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Neutron Radiography in Field Use

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Abstract

Some of the basic aspects of neutron radiography are reviewed with particular emphasis on the physics of this non-destructive testing method.

The results of an experimental evaluation program are presented which show conclusively that isotopic antimony-beryllium photoneutron sources can be used for neutron radiographic applications. This program provided valuable new information regarding neutron moderation and beam collimation requirements.

Based on this experimental evidence, a portable device has been designed and is described herein. The device employs a portable radiographic camera, with an antimony-beryllium photoneutron source, in conjunction with a neutron moderator and beam collimator configuration. This development makes available, for the first time, a means of obtaining economical inspection neutron radiographs in field application usage.

I. Introduction

The employment of penetrating radiation to obtain radiographic images has become a widely accepted part of nondestructive testing investigations. However, the potential usefulness of neutrons in the field of nondestructive testing has only begun to be investigated. Neutron radiography is still in the advanced developmental stage but the pace of this development is quickening. The possible uses of neutron radiography are many and varied. The existence of alternate approaches, such as fast versus thermal neutron and direct versus transfer image techniques, leaves open a large area of complementary development within the overall field of neutron radiography. In the opinion of the author neutron radiography should be viewed from two standpoints:

a. As an alternative or supplement to X and gamma radiography for specialized cases where these more conventional methods either fail or are only possible with much difficulty. One very important example of this is the case of radiography in high radiation fields which is a real problem in work involving nuclear reactor power plants.

b. As a new dimension in radiography which is capable of carrying radiographic investigations into totally new areas. This latter aspect is due to the peculiar nature of the neutron as a particle and the behavioral pattern of neutrons in transmission through various materials.

Although it is not new from a theoretical standpoint, e.g., References (1) and (2), neutron radiography is quite new as regards technological development. Recent work in the field has demonstrated the tremendous potential use of neutrons for radiographic work (References (3) through (8)). However, no economical device has been developed which offers the portability required for field applications. Until such time as devices of this nature become commercially available, a true understanding of the import of neutron radiography will not be forthcoming.

A brief review of the physics of thermal and fast neutron radiography is presented. The effects of neutron image formation, neutron moderation, and beam collimation from an antimony-beryllium (Sb-Be) source were evaluated experimentally and the results obtained are described in some detail. A portable radiographic device has been designed which reflects the experience gained in this experimental program. This device is described herein. A number of areas of applicability are discussed with particular emphasis on those things which are best suited to the employment of slow energy neutrons.

II. Some Aspects of the Physics of Neutron Radiography

There are two distinct types of neutron radiography as classed according to the neutron velocity (or energy) involved, i.e., thermal and fast neutron radiography. This is quite different from the case of gamma radiography, where increasing energy simply means increasing penetrability with an incumbent loss of image sharpness in most cases[a]. The

[a]The degraded image is due to the increase in the scattered component in the emergent radiation beam. This is a result of compton scattering collisions within the object under investigation.

cross sectional dependence of various materials on neutron energy makes energy differences of paramount importance in applications involving neutrons.[b] For this reason, the first

[b]A cross section is the probability of an interaction of a specific type between an incoming particle (e.g., neutron or gamma ray) and the atoms (or nuclei) of a target material. Any number of interactions could take place; however, we are interested principally in absorption and scattering interactions in radiographic applications. Some absorptions lead to activation of the materials in question. This aspect is important in neutron radiography.

type, thermal neutron radiography, relies on the employment of very slow neutrons in the energy range from zero to several electron volts (ev).

The second major type, fast neutron radiography, relies on neutrons of a very high velocity, associated with energies in the 14 mev range. These high energy neutrons are produced by machines frequently called neutron generators or neutron accelerators. The differences between thermal and fast neutron radiography are somewhat analogous to the differences between thermal and fast nuclear reactors. The physics aspects of the two are dissimilar in several important aspects, some of which are discussed briefly below:

A. <u>Thermal Neutron Radiography</u>

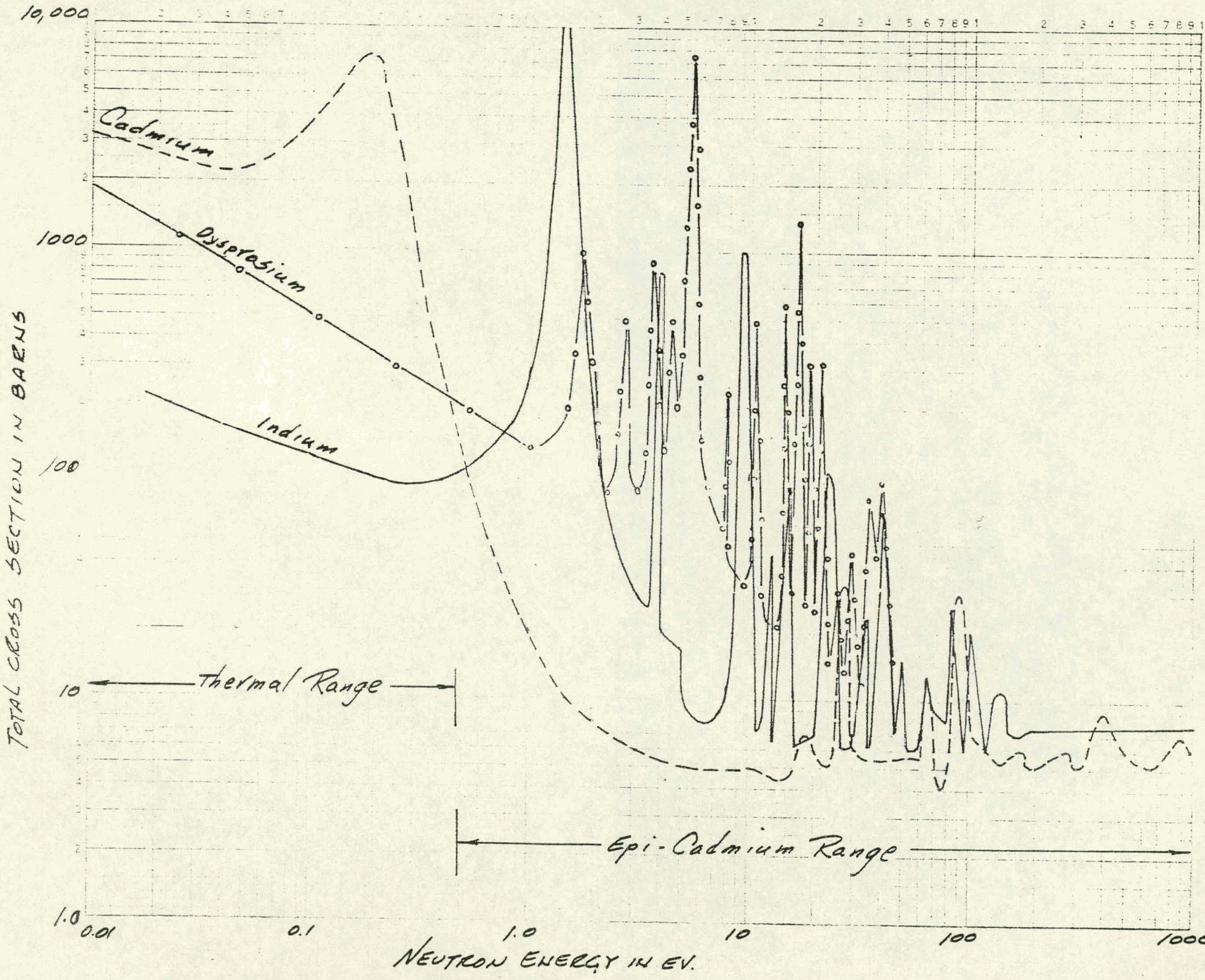
A radiographic image can be obtained by exposing an X-ray film coupled with a neutron sensitive screen or converter in what is known as the direct exposure technique. An alternative approach is to expose a neutron sensitive foil to obtain an image on the foil formed by neutron activation; this image is then transferred to standard X-ray film in a radiographic cassettes type device. This latter approach, known as the transfer technique, offers one very great advantage in that it is independent of the amount of gamma radiation present. Therefore, it is quite useful for radiographic work in gamma radiation areas or for work on radioactive components.

Although thermal or low energy neutrons do not penetrate matter as readily as fast neutrons, they have the advantage that detector materials are available which have very high cross sections[b] for thermal neutron activation. As a general rule, the cross-section increases rapidly with decreasing energy. Figure (1) shows how the neutron cross sections of indium, dysprosium, and cadmium compare. The peak areas on the indium and dysprosium curves are known as resonance regions. These occur due to the nuclear physics aspects of the relationship of target nuclei to incoming neutrons. It can be seen that neutron absorption rates are high for the energies where these peaks occur. If the energy spectrum of the neutrons, emerging from the test piece, is not in the thermal range, then the existence of these peaks is important for image detection of activations caused by these higher energy neutrons. Indium is a better image detector than dysprosium for such a spectrum of high energy neutrons by nature of its high resonance regions.

Several different sources are available and can be used for thermal neutron radiography. The image formation and transfer techniques are virtually the same in any case. The choice of a source of neutrons, on the other hand, varies widely and is one of the

FIG. 1

TOTAL NEUTRON CROSS SECTIONS FOR INDIUM, DYSPROSIUM, CADMIUM



Data taken from Reference VI

most important aspects of neutron radiography. Three major sources of thermal neutrons are presently available for such applications. They are nuclear reactors, moderated neutron generators, and radioisotopes in combination with beryllium.

1. <u>Nuclear Reactor Sources</u>

Beam holes and thermal columns, which allow neutrons to leak out from operating reactors, offer very high yields of thermal neutrons. One such beam hole, at the CP-5 reactor at Argonne National Laboratory, was used in conjunction with a neutron spectrometer in order to obtain a nearly parallel beam of neutrons with insignificant gamma ray inclusion. Reference (3) describes that device. References (5) and (8) describe the employment of thermal columns with almost no physical modification, such as the crystal diffraction apparatus of Reference (3). A great deal of success has been achieved with reactor sources but they are seriously limited by lack of portability. However, they will be useful even when portable devices become available because of the high neutron flux level obtainable (i.e., 10^6 to 10^8 n/cm^2 sec. at the image detector location).

2. Moderated Neutron Generator Sources

A number of neutron generators are commercially available (References (9) and (10)). These generators produce high energy neutrons by bombardment of target nuclei (such as Ti-H^3) with ions accelerated in magnetic fields (usually deuterium ions, i.e., d, t reaction).

In order to be used for thermal neutron radiography, these neutrons must be moderated, or slowed down, by means of successive scattering collisions. Some good moderating materials are graphite, paraffin, polyethylene, and water. Thermal neutron fluxes in the order of 2×10^8 n/cm^2 sec. are obtainable from less portable versions of these devices (Reference (10)). However, they are only portable insofar as they can be moved from place to place with considerable difficulty and must be shielded by several feet of neutron shielding material. These devices employ a console unit located somewhat removed from the shooting area. The cost of such devices ranges from $20,000 to $1,000,000 (Reference (9)). Although, admittedly more economical than buying a nuclear reactor, these sources are not nearly economically competitive with isotopic sources of neutrons, such as the device described herein, or of isotopic gamma ray sources including remotely operated camera devices. They have serious limitations for field usage, but offer higher fluxes than are obtainable from isotopic sources and are therefore useful provided heavily shielded shoot rooms are available.

3. Isotopic Sources

Several isotopes yield alpha or gamma radiations which are capable of producing neutrons when surrounded by certain materials such as beryllium. Several such sources in combination are mentioned in Reference (11). They are americium-beryllium, californium-beryllium, polonium-beryllium, plutonium-beryllium, radium-beryllium, and antimony-beryllium. The first two cannot be considered for neutron radiography at the present time because they are not commercially available. They are a theoretical possibility for the time when such materials are economically available in quantity. They could serve as sources for a second generation of isotopic neutron radiography devices. The next two (polonium-beryllium and plutonium-beryllium) are not promising because they are not available in amounts greater than 100 curies (unless a number of sources are grouped and the cost becomes prohibitive). They emit a spectrum of neutrons which averages in the neighborhood of 4 mev. These fast neutrons must then be moderated, or slowed down to the thermal range, with subsequent loss in flux during the moderating process. These restrictions make them unattractive for thermal neutron radiography. Radium-beryllium sources are too costly for the fluxes required in neutron radiographic applications.

Finally, the last of the sources mentioned above, antimony-beryllium, (Sb-Be) is, in fact, capable of providing a sufficiently high yield of thermal neutrons to make it useful in thermal neutron radiography. This fact has been recently experimentally established and is reported in this article. Little loss in flux is experienced due to moderation because only a small amount of moderator is required. This is due to the low energy spectrum of neutrons emitted from this source. The average energy is in the area of

20,000 electron volts (20 kev) from this source. See References (12) through (15). Source strengths in the order of 1,000 curies have been reported (Reference (12)) for Sb-Be source combinations. Reference (15) describes the essential aspects of Sb-Be as well as other photoneutron sources.[c]

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[c]The yields of neutron sources are expressed in terms of neutrons emitted per unit time (n/sec). This yield, in turn, is based on the source strength of the radioisotope initiating the neutron release reactions. In the case of Sb-Be photoneutron sources, the radioisotope is Sb-124. The source strength can be quoted in terms of disintegrations per second (dps) or curies where one curie is that quantity of radioactive material which results in 3.7×10^{10} disintegrations per second.

B. Fast Neutron Radiography

The neutron generators described in the preceding section can be used without a moderator thus emitting a beam of 14 Mev neutrons. This beam can be used in conjunction with either the direct exposure or foil transfer techniques. However, the choice of detector materials must be predicated on their cross sections for high energy neutrons.

Due to the highly penetrating nature of 14 Mev neutrons, the shielding and radiation hazards problems are more complicated for applications involving neutron generators. Another very difficult problem associated with the use of such devices, for fast neutron radiography, is the fact that the ion target life is very short (i.e., measured in hours of continuous usage). The target life of the generator described in Reference (10) is twenty-six hours of continuous operating time.

The shielding aspects of neutron generator source usage make fast neutron radiography more expensive than the thermal neutron radiographic application of the same device, when used with a moderator, as discussed above, since the moderator also plays an important shielding role.

The great penetrating power of high energy neutrons make fast neutron radiography particularly attractive for specialized applications, especially where large thicknesses of high density materials are involved, e.g., steel in excess of five inches thick.

However, the safety precautions and neutron shielding aspects of the employment of fast neutron radiography will most certainly limit field usage.

C. Radiation Attenuation Characteristics

Neutrons are attenuated, in traveling through a material, by either absorption or scattering processes in which the neutrons interact with the nuclei of the materials atoms. Gamma rays and X-rays, however, are attenuated by interactions with the electrons which surround the nuclei of these atoms. The amount of orbital electrons present in a material (the electron density) is determined by the atomic number (or material density)[d]. As a result, the probability for

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[d]The density of a material is the combination of the number of electrons (electron density) and the number of protons and neutrons (in the nucleus) for a unit volume. The atomic number (i.e., the number of protons in the nucleus) is the principal influencing factor in determining a material's density.

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interaction (i.e., the cross section) increases with increasing material density for the case of X-rays and gamma rays. Neutron attenuation is influenced only by the properties of the nuclei of the materials atoms. The physics of the atomic nucleus is such that material density is only one of many factors affecting neutron attenuation. The attenuation of thermal neutrons is quite different and, in fact, is almost the reverse of the attenuation found with increasing density for gamma and X-rays. That is to say, most light materials are good attenuators of neutrons, whereas neutrons can penetrate highly dense materials much more readily than X or gamma rays. This nearly reversed effect is obvious in a number of radiographic applications where areas of the film which are dark for X-rays are light for neutrons, etc.

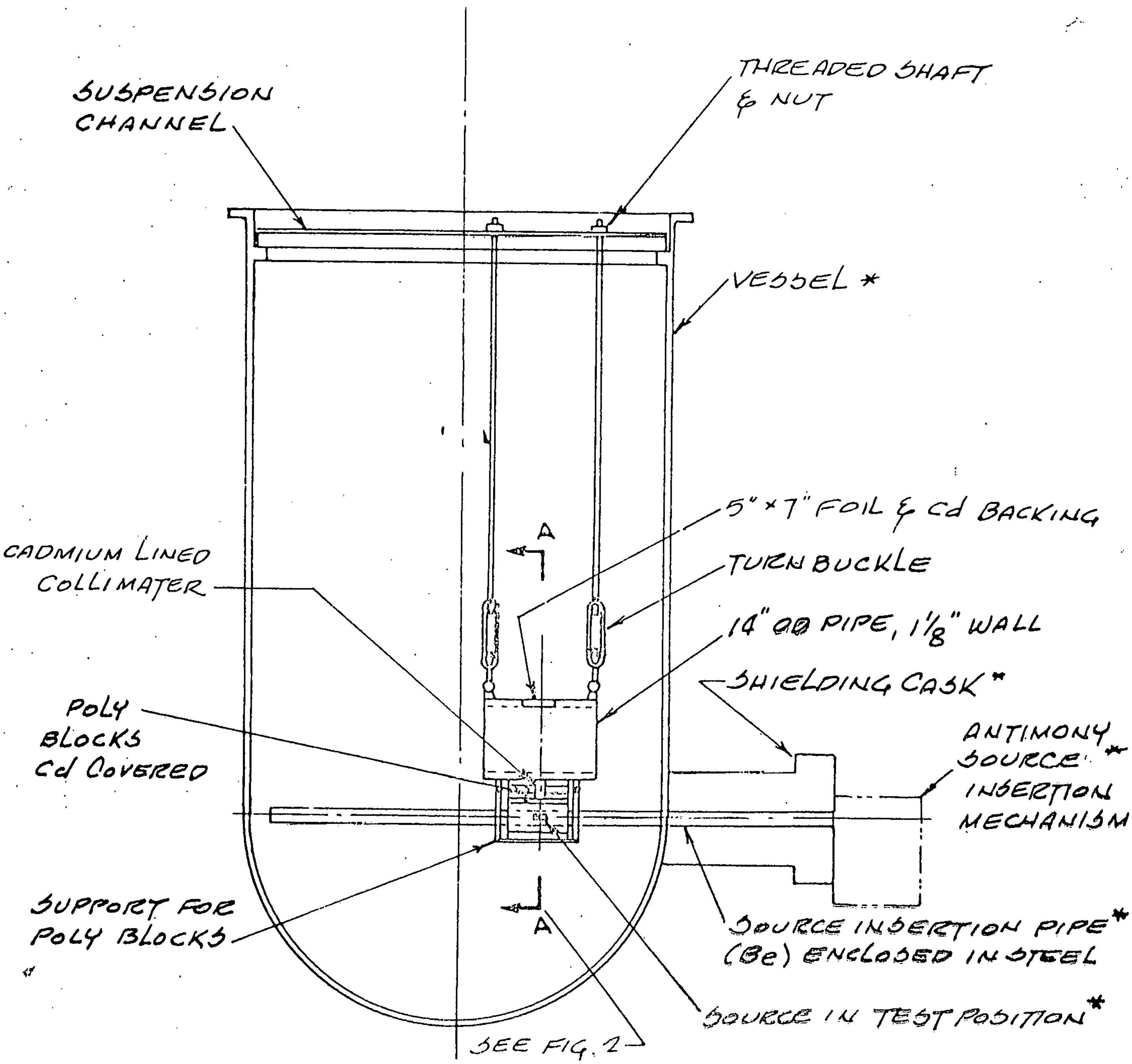
III. Experimentation with Antimony-Beryllium Sources

A high yield photoneutron source was described by Hennelly in Reference (12). This type of source represents a high enough neutron yield to make isotopic neutron radiography a real practicality. Based on this realization, our laboratory recently experimented with this antimony-beryllium source in order to obtain the first reported radiographs employing an isotopic neutron source and the first reported known use of antimony-beryllium in the field of neutron radiography.

Several test objects were radiographed with a combination moderator and collimator device constructed of polyethylene and cadmium. Figure (2) shows a typical test arrangement employed in obtaining these radiographs. In this figure, a twelve inch diameter pipe section is shown suspended over a collimator-moderator arrangement which was designed to fit around a stationary source tube. The source tube contains a beryllium cylindrical shell that serves as a receptacle for a cylindrical antimony source which is

FIGURE 2

TEST ARRANGEMENT FOR EXPERIMENTAL EVALUATION OF Sb-Be SOURCE EMPLOYMENT FOR NEUTRON RADIOGRAPHY



* EXISTING EQUIPMENT AT SAVANNAH RIVER LABORATORY

inserted and retracted to a shield cask by a remotely operated drive mechanism. The Antimony 124 cylinder is only a gamma ray emitter and no neutrons are available until this source enters the beryllium receptacle.

The combination moderator-collimator device was constructed from nine inch diameter polyethylene disks, one inch thick. The polyethylene surrounding and backing up the source tube served as a moderator and back-scatterer.[e] The flat disks in between

[e] A source of this nature is effectively an isotropic (or 4π solid angle) emitter. Some of the neutrons directed away from the test piece can be saved from being lost to the system by providing a layer of polyethylene to scatter them back into the beam.

the source and test object were necessary for moderation of the low energy spectrum of Sb-Be neutrons to the even lower thermal energy range. Finally, the top disks with the center hole formed a beam collimator. The entire arrangement was surrounded by 20 mil[f] cadmium except in way of the beam hole. This thickness

[f] A mil is defined as 0.001 inch.

of cadmium serves to effectively absorb the thermal neutrons which would otherwise leak out thereby distorting the image quality of the radiographs. The beam hole was also lined with cadmium.

Four major aspects of these experiments - image formation, neutron moderation, beam collimation, and radiographic results are discussed in turn below.

A. Image Formation

Since antimony-beryllium sources emit a great amount of gamma radiation which is not used in the photoneutron reactions, the gamma ray dose rate near a high yield Sb-Be source is therefore very high. A 1,000 curie source, as was used in these experiments, results in an unshielded gamma ray dose rate of roughly 1,500 r/hr at one meter. The average gamma ray energy is 1.69 mev as compared to the Cobalt 60 average of 1.25 mev.

As a result of these gamma ray emissions, the transfer foil technique must be used with an Sb-Be source, in most cases, since this technique is independent of the amount of gamma radiation present. However, if a lead shield were designed to surround such a source arrangement, with gamma rays being allowed to escape only in the neutron beam hole, then the direct exposure technique could very well be used. The effect would be to have a combined neutron and gamma ray radiograph. The exposure time for such radiographs would be extremely short (i.e., a few seconds).

During the experimental program recently completed, only the transfer method of image formation was employed. In this method, indium or dysprosium foils were exposed to the neutron beam after it had traveled through the test objects. An image of the transmission effects of the test objects was obtained by neutron activation reactions in the foils. In the case of indium, this induced activity decays a factor of two every fifty-four minutes (i.e., a fifty-four minute half life). Dysprosium, on the other hand, has a two and one-half hour half life.

During this series of tests, 10 mil thick indium and dysprosium foils were used exclusively for image formations. This choice was based on the work reported by Berger in References (3) and (6). A number of other activation foils may be employed with Sb-Be sources; however, time did not allow for evaluation of these at this time. Foils of this thickness are sufficiently thin to allow transfer of the induced image to two X-ray films simultaneously, with one located on either side of the foil in a film cassette. The photographic images thus obtained are not distinguishable as regards the side of the foil from which the film was transferred. The foils used in these experiments were five inches wide and seven inches long.

B. Neutron Moderation

The photoneutrons emitted from Sb-Be sources have energies which range up to slightly greater than 25 kev. It is necessary to moderate or slow these neutrons down to the range where they can more readily be absorbed by the detecting foils. The cross sections for activation are generally highest for thermal energies but resonances exist in the cross section curves of both indium and dysprosium as shown in Figure (1). One means of finding the optimum amount of moderating materials required for neutron radiography work is to expose the foils with varying thicknesses of moderator and measure the gamma ray dose rate due to activation. This was done for indium foils in this experiment. The dose rates were measured roughly two minutes after each exposure with a "cutie pie" ionization chamber detector.

The center of detection was located three inches from the foil surface for each contact reading. The results of this investigation are shown graphically in Figure (3). It can be seen from the figure that slightly greater than three-quarters of an inch of polyethylene was optimum in that this thickness of moderator results in the highest amount of induced activity. Time did not permit a similar evaluation for dysprosium, but the data of Figure (4) would indicate that a slight increase in

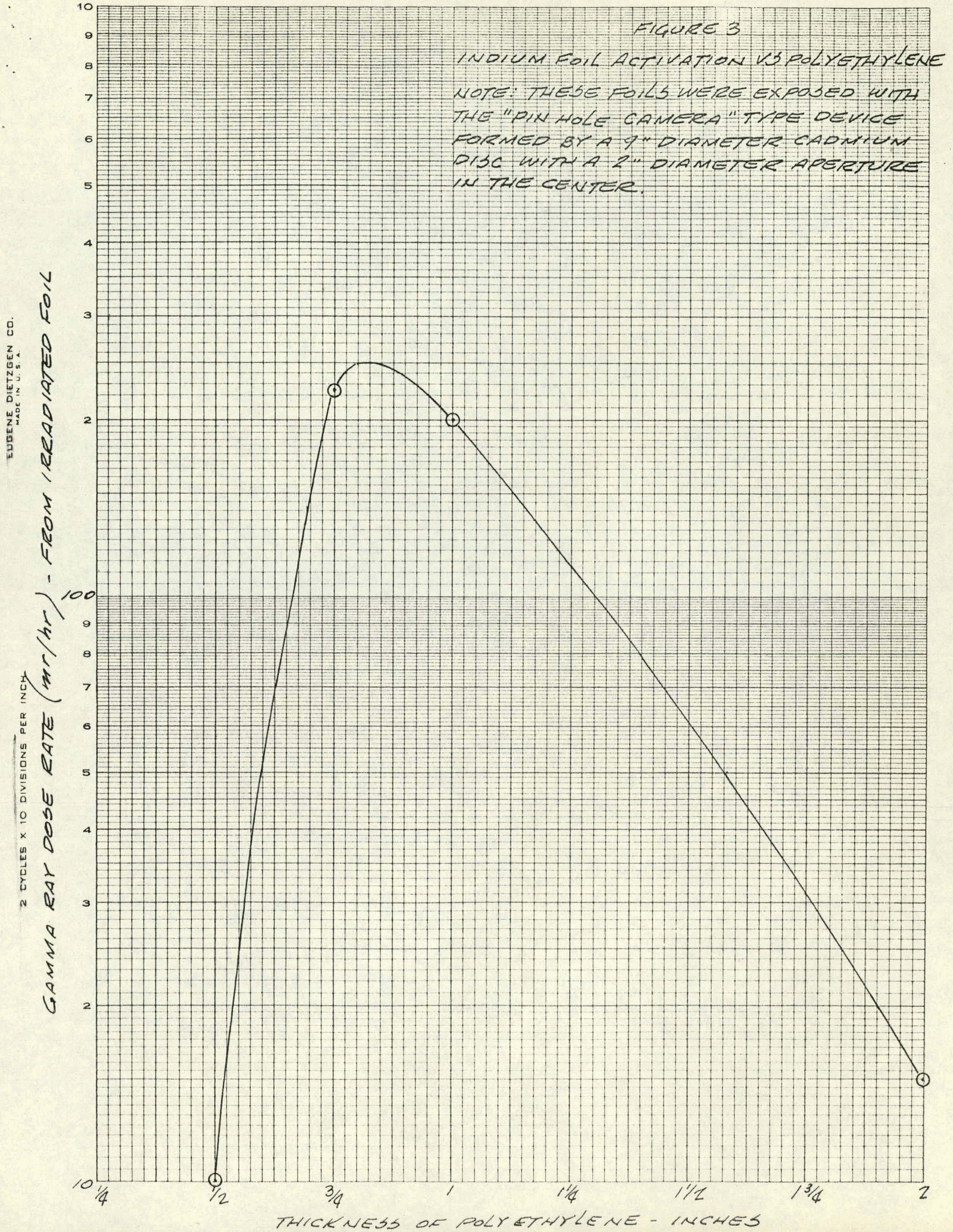


FIGURE 3
INDIUM FOIL ACTIVATION VS POLYETHYLENE
NOTE: THESE FOILS WERE EXPOSED WITH THE "PIN HOLE CAMERA" TYPE DEVICE FORMED BY A 9" DIAMETER CADMIUM DISC WITH A 2" DIAMETER APERTURE IN THE CENTER.
GAMMA RAY DOSE RATE (mr/hr) - FROM IRRADIATED FOIL
THICKNESS OF POLYETHYLENE - INCHES
10
9
8
7
6
5
4
3
2
100
10
1/4
1/2
3/4
1
1 1/4
1 1/2
1 3/4
2
EUGENE DIETZGEN CO.
MADE IN U. S. A.
2 CYCLES X 10 DIVISIONS PER INCH

polyethylene thickness would be advantageous for dysprosium due to the higher cross section at thermal energies and the relative relationship between the thermal and resonance cross sections of indium and dysprosium. No experimental evaluation has been made to date of the effects of other moderators, such as graphite. No discernible film density changes could be obtained for an unmoderated source with either dysprosium or indium foils. This showed conclusively that some moderation is necessary in order to make Sb-Be sources adaptable to neutron radiographic applications.

C. <u>Beam Collimation</u>

Since a neutron moderator is required for the use of Sb-Be sources, the geometry of the neutron sources then effectively becomes that of the moderator due to the fact that slow neutrons are emitted throughout the moderator. Such a geometric distribution is quite undesirable for neutron radiographic work. As a result, some type of collimator or aperture device must be employed. Three techniques were attempted during these tests (see Figure (4)). The first involved a two inch diameter hole in a cadmium wrapped polyethylene moderator. The second involved a similar arrangement but with a second cadmium disk, with a two inch hole, spaced two inches away with the two holes lined up to form an

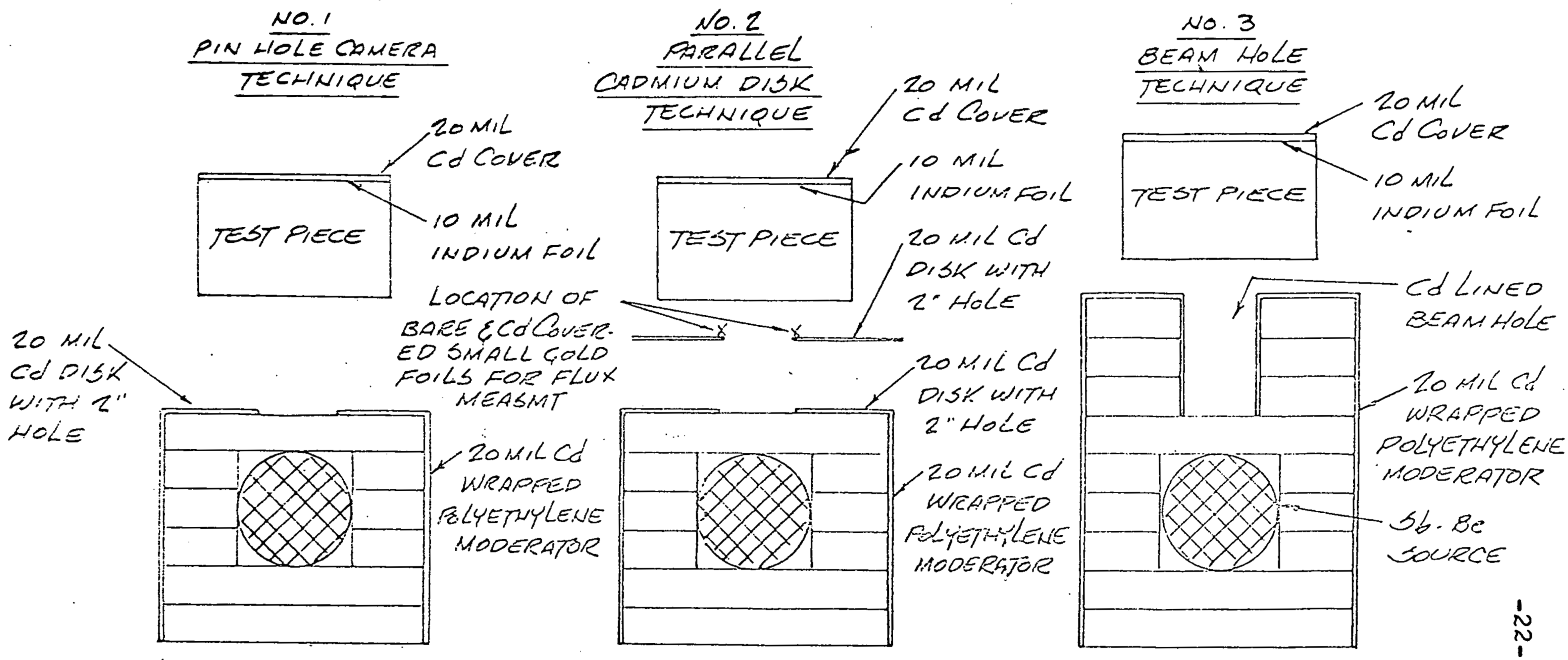


FIGURE 4

APERTURE & COLLIMATER TECHNIQUES

Note: No cadmium covers were provided at the bottom of the moderator assembly.

"effective" collimator.

A third type of collimator, a "beam hole" type was confirmed to be the best means of obtaining the highest possible amount of parallel component in the neutron beam. In this case a tube was constructed of 20 mil cadmium, with a diameter of two inches and a length of three inches. This tube was surrounded by polyethylene and the entire configuration was wrapped with cadmium.

A major factor in the decision to test a beam hole device, surrounded by polyethylene, was the result obtained in a neutron flux measurement for the second device shown in Figure (4). In this measurement two small gold foils were positioned at the test object location, one on either side of the second cadmium disk cutout hole. One of these foils was put in a cadmium jacket, or cover, while the other was left bare. The activity induced in these foils was counted and a determination was made of the equivalent thermal neutron flux. The flux at these locations was roughly 4×10^6 n/cm^2 sec for neutrons below the cadmium cutoff point, i.e., thermal neutrons.

However, a cadmium ratio[g] of only slightly more

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[g] The cadmium ratio is simply the ratio of the induced activity of the bare foil to that of the cadmium covered one. A cadmium ratio of ten means that for every neutron

activation reaction in the cadmium covered foil, there were nine taking place in the bare foil. (See Figure (1) for further information concerning energy ranges.)

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than one was obtained. This meant that an almost equivalent flux of epithermal (or above thermal) neutrons was present. In other words, the cadmium wrapping was not doing its job effectively, not because it failed to absorb thermal neutrons which would otherwise leak out, but because not enough polyethylene was provided to moderate these neutrons so that they could be absorbed by the cadmium. (Reference (16) provides further information on this measurement technique.)

The third type of device, the beam hole type described in Figure (4), was designed to correct this very deficiency before the experiment was undertaken. The experimental confirmation was noteworthy.

By employing a beam collimating device, a parallel component results in the field of neutrons impinging on the test object. This is an important factor in improving contrast sensitivity. Flux losses are encountered in this collimation but the remaining flux proved to be sufficiently high for most applications. The loss of flux encountered in radiographing thick objects can be compensated for by the use of faster film for the transfer of the induced image. However, this feature has its natural limitations. These limits were not evaluated during this set of experiments.

D. Photographic Neutron Image Detection Results

Figure (5) is a radiograph of a 20 mil thick cadmium disk with holes drilled from the center out 3/16" apart. The hole diameters were 16, 20, 24, 32, 40, 42, 47, 59, and 70 mils. A 10 mil indium foil was exposed for twenty-five minutes adjacent to the test piece, with a 2" diameter pin hole device. The test piece was one inch above the aperture. The induced image was transferred for forty-five minutes to Kodak AA film.

A radiograph of a 1" diameter 0.229" thick pipe section is reproduced in Figure (6). This object was located 1/4" from a 1" diameter pin hole aperture. A 10 mil indium foil was mounted on two polyethylene rings so as to rest on the top of the pipe section. It was exposed for fifty-four minutes and the induced image was allowed to transfer to type AA film for fifty-four minutes. The center weld is clearly visible in this shot. The cylindrical objects in this radiograph are the polyethylene rings which were used for support. The identification label "IN-21" shows how a 30 mil masking tape thickness is observable in this technique.

Figure (5) Radiographic reproduction of 20 mil cadmium test piece obtained by the indium transfer method with a 2" diameter pin hole camera device.

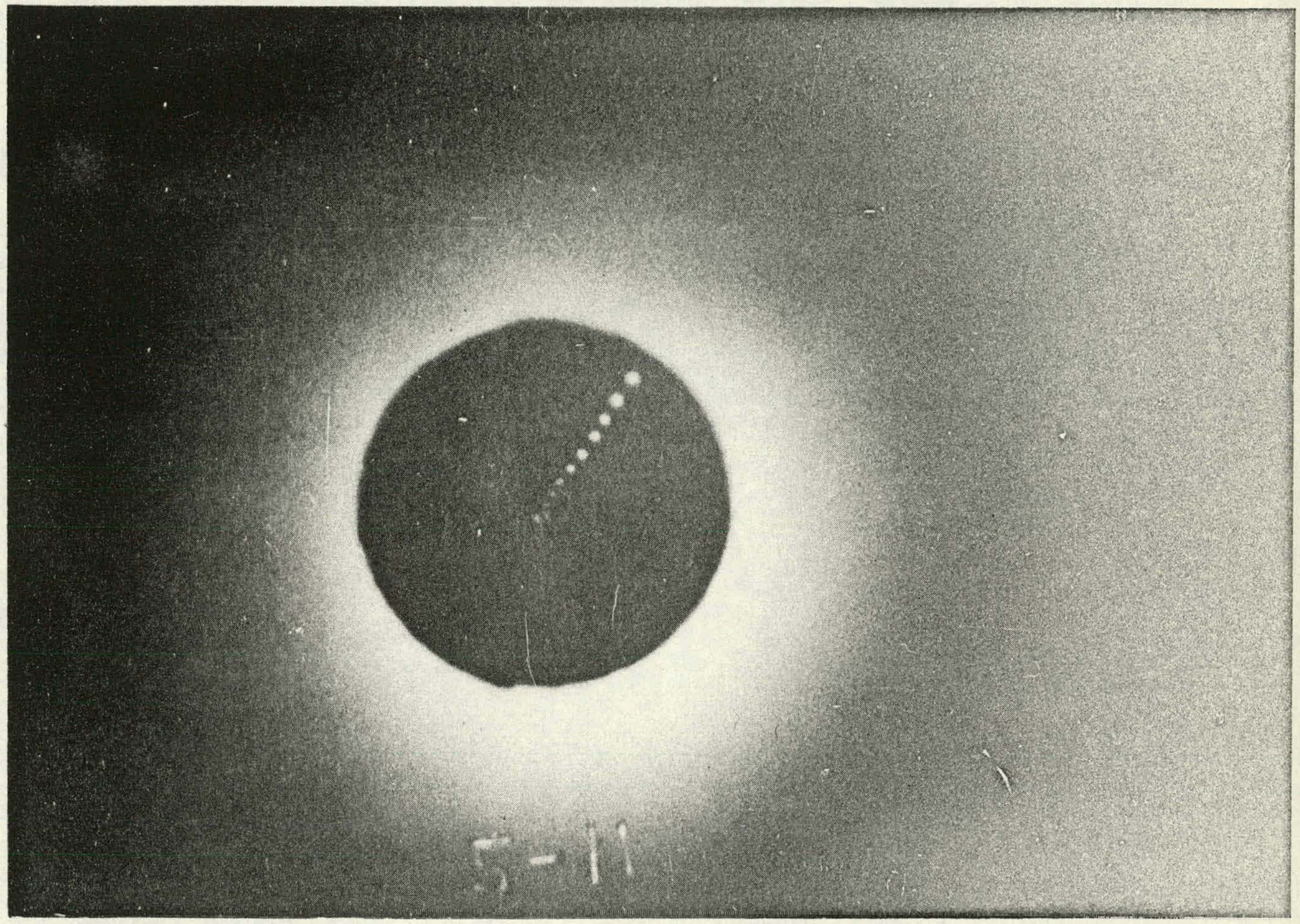
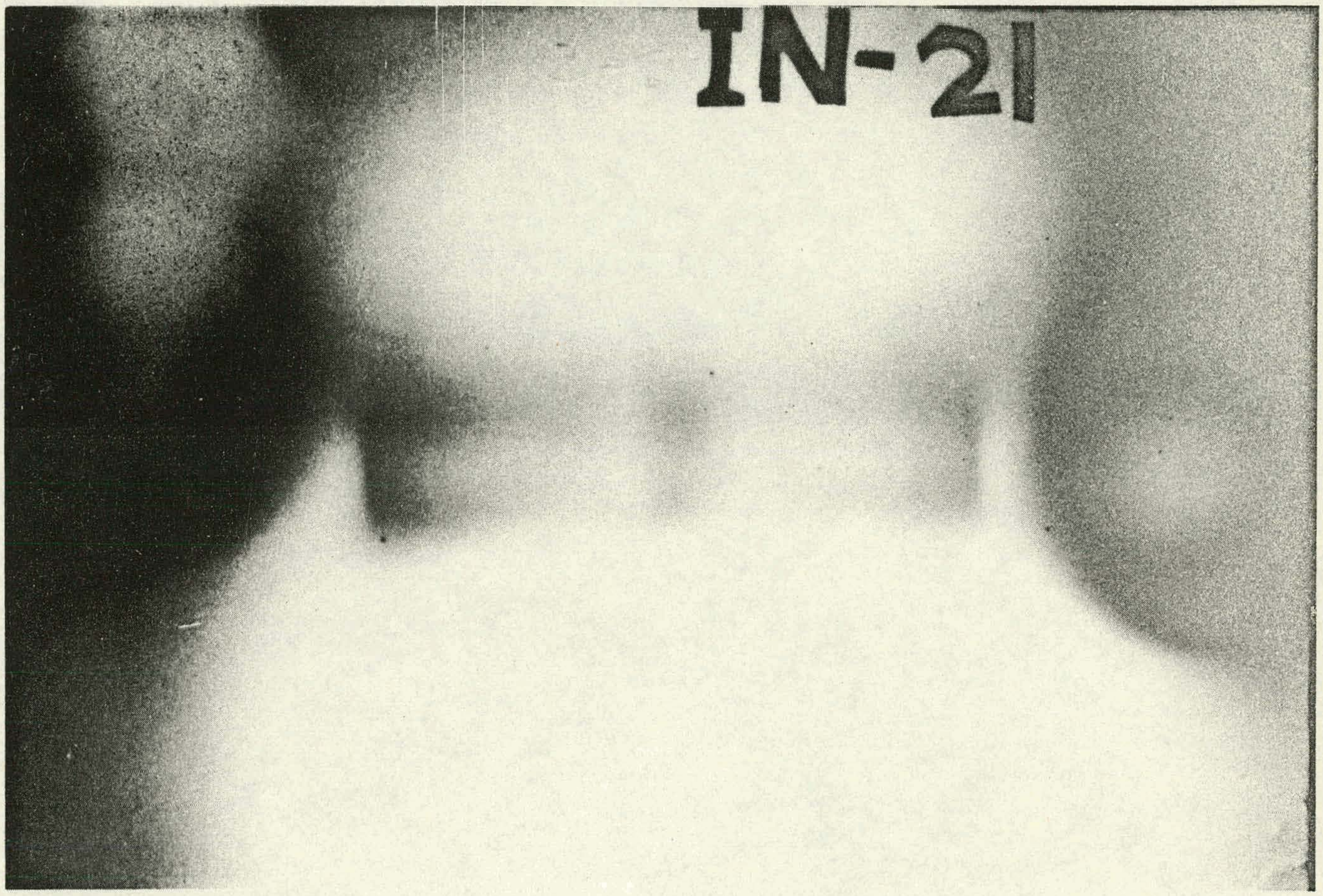


Figure (6) Radiographic reproduction of a 1" diameter pipe section obtained by the indium transfer method with a 1" diameter pin hole camera device.



The employment of an isotopic source of neutrons means that a continuous emission source is made available for neutron radiographic work. This is not the case for reactor beam holes which are subject to power changes and shutdown times due to reactor operations. Nor is it possible to obtain continuous emission from a neutron generator source.

A source intensity of 100 curies of antimony would suffice for radiographic inspection of many objects. However a 500 curie source would be required for big jobs such as the radiography of the twelve inch diameter pipe section described in the preceding section. A source of this nature could be used routinely within the compartment shielding of a nuclear reactor installation. Shoot room applications could be accomplished in a concrete shielded room which would not be of unusual design, as compared to the shielding requirements for high yield gamma radiography. Sb-Be shielding requirements are essentially a gamma shielding problem since the neutron energy spectrum is low. The half life of Antimony 124 is sixty days. This compares to a value of seventy-eight days for Iridium 192, which has been found to be an acceptable decay rate for routine gamma radiography applications.

IV. Description of Portable Device for Field Use

A remotely operated portable device which is capable of obtaining neutron radiographs in field usage has recently been designed and is presently under development. Figure (7)

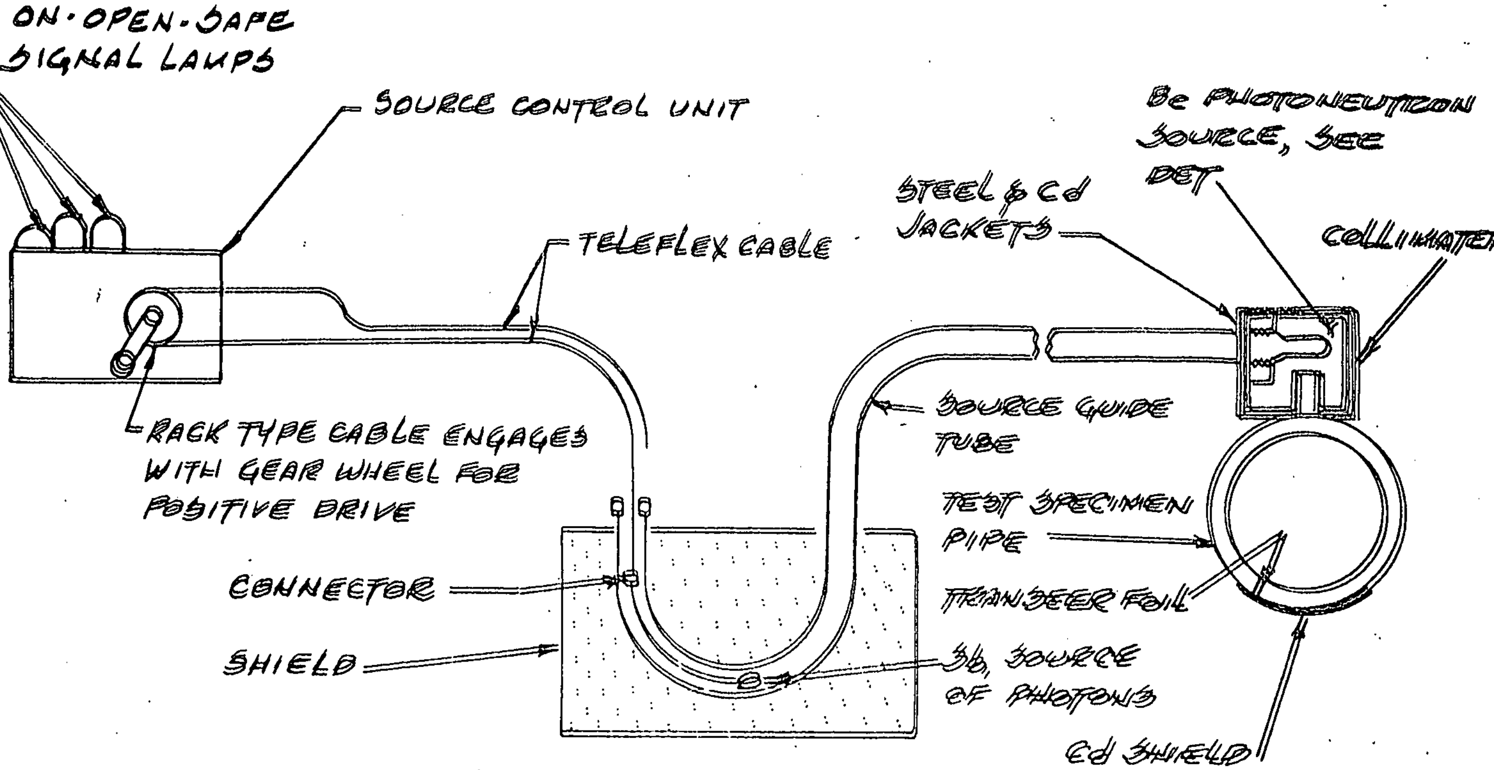


FIGURE 7

TYPICAL ARRANGEMENT FOR TAKING RADIOGRAPHS WITH PORTABLE ISOTOPIC NEUTRON RADIOGRAPHIC DEVICE shows the basic features of this device. The device employs a standard radiographic camera method of remotely cranking out an antimony gamma ray source from a shielded container. The differences lie in the fact that the end of the standard teleflex cable is fitted with a beryllium receptacle. This beryllium absorbs the emitted gamma rays and consequently gives off a high yield of photoneutrons. The beryllium thickness is determined such that optimum photoneutron production is realized. The beryllium receptacle is surrounded by varying thicknesses of polyethylene with a cadmium lined hole. The entire arrangement is surrounded by a cadmium wrapping 30 mils thick, except in way of the beam hole, which ranges from one to three inches in diameter, depending on the application.

The collimated beam hole is pointed toward the object to be radiographed. A neutron sensitive image detector is located on the opposite side of the object under investigation, much in the same manner that an X-ray film is located in X or gamma radiography. This image detector is either indium or dysprosium depending upon the application. Some use of europium and/or fissionable material foils (e.g., UO_2) is expected at a later date. In most cases the neutron sensitive foil will be approximately 10 mils thick and will be followed by a cadmium foil 20 mils thick to prevent any effects of backscattered neutrons.

The image picked up by the detector foils is then transferred to standard X-ray film in an area removed from the source exposure location so that additional exposures may be continued while the results of the previous exposure are being transferred to film. Kodak type AA, KK, and M films each has been found to be suitable for various film transfers. However, any number of X-ray type films may be used with this device.

The radiographic remote crankout tool (camera) feature is not new. What is new in this regard is that no such camera has been made to employ an antimony source in connection with a beryllium receptacle to form a portable radiographic nuetron source. Gamma radiography is the only known use to which these comparable devices have been put to date.

A major feature of this approach is that as long as the antimony is separated from the beryllium no source of neutrons exists. This was also the case of the source of Reference (12). For this reason, a relatively small (i.e., approximately twenty inch diameter) lead shield can be used for the camera device. An entirely different shield would be required if the source were to be permanently attached to the beryllium. This would be needed due to the creation of gamma sources due to neutron captures. Local shielding can be used, around the object to be radiographed, if it is not located in a shielded shoot room or within the compartment shield of a nuclear reactor. Distance has the same effect in reducing shielding requirements as it has for gamma radiography.

A device similar to the one described above would cost only a fraction of the cost of a portable neutron generator designed to supply the eouivalent thermal neutron flux at the image detector location. There is no economic comparison between this device and a nuclear reactor source of neutrons.

V. Applications of Neutron Radiography

As was stated initially in this discussion, neutron radiography could be viewed from two aspects:

a. Those applications where it can supplant gamma and X radiography when they fail to give the desired results.

b. Those applications which result directly from the unique nature and behavior of neutrons as regards transmission through, and identification of, various materials.

The following lists of applications of neutron radiography are categorized according to these two aspects. These listings include some applications already suggested by Watts in Reference (4) and Berger in References (3) and (6).

Table I

Applications of Neutron Radiography As a Supplement To or Replacement for X and Gamma Radiography

1. Radiography in high radiation fields or of components which are themselves radioactive or contain radioactive materials such as crud deposits. (Berger has recently demonstrated that highly radioactive spent reactor fuel elements can routinely be neutron radiographed with the beam hole at Argonne National Laboratory's Juggernaut Reactor (Reference (18)).
2. Nondestructive testing of metal castings and forgings.
3. Inspection radiography of weldments.
4. Inspection of very large thicknesses of heavy metals where excessive scatter and transmission losses make X and gamma radiography very difficult, or impossible.
5. Examination of spot welds in steel enclosures of thick uranium and tungsten configurations which present very difficult problems for X and gamma ray radiography.
6. Inspection of new (or unirradiated) reactor fuel elements and reactor control rods. The affinity of fuel and poison materials for neutrons makes neutron radiography an ideal replacement for X and gamma radiography in these areas.
7. Provided an appreciable parallel component exists in the neutron beam, neutron radiography can improve the image sharpness and contrast obtainable for certain materials with X and gamma ray devices, e.g., for crystalline structure evaluations in metallagraphic applications.

Table II

Applications of Neutron Radiography Based on the Unique Nature Of the Neutron and Neutron Attenuation Characteristics

1. Studies of inclusions in metals where there are cross sectional differences due to the materials in question.
2. Evaluation of hydrogen content in various materials.
3. Nondestructive testing of assembled components to ascertain the location and condition of rubber "O" rings and gaskets. The cross sections of both hydrogen and carbon in hydrocarbons such as rubber make these materials easily identifiable with neutron transmission techniques.
4. Inspection of hollow portions of metal objects such as turbine blades. The hollow portions are filled with a hydrogenous material prior to the inspection. This material then acts as an almost opaque object to the neutron beam.
5. Examination of a combination of material which are close in density (therefore, barely discernible with gamma or X-rays), but have different neutron cross sections making them readily definable with neutrons. One such example of this is a combination of tantalum and tungsten.
6. Inspection of plastic and rubber materials such as electrical insulation for flaws and defects.
7. Biological and medical studies of such specimens as plant or animal tissues can be accomplished with greater contrast than with X-rays in those cases where highly absorbing materials are present (e.g., boron or barium).

The above listings are not intended to be exhaustive but are representative of the variety of applicable areas of investigation that can benefit from further development and application of neutron radiography. In general, the tabulations apply more to thermal neutron radiography. Fast neutron radiography would be very useful in such areas as the nondestructive testing of such things as large thicknesses of cast solid rocket fuel for the existence of cracks or fissures.

The number and variety of applications will obviously be increased as the operation of a quantity of devices in field use are realized.

VI. Conclusions

One of the major obstacles in the development of practical and economical neutron radiography has been the lack of available low-cost neutron sources. With the experimental verification of the applicability of Sb-Be sources and the subsequent description of a portable device, as reported in this paper, it is concluded that neutron radiography should now advance even more rapidly than has been the case to date.

The work reported here on the moderation and beam collimation of Sb-Be neutron source emissions should prove valuable to other investigators. Roughly 7/8 inch of polyethylene moderator was found to be optimum for indium transfers. The high rate of leakage of epicadmium energy neutrons, in the disk collimator approach, was clear evidence that a beam hole collimator must be surrounded by sufficient moderator to allow the configuration's cadmium wrapping to be most effective. This demonstrated the advantages of the cadmium lined beam hole type of collimator.

The reproductions of photographic neutron image detections represent the first such reporting of the use of an isotopic neutron source for neutron radiography. Additional experimentation is desirable, in the areas discussed in this paper, in order to refine some of the features of the portable radiographic device. Refinements in such things as beam collimation will improve photographic image sensitivity. Further experimentation will also demonstrate that exposure times can be substantially reduced with the expanded use of fast X-ray and beta sensitive film. We plan to conduct experiments of this nature in the near future in conjunction with Monte Carlo computer code analyses of the neutron moderator and collimator configurations.

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