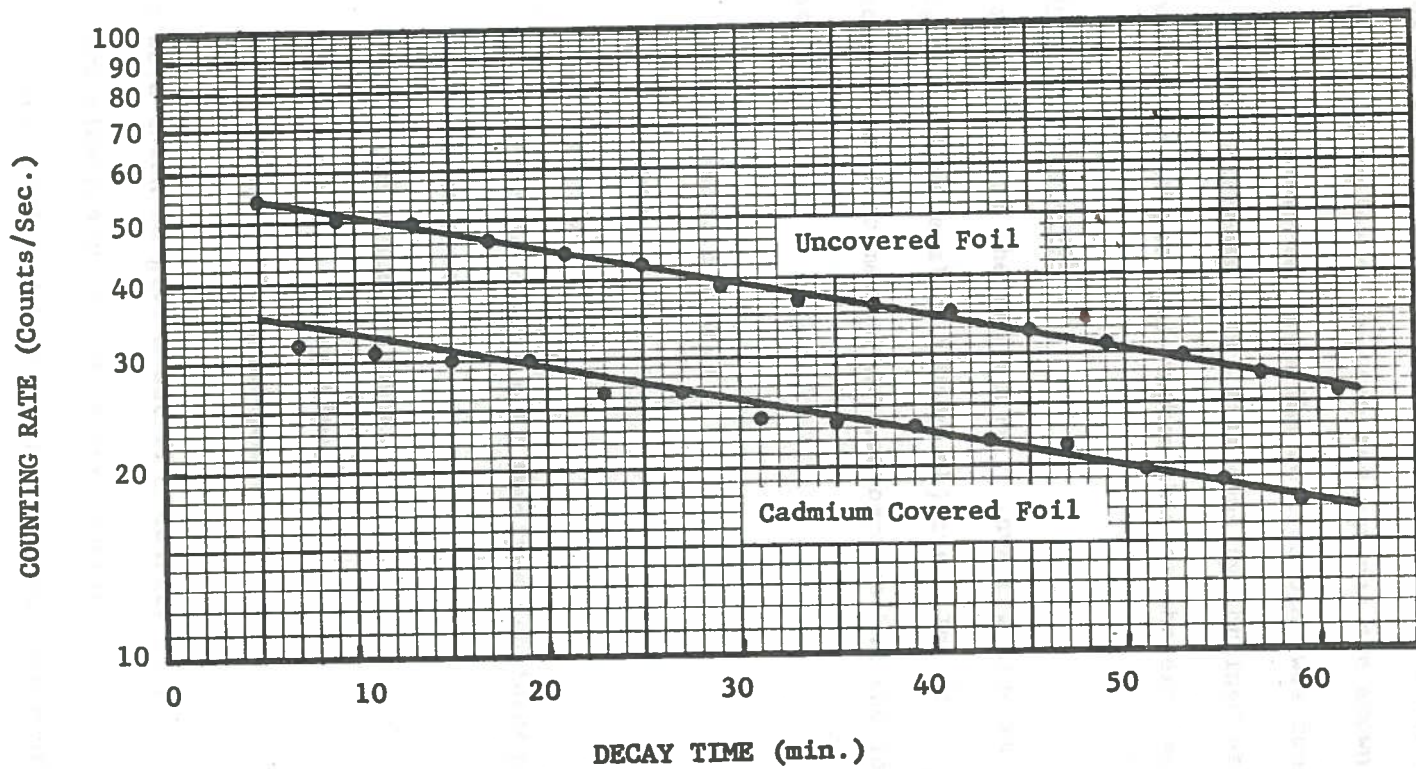
Figure 4-12.   Cadmium Ratio Determination Using Indium-116m
Isotope Decay.

to radiograph thick objects. As a result only objects less than about three-eights of an inch thick could be radiographed with any suitable degree of clarity. Examples of neutron radiographs are shown in the next section. In the examples shown the neutron beam was found to cover the foil area fairly uniformly. The film density obtained at the center of the foils was about 10 per cent higher than at the extreme corners.

Examples of Neutron Radiography.

The final portion of the experimental investigation was to make neutron radiographs of several different objects. The final experimental setup and procedure used to make these radiographs had the following important features:

1. Direct exposure method.
2. (10-10) indium foils.
3. KK x-ray film.
4. Target to film distance of twenty-seven inches.
5. Aluminum cassette.
6. Lead lined neutron shield.
7. Three hour foil decay time.
8. Eight minute film development.

The exposures were taken to give a net film density of 2.0. Exposure times varied from eleven minutes for a new generator target to sixty minutes for a target which had been used for about four hours.

Several x-ray radiographs of the test objects were taken for comparison. A Philips Electronics Inc., MG 300 x-ray unit was used at a

voltage of 75 Kv. The beam current was three milliamperes and exposure times were twenty seconds. KK x-ray film was used without any lead screens.

The neutron and x-ray radiographs shown are positive prints made from radiographic negatives. Dark areas are areas of high neutron or x-ray absorption. All objects are shown full size.

The objects shown in Figures 4-13 to 4-18 are as follows,

Figure 4-13. A small connector for a dry cell battery, a portion of an electrical connector, and a piece of coaxial shielded cable with the outer insulation stripped back about one-half inch.

Figure 4-14. An aluminum tube containing iron, lead, paraffin, aluminum, rubber, copper and cadmium wafers,

Figure 4-15. An electrical connector.

Figure 4-16. A thin wall stainless steel tube with copper wires inside. The insulation is stripped back on the wires in several places. There is also a connection, covered with several layers of electrical tape.

Figure 4-17. Two rubber grommets, one is mounted on top of a one-quarter inch thick lead disk.

Figure 4-18. The cadmium and lead test pieces. Radiographs were made using both the direct and transfer method of neutron radiography.

Figure 4-13 is a good example of the contrast differences between x-ray and neutron radiography. The battery connector, at the top of the x-ray radiograph, shows only the metallic wires, plugs and connectors. The plastic sheathing on the wires (adjacent to the connectors) and the pressed board portion of the plug do not appear. This is just the opposite of the neutron radiograph in which the plastic portions of
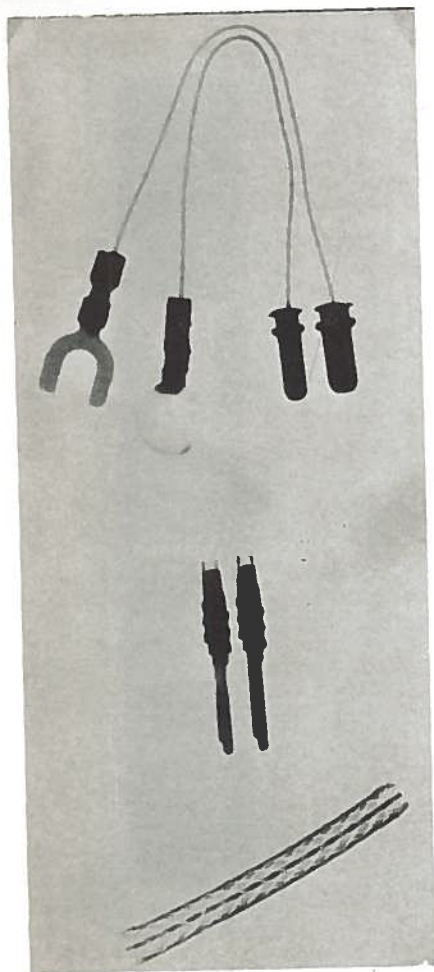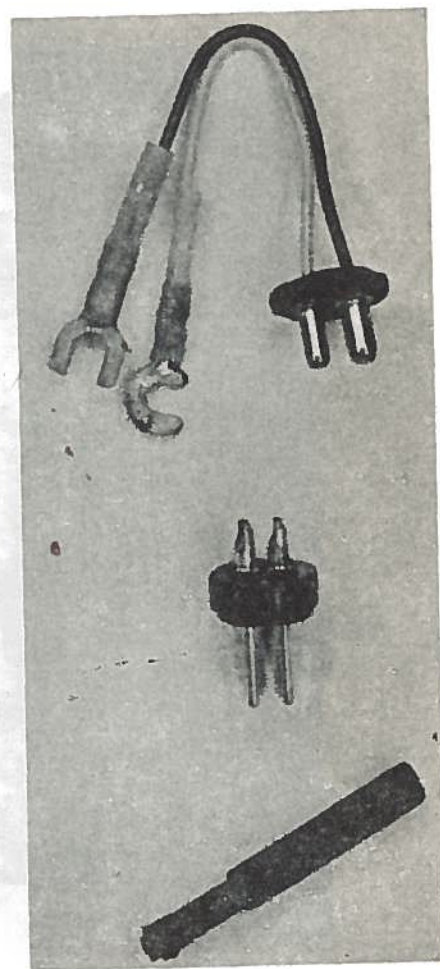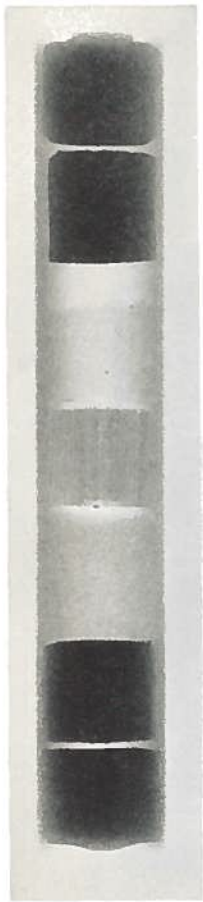
X-ray Radiograph   Neutron Radiograph   Electrical Components

Figure 4-13. Neutron and X-ray Radiography of Electrical Components.

X-ray Radiograph   Neutron Radiograph   Various Materials
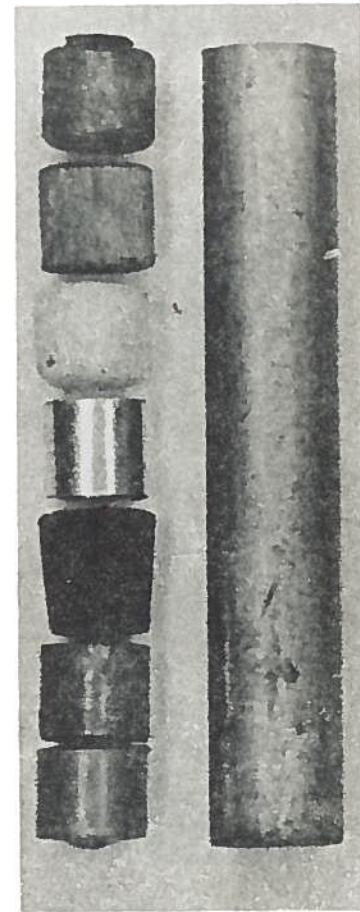
Iron

Lead

Paraffin

Aluminum

Rubber

Copper

Cadmium
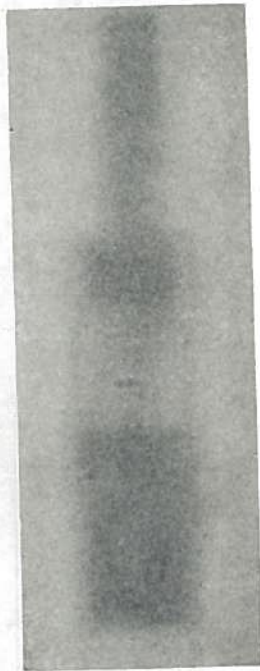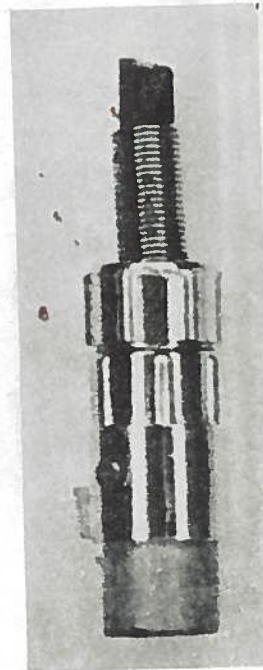
Figure 4-14. Neutron and X-ray Radiography of Various Materials.

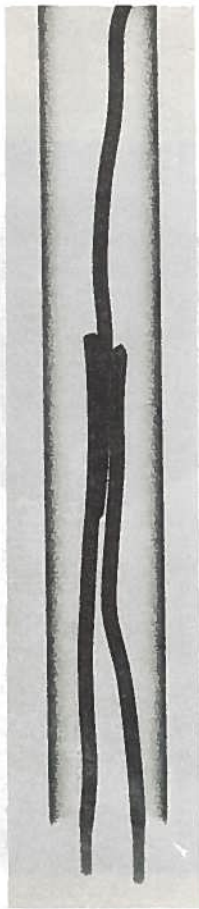X-ray Radiograph   Neutron Radiograph   Electrical Connector
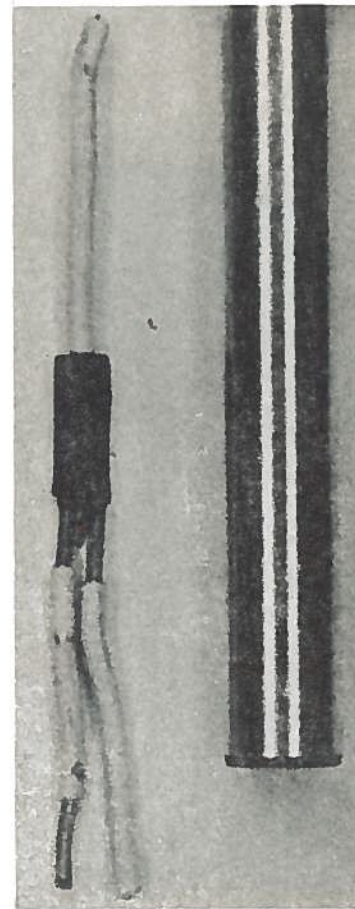
Figure 4-15. Neutron and X-ray Radiography of Electrical Connector.
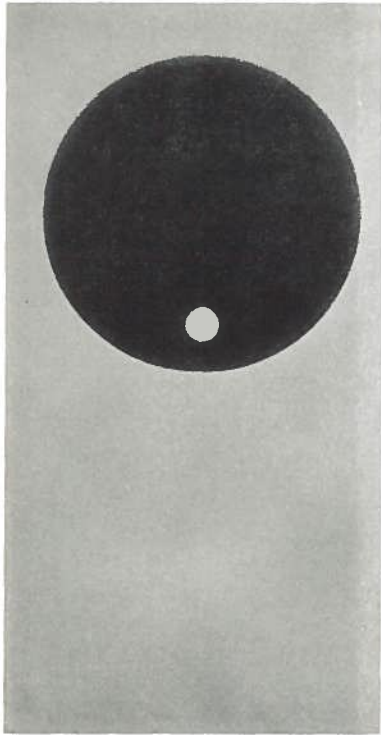
X-ray Radiograph   Neutron Radiograph   Wires and Tube
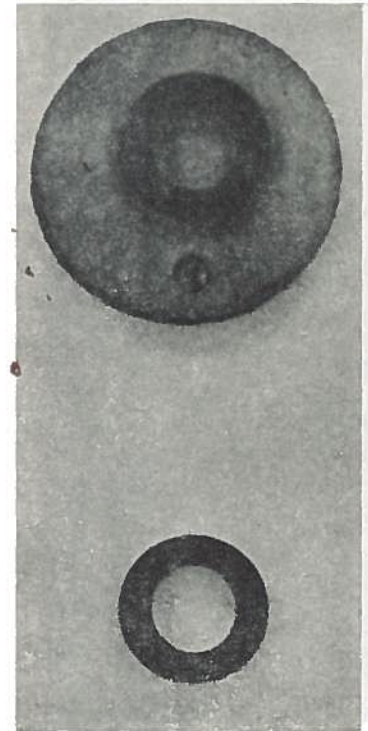
Figure 4-16. Neutron and X-ray Radiography of Wires in Steel Tube.
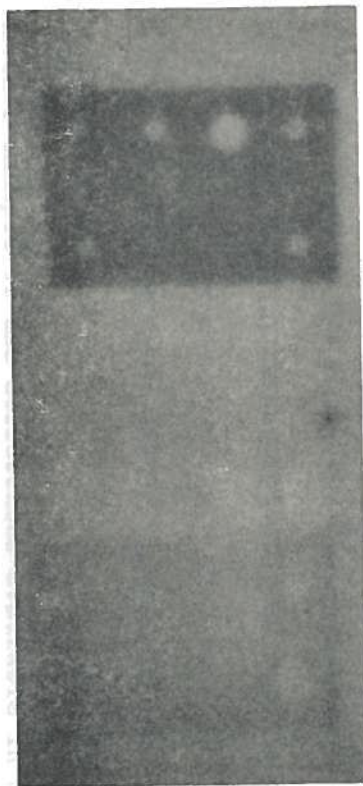
X-ray Radiograph   Neutron Radiograph   Lead Disk and Grommets

Figure 4-17. Neutron and X-ray Radiography of Rubber Grommet Mounted
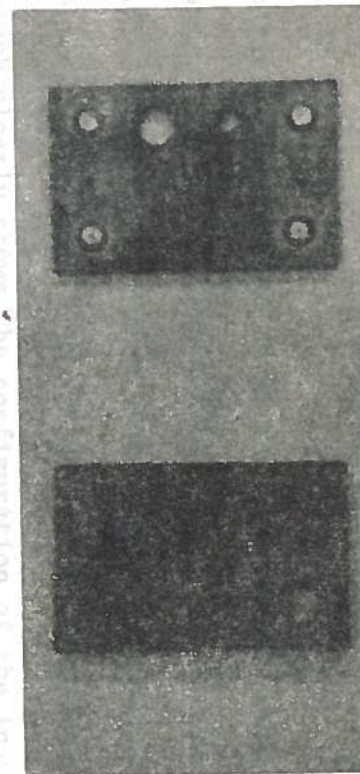on Lead Disk.

Figure 4-18. Direct and Transfer Method Neutron Radiography of Cadmium
and Lead Test Pieces.

the assembly show most clearly. The metallic portions of the object are almost invisible in the neutron picture. The small piece of an electrical connector, in the center of the radiographs shows these same reversals. The metal plugs can be seen in the x-ray radiograph while the plastic body of the piece shows best in the neutron radiograph. At the bottom of Figure 4-13 the coaxial shielded cable in the neutron radiograph clearly shows the configuration of the insulation. The x-ray radiograph shows only the metallic braided shield and center wires.

The relative absorption difference among various materials, for x-rays and thermal neutrons is well illustrated in Figure 4-14. In the x-ray radiograph the rubber and paraffin, and to a less extent the aluminum, are the most transparent to the x-rays. In the neutron radiograph the rubber and paraffin are among the best absorbers, being comparable to the cadmium and iron in this respect. The lead and copper show the opposite effect. In the x-ray exposure they are among the best absorbers, in the neutron radiograph, along with the aluminum, they are transparent.

Another example of the differences available in neutron and x-ray radiographs is shown in Figure 4-15. The internal structure of the electrical connector is markedly different for the neutron and x-ray exposure. In particular, the forward end of the connector shows a complete reversal. In the x-ray radiograph the metallic receptables are visible, in the neutron radiograph the image of the insulation surrounding the receptacles is shown.

Figure 4-16 again shows the different portions of an assembly which can be distinguished by each method. With x-rays the details

of the copper wires are revealed. In the neutron radiograph the insulation and tape are visible; the bare copper wires (just below the taped connection) cannot be seen.

The ability of the neutron radiographs to detect the position and condition of insulation on wires and other electrical components inside of a metal object, points out a possible area of application.

In Figure 4-17 the higher penetrating power of neutrons in a heavy material (lead), and their high absorption in a hydrogenous material (rubber), is clearly shown. The lead disk is one-quarter inch thick; the rubber grommet is also one-quarter inch thick. All attempts to make x-ray radiographs showing these same objects produced nothing but an image of the round lead disk. The rubber grommets were always obliterated when exposures were increased to try to penetrate the lead.

The examples of neutron radiography shown here have been chosen at random. Since this investigation had no particular applications in view, objects were selected to illustrate some of the general features of this technique. It is obvious from several of these examples that neutron radiography can be useful in many instances where x-ray radiography cannot be used.

As can be seen in these examples, the primary limitation on the experimental setup is the poor resolution. The low cadmium ratio and gamma ray content of the beam do not, at this time, seem to be serious problems.

Transfer Method Radiograph. For comparison purposes a transfer
method radiograph was made using the same radiographic setup and proce-
dure as for Figures 4-13 to 4-17. Figure 4-18 shows this radiograph
along with the direct exposure method radiograph of the same objects.
The lead and cadmium test pieces have been described previously
(Figure 4-4). Figure 4-18 illustrates very well the gamma ray content
of the imaging neutron beam. In the transfer method an activated, image
carrying, indium foil is removed from the neutron beam and placed in
contact with the x-ray film. Since the film is not present to record
any of the gamma radiation in the imaging beam a "pure" neutron radio-
graph is obtained. The unwanted gamma image cannot superimpose itself
on the neutron image as it will in the direct exposure method. For this
reason the lead test object is more difficult to distinguish in the
transfer radiograph then in the direct exposure.

The relative photographic speed for the transfer method is much
slower than for the direct method. In both methods shown in Figure 4-18
the (10-10) indium foils were given the same activation. The foils were
activated for eleven minutes in a relative flux monitor count of
1,500,000; both methods were allowed foil decay times of three hours.
The net film density for the direct method was 2.02, (it would be about
1.75 without the three hour decay) for the transfer method it was 0.76.
Even when the exposure caused by gamma rays (about 32 per cent) is
subtracted the direct method is still much faster. In comparison to
the values found in Table 4-1 the relative photographic speed of the
transfer method exposure would be 0.23. The direct method (10-10)
indium combination is 1.00.

As would be expected, the resolution of the transfer method is better than the direct method. The smallest hole in the cadmium test piece still could not be distinguished, but the other holes appear to be sharper. In the transfer method the film darkening is caused by beta particles from indium-116m decay. The highly penetrating gamma radiation in the neutron beam, and from neutron capture in the foil, do not reduce the image clarity.

Another interesting feature of the transfer radiograph is that it confirms the cadmium ratio determination. The cadmium ratio is defined by Equation 4-16. In a transfer radiograph using indium foils film darkening is due to the decay of indium-116m. This is the same activity which was counted in the cadmium ratio determination. The ratio of the relative exposure of the x-ray film caused by the indium foil which was not covered, to that which was covered by the cadmium test piece was found to be 1.55. This is in good agreement with the value of 1.50 found previously.

CHAPTER V

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

If neutron radiography is to be more widely used in industry and laboratories, small inexpensive neutron sources will have to be utilized. This investigation describes techniques by which radiographs can be obtained using a Cockcroft-Walton type accelerator.

The neutron absorption characteristics that are desirable for radiography exist primarily in the thermal neutron energy region. This study is, therefore, concerned with producing and detecting a thermal neutron beam.

The optimum thermal neutron beam was obtained by placing a four inch thick paraffin moderator between the accelerator target and the film cassette. This arrangement gives the maximum number of thermal neutrons at the imaging plane.

In order to make useful radiographs an experimental setup was devised. Shielding was provided to protect the image detector from both unwanted gamma rays and scattered neutrons. Two inch thick lead shielding reduced the gamma ray exposure to an acceptable level. A paraffin and boric acid shield, developed by a previous investigator, reduced the effects of scattered neutrons.

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An aluminum cassette was built and tested; it gave better results than a standard x-ray cassette. The x-ray cassette is made from a hydrogenous material (a good neutron scatterer) which degrades the image sharpness by scattering neutrons which have already passed through the test objects. Aluminum has a very low scatter cross section.

The aluminum cassette was rather flexible and difficulties were encountered in maintaining good foil-film contact. This factor contributed to the poor resolution obtained in the experimental radiographs.

Several metallic converter foils, sandwiched around Kodak type KK industrial x-ray film, were evaluated. Indium foils 0.010 inch thick gave the best results. Numerous exposures were made with the indium foil converters and an exposure curve for this combination was plotted (Figure 4-9). The use of the exposure curve consistantly gave repeatable results.

The Cockcroft-Walton accelerator used in the investigation had a rated maximum output of 14 Mev neutrons of 1.2×10^{11} n/sec. During the experimental work the maximum neutron output that could be obtained was about 1.3×10^{10} n/sec. The important characteristics of the neutron beam extracted from the accelerator are:

1. A maximum total neutron flux at the imaging plane of about 2.0×10^5 n/cm^2-sec. This is the average flux during an eleven minute activation using a fresh target.

2. A cadmium ratio of 1.50. One-third of the beam is thermal neutrons; the rest epithermal energies.

3. The gamma ray content of the neutron beam was calculated to be responsible for 32 per cent of the film exposure.

   4. The neutron beam was not well collimated. As a result
       resolution capabilities were very poor. The smallest
       hole (0.020 inch diameter) in the cadmium test piece
       could not be distinguished.

Several neutron and x-ray radiographs of various test objects are

presented. These radiographs illustrate the contrast differences avail-

able between x-rays and neutrons. The high neutron absorption of light

materials, particularly hydrogenous ones, and the transparency for

neutrons of heavy materials, such as lead, is also apparent.

A transfer method radiograph was made and varifies the original

assumptions regarding this technique. The transfer method exposure gives

considerably less film darkening than the direct method, but it does give

better resolution. The gamma ray image of the test objects is eliminated

in the transfer radiograph.

Conclusions

The investigation demonstrates that a small accelerator can be applied to neutron radiography. Improvements in the neutron beam characteristics will have to be made before the present facilities can be used for routine inspection problems.

The usefulness of the present setup is limited by the poor resolution that can be obtained. The high gamma ray content and low cadmium ratio of the neutron beam do not seem to be a problem. When better collimation of the beam is provided, and more detailed radiography is attempted, the unwanted gamma rays and epithermal neutrons may be troublesome.

The fact that lack of collimation is the main problem with the present facility leads to a rather pessimistic outlook for metallic converter foils. If longer target to film distances and/or collimating devices are used to improve resolution, the neutron flux at the imaging plane will be considerably reduced. This would result in very long exposure times. A loss of only one order of magnitude of flux would require a ten minute exposure to be increased to about two hours. This increase in exposure time is not practical because of the neutron flux decline as a result of target burnup.

Recommendations

In view of the findings of this investigation the recommendations for further study and evaluation are:

1. Investigation of various methods of improving resolution capability. A Soller slit type collimating device should be evaluated. A more restricted neutron window in the present setup might be helpful. Use of a smaller opening would better approximate point source characteristics. This opening could take the form of a small diameter cadmium lined hole through a paraffin block. Longer target to film distances might also help improve resolution.

2. Since any improvement in the neutron beam characteristics will undoubtedly reduce the available neutron flux the most efficient types of neutron detectors will have to be used. A thorough evaluation should be made of the faster scintillator screen converter materials. The possibility of using an intensifier such as a vacuum tube type which has been described should be considered.

3. Improving the yield of the neutron generator should be a primary concern. The generator is capable of one order of magnitude higher output than was obtained during this investigation. As improved targets with higher yields become available they should be used. Higher generator outputs, by reducing exposure times, will enhance any other improvements which can be made in the neutron beam characteristics.

4. A rigid aluminum cassette should be obtained. A spring loaded or vacuum type cassette would help improve resolution and reliability by providing a positive means of maintaining good converter-film contact.

5. Investigation to improve the cadmium ratio of the neutron beam should be carried out. Other moderating materials such as carbon or beryllium could be evaluated. These materials will capture fewer of the thermal neutrons than paraffin. This will help eliminate some of the capture gamma rays in the neutron beam as well as leave more thermal neutrons for imaging.. By changing the geometry of the experimental setup so that the film does not "see" the fast neutron source (e.g. extract a thermal beam at a right angle to the present beam) should improve the cadmium ratio. This arrangement will, however, result in a large loss in neutron flux.

6. Further reduction of the gamma ray content of the neutron beam should be investigated. Improved lead shielding of the cassette might prove helpful. Changes in the experimental setup so that the film is not directly exposed to the generator target assembly, should be tried. Neutron capture in and activation of the aluminum generator target assembly is probably one of the primary sources of unwanted gamma rays. A study of target assemblies made from other materials such as plastic or stainless steel

should be conducted. The activity induced by fast neutrons in these materials will be less than that for aluminum.

7. Evaluation of the possibility of using the exposure facility in an open area. By removing shield material from the area of the accelerator the problem of scattered neutrons and capture gamma rays can be reduced. Although this is not practical with the facilities used in this investigation it could be helpful in future applications of neutron radiography.

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APPENDIX A

$$N_t = \sigma P N_n t \frac{ML}{W} \tag{4-5}$$

$$N = 1.44 \ \sigma P N_n \frac{ML}{W} T (1-e^{-\lambda t}) \tag{4-6}$$

$$N_{t_1} = N e^{-\lambda t_1} \tag{4-7}$$

$$N_n = \frac{N_r W}{EB \ 1.44 \ \sigma PMLT \ (1-e^{-\lambda t}) \ (e^{-\lambda t_1} - e^{-\lambda t_2})} \tag{4-9}$$

N_t = Total number of atoms of isotope produced.

N = Number of atoms of radioactive isotope which exist at end of activation period.

N_{t_1} = Number of radioactive atoms which exist at time t_1 after activation has stopped.

N_n = Neutron flux, usually measured in neutrons/cm^2-sec.

N_r = Number of counts recorded by detecting equipment in the time t_2-t_1.

σ = Neutron cross section for reaction under investigation.

P = Isotopic ratio of atoms under consideration.

M = Weight of foil.

L = Avogadro's number.

W = Atomic weight.

T = Half-life of isotope formed.

λ = Decay constant of isotope formed, $\lambda = 0.693/T$.

t = Total activation time

t_1 = Time after activation has stopped (counting starts).

t_2 = Time after activation at which counting stops.

E = Efficiency (yield) of counting equipment.

B = Branching ratio.

VITA

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Secondary education was obtained in New York City at Newtown High School, from which he graduated in 1956. In September, 1956, he entered the City College of New York, where he received the Bachelor of Mechanical Engineering Degree in January, 1961.

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