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UCRL-51906

THE NEUTRON RADIOGRAPHIC FACILITY AT THE 3-MW LIVERMORE POOL-TYPE REACTOR

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September 10, 1975

MASTER

Prepared for U.S. Energy Research & Development
Administration under contract No. W-7405-Eng-48

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Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$ *; Microfiche \$2.25

<u>*Pages</u>	<u>NTIS Selling Price</u>
1-50	\$4.00
51-150	\$5.45
151-325	\$7.60
326-500	\$10.60
501-1000	\$13.60

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University of California/Livermore, California/94550

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THE NEUTRON RADIOGRAPHIC FACILITY AT THE 3-MW LIVERMORE POOL-TYPE REACTOR

Abstract

This report describes the neutron experimental radiographic facility at the Livermore Pool-Type Reactor. This facility was installed in 1974 to assist Lawrence Livermore

Laboratory research programs. Some of the testing techniques used to modify the neutron beam and the present radiographic parameters are also discussed.

Introduction

The Livermore Pool-Type Reactor (LPTR) is an intermediate-power research reactor used in support of Lawrence Livermore Laboratory (LLL) research programs. It is an open-tank reactor, moderated and cooled by light water, with an operating power level of 3 MW. Irradiation facilities include two thermal columns, six horizontal beam ports, four S-tubes, and various in-core irradiation apparatus.¹

In 1974, a neutron experimental radiographic facility (NERF) was installed in the LPTR to assist various LLL research programs. The purpose of this report is to describe the facility, some of the testing techniques used to modify the neutron beam, and the present radiographic parameters.

Neutron radiography is a non-destructive inspection technique. It is very similar in principle to x-ray radiography. Both methods utilize penetrating radiation (neutrons, x-rays), detected and registered on a suitable imaging system, to obtain a visual image.

Neutron radiography and x-ray radiography complement each other. Figure 1 shows that when the mass absorption coefficient is plotted as a function of atomic number the following occurs: for x-rays, the values increase smoothly as a function of atomic number; for neutrons, the values fluctuate from element to element.

Neutron radiography capitalizes on the attenuation differences between x-rays and neutrons. It allows a

Fig. 1. Comparison of neutron radiography and x-ray radiographic adsorption coefficients.

contrasting image to be obtained for elements of similar Z . Also, low Z elements can be imaged even when shielded by large thicknesses of high Z material.

The basic neutron radiography system consists of a neutron source, a moderator and collimator system, and an imaging system. The neutron source for the LLL system is the LPTR core. The neutron energy utilized is thermal (0.025 eV). The moderator-collimator system is described in this report. Various imaging systems

are available and the one used depends on the experimenter's needs.

The radiographic system can be used in either the direct or transfer exposure mode. Both utilize a converter screen. This screen changes the neutron image to ionizing radiation, which is detectable by x-ray film.

In the direct exposure method, the converter screen is a plate coated with a 0.025-mm-thick layer of gadolinium. The gadolinium promptly emits a predominantly soft gamma ray

spectrum and internal conversion electrons upon neutron capture. The 70-KeV electrons are most instrumental in forming the image. The converter and x-ray film are placed inside a 35.6-cm $\times$ 43.2-cm vacuum cassette and placed in the NERF beam behind the object (see Fig. 2). This method's advantages are: it has the highest resolution and the fastest speed currently possible, and the screen can be re-used immediately following an exposure. The disadvantages are: x-ray film is exposed to beam gammas and blemish-free screens are difficult to obtain and very expensive.

The transfer exposure method is shown in Fig. 3. It differs from the direct method in that the x-ray film is not exposed to the neutron beam. The transfer method is used when the object is radioactive or the neutron beam contains a high proportion of

gamma rays. A converter screen is used that retains radioactivity for a period of time. Two commonly used screens are indium and dysprosium, whose half-lives are 3240 and 8400 s, respectively. These foils are placed behind the object and irradiated in the neutron beam for several half-lives. They are then removed from the beam and placed adjacent to an x-ray film in a lighttight cassette for three or four half-lives of the converter foil. The advantages of the transfer method are: the film is not exposed to beam gamma or detrimental radiation from the object, and higher contrast may be obtained. The disadvantages are lower resolution, longer turn-around time (because the screen must decay to prevent a latent image), and more than one exposure is usually required to cover a complete object. This is because large converter screen foils are not readily available.

Fig. 2. Imaging system for direct exposure method.

Fig. 3. Imaging system for transfer exposure method.

Both methods are used at the LPTR depending on the nature of the object and the experimenter's need. For both methods, Kodak^{*}

Industrial type R (single-coated) x-ray film is used. This film has ultrafine grain and yields high contrast.

Facility Description

GENERAL LAYOUT

The NERF is located in the thermal column of the LPTR. Figure 4, a cross-sectional plan view of the reactor, indicates its location with reference to the reactor core. The NERF centerline is 22.9 cm below the core centerline and 12.2 cm beyond the edge of the beryllium reflector elements. This location for the NERF line of sight was dictated by the existing beam tubes and other facilities. A stepped hole in the thermal column graphite allows neutrons to pass from the reactor pool to the radiographic cave.

The NERF collimator is inserted into this hole. The collimator may be changed, so a tube fabricated from aluminum alloy 1100 sleeves the hole. The tube surface is more wear-resistant than graphite. This simplifies the collimator alignment and

eliminates possible contamination by graphite dust. The tube has a square cross section and is stepped in 10.1 cm multiples to match the size of the thermal column cavity. Figure 5 is an elevation view of the entire facility. Proceeding from the reactor pool, the order of items is:

- collimators
- inner shutter
- neutron shutter
- inner cave door
- outer shutter
- radiograph cave
- beam stop
- outer cave door

These items and related systems are described in detail in this section.

COLLIMATORS

The collimator design was dictated by geometric considerations. The largest possible beam area and high resolution were desired. Because of the NERF's proximity to another facility at the rear of the inner cave

^{*}Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research & Development Administration to the exclusion of others that may be suitable.

Fig. 4. Cross-sectional plan view of the LPTR reactor showing the location of NERF with reference to the reactor core.

door, beam diameter was limited to 60.0 cm.

The film plane location can be varied from 40.0 to 95.0 cm behind the inner cave door. With the present aperture diameters of 12.7 and 17.2 mm, this provides geometric beam resolution ranging from 190 to slightly over 300. The maximum beam divergence half angles are 5.07° and 4.92° , respectively. The geometric beam resolution (L/D) is defined as the aperture to film distance divided by the aperture diameter.

The collimator internal shape is a divergent cone. The external shape corresponds to the square cross section of the sleeve in the thermal column graphite. The collimator

was partitioned into three pieces to make the fabrication and installation easier (see Fig. 6). With this design, the portion containing the aperture can be made small, as shown in Fig. 7. To change the beam resolution, the collimator section containing the aperture is withdrawn. The forward end of the cone may then be removed or added to, as appropriate. Thus, the divergent angle remains fixed and the remainder of the collimator is not disturbed. An alternate method, which is sometimes easier, is to replace the collimator section with a new one.

The collimator's sides are encased with aluminum alloy 6061 to facilitate fabrication and handling.

Fig. 5. NERF elevation view.

Fig. 6. NERF collimators.

Fig. 7. Aperture collimator and plugs.

The shielding material is a mixture of pig lead, 99.99% pure with 3.5 to 4.0 wt% plating-type cadmium, 99.99% pure. Cadmium was selected as the neutron absorber for economic reasons and because it can be homogeneously mixed with lead. Cadmium's lack of a large absorption cross section

in the epithermal and higher energy region was not considered detrimental. The neutron energy in the thermal column and pool water is predominantly thermal. The 3.5 wt% cadmium loading essentially eliminates thermal neutron transmission through the collimator shielding. It also provides adequate protection against burnout of the absorber. Based on the LPTR's present operating schedule (32 hr/wk for 50 wk/y) and the highest thermal flux seen (2×10^{11} n/cm²-s), it will take at least 4 y to burn out 25% of the cadmium. At that time, the transmission for a centimeter thickness of the Pb/Cd mixture would have increased from about 0.5 to 2.0%.

In the design phase, it was felt that the prompt gamma rays from neutron capture in the cadmium and subsequent radioactive decay gamma rays would not affect the gamma content of the beam at the film location. According to the ASTM Image Quality Indicator report,³ low energy gamma rays up to 200 or 300 KeV are the most detrimental to film quality. Examination of cadmium's prompt gamma ray spectrum⁴ indicates that there are approximately 40 gamma rays released in the energy region below 300 KeV per 100 neutron captures. However, the collimators are primarily to prevent neutrons from the thermal column graphite entering the beam.

Therefore, most of the neutron capture and resulting prompt capture gamma rays would originate at the collimator outer surface. The Pb/Cd mixture would attenuate these gammas before they entered the cone of the collimator. It was anticipated that some higher energy gammas would interact and be scattered into the energy range of interest; however, there was no easy way to determine this contribution. The 2.3-m distance between the end of the collimator and the film plane also would diminish the effect of the capture gamma rays on the film.

The amount of neutron capture along the inner surface of the collimators was expected to be minimal. The initial collimator design had a short converging cone before the aperture. In addition, the aperture section was surrounded for its entire length by Pb/Cd shielding. This in essence limited the neutron source to a region in the pool. Therefore, neutrons passing through the aperture were already aligned by virtue of a tube-like collimator 5.7 cm in diameter by 38.1 cm long. After the NERF became operational, the converging cone was removed and the forward shielding was replaced by graphite. This was an effort to increase the thermal neutron flux and cadmium ratio. It was not a successful effort

but did provide the knowledge that the effective neutron source is in the pool. Very little, if any, thermal neutrons come from the thermal column graphite. The defining aperture for the 12.7-mm-diameter collimator is a sheet of 0.51-mm-thick, 99.99% pure gadolinium metal. Its effective life is about 40 wk based on the previously stated flux and operating schedule. At that time it will have burned out and must be replaced in order to maintain a constant aperture size. The 17.2-mm-diameter aperture has a 0.76-mm-thick sheet and has a life expectancy of 62 wk. Gadolinium was selected as the aperture material because its use compliments the gadolinium conversion plate. In other words, very few neutrons of energies that interact with the conversion plate would be transmitted through the aperture plate.

SHUTTERS

The NERF has an inner shutter, a neutron shutter, and outer shutter. These shutters were designed in the inverse order of what one might expect. Due to scheduling considerations, the outer shutter was designed and fabricated first. The gamma dose rate at the shutter surface was determined with several thermoluminescent detectors to be 5400 rem/hr.

The gamma energy spectrum was assumed to be identical to the Bulk Shield Reactor prompt fission gamma ray spectrum.⁵ Calculations indicated a dose rate of 40 mrem/hr could be expected behind a lead shield 20.3 cm thick. This value agrees with the background dose rate in the cave before the NERF was installed. It was presumed that the collimators and neutron shutter (when designed and installed) would decrease the primary gamma dose rate and this decrease would more than balance any increase due to capture gamma rays. Later results verified this assumption.

The outer shutter fits over the hole in the inner cave door. The shutter, shown in Fig. 8, is a lead disk 71.1 cm in diameter by 20.3 cm thick. It overlaps the exit diameter of the hole by 5.9 cm.

The neutron shield design was based on tests run in the early stages of the NERF installation. Neutron spectrum measurements made before the collimators were installed indicated a large portion of the neutron flux was high energy (see Table 1). To obtain an acceptable radiation exposure rate in the radiographic cave, it was necessary to slow down and capture the fast neutrons. Polyethylene was selected to moderate the neutrons to a thermal energy where they could be more

Fig. 8. NERF outer shutter.

readily captured. Polyethylene has a high hydrogen content, small activation cross section, reasonable radiation stability, and is easily shaped. Radiation damage was not expected to reduce the polyethylene's effectiveness until 1×10^4 J (1.1×10^9 rad). This corresponds to a life of about 50,000 hr for our facility. According to the literature, lead and or iron on the front face of the shield would be effective in reducing the fast neutron energies by inelastic scattering. The activation of iron and its 1.5-MeV decay gamma ray precluded its use even though it is more effective than lead.

Accordingly a rough shield of lead, boral, and polyethylene was

Table 1. Neutron spectrum.

Energy (MeV)	Flux (10^8 n/cm ² -s)		
	Without scatter box or collimation ^a	Scatter box and no collimation ^a	Collimation and no scatter box ^b
Thermal	Not measured	34.90	0.0230
0.01 - 0.60	4.10	6.20	0.03500
0.6 - 1.0	0.55	1.20	0.0124
1.0 - 3.0	0.84	0.93	0.0049
≥ 3.0	0.16	0.26	0.0020

^a Measured by rear face of graphite thermal column.

^b Measured at film plane.

made up and tested in the beam. Preliminary calculations indicated about 60 cm were required to reach an acceptable neutron dose rate. Two arrangements of the lead and polyethylene were tested. One with 10 cm of lead on the front face and the other with the lead in two 5-cm layers interspersed amongst the polyethylene. Although the transmitted neutron spectrums differed, the dose rates were equal. Subsequently, the neutron shield was designed as two shutters: an inner shutter for inelastic scattering purposes, and a neutron shutter for thermalization and capture. The inner shutter is a 6.4-mm-thick sheet of boral, 35 wt% boron carbide, backed by 98.6 mm of lead. It is located at the rear face

of the thermal column graphite and overlaps the collimator exit diameter by 10.3 cm and is shown in position in Fig. 9. This shutter has a dual purpose. Periodically, during a reactor shutdown, inspection and/or maintenance work is performed at the

Fig. 9. NERF inner shutter.

thermal column face. With the NERF unshielded, there is a 1- to 2-R/hr gamma ray beam from the hole. The inner shutter eliminates this "hot" spot. Its second purpose is to reduce the energy of the fast neutrons in the beam by inelastic scattering by the lead. The boral on the shutter face reduces the activation of any impurities in the lead.

The neutron shutter is located behind the inner shutter and consists of a box made from 6.4-mm-thick boral sheets. The box is filled with slabs of low density polyethylene with a total thickness of 66.0 cm. The neutrons are slowed down in the polyethylene and captured in the boral liner. In addition, the boral prevents thermal neutrons from external sources from adding to the polyethylene radiation dose. The shutter overlaps the hole in the inner cave door from a minimum of 6.2 cm to a maximum of 21.5 cm. The neutron beam diameter at the front face of the neutron shutter is 22.9 cm.

When all three shutters are in the closed position, the gamma and neutron dose rates at the rear surface of the outer shield are 6 mrem/hr and 75 mrem/hr, respectively. At the working position for personnel in the radiograph cave, the total dose rate is 35 mrem/hr.

SHUTTER DRIVE SYSTEMS

The inner shutter and neutron shutter are each operated remotely by an endless cable and pulley system. They are driven by reversible, fractional horsepower, gearmotors located in a low radiation area. The motors will open or close the shutters in 5.0 s. They are mounted on spring-loaded bases that maintain tension on the drive cables. This eliminates the possible problem of a slack cable jumping out of the pulley groove when the drive motor is reversed. The high radiation levels at the location of the shutters made it impractical to mount motors or cylinders that would drive the shutters directly.

The outer shutter is operated by a 15.2-cm-diameter air cylinder. It uses building compressed air at 689 KPa (100 psi). Because this shutter is located in the cave area, there is no radiation problem associated with its drive unit. The shutter closes on loss of air or electrical power. It opens in 5.0 s and closes in less than 1.0 s. The shutter speeds represent a compromise between what is desirable (zero) and what is practical for the distance and mass involved.

CAVE

The radiograph cave is a space 2.13 m high by 2.13 m wide by 1.34 m long. It is enclosed on two sides and the top by 1.22-m-thick blocks of high density magnetite concrete. The front wall is formed by the 1.02-m-thick inner cave door. The rear wall is the 61-cm-thick outer cave door. Both the doors are high density magnetite concrete. The doors are mounted on wheels which ride on rails flush with the floor. The doors are moved by a motor-driven chain that runs in a slot beneath the doors. The floor, roof, and two wide walls are lined with 6.4-mm-thick boral plate. The rear wall is covered by 3.2 mm of lead, 6.4 mm of masonite, and a layer of gadolinium oxide paint.

The lead covering was used to reduce the energy (current) albedo of gamma rays in the energy region below 300 KeV. A 3.2-mm layer of lead reduces the gamma backscatter by a factor of 70 over that of concrete. This reduction is somewhat diminished because the lead is covered by 6.4 mm of masonite. If the masonite is assumed to be similar to concrete in its albedo properties, then the reduction is a factor of 12. The reduction still occurs because of the

relative thinness of the masonite layer over the lead.

BEAM STOP

The beam stop is mounted on the outer cave door as shown in Fig. 10. Its main purpose is to reduce the back scatter of gamma rays and neutrons into the filming area. The beam diameter is 73.3 cm at the face of the beam stop. To provide the maximum space for the object to be radiographed, it was desirable to limit the beam stop depth to 40.6 cm or less. We used therefore a 91.4-cm square by 20.3-cm-thick block of 5.0%

Fig. 10. NERF beam stop and cassette holder.

boron-polyethylene placed against the outer cave door. It is faced with 12.7 mm of lead.

Radiographs have been taken with the cassette placed from 28 to 68 cm from the beam stop face. The effect of backscattering gamma rays and thermal neutrons has been negligible. We have not tried to determine if this is the result of separation distance or beam stop design. As an added benefit, the beam stop increases the outer cave door shielding to reduce the dose rate beyond the cave. This is especially advantageous when the shutters are all open during radiographing.

CONTROL SYSTEM

The radiation dose rate in the cave is very high when a shutter is open. Because of the potential of this hazardous situation occurring with personnel in the cave, there must be interlock circuits in the NERF control system. Also, there must be indicators to inform the operator of the status of the radiographic system. With these criteria in mind, the following safety items were provided.

- There is a remote area monitor head inside the cave with readout at the control panel

so that the operator can check the radiation level before entering the cave area.

- There is an emergency button which allows anyone inside the cave to open the outer cave door. There is also a call box inside the cave which allows contact with the reactor control room.
- The electronic control circuitry is such that the NERF shutters can only be opened when both the inner and outer doors are in their proper positions. If either door is out of position, the shutter power is off. If a shutter is open, the door power is off.
- The NERF control system is hooked to emergency power with redundancy designed into the safety circuit.
- The lead outer shutter closes on loss of air or electric power.
- There are indicator lights for all shutters and doors showing their position.

Figure 11 shows the NERF control console and radiation indicator.

Fig. 11. NERF control console.

Beam Characterization

The radiographic beam is composed of neutrons and gamma rays. The goals in neutron radiography are to maximize the thermal neutron flux and minimize the gamma and scattered neutron flux.

A variety of techniques were used to measure these beam constituents. A set of gold foils 0.06-mm thick were used to measure the neutron flux. A bare gold foil indicates total flux and a cadmium-covered gold foil indicates flux about 0.4 eV. A series of foils plus uranium, neptunium, indium, and sulfur pellets were used to obtain

the neutron spectra shown in Table 1. The detector assembly is shown in Fig. 12. The Beam Purity Indicator (BPI)³ was used to analyze the beam for thermal neutron content, scattered neutron content, epithermal neutron content, and low energy gamma content (energy less than 200 KeV). The BPI yields both quantitative and qualitative information concerning those components which contribute to film exposure and can affect the overall image quality.

The Visual Image Quality Indicator (VISQI)⁶ was also used.

Fig. 12. Flux detector assemblies.

The VISQI is sensitive to a wide range of neutron and gamma ray energies. It will reveal significant changes in radiographic performance due to changes in any of the following parameters:

- Inherent unsharpness of system
- Basic contrast of system
- Neutron/gamma ray ratio
- Neutron spectrum effect: thermal, resonance, fast
- Combined effects on resolution from scattered radiation, beam absorption, and geometric unsharpness
- Combined effects on contrast from scattered radiation, beam absorption, and geometric unsharpness.

The VISQI results are given in the number of contrast and resolution faults. Hence, a low value of each is desirable. The third indicator

used was the image quality indicator (SYQI).⁷ The purpose of the SYQI is to provide a simple yet quantitative evaluation of overall performance of new systems. A radiograph of the BPI, VISQI, and SYQI are shown in Appendix A. The BPI and VISQI show relative resolution and contrast characteristics. The SYQI is provided for comparison.

The first data was gathered shortly after the collimators were placed in the thermal column. The BPI, VISQI, and flux results are shown in the first data listing of Table 2. The thermal neutron flux and epithermal neutron content results are acceptable. However, the thermal neutron content and gamma content are unacceptable for high quality neutron radiography. There are no hard-and-fast requirements but generally the thermal neutron content should be above 60% and the gamma content below 2%. Exact values for these parameters depend on the object to be radiographed and what information is desired.

BEAM MODIFICATION

The first attempt to modify the NERF beam actually occurred before the collimators were installed. The initial neutron energy spectrum measurements (Table 1) indicated a

hard spectrum. It was felt that a moderator other than water would soften the spectrum. Accordingly, a scatter box was placed in the pool in the NERF line of sight. The scatter box is composed of graphite blocks and is about 37.0 cm thick on the NERF centerline. The resulting spectrum is shown in Table 1. As can be seen, the spectrum actually became harder and use of the scatter box was discontinued.

The collimator was then installed and the spectrum measurements repeated (see Table 1). The effect of the collimator, after making allowance for the different distances involved, resulted in reducing the fast flux by a factor of 20. The reduction in the thermal flux is estimated to be on the order of 250. This is the consequence of eliminating the thermal neutrons that originated in the thermal column graphite. Also, the collimator materials are much more effective in attenuating lower energy neutrons. Next, the beam was modified by inserting plugs of various materials and thicknesses on the core side of the gadolinium aperture. Graphite, lead, bismuth, and deuterium were tried. The object was to reduce the gamma flux without decreasing the thermal flux appreciably. The effects of the various materials are shown in Table 2. The results were not too

Table 2. Aperture plug - material vs BPI and VISQI readings.^a

Aperture plug (mm)	Thermal neutron flux (10^5 N/cm ² ·s)	Beam purity indicator reading (%)				VISQI _f reading
		n_{th}^b	n_{γ}^c	n_{ep}^d	n_{sc}^e	
Nothing in aperture	23	43	8	4.2	< 0.03	C = 9 R = 2 T = 11
Bismuth 25.4	7	55	6	5	1	C = 9 R = 2 T = 11
Bismuth 50	17	41	3	2	< 0.03	C = 10 R = 2 T = 12
Bismuth 102	12	37	4	1	< 0.03	C = 11 R = 2 T = 13
Lead 19	12	47	4	3	< 0.03	C = 13 R = 3 T = 16
Lead 50	51	37	6	2	< 0.03	C = 13 R = 2 T = 15
Lead 70	32	34	4.8	1	< 0.03	C = 13 R = 2 T = 15
Lead 83	24	34	3.7	1.4	< 0.03	C = 11 R = 3 T = 14
Deuterium 6.35	84	57	5.8	4.1	< 0.03	C = 9 R = 1 T = 10
Deuterium 25.4	47	48	9.4	5.0	< 0.03	C = 9 R = 1 T = 10
Deuterium 76.2	34	37	11.0	6.0	< 0.03	C = 10 R = 1 T = 11
Graphite 177.8	1	33	6	1.7	< 0.03	C R < 0.03 T

^a All readings were done with L/D = 265.^d n_{ep} = epithermal neutron content.^b n_{th} = thermal neutron content.^e n_{sc} = scattered neutron content.^c n_{γ} = gamma content. When values are over 5%, n_{th} is unreliable.^f C = contrast faults, R = resolution faults, and T = total faults.

encouraging. It was concluded that the gamma source was not in the pool region but in the thermal column graphite.

A 6.4-mm-thick lead sheet was placed over the entire rear face of the thermal column to attenuate the low energy gamma rays. A part of the rear face that could be "seen" at the cassette was covered with an additional 19 mm of lead. However, a large uncovered area of the thermal column remained that was visible to the cassette. It was then decided to place a lead filter directly in the beam to attenuate the gamma rays. Figure 13 indicates the effect of various thicknesses of lead on the gamma content, thermal neutron content and flux, and exposure time. Table 3 illustrates the corresponding effect on all the BPI and VISQI readings.

A 32-mm-thick lead filter is currently used. As shown in Fig. 13,

the thermal neutron and gamma content have leveled out at this thickness. The exposure time is increasing rapidly as a result of the decrease in thermal neutron flux. There is obviously no advantage in increasing the lead thickness further.

Since the lead filter provided good contrast without loss of resolution, the next test attempted to soften the neutron spectrum and perhaps increase the thermal neutron flux and cadmium ratio.

With this in mind, various plugs of deuterium were inserted into the aperture section of the collimator. Table 4 shows the results on the BPI parameters. Figure 14 shows the deuterium effect on the thermal flux and also compares the effect with that of lead and bismuth. From this data, it was decided to leave the aperture section empty and only use a lead filter in the beam. Table 5 lists the result obtained with this system.

Conclusion

Table 5 shows the results attained with various L/D's. Presently the radiographic facility uses the full range of L/D's listed. The unique feature of this facility is its versatility. The beam can be quickly tailored to meet the

experimental need. Also the fact that large objects can be radiographed in one shot may benefit experimenters. The facility also can radiograph explosives and "hot" fuel. Appendix A shows some representative radiographies from the facility.

Fig. 13. Lead filter thickness vs radiographic parameters.

Table 3. Lead filter thickness vs BPI and VISQI reading.^a

Lead filter (mm)	BPI reading (%) at L/D = 265				BPI reading (%) at L/D = 300				VISQI readings ^f
	n _{th} ^b	n _γ ^c	n _{epth} ^d	n _{sc} ^e	n _t ^b	n _γ ^c	n _{epth} ^d	n _{sc} ^e	
31.75	68	0.5	2.8	1.4	67	0	1.8	0	C = 13 R = 1 T = 14
25.4	68.3	0.9	2.5	0.9	67.5	0.4	2.9	0	C = 12 R = 1 T = 13
19.05	67.2	0.8	2.8	0	65.0	0.3	3.2	0	C = 9 R = 2 T = 11
12.70	65	1.4	3.2	0	61.6	0.9	3.1	0	C = 11 R = 0 T = 11
6.35	59.9	1.5	0	3.4	57.8	0.8	2.9	0	C = 9 R = 1 T = 10
0	53.1	8	0	4.3	50.5	5	3.4	0	C = 12 R = 1 T = 13
L/D = 190 ^g					L/D = 214 ^g				
31.75	66.2	0	4	0	71.2	0	4	0	C = 9 R = 2 T = 11

^aAll readings with 12.7-mm-diam aperture, except as noted.^bn_{th} = thermal neutron content.^cn_γ = gamma content.^dn_{epth} = epithermal neutron content.^en_{sc} = scattered neutron content.^fC = contrast faults, R = resolution faults, and T = total faults.^g17.2-mm-diam aperture.

Table 4. Deuterium plug length vs BPI readings.

Deuterium aperture plug (mm)	BPI readings (%)				BPI readings (%)			
	at L/D = 265				at L/D = 300			
	n_{th}^a	n_{γ}^b	n_{epth}^c	n_{sc}^d	n_{th}^a	n_{γ}^b	n_{epth}^c	n_{sc}^d
6.35	68.5	0.4	3.3	1.4	67.9	<0.03	2.9	<0.03
25.4	62.1	1.3	2.9	0.4	61.8	0.4	3.1	<0.03
76.2	46.4	1.2	1.1	10.7	50.5	1.0	2.1	<0.03

n_{th}^a = thermal neutron content.

n_{γ}^b = gamma content.

n_{ep}^c = epithermal neutron content.

n_{sc}^d = scattered neutron content.

Table 5. L/D ratio vs BPI readings.

L/D ratio	BPI readings ^a (%)			
	n_{th}^b	n_{γ}^c	n_{epth}^d	n_{sc}^e
300	70.1	<0.03	-	<0.03
265	70.6	<0.03	2.8	<0.03
214	78.3	<0.03	2.9	<0.03
190	80.2	<0.03	2.8	<0.03

^aAll readings are with 32-mm lead filter in beam.

n_{th}^b = thermal neutron content.

n_{γ}^c = gamma content.

n_{ep}^d = epithermal neutron content.

n_{sc}^e = scattered neutron content.

Fig. 14. Aperture material vs thermal neutron flux. Flux measured with gold foil accuracy is $\pm 10\%$. All film densities at 2.0.

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Appendix A: LPTR Radiographs

Fig. A-1. Sample radiograph.

Fig. A-2. Radiograph of a leaf taken through 2.54 cm of uranium 238.

Fig. A-3 (a). Radiograph of a brass vacuum valve, showing elastomer "O"-rings, braze joint, and valve bellows. (b) Comparison x ray.

(a)

(b)

Fig. A-4. (a) Radiograph of explosive actuated valves with stainless steel bodies. Left valve is fired, right valve is unfired.
(b) Comparison x ray of the fired explosive valve.

Fig. A-5. Radiograph indicators - exposed at L/D=265. SYQI, BPI, VISQI, and Types B and D sensitivity indicators are shown.

Fig. A-6. Radiograph indicators exposed at $L/D=190$. SYQI, BPI, VISQI, and Types B and D sensitivity indicators are shown.

Fig. A-7. Radiograph indicators exposed at L/D=297. SYQI, BPI, VISQI, and Types B and D sensitivity indicators are shown.