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FAST NEUTRON (14.5 MeV) RADIOGRAPHY:
A COMPARATIVE STUDY

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**FAST NEUTRON (14.5 MeV) RADIOGRAPHY:
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Abstract

Fast neutron (14.5 MeV) radiography is a type of non-destructive analysis tool that offers its own benefits and drawbacks. Because cross-sections vary with energy, a different range of materials can be examined with fast neutrons than can be studied with thermal neutrons, epithermal neutrons, or X rays. This paper details these differences through a comparative study of fast neutron radiography to the other types of radiography available.

The most obvious difference among the different types of radiography is in the penetrability of the sources. Fast neutrons can probe much deeper and can therefore obtain details of the internals of thick objects. Good images have been obtained through as much as 15 cm of steel, 10 cm of water, and 15 cm of borated polyethylene. In addition, some objects were identifiable through as much as 25 cm of water or 30 cm of borated polyethylene.

The most notable benefit of fast neutron radiography is in the types of materials that can be tested. Fast neutron radiography can view through materials that simply cannot be viewed by X rays, thermal neutrons, or epithermal neutrons due to the high cross-sections or linear attenuation coefficients involved. Cadmium was totally transparent to the fast neutron source. As much as one centimeter of cadmium was placed in front of a sample with little loss in image density or resolution.

Fast neutron radiography is not without drawbacks. The most pronounced drawback has been in the quality of radiograph produced. The image resolution is only about 0.8 mm for a 1.25 cm thick object, whereas, other forms of radiography have much better resolution. Also, since the cross-sections at 14 MeV do not vary significantly among the different materials, it can be difficult to differentiate between some materials.

Introduction

Radiography is used to non-destructively view the internals of objects. Depending on the source, different information can be obtained from radiographs. X-rays are

used for viewing heavy objects (high atomic number materials) in light materials (low atomic number materials like hydrogen and carbon). Whereas, thermal neutrons are used for imaging light materials and outlining neutron absorbing materials. Other forms of radiography, such as gamma and epithermal neutron radiography, are primarily employed for greater penetrability of the samples while still viewing the same types of materials. With 14 MeV neutrons, both types of objects show up clearly. In addition, fast neutron radiography offers the advantage of much deeper penetrability.

The advantages and limits of 14 MeV neutron radiography have been explored in a limited sense by numerous researchers (refs 1-10). Richardson (ref. 9) postulated that to obtain a given film contrast the thickness of sample is related by

$$x = k_1 \left(\frac{A^{1/3}}{\rho} \right)$$

where x is the sample thickness, k_1 is a constant, A is the atomic number of the sample, and ρ is the density of the sample. He found that samples of aluminum, lucite, polyethylene, and cadmium were in agreement with the postulation. A more recent publication by J.S. Brzosko, et al. (ref. 10) explores the advantages and limitations of fast neutron radiography from calculations performed using monte carlo techniques. J.S. Brzosko claims that fast neutron radiography is superior to thermal neutron radiography when the sample thickness is greater than 1 cm and requires a resolution better than 0.1 mm.

This paper addresses the findings of these researchers through a comparative study of the different types of radiography of similar samples. Resolution test pieces were radiographed with x-rays, thermal neutrons, epithermal neutrons, and fast neutrons (14.5 MeV) and the results compared.

Experimental Procedure

To produce fast neutron radiographs, a simple but versatile system was designed and installed at Argonne National Laboratory (ref. 11). The neutron source is an MF Physics A-711 neutron generator which produces 2.98×10^{10} neutrons per second (at a setting of 150 kV and 2.5 mA) with an average energy of 14.55 MeV (ref. 12). A light-tight DuPont Cronex® film cassette was loaded with a 1.5 mm thick piece of plastic and two Kodak Lanex® Fine screens. One sheet of Kodak T-Mat® G/RA diagnostic film was placed between the screens and a label was attached to the back screen. The cassette was placed 140-150 cm from the neutron generator with the samples placed in front of the cassette. Exposure times for this configuration were typically 15 to 30 minutes.

The Argonne National Laboratory Neutron Radiography Reactor (NRAD) was used to produce the thermal and epithermal neutron radiographs (Ref. 13). NRAD employs the foil transfer method for indirect radiography (dysprosium for thermal radiographs and indium for epithermal radiographs). The foils are activated simultaneously in a mixed beam and then transferred to Kodak Industrex® SR

radiography film. The foils remain on the film overnight and are processed the following day. Exposure times are on the order of 20 to 30 minutes to obtain a film density of 2.0.

A Seifert 320 x-ray machine was used to produce the x-radiographs of the resolution test pieces. Settings were typically 320 kV, 10 mA, and 0.3 minutes with a source-to-film distance of 120 cm. The exposures were performed with Kodak M-8® industrial x-ray film and processed according to the manufacturers instructions.

To provide uniformity for comparison purposes, three resolution test pieces were constructed. The resolution test pieces are solid pieces (1.25 cm x 5 cm x 20 cm) of aluminum, carbon steel, and polyethylene with holes (2.54 cm, 1.905 cm, 1.27 cm, 0.9525 cm, 0.635 cm, 0.47625 cm, 0.3175 cm, 0.238125 cm, 0.15875 cm, 0.11906 cm, and 0.079375 cm) drilled through the 1.25 cm thickness.

For each of the four types of radiography (x-ray, thermal neutron, epithermal neutron, and 14.5 MeV neutron) the resolution test pieces were radiographed with varying thicknesses of polyethylene and steel placed between the source and test pieces. Steel with thicknesses of 1.25 cm, 2.5 cm, and 5 cm was used for the first series of radiographs. Polyethylene with identical thicknesses was used for the second series of radiographs. The third set of radiographs used several combinations of steel and polyethylene (1.25 cm Fe - 1.25 cm Poly, 2.5 cm Fe - 1.25 cm Poly, 2.5 cm Fe - 2.5 cm Poly) with the polyethylene placed nearest the film.

Additional tests were performed with the fast neutron radiography system. These tests included radiographing the resolution test pieces through: (1) approximately 1 cm of cadmium, (2) 15 cm of steel, (3) 15 cm of polyethylene, and (4) 30 cm of borated polyethylene. A radiograph of a steel block in a water-filled steel can that was surrounded by 0.5 cm of cadmium is also included. Other radiographs performed include a radiograph of a hafnium sponge and a radiograph of a small steel object (spoon) in a water-filled container (coffee mug).

Results

The radiographs are shown in Figures 1-5. It should be noted that the radiographs shown in Figures 1-5 are positive prints of the images and have been produced from the original radiographs. However, some detail has been lost due to the large density gradient on the original radiographs. Every attempt has been made to reproduce the images with as much of the detail as possible. Observations based on the original radiographs are listed in Tables 1-4 for comparative purposes.

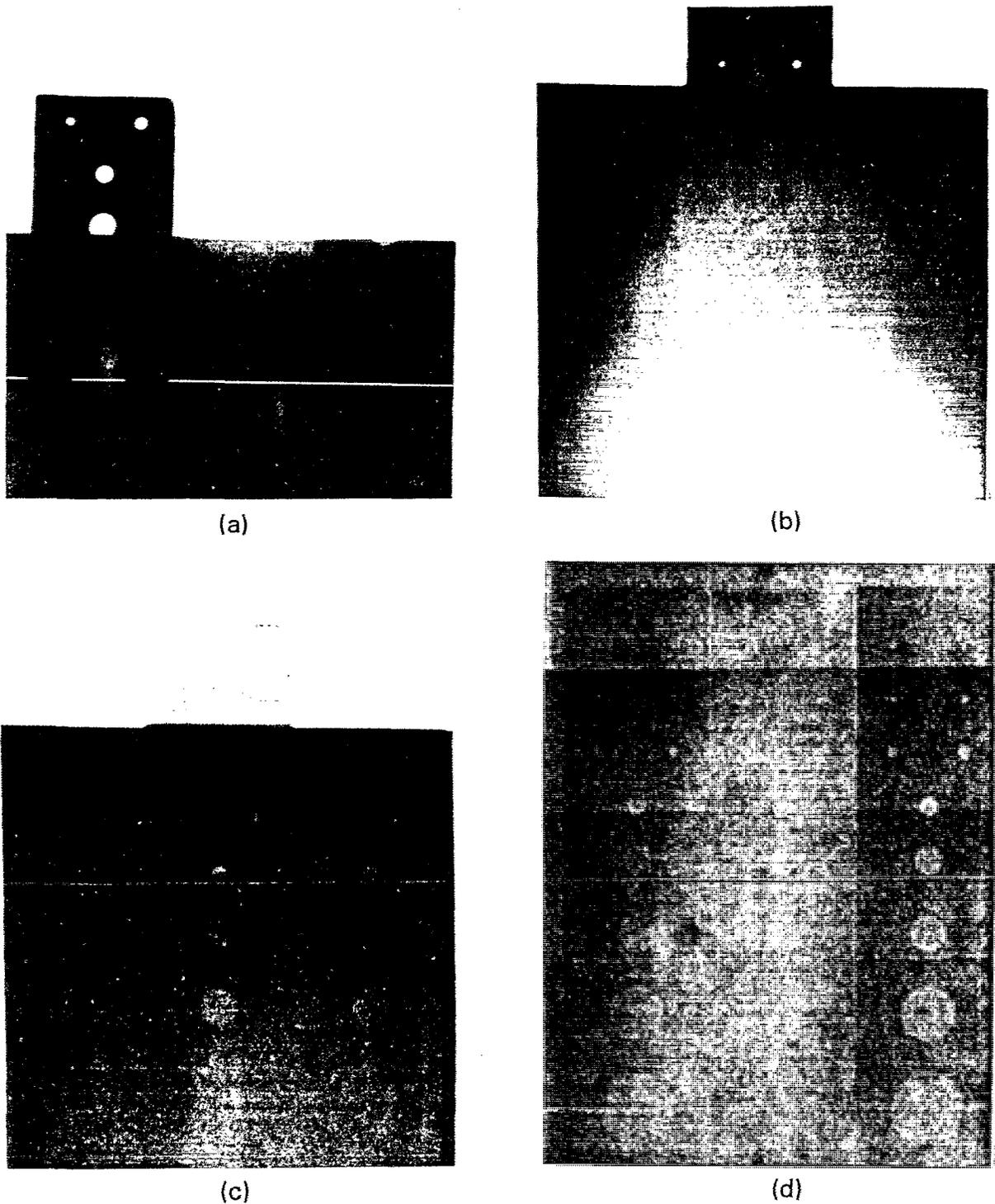
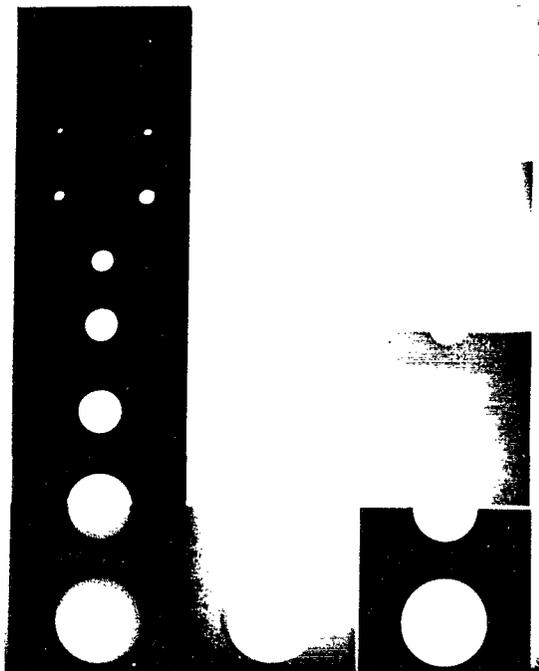


Figure 1: Radiographs of resolution test pieces through varying thicknesses of steel - (a) x-ray, (b) thermal neutron radiograph, (c) epithermal neutron radiograph, and (d) 14.5 MeV neutron radiograph. The lower portion of each image is through 5 cm of steel, the middle portion is through 2.5 cm of steel, and the upper portion is through 1.25 cm of steel. A fourth region may show at the top of some of the images. This region has no steel between the source and samples.

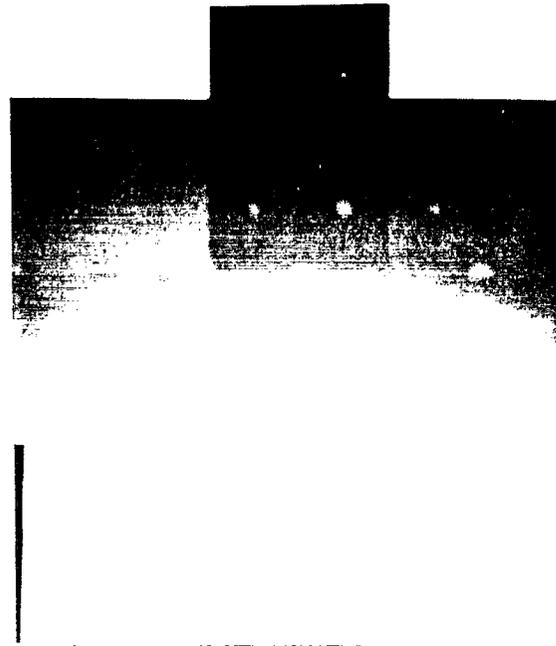
Table 1

Observations from Radiographs through Steel (Figure 1)

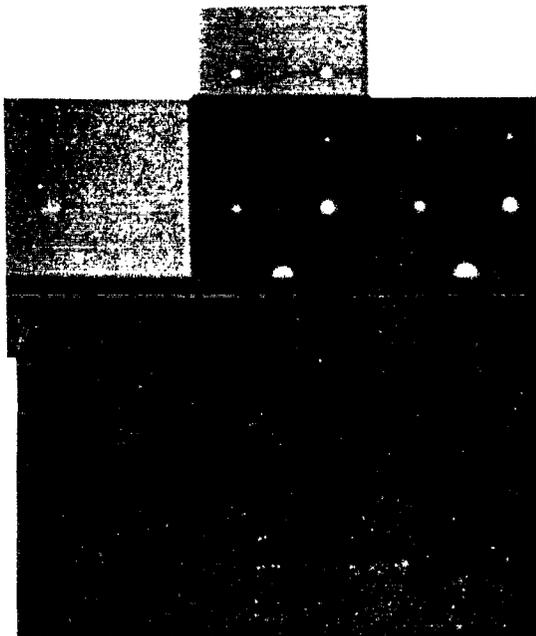
Type of Radiography	Observations
x-ray	<p>No Steel - poly and aluminum blocks are blacked out with no detail evident, the holes are observable in the steel block</p> <p>Through 1.25 cm Steel - all holes are easily observable, good contrast between steel, poly, and Al blocks</p> <p>Through 2.5 cm Steel - all holes are observable, can easily differentiate between steel, poly, and Al blocks</p> <p>Through 5 cm of Steel - holes in steel block are faintly observable, no holes are evident in the poly and Al blocks, can differentiate between poly and steel blocks but not between the poly and Al blocks</p>
thermal neutron	<p>1.25 cm steel: all holes in all blocks are easily observed, very good definition between the 3 blocks</p> <p>2.5 cm steel: all holes in all blocks are observable, the holes in Al block are weak, good differentiation between the 3 blocks</p> <p>5 cm steel: holes barely discernable in poly and steel blocks, holes in steel block are very weak, no holes can be seen in the Al block, can barely differentiate between the 3 blocks</p>
epithermal neutron	<p>1.25 cm steel: all holes in all blocks are easily observed, very good definition between the 3 blocks</p> <p>2.5 cm steel: all holes in all blocks are observable, the holes in Al block are slightly weak, good differentiation between the 3 blocks</p> <p>5 cm steel: holes in poly and steel are observable, holes in steel block are slightly weak, no holes can be seen in the Al block, can differentiate between the 3 blocks</p>
fast neutron	<p>All holes down to 0.159 cm are clearly observable in all 3 blocks, the 0.119 cm hole in the steel block is easily observable while the 0.079 cm hole is weak, no holes less than 0.159 cm are observable in the poly or Al blocks, good contrast between all 3 blocks</p>



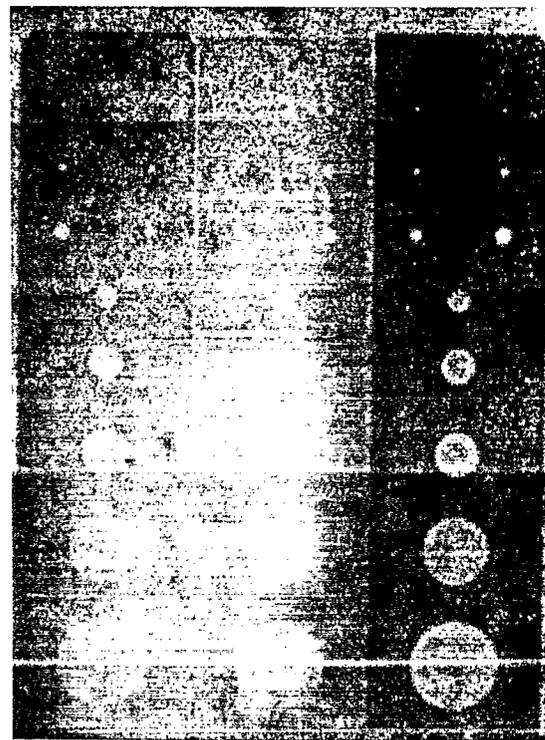
(a)



(b)



(c)



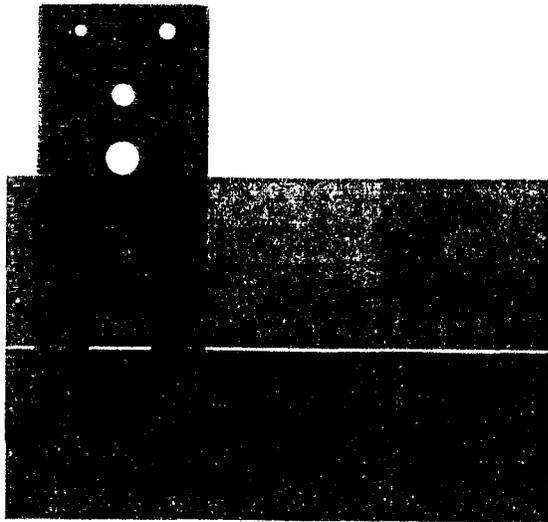
(d)

Figure 2: Radiographs of resolution test pieces through varying thicknesses of polyethylene - (a) x-ray, (b) thermal neutron radiograph, (c) epithermal neutron radiograph, and (d) 14.5 MeV neutron radiograph. The lower portion of each image is through 5 cm of poly, the middle portion is through 2.5 cm of poly, and the upper portion is through 1.25 cm of poly. A fourth region may show at the top of some of the images. This region has no poly between the source and samples.

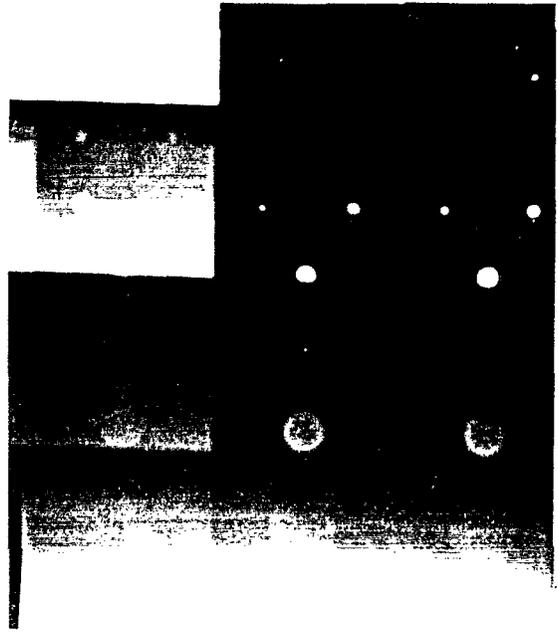
Table 2

Observations from Radiographs through Polyethylene (Figure 2)

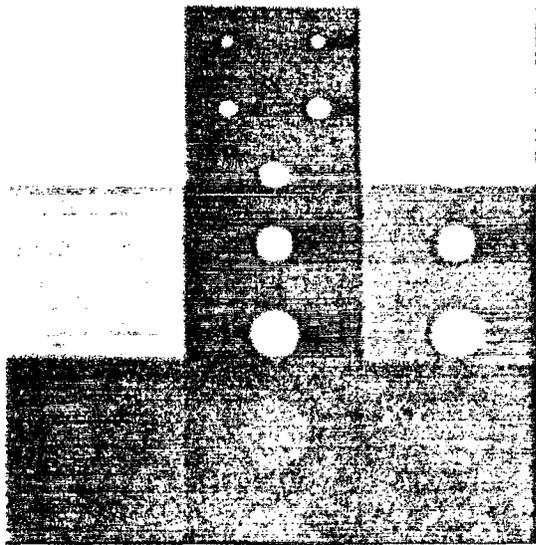
Type of Radiography	Observations
x-ray	All holes were evident, the poly block was very dark with the smallest holes barely visible from background, there was good contrast between the blocks, observable contrast changes between the sections with different thicknesses of poly
thermal neutron	1.25 cm poly: could clearly observe all holes in poly and steel blocks, no holes can be seen in the Al block, density of blocks are as expected 2.5 cm and 5 cm poly: no holes are observable, no differentiation between the 3 blocks
epithermal neutron	1.25 cm poly: holes observable in all 3 blocks, 0.159 cm holes are very weak, good differentiation between all 3 blocks 2.5 cm poly: holes clearly observable in poly and steel blocks, no holes can be seen in the Al block, could barely differentiate between the poly and Al blocks, could not differentiate between poly and steel blocks 5 cm poly: no holes are observable, could not differentiate between the 3 blocks
fast neutron	All holes down to 0.159 cm are observable in all 3 blocks, the 0.119 cm and 0.079 cm holes are also observable in the steel block, the 0.119 cm hole can also be seen in the poly block, the small holes in the Al block are faintly observable - realistically, these holes are not detectable, good contrast between all 3 blocks



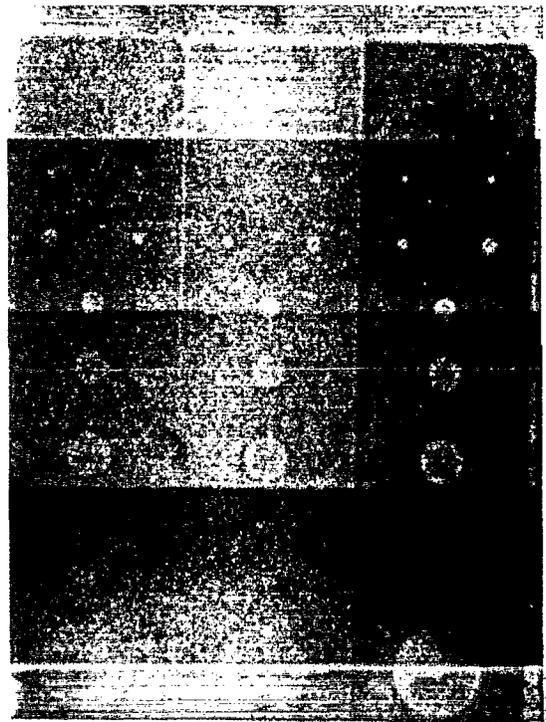
(a)



(b)



(c)



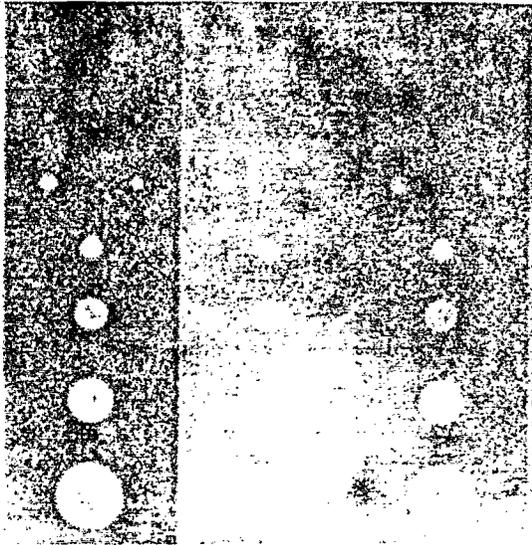
(d)

Figure 3: Radiographs of resolution test pieces through varying thicknesses of steel and polyethylene- (a) x-ray, (b) thermal neutron radiograph, (c) epithermal neutron radiograph, and (d) 14.5 MeV neutron radiograph. The lower portion of each image is through 2.5 cm of steel and 2.5 cm of poly, the middle portion is through 2.5 cm of steel and 1.25 cm of poly, and the upper portion is through 1.25 cm of steel and 1.25 cm of poly. A fourth region may show at the top of some of the images. This region has no steel or poly between the source and samples.

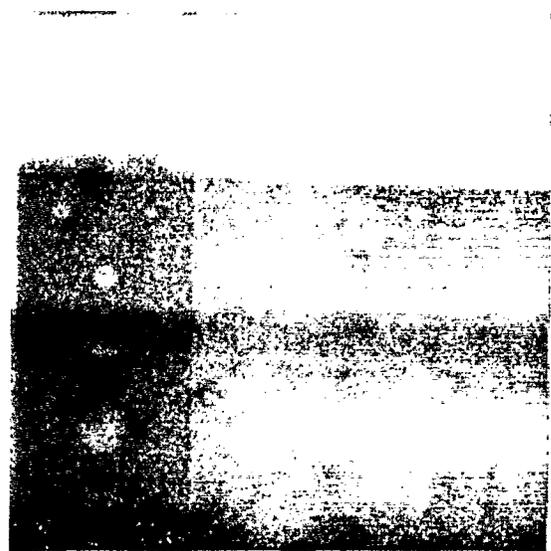
Table 3

Observations from Radiographs through Steel and Polyethylene (Figure 3)

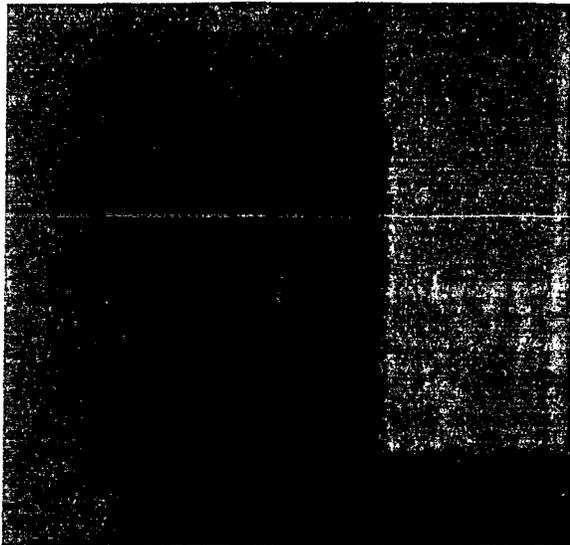
Type of Radiography	Observations
x-ray	All holes are observable through all combinations tested, the holes in the poly block are very faint for thicker steel-poly sections, clear differentiation between the blocks, for the uncovered portion the poly and Al blocks are blacked out whereas the holes were observable in the uncovered steel block
thermal neutron	1.25 cm steel - 1.25 cm poly: 0.318 cm holes faintly observable in poly and steel blocks, no holes can be seen in the Al block, differentiation between the blocks are faintly observable 2.5 cm steel - 1.25 cm poly: nothing observable 2.5 cm steel - 2.5 cm poly: nothing observable
epithermal neutron	1.25 cm steel - 1.25 cm poly: holes in poly and steel blocks are easily observable, no holes can be seen in the Al block, differentiation between the 3 blocks is easily observable 2.5 cm steel - 1.25 cm poly: holes in poly and steel block are observable, no holes can be seen in the Al block, differentiation between poly and Al block easily observed, differentiation between poly and steel block is observable but very weak 2.5 cm steel - 2.5 cm poly: nothing observable
fast neutron	Uncovered portion: the 0.079 cm and 0.119 cm holes can be seen in the steel block but not in the poly and Al blocks 1.25 cm steel - 1.25 cm poly: clear differentiation between all 3 blocks, all holes \geq 0.159 cm are observable, the holes in steel block are clear, the 0.159 cm hole in poly is very weak and the 0.238 cm hole and 0.159 cm hole in Al block are weak 2.5 cm steel - 1.25 cm poly: all holes are clearly observable in all 3 blocks, very weak differentiation between poly and Al blocks, clear difference between poly and steel blocks 2.5 cm steel - 2.5 cm poly: all holes clearly observable in all 3 blocks, no differentiation between poly and Al blocks, clear differentiation between poly and steel blocks



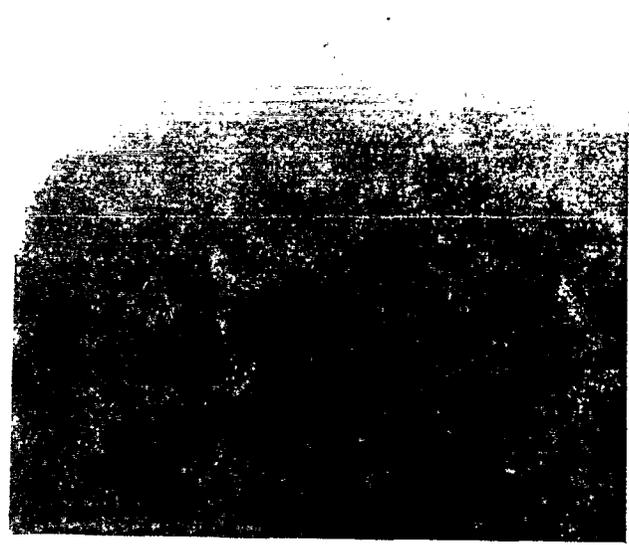
(a)



(b)

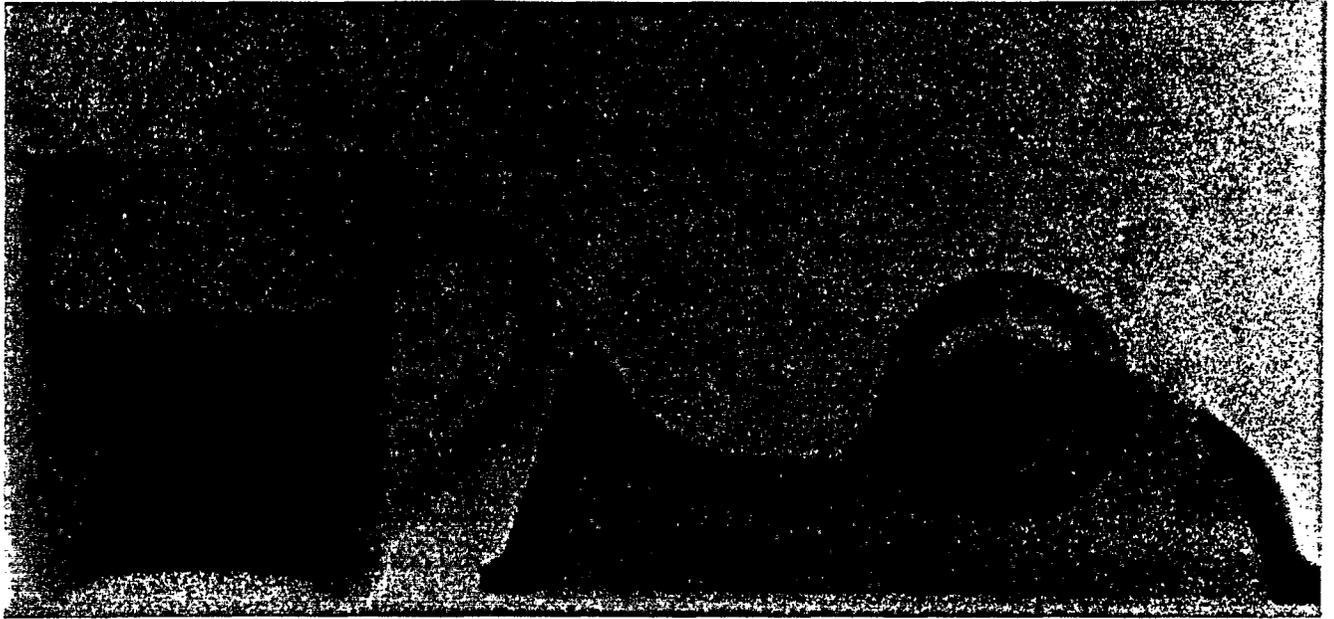


(c)

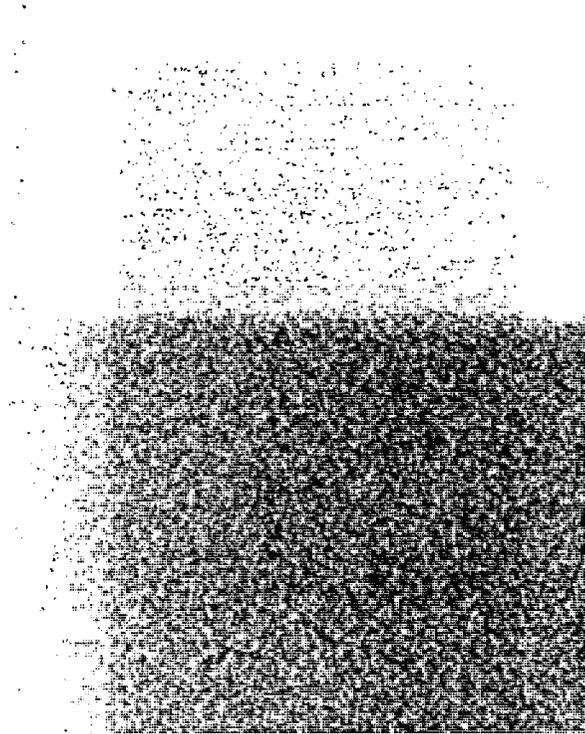


(d)

Figure 4: 14.5 MeV neutron radiographs. (a) test pieces shot through 1 cm of cadmium. (b) test pieces shot through 15 cm of steel (lower portion), 15 cm of poly (middle portion), and 2.5 cm steel - 2.5 cm poly - 0.625 cm aluminum (upper portion). (c) test pieces shot through 30 cm of borated poly. (d) radiograph of hafnium sponge in a sealed container. The container was filled with argon and has been sealed since 1965. Radiograph (d) was shot using DuPont Quanta® Super Rapid screens with DuPont Cronex® 10TL film.



(a)



(b)

Figure 5: 14.5 MeV neutron radiographs. (a) radiograph of a tape dispenser and coffee mug. The coffee mug is filled with water and has a steel spoon in it. (b) radiograph (viewed from side) of a steel container wrapped with 0.5 cm of cadmium. The steel container is filled with water (water line evident) and has a steel block (2.5 cm) in the water. Both of these radiographs were shot using DuPont Quanta® Super Rapid screens with DuPont Cronex® 10TL film.

Table 4

Observations from Fast Neutron Radiographs (Figures 4 and 5)

Object Being Radiographed	Observations
Steel, aluminum, and poly resolution test pieces shot through 1 cm of cadmium (Figure 4a)	Images clearly show all holes down to 0.159 cm, good differentiation between steel and poly blocks, weak differentiation between poly and Al block, 0.119 cm hole shows in steel block
Resolution test pieces shot through 15 cm of steel (lower portion of Figure 4b)	Edges of holes are weakly observable in all 3 blocks, reasonable differentiation between the 3 blocks
Resolution test pieces shot through 15 cm of poly (middle portion of Figure 4b)	Holes are clearly observable in the steel block, holes in the poly and Al block are observable, the edge distortion of the poly blocks covers the smaller holes, Clear differentiation among the 3 blocks
Resolution test pieces shot through 30 cm of borated poly (Figure 4c)	Holes down to 0.95 cm in steel block are faintly observable, distortion penumbra becomes extreme due to scattering, clear differentiation between steel and poly blocks
Hafnium sponge in a sealed container (Figure 4d)	Details of the hafnium sponge are visible, the sponge appears to be a very porous material made up of fragmented pieces 2 to 3 cm in diameter
Coffee mug filled with water with a steel spoon in it and a steel tape dispenser with tape (Figure 5a)	The steel spoon can be seen within the water inside the coffee mug, the density of the spoon is consistent above and below the water line in the mug, Both the plastic components (tape and ring inside tape roll) and steel components are visible in the tape dispenser, the small serrated metal tape cutter also shows clearly in the radiograph along with details of the tape roll
Steel block (2.5 cm thick) in water (25 cm) inside a steel container wrapped with 0.5 cm of cadmium (Figure 5b)	The edge of the steel block can clearly be seen above and below the water line

Conclusions

As shown in the radiographs, x-rays are useful for viewing through poly and less than 2.5 cm of steel. x-rays are probably the preferred method in these cases as they provide the best resolution and clearest images. However, x-rays cannot penetrate 5 or more cm of steel to provide a useful image. The x-rays provided good images for all combinations of steel and poly tested. Several of the drawbacks of x-rays are: 1. in showing details in poly and steel simultaneously, usually the contrast between poly and steel is too extreme, i.e. steel is white while poly is black, and 2. x-rays cannot show details through 5 cm of steel or 2.5 cm of steel with 2.5 cm poly simultaneously with uncovered sections. The contrast is too great; the thinner sections get burned out before detail in the thicker sections is evident. The key is that contrast between high Z and low Z materials is too extreme for x-rays, therefore, large changes in density or material cannot be viewed simultaneously with x-rays due to a large change in the mass attenuation coefficient, μ/ρ . Whereas, for fast neutrons the total cross-section does not vary significantly so these regions can be viewed simultaneously. This is observed in the radiographs as holes can be observed through 5 cm of poly or steel and can still be observed in the uncovered sections.

Thermal neutron radiography (TNR) is not useful when the poly thickness is 2.5 cm or more. Scattering from the poly becomes too large of a contributor to exposure and details within the sample are lost. TNR is only marginally useful when the poly thickness is 1.25 cm, that is, only very large differences in cross-section can be observed. TNR is also very marginal when the steel thickness is 5 cm or more. It can be useful for steel thicknesses of 2.5 cm, and is very good when the steel thickness is 1.25 cm or less. TNR is also a preferred method when the steel thickness is 1.25 cm or less. TNR did not produce useful images when the sample contained 1.25 cm of poly and 1.25 cm of steel or more.

Results of epithermal neutron radiography (ENR) are similar to FNR except that the penetrability is improved. ENR is useful for viewing through 1.25 cm of poly whereas TNR was only marginally useful. ENR still does not produce any images when the poly thickness is 5 cm or more. In addition, ENR is marginal for steel thicknesses of 5 cm or more, but is good for steel thicknesses of 2.5 cm, and is very good for steel thicknesses of 1.25 cm or less. ENR can also be used to view composite samples that contain 1.25 cm of steel and 1.25 cm of poly, and is also marginally useful for thicker samples

Figures 1-3 demonstrate the usefulness of fast neutron (14.5 MeV) radiography (FNR) over the other types described previously. In all cases, the holes in the resolution test pieces were observable. For a given radiograph, the holes were evident in the uncovered samples as well as in the thicker portions which contained as much as 5 cm of steel, poly, or steel-poly combination. In addition, the holes were evident in all three of the test pieces not just one material or another. FNR allows gross defects to be viewed simultaneously in a broad range of materials from low atomic number materials to higher atomic number materials. Figures 4 and 5 expand the range of usefulness of FNR beyond other types of radiography. Images were produced through as much as 15 cm of steel or poly, and marginally useful

images were produced through as much as 30 cm of borated poly. It is clearly demonstrated that cadmium has little effect on FNR and can be viewed through with little or no loss in image resolution. The most telling radiograph is that of the steel block in water inside a cadmium wrapped steel container. The outline of the steel block is apparent in the FNR, whereas, no other form of radiography tested could produce a useful radiograph. The cadmium and water are problems for TNR and ENR, and the cadmium and steel are problems for x-rays.

It is also apparent from the radiographs that polyethylene, aluminum, steel, and water agree with the predictions made by Richardson (Ref. 9) for film contrast vs. sample thickness. This prediction is also the reason why it becomes increasingly difficult to discriminate between the test pieces as more and more material is placed in front of them. As the total sample thickness is increased, the difference in the term, $A^{1/3}/\rho$, between the samples decreases.

FNR is not without drawbacks. It is apparent in the radiographs that the image resolution is not as good as other forms of radiography. The best resolution that could be obtained was 0.079 cm. However, applications of FNR typically include viewing much thicker objects which simply cannot be viewed by other forms of radiography, whereas, any resolution is beneficial. The resolution obtained is not as good as the 0.1 mm that J.S. Brzosko claims (Ref. 10). However, the claims made in reference 10 are based on monte carlo calculations only and are not supported by data from actual radiographs. In addition, the resolution obtained is better than any previously obtained. (Ref.1-9)

Acknowledgement

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