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A SYSTEM FOR FAST NEUTRON RADIOGRAPHY

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DISCLAIMER

A SYSTEM FOR FAST NEUTRON RADIOGRAPHY

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A system has been designed and a neutron generator installed to perform fast neutron radiography. With this system, objects as small as a coin and as large as a 19 liter container have been radiographed. The neutron source is an MF Physics A-711 neutron generator which produces 3 x 10^{10} neutrons/second with an average energy of 14.5 MeV. The radiography system uses x-ray scintillation screens and film in commercially available light-tight cassettes. The cassettes have been modified to include a thin sheet of plastic to produce protons from the neutron beam through elastic scattering from hydrogen and other low Z materials in the plastic. For film densities from 1.8 to 3.0, exposures range from 1.9 x 10^7 n/cm^2 to 3.8 x 10^8 n/cm^2 depending on the type of screen and film. The optimum source-to-film distance was found to be 150 cm. At this distance, the geometric unsharpness was determined to be approximately 2.2-2.3 mm and the smallest hole that could be resolved in a 1.25 cm thick sample had a diameter of 0.079 cm.

INTRODUCTION

Radiography was first invented in 1895 with the discovery of X-rays by Roentgen. Radiography utilizing neutrons was first developed in the 1930's and 1940's by Kallman and Kuhn using a small accelerator source. The methods and processes developed by these researchers outlined in a 1948 publication are still being used today to perform thermal neutron radiography.[1] Although thermal neutron radiography has been thoroughly developed and is commercially available, fast neutron radiography has not been developed as extensively.

Prior to 1970, fast neutron radiography was explored by several researchers.[2-5] It was reported by Berger that fast neutron radiography with activation foils is possible.[2] Since the 1960's and early 1970's, researchers in the United States and Japan have continued to investigate fast neutron radiography. The research has focused primarily on fast neutron radiography at neutron energies at or below 1 MeV, as there is only one reference cited since 1972 to neutron radiography being performed at neutron energies near 14 MeV.[6] Richardson used calcium tungstate scintillator screens to obtain some reasonable 14.5 MeV neutron radiographs of objects such as a transistor radio, a flashlight, a cigarette lighter, and screws.[6] With the advent of stronger neutron sources and a wider array of scintillator and converter screens in recent years, fast neutron radiography has been examined at Argonne National Laboratory (ANL) and enhanced to the point of being useful for radiographic applications.

SYSTEM DESCRIPTION

General System

The neutron source and radiography system are installed in a small shielded room located below grade. The walls of the room are 1.8 meters thick consisting of boron impregnated concrete (0.16 wt% boron). The ceiling is 0.6 meters thick of concrete impregnated with boron (0.33 wt%) and then backfilled by 2.8 meters of gravel. The room has a shaft allowing samples to be lowered from the room above. Entrance to the room is restricted and requires manually opening a large shield door which glides on air bearings.

The radiography system which includes a neutron generator, two support tables, a film cart, film cassettes, and lead shielding, is inherently simple but offers the widest range of flexibility in specifying process variables. Figure 1 shows the basic components of the system, however, the components necessary to support the operation of the neutron generator are not shown in the photograph.

The source-to-detector distance can be varied from 0.01 to 2.5 meters by moving the film cart along a track mounted on the sample table. A ruler is affixed to the table adjacent to the track for direct indication of the source to image distance. The film cart uses two adapters- one to hold 18x43 cm cassettes and one to hold 35x43 cm cassettes. The adapters hold the cassettes in either a vertical or horizontal position with the center of the cassette in line with the neutron generator. The sample

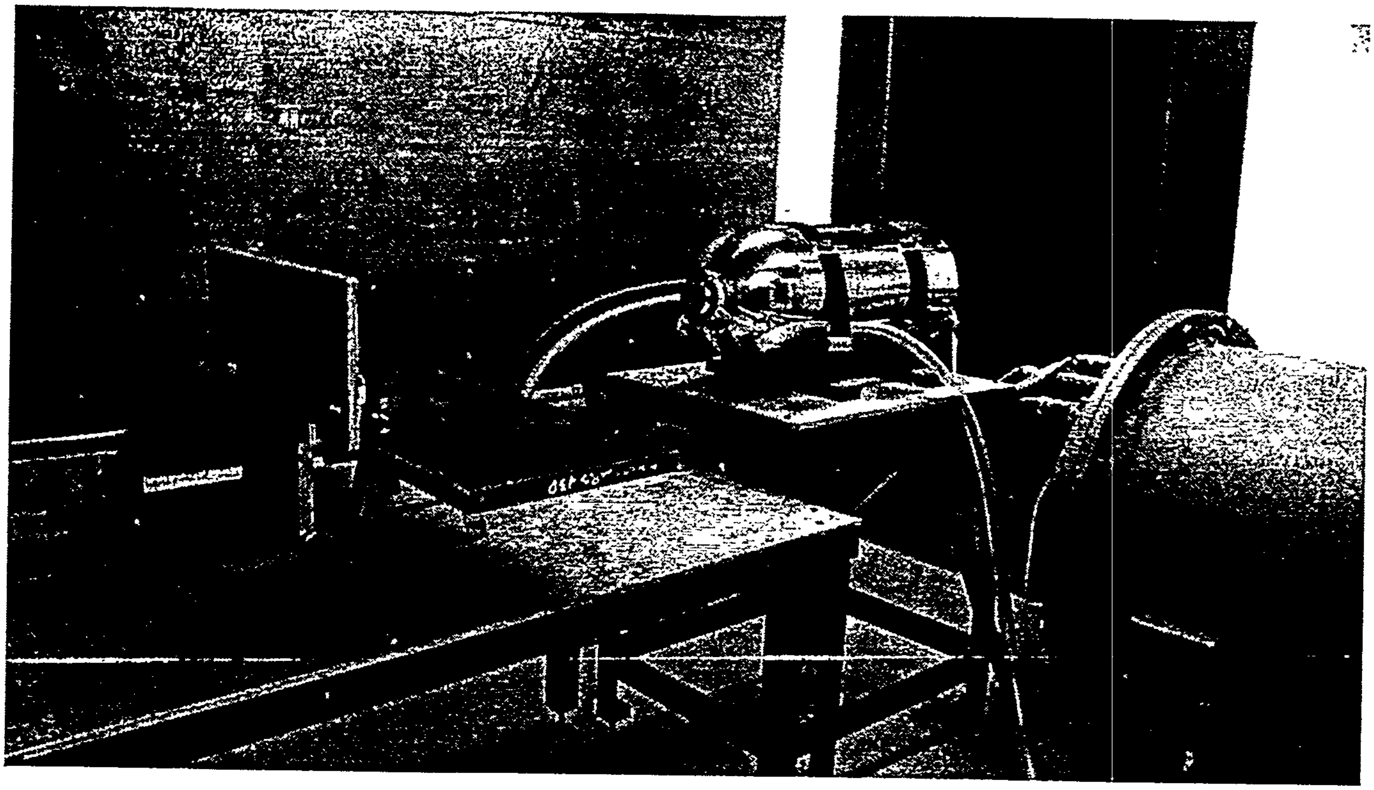

FIGURE 1. Fast neutron radiography system located in the north radiography station cell at Argonne National Laboratory

table can handle reasonably large objects and loads up to 250 kg.

Operation of the system is very simple. To radiograph an object: 1. the neutron generator operating parameters are set, 2. the film cassette is loaded in a darkroom, 3. the object is placed on the sample table, 4. the film cassette is placed on the film cart, 5. the film cart is positioned behind the sample, 6. the room is secured, 7. the neutron generator is operated for a specified time, and 8. the cassette is removed and taken to the darkroom for processing.

Neutron Source

The neutron source is a Model A-711 continuous yield neutron generator manufactured by the MF Physics Corporation. The neutron generator utilizes the $H^3(d,n)He^4$ reaction in a miniature sealed tube accelerator to produce a high output of fast neutrons from a collision of a mixed beam of deuterium and tritium ions with a deuterium-tritium loaded target. The neutron generator head (shown in the photograph) contains a Penning ion source, gas occlusion filaments, a scandium tritide/deuteride target and focusing and accelerating electrodes. Also shown in the photograph is a pressurized enclosure which contains the high voltage power supplies and a full-wave voltage doubler. The balance of the system is located outside the room and includes a control console and a closed loop cooling source that uses clean tap water to cool the target and freon-113 to cool the ion source.

The average neutron energy was determined by measuring the ratios of saturation activities and comparing them to the ratios of the cross-sections for the following reactions: (1) $Ni^{58}(n,p)Co^{58}/Ni^{58}(n,2n)Ni^{57}$, and (2) $Al^{27}(n,\alpha)Na^{24}/Ni^{58}(n,2n)Ni^{57}$. Based on these measurements, the average neutron energy was found to be 14.55 ±0.09 MeV. Using the same reactions, the source was found to produce 2.98×10^{10} ±8.1% neutrons/second at an operating voltage of 150 kV and beam current of 2.5 mA.[8]

Radiography Cassettes and Recording Media

Three different types of film cassettes are used - DuPont Cronex®, Kodak X-Omatic®, and spring-loaded aluminum cassettes that are used at ANL for thermal neutron radiography. The cassettes are loaded with two scintillating screens -one in front and one behind the film. Numerous scintillating screens were tested before Kodak Lanex® Fine screens were selected.[9] These screens were found to offer the best resolution although several artifacts from the screen are apparent on the radiographs in the form of small slightly darker patches or spots as shown in

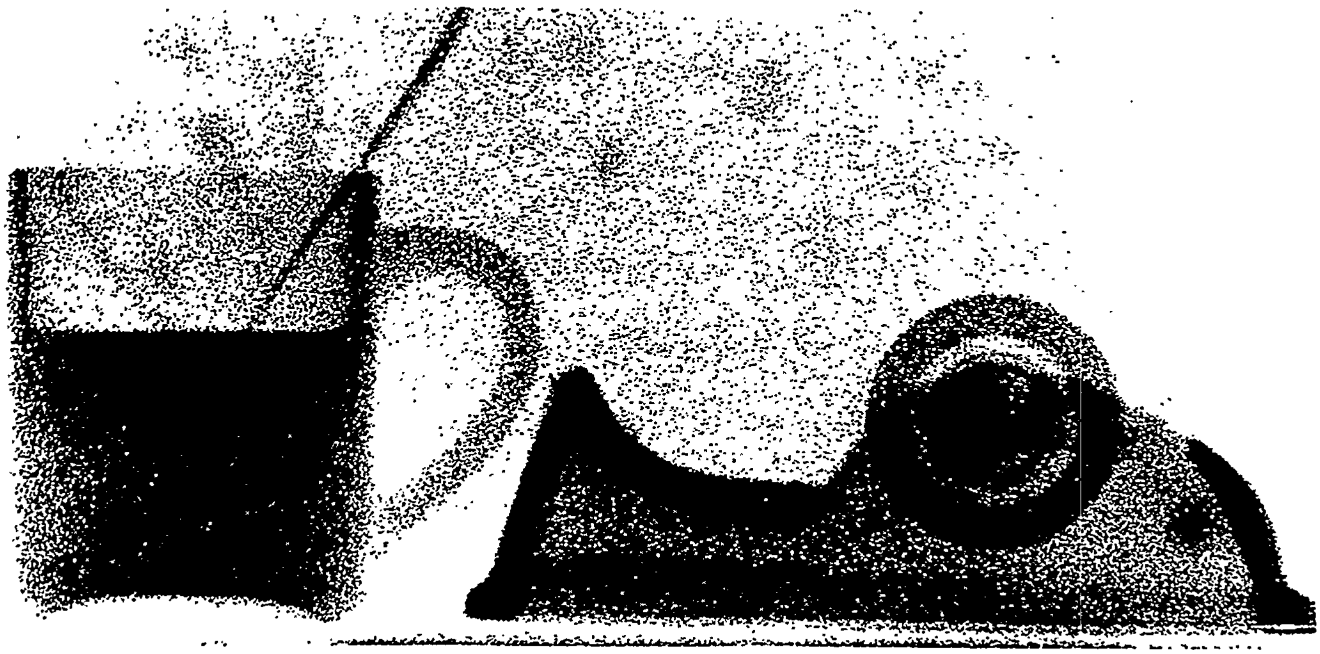

FIGURE 2. Radiograph of a tape dispenser and coffee mug taken with the FNR system at a distance of 150 cm. Exposure time was 15 minutes using Kodak Lanex® Fine screens with Kodak TMG film. Film processing time was 2 minutes.

TABLE 1. Geometric Unsharpness and Enlargement at L=150 cm

Object	w	L_s	L_f	E_g	M_R	U_g
5 cm steel block	50.8	1449.2	50.8	0.89	57	2.2
10 cm steel block	50.8	1402	98	1.78	59	2.3

Fig. 2. A thin (1.5 mm) piece of plastic is placed between the front of the cassette and the front screen. The plastic serves as a proton source by elastic scattering from hydrogen and other low Z materials in the plastic. This plastic sheet is essential, as without it, the exposure times are excessive.[9]

RADIOGRAPHIC PARAMETERS

Geometric Unsharpness and Enlargement

When a radiograph is produced, a certain amount of distortion occurs. The distortion is a combination of geometric enlargement due to the object generally being larger than the source aperture and geometric unsharpness due to the distortion penumbra caused by a finite aperture size. The length to diameter (L/D) ratio is widely used as a simple means of characterizing the collimation of a system. The L/D ratio directly determines the resolution of the system. The resolution, or geometric unsharpness, is defined as $U_g=(D/L_s)\cdot L_f$ where L_f is the image to object distance, D is the source aperture size, and L_s is the source to object distance.[7] However, in an uncollimated system, the L/D ratio is no longer meaningful and the geometric unsharpness has to be determined from measurements. For a point source, the geometric enlargement is defined by $E=(w/2L_s)\cdot L_f$ where w is the width of the object. By measuring the size of an image on a radiograph compared to the actual size of the object, the geometric unsharpness can be determined by $U=[(M_R-w)/2] - E_g$ where M_R is the width of the image on the radiograph as measured to the edge of the distortion penumbra. Measurements for the fast neutron radiography system determined the geometric unsharpness to be approximately 2.2-2.3 mm as shown in Table 1. The geometric unsharpness is considerably worse than values for thermal neutron radiography with L/D ratios greater than 10, but it must be remembered that this is an uncollimated system.

Exposure Rate

The plane of radiography can be varied as mentioned previously, however, 1.5 m was found to be the optimum source-to-film distance when considering exposure time vs. image clarity. An exposure of 3.7×10^8 n/cm^2 is needed to produce a radiograph with a density of 1.8 using Kodak Lanex® Fine screens with Kodak TMG general radiography film.[9] At 1.5 m, the neutron flux is 4.2 x 10^5 n/cm^2-sec which results in an exposure time of 15 minutes. It should be noted that the DuPont Cronex®, Quanta®, and UV® screens require considerably less exposure 1.9 x 10^7 n/cm^2 to 1.3 x 10^8 n/cm^2 for film densities between 2.2 and 3.0 (exposure time of 3 minutes) at the price of image resolution.[9]

BENEFITS AND LIMITATIONS OF FAST NEUTRON RADIOGRAPHY

Fast neutron radiography can offer a glimpse at the internals of objects where other traditional non-destructive analysis techniques fail. Thick objects, such as 19 liter steel containers, have been probed with this system. In addition, it has been used to probe materials that are traditionally used as absorbers or shields for thermal neutrons and gamma rays like borated polyethylene, cadmium, hafnium, steel, lead, polyethylene, water, and concrete.[10]

One immediate benefit over other forms of radiography is apparent in Figure 2. The radiograph shows a steel tape dispenser and a mug filled with water with spoons in it. Looking at the tape dispenser, it is evident that both the steel and plastic objects are clearly shown. Other forms of radiography only show detail in one material or the other. In this radiograph, considerable detail shows in the center of the tape through the dispenser and above it. The image of the mug clearly shows the water level in the mug, the hollow bottom of the mug, and the outline of the metal spoon in the water. The same result occurred when radiographing a steel can filled with water in which steel, aluminum, and poly objects were placed in the can.[10] Based on these results, fast neutron radiography offers significant advantages over other forms of radiography- such as thermal neutron, epithermal neutron, x radiography, and gamma radiography. In addition, this radiograph was shot through a 0.5 mm thick piece of cadmium. Other fast neutron radiographs were produced through as much as 2.5 cm of cadmium with no loss of image clarity or film density.[10] This clearly demonstrates a useful benefit of fast neutron radiography over thermal neutron radiography in that fast neutrons can penetrate thermal neutron absorbers, such as cadmium, gadolinium, or boron, which thermal neutrons and x rays cannot penetrate.

CONCLUSIONS

Fast neutron radiography has been developed at Argonne National Laboratory to the point of being useful for producing radiographs. This system can be easily modified for industrial applications, by relocating the system under the specimen shaft so that large samples can be more easily placed on the sample table, and by including a remotely operable film changer so that personnel do not have to enter the room to switch film cassettes.

Fast neutron radiography has been shown to be a useful tool for non-destructive analysis where other more traditional techniques have failed. Also, since cross-sections vary differently with energy, fast neutron radiography can be used as a complement to other forms of radiography that are commercially available.

ACKNOWLEDGEMENTS

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