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DEVELOPMENT AND OPERATION OF A HIGH-INTENSITY, HIGH-RESOLUTION NEUTRON RADIOGRAPHY FACILITY

B. E. Foster
S. D. Snyder
V. A. DeCarlo
R. W. McClung

OAK RIDGE NATIONAL LABORATORY
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DEVELOPMENT AND OPERATION OF A HIGH-INTENSITY, HIGH-RESOLUTION NEUTRON RADIOGRAPHY FACILITY

B. E. Foster, S. D. Snyder, V. A. DeCarlo, and R. W. McClung

DECEMBER 1971

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
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DEVELOPMENT AND OPERATION OF A HIGH-INTENSITY, HIGH-RESOLUTION NEUTRON RADIOGRAPHY FACILITY

B. E. Foster, S. D. Snyder, V. A. DeCarlo,[1] and R. W. McClung

ABSTRACT

A neutron radiography facility has been put into operation at the 30-MW Oak Ridge Research Reactor (ORR) 24 ft below the surface of the pool near the face of the reactor core. With this facility, 4- × 20-in. radiographs can be made of highly radioactive objects irradiated in the ORR pool facility, within the reactor core, or elsewhere. Specimens as long as 10 ft can be examined by sequential exposures. Indium foil is used as the primary detector for subsequent transfer to x-ray film. The high (collimated) thermal neutron flux available (1.7×10^8 neutrons cm^{-2} sec^{-1}) allows the use of very small apertures and large ratios (270 to 1000) of collimator length to aperture size so that high-quality radiographs can be obtained with relatively short exposure times (3–5 min). The image quality is adequate to resolve 0.020-in.-diam holes spaced only 0.001 in. apart in a cadmium strip and to display a 0.003-in.-diam wire separated from the image plane by 2 9/16 in. A principal application of the facility is the periodic inspection of nuclear fuels irradiation test capsules to determine the condition of the fuel, fuel and cladding dimensional changes, and location of thermocouples.

INTRODUCTION

There has long been a need at ORNL for a method that enables one to nondestructively examine highly radioactive materials, particularly irradiation test capsules or assemblies. A new facility using neutrons to make radiographs for this type of nondestructive examination has been installed in the 30-MW ORR. The facility is located in the pool with the aperture within 0.5 in. of the face of the reactor core. The collimated neutron beam passes through the specimen and impinges on a detector foil to produce the latent radioactive image. The image is transferred to a fine-grained x-ray film by autoradiography.

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[1]Formerly in the Reactor Division; now with Chemical Technology Division.

Neutron radiography, although a relatively new technique, is rapidly gaining international recognition and use[2–4] because of some of its unique capabilities. The use of neutron radiography is not limited to radioactive materials. Since neutrons interact only with the nucleus of the atom, and these interactions are independent of the density of the element, high contrast between some elements of adjacent atomic number is possible. This contrast could not be achieved with x radiography. With neutrons, for example, it is possible to distinguish hydrogen-bearing materials within much heavier materials such as steel or lead. Also, the muscle structure in animals can be viewed with good detail since the bones are relatively transparent to the neutrons and offer little interference. This report covers the design, operation, and evaluation of the neutron radiography facility in the ORR, including a few applications.

DESCRIPTION OF THE FACILITY

The facility is located in the P-9 position near the core of the ORR at a depth of 24 ft below the surface of the pool. The reactor core serves as the neutron source and the pool water serves as a biological shield. As shown in the isometric drawing of Fig. 1, the two major assemblies of the facility are a camera and a collimator. The camera is detachable from the collimator and is designed for easy removal from the pool for periodic maintenance. The entire facility is held in place by its own support structure, which rests on the floor of the reactor pool and is weighted to prevent flotation. The collimator is attached to a base plate near the reactor core. An alignment bar on the side of the collimator slides into an adapter fixture which is attached to the base plate to position the collimator in relation to the face of the reactor.

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[2]H. Berger, A Summary Report on Neutron Radiography, ANL-6846 (1964).

[3]R. S. Matfield et al., The Measurement of Small Dimensional Changes by Neutron Radiography, AERE-R 5703 (1969).

[4]H. Berger, Neutron Radiography, Elsevier Publishing Company, Amsterdam, 1965.

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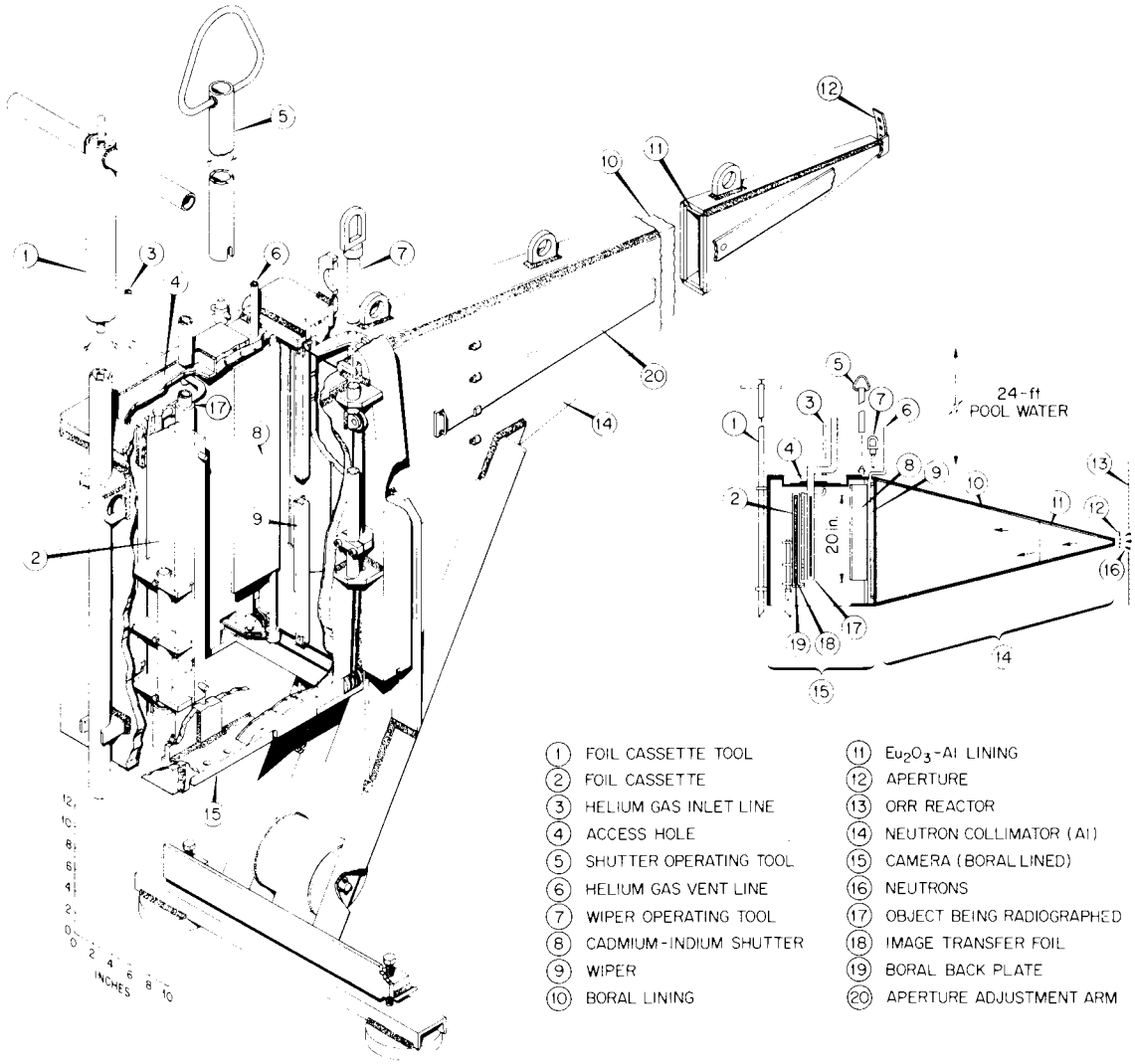

Fig. 1. Neutron Radiography Facility in the Oak Ridge Research Reactor.

Irradiation test capsules or assemblies were used as reference subjects for design of the facility. However, general use of the facility by other experimenters was anticipated and, consequently, a versatile design was developed.

Collimator

As shown in Fig. 1, the collimator is a flat-sided aluminum funnel (pyramid shaped) 64 9/16 in. long. It is lined with neutron absorbing

materials except at the ends. The first 18 in. (from the small end) is lined with Eu_2O_3-aluminum dispersion 1/4 in. thick, and the remainder is lined with 1/4-in.-thick boral plate. The collimator is continuously purged with dry air. This purge reveals any developing water leak in the collimator and prevents the buildup of any radiolytic gas.

As fabricated, the collimator has a fixed aperture of 0.3 in. square. Attached to the collimator is a curved plate with variable apertures which can reduce the opening to 0.2 or 0.14 in. squares or tc a 0.08-in.-diam circle. These apertures are in a Eu_2O_3-aluminum dispersion material 3/16 in. thick, encased in 1/32-in.-thick aluminum. The top portion of the multiaperture assembly is made of solid aluminum, and when it covers the end of the collimator, the 0.3-in. square opening is effective. Aperture selection is by movement of a lever that fits into any one of four slots located on the side of the collimator. The uppermost slot positions the solid aluminum portion over the collimatcr opening, and the other three slots, in descending order, position the 0.2-, 0.14-, and 0.08-in. apertures, respectively. Figure 2 is a photograph of the system as viewed from the front end (aperture) of the collimator prior to installation in the pool. The multiaperture assembly and adjustment arm are not attached in this picture.

The length of the collimator-camera assembly was limited to about 80 in. by the space available in front of the reactor core. However, the selection of aperture sizes was based on the calculated geometric image unsharpness for a given combination of aperture-to-specimen distance, aperture size, and specimen-to-foil distance. The geometric unsharpness, U, is defined by the relationship

$$U = \frac{FD}{L} ,$$

where F is the specimen-to-foil distance, D is the size of the aperture, and L is the aperture-to-specimen distance. Thus with our largest aperture (0.3 in.) the resulting geometric unsharpness for an object 2 in. from the foil would be about 0.008 in. However, for the smallest aperture (0.08 in.) the geometric unsharpness with the same 2 in. space between object and foil would be only about 0.002 in. For specimens

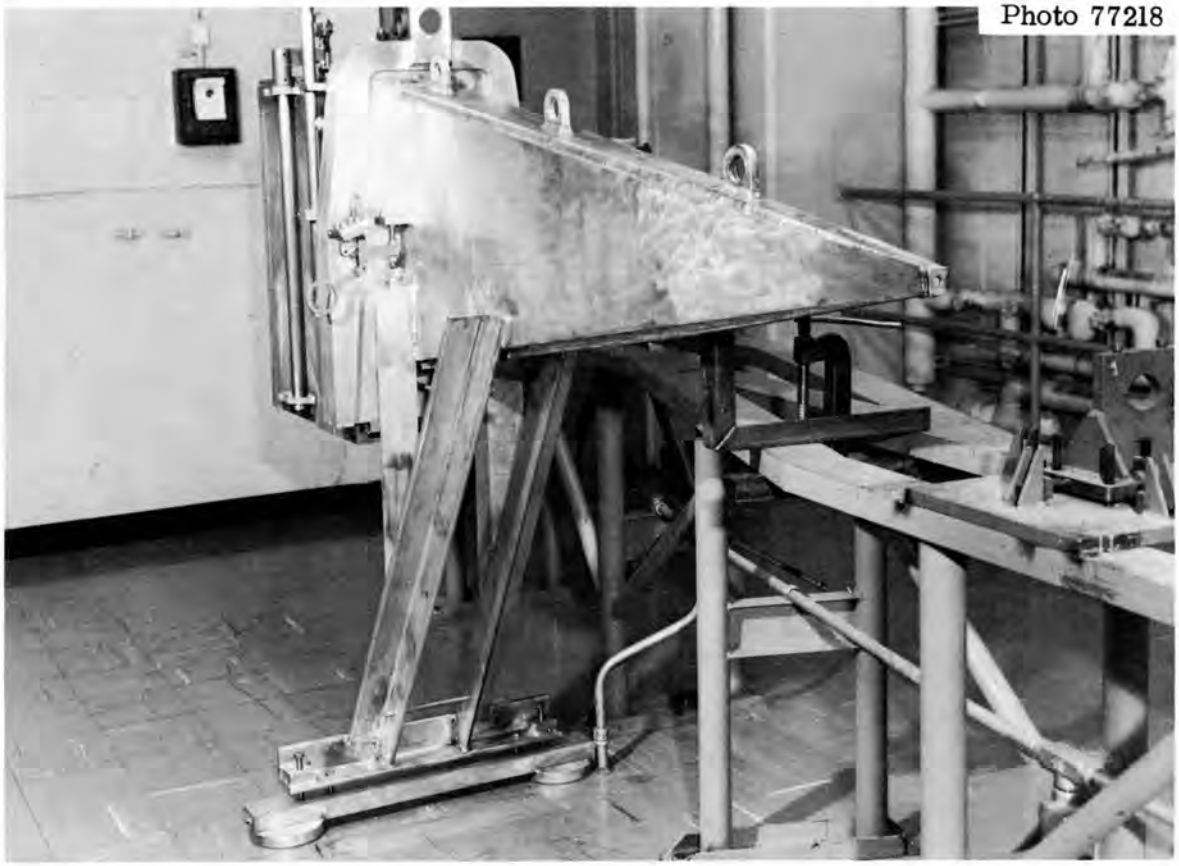

Fig. 2. External View of Collimator from the Aperture End. (Variable aperture and adjustment arm are not attached in this picture.)

within 1/2 in. of the foil, the geometric unsharpness would be only 0.002 and 0.0005 in. for the largest and smallest apertures, respectively. The L/D ratios available with our facility are 1000, 570, 400, and 270. It is generally agreed that a L/D ratio of at least 150 is needed for good resolution.

Camera

The camera chamber is made of 1-in.-thick type 6061 aluminum plate. The chamber, with inside dimensions of 9 15/16 in. wide, 19 1/2 in. long, and 26 13/16 in. deep, fits onto the large end of the collimator as seen in Fig. 1. The chamber is lined with 1/8-in.-thick boral plate, is open at the bottom, and contains a shutter mounted at the collimator end. The shutter of the camera is 20 3/4 in. long × 4 3/8 in. wide × 1/4 in. thick.

It was fabricated by sandwiching 0.01-in.-thick indium foil between two sheets of cadmium 0.025 in. thick. Two cover plates of type 1100 aluminum, 1/16 and 1/8 in. thick, were added for rigidity.

In front of the shutter is a wiper which is operated by a push-pull motion of a rod extending out of the camera. The rod is coupled to the wiper by a series of pulleys and cables. The wiper action removes any droplets of water from the face of the collimator to which the camera is sealed. Figure 3 is a photograph of the chamber, wiper, and shutter as

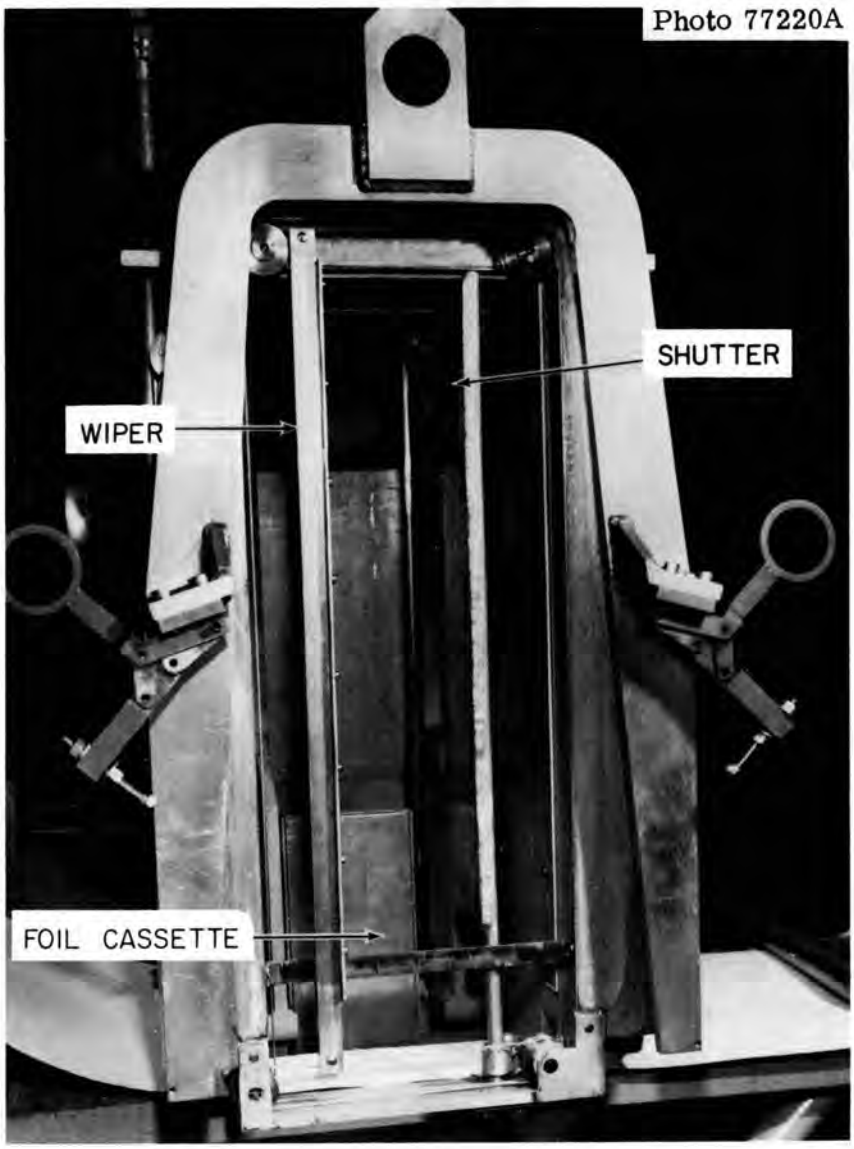

Fig. 3. Internal View of Camera Chamber from the Collimator Face Showing Wiper, Shutter, and Foil Cassette.

viewed from the collimator face. The photograph in Fig. 4 is an external view of the camera attached to the collimator. The camera also contains small gas jets which are directed toward the position of radiographed objects and the foil holder. Figure 5 shows these jets in relation to the foil holder as viewed from the top of the camera. The water in the camera is displaced through the open bottom by a flow of helium through these jets. After the water is removed, the continuous helium flow through the jets serves to dry the specimen and front face of the foil holder.

The top plate of the camera, shown in Fig. 6, has an opening 4 5/16 × 6 in. through which specimens can be inserted. After placement of the specimen and before radiography, the top opening must have a gas-tight seal before the water is displaced. There are three

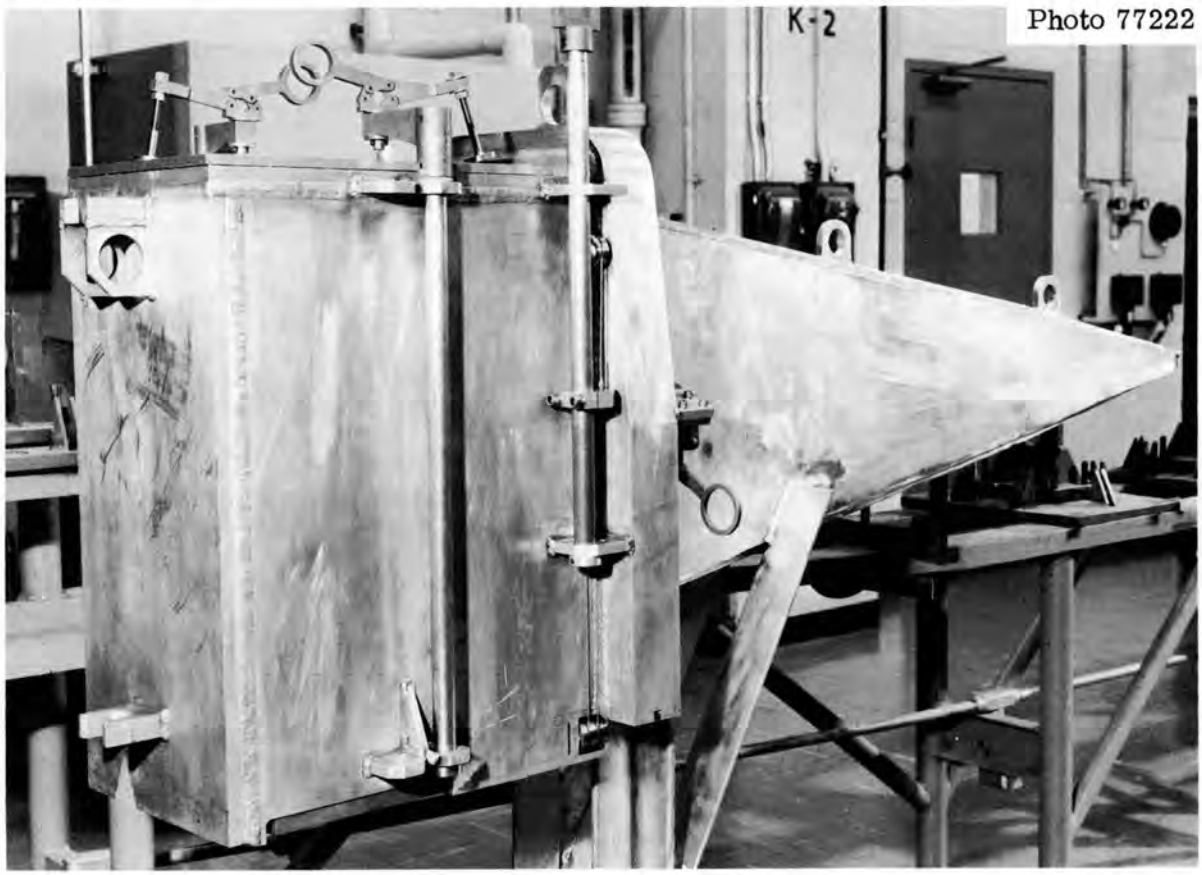

Fig. 4. External View of Camera Attached to the Collimator.

Photo 77221A

Fig. 5. View Through Top of Camera Showing Foil Cassette in Position and Helium Gas Jets.

Photo 77216A

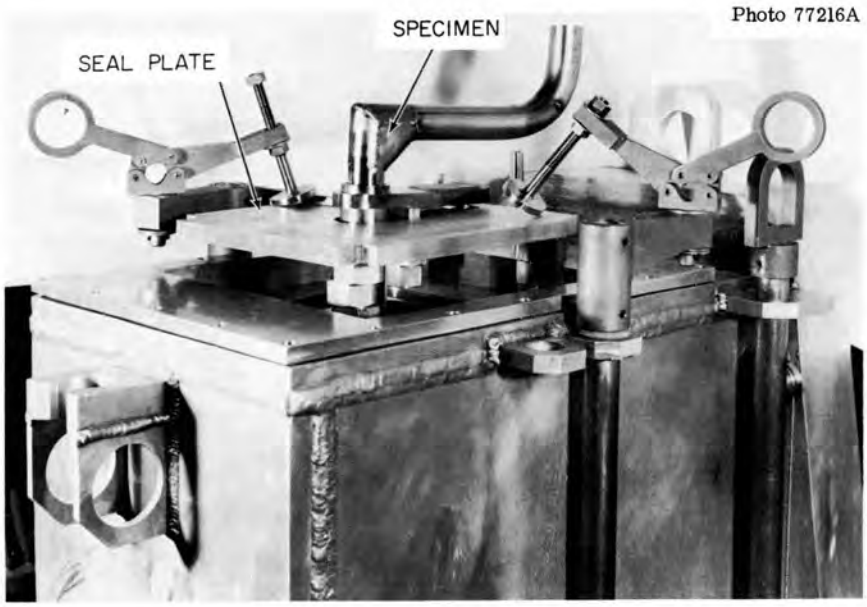

Fig. 6. Top of Camera and Seal Plate Containing a Small Opening for Insertion of the Specimen (Shown in Position).

methods by which objects to be radiographed can be placed in the camera and the gas-tight seal effected. The one illustrated in Fig. 6 uses a clamped sealing plate arrangement between the object and the top of the camera. As shown, this plate contains a small opening for insertion of specimens of smaller diameter than this opening. This is typical of the arrangement for radiographing irradiation test capsules from the ORR. This method requires that a matching sealing flange for the smaller opening be fabricated on the object.

Another method is to employ a liquid N_2 ice-seal adapter as shown in Fig. 7 to seal irregularly shaped objects (or those which do not have a matched sealing flange). The third method, and certainly the simplest, is to attach the object to the foil holder or place it in a holder attached to the foil package. When using this latter method, the camera is sealed with a solid cover plate and objects are limited to a maximum length of about 20 in.

Photo 77215A

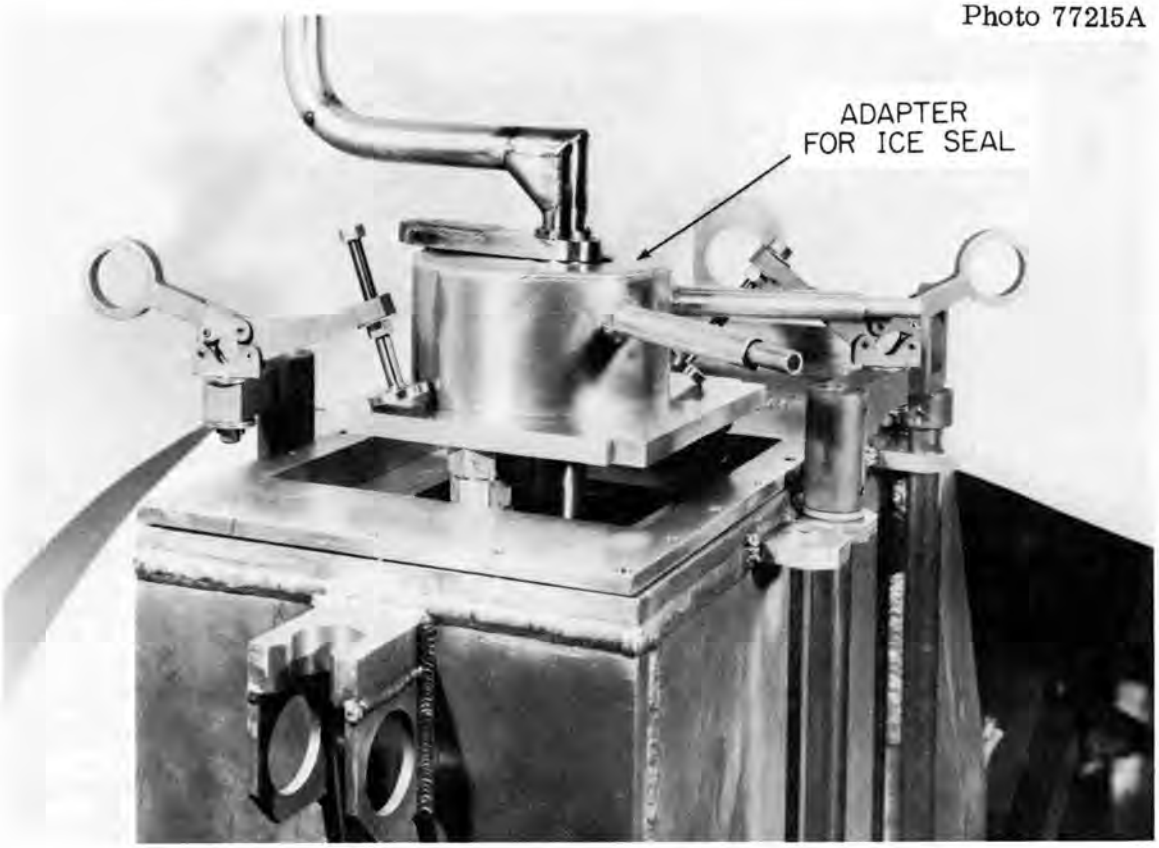

Fig. 7. Top of Camera with Adapter for Ice Seal.

Foil Cassette

The foil cassette is 21 7/16 in. long × 5 1/16 in. wide × 1 3/16 in. thick and contains two aluminum sheets each 0.016 in. thick. The indium foil to be used for image transferring is placed between the aluminum sheets. This sandwich of aluminum-indium-aluminum slides into a slot in the foil cassette as shown in Fig. 8. The slot is between the 1/4-in.-thick boral backplate (which absorbs neutrons and prevents backscatter) and the 0.016-in.-thick aluminum front cover of the foil cassette. The assembly will accept a 21- × 4 1/2-in. sheet of foil up to 0.015 in. thick. The cassette is sealed from the pool water with a plate containing an O-ring seal.

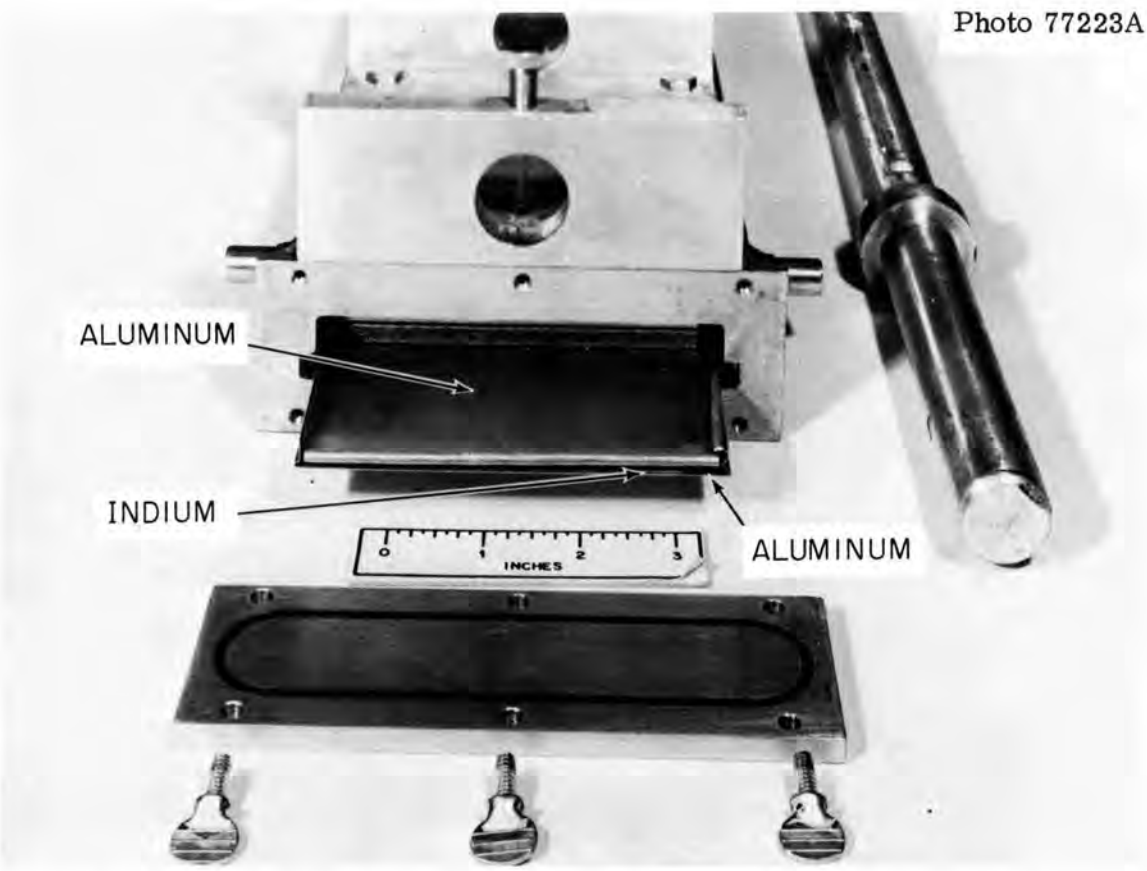

Fig. 8. Foil Cassette Showing the Aluminum-Indium-Aluminum Assembly Partially Inserted.

Figure 9 shows the foil cassette inserted through the open bottom of the camera into slots that guide and position the cassette for near contact (about 0.030-in. spacing) with the specimen. The view is from the face of the collimator and shows the cassette at the midway point, a specimen in position, the wiper assembly, and the shutter in the open position. Figure 10 shows the cassette fully inserted as viewed from the opening in the bottom of the camera. The shutter is in the open position. The helium gas jets and specimen are also visible.

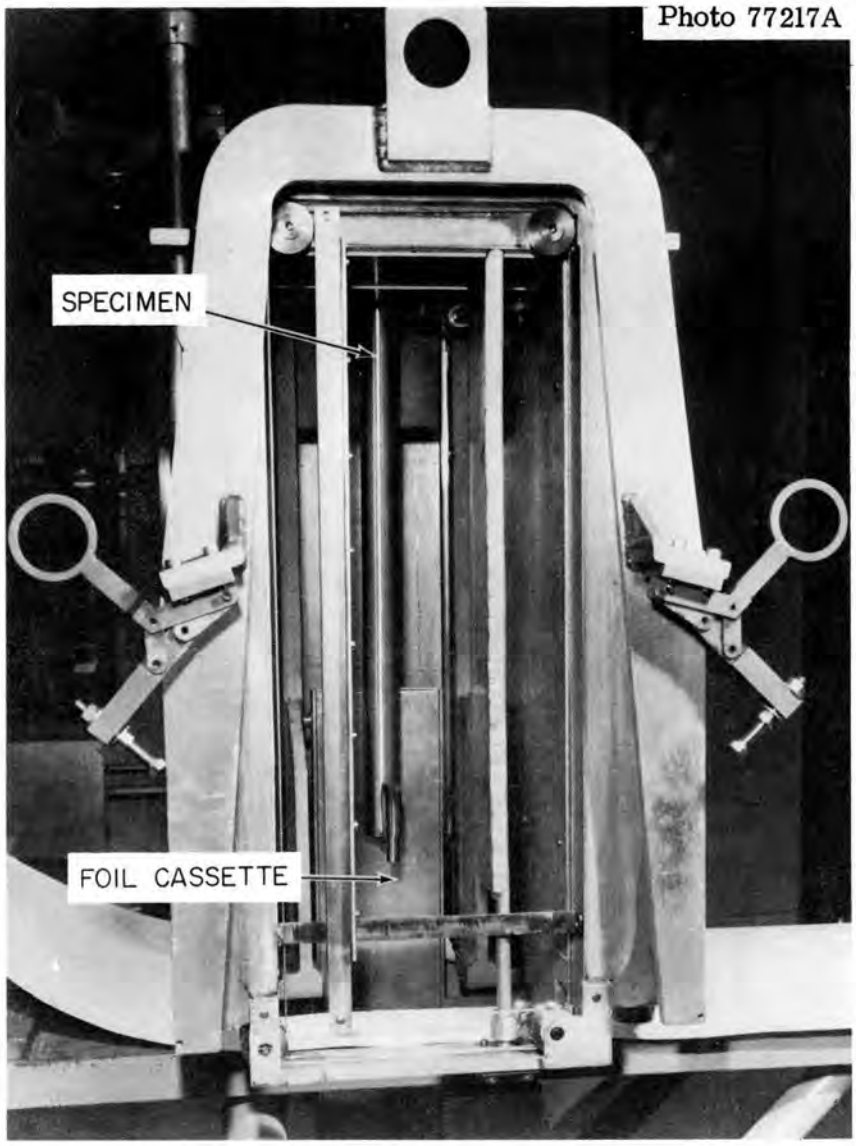

Fig. 9. Internal View of Camera with Specimen in Position and Foil Cassette at Midpoint.

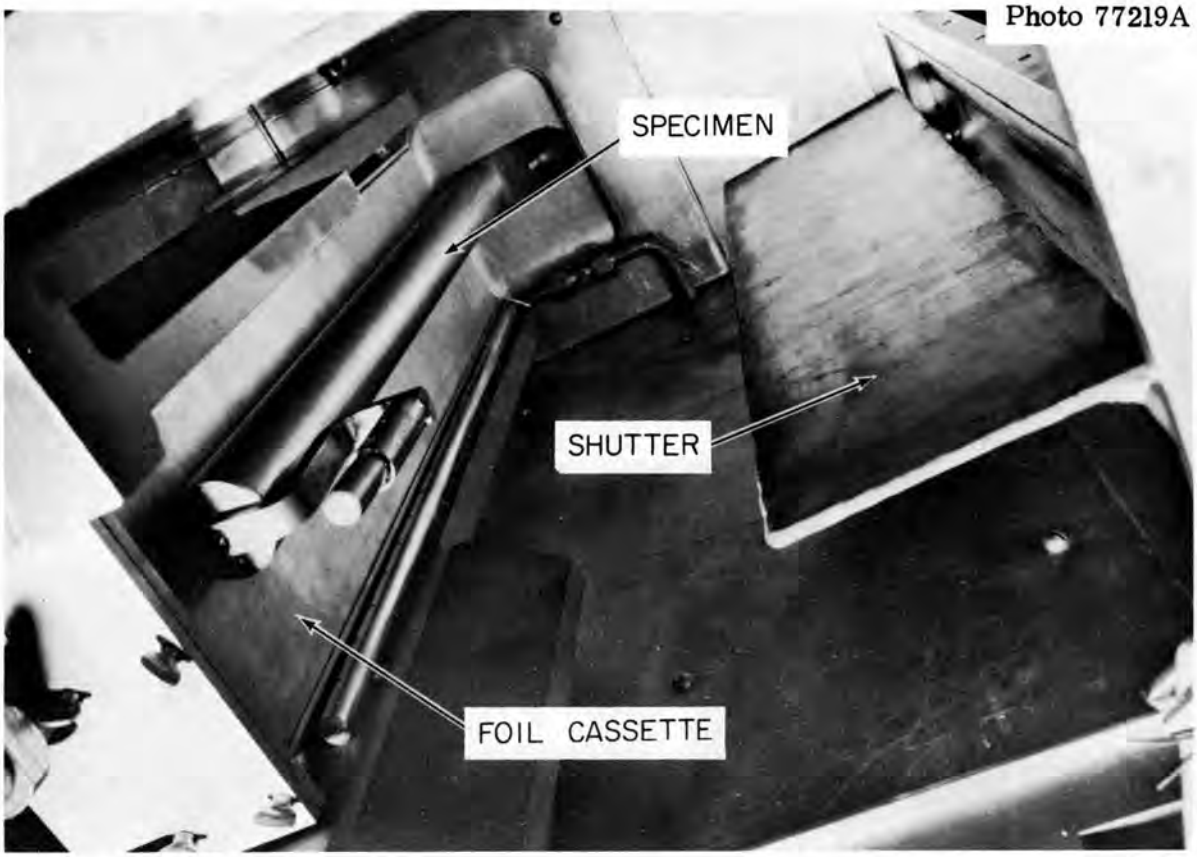

Fig. 10. Internal View of Camera from the Bottom with Specimen in Position, the Shutter Open, and the Foil Cassette Fully Inserted.

OPERATION OF THE FACILITY

The object to be radiographed and the foil holder containing the indium foil are placed in the proper position in the camera. The water in the camera is then removed using the helium pressurizing system, a flow diagram for which is shown in Fig. 11. This is done by closing valve No. V-2 on the outlet side of the camera. When the camera is fully pressurized, helium bubbles will emerge from beneath the camera. The helium flow is then reduced by regulating valve No. 1 to a flow which will sustain a small stream of bubbles from the camera. Any droplets of water on the specimen or foil cassette will be removed by the helium jet purge. Operation of the wiper assembly will remove water droplets from the interface of the collimator and camera. The shutter is then opened for the time required for the exposure (typically 3–5 min) and then

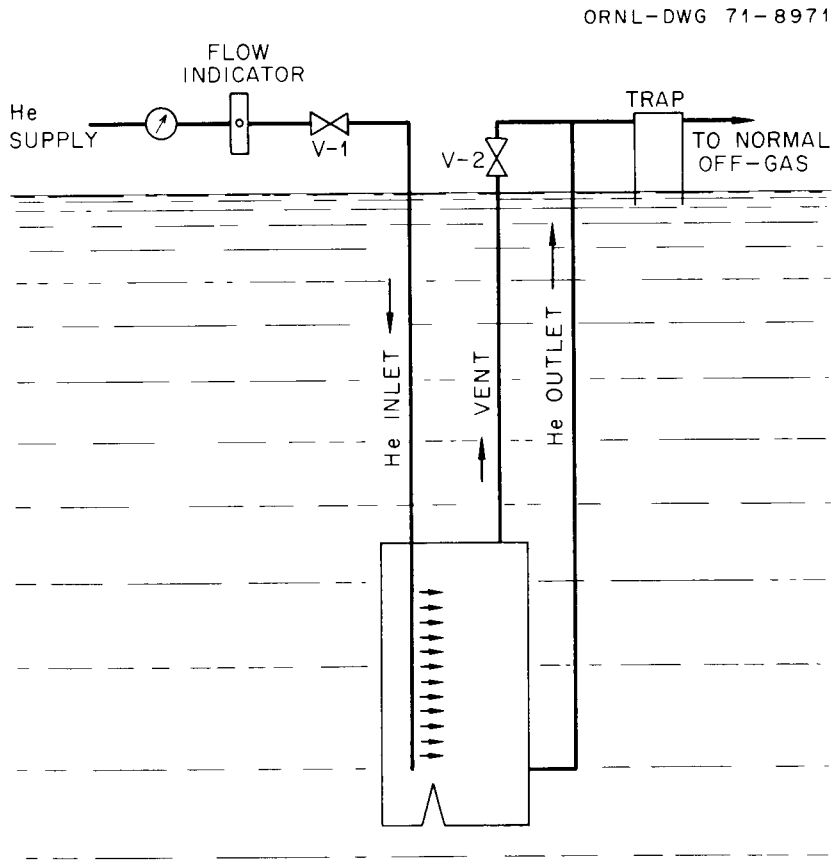

Fig. 11. Helium Pressurization System for Camera.

closed. Valve No. V-2 is then opened to vent the helium and depressurize the camera. This depressurization is not required between successive exposures when the specimen is attached to the foil pack. However, depressurization conserves the helium in most instances. The foil cassette is removed and the foil is placed in a shielded cassette which is then transported to a photographic darkroom. The activated (≈ 10 R/hr at 3 in.) indium foil is placed in contact with x-ray film. Normally Type AA film is used and the transfer time is 20 min. Standard photographic development procedures are followed for processing the film.

The combination of the fine-grained Type AA film, the high thermal neutron flux and the indium foil with a 54 min half-life allows as many as eight autoradiographs (four transfers with film on both sides of the foil) of similar quality from one activated indium foil. Typical transfer times for multiple autoradiographs are:

1st transfer – 21 min,
2nd transfer – 30 min,
3rd transfer – 46 min,
4th transfer – 117 min.

Of course after the indium foil has decayed for seven half-lives (6.3 hr) the activity is negligible and the foil can be reused.

BEAM QUALITY STUDIES

The thermal neutron flux at various positions along the length and width of the object plane with the 0.3 in. aperture was determined with a series of pairs of 0.001-in.-thick gold foils. One foil in each pair was covered with 0.020-in.-thick cadmium. The location of each strip as imaged on the indium foil within the foil cassette is shown in Fig. 12. This arrangement of foils yielded accurate data on the thermal and fast neutron flux at different positions in the object plane, thus providing valuable information on the beam uniformity.

The stable ^{197}Au isotope is activated to ^{198}Au when exposed to neutrons by the (n,γ) reaction. The cadmium-covered gold is activated only by the epithermal neutrons while the bare gold foil is activated by both thermal and epithermal neutrons. By measuring the gamma activity of the gold foils and applying standard activation equations,[5] the neutron flux to which the foils have been exposed can be calculated. The thermal neutron flux is calculated by subtracting the epithermal neutron flux values obtained with the cadmium-covered foils from the total neutron flux values obtained with the bare gold foils.

The data from the gold foil activation are summarized in Table 1. There is a decrease in flux from the top to the bottom ($\sim$ 30%) and from left to right ($\sim$ 20%) of the object plane. These flux gradients, of course, cause small density gradients on the final radiograph. The average ratio of the thermal to fast flux (more commonly called cadmium ratio) is about 7 as determined from the data in Table 1. The average

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[5]W. S. Lyon, Jr., Guide to Activation Analysis, D. Van Nostrand Co., Inc., New York, New York, 1964.

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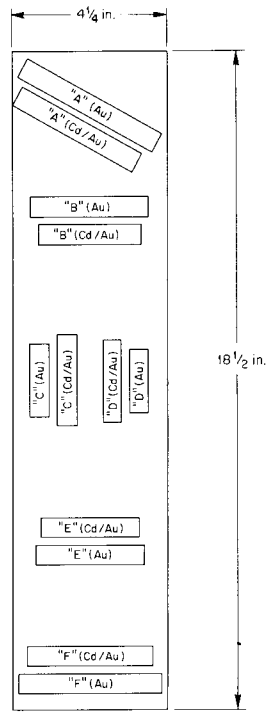

Fig. 12. Arrangement of Strips of Bare Gold Foil and Gold Foil Covered with Cadmium.

Table 1. Summary of Neutron Flux Measurements in Object Plane

Position on Indium Foil[a]	Flux, neutrons cm^{-2} sec^{-1}			Cadmium Ratio[b]
	Total (Bare Gold Foil)	Epithermal (Cadmium-Covered Gold Foil)	Thermal	
	$\times 10^8$	$\times 10^7$	$\times 10^8$	
A	2.3	2.6	2.0	7.7
B	1.8	2.6	1.5	5.8
C	2.2	2.7	1.9	7.0
D	1.7	2.3	1.5	6.5
E	1.9	2.2	1.7	7.7
F	1.6	2.0	1.4	7.0

[a]See Fig. 12.

[b]Ratio of thermal neutron flux to flux of neutrons with energy > 0.5 eV. (The higher the ratio, the higher the thermal neutron component of the beam.)

thermal flux at the object plane is about 1.7×10^8 neutrons cm^{-2} sec^{-1} with the 0.3 in. aperture which makes this facility one of the most intense neutron radiographic facilities in the world.

The indium foil that was in the cassette during irradiation of the gold foil was placed in contact with Type AA x-ray film for 25 min. Film density readings were taken on the radiograph of the gold foils at three positions within the area of each cadmium-covered foil. In addition to the vertical gradient discussed earlier, there is a small horizontal flux gradient that causes a gradient of about 0.1 to 0.2 film density units as seen in Fig. 13. Slight misalignment of the variable aperture during

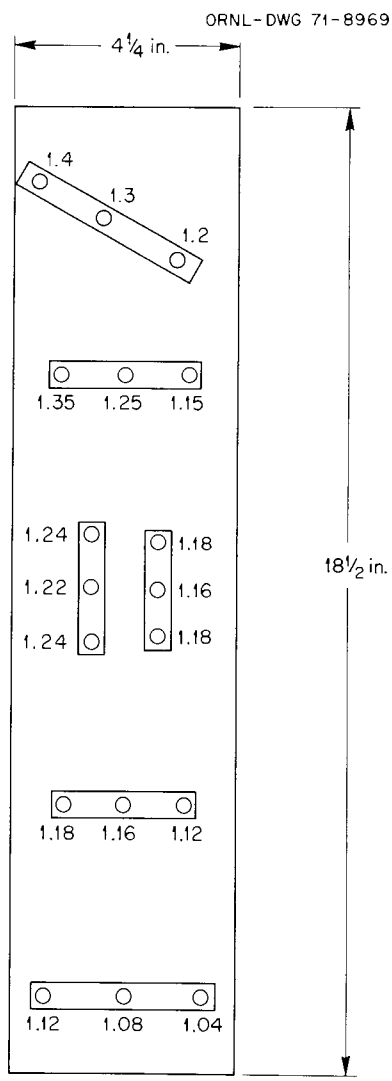

Fig. 13. Arrangement of Strips of Gold Foil Covered with Cadmium Showing the Film Density Measurements.

installation of the facility could be causing the nonuniformity. However, such minor gradients have little significance in the interpretation of the radiographs.

We evaluated the resolution capabilities of our facility using a system image quality indicator (IQI) that was courteously loaned to us by J. P. Barton of Argonne National Laboratory. The assembly of the "system IQI" is shown in Fig. 14. The IQI consists of eight thin aluminum plates separated by spacers and bolted at the four corners. Mounted on Plate No. 1 (nearest the detector) is test strip A (see Fig. 15) containing 19 squares of different absorber materials which can be used to determine the ratio of thermal to fast neutron flux (as described above, we used the more accurate method of gold activation). In addition to the absorbers, there is a cadmium strip with small holes of various diameter and spacing. This strip is used to determine the image resolution of the facility.

According to the design, each of the eight plates also contains another strip, designated B, containing a series of plastic and cadmium

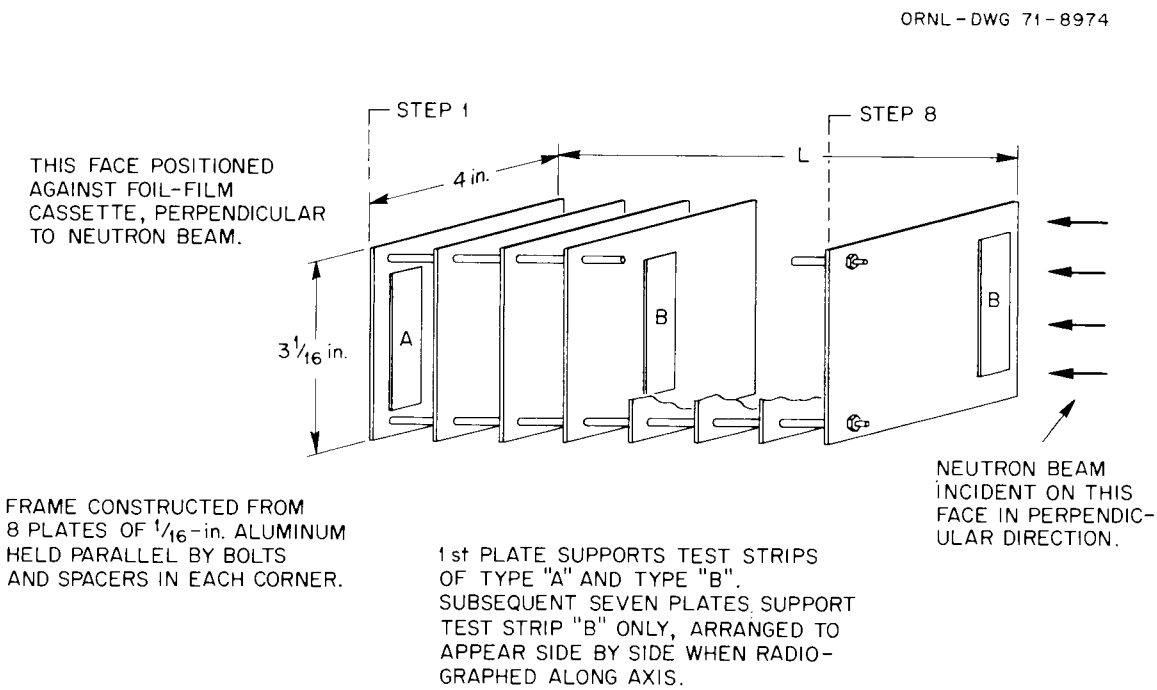

Fig. 14. Assembly Drawing of System Image Quality Indicator.

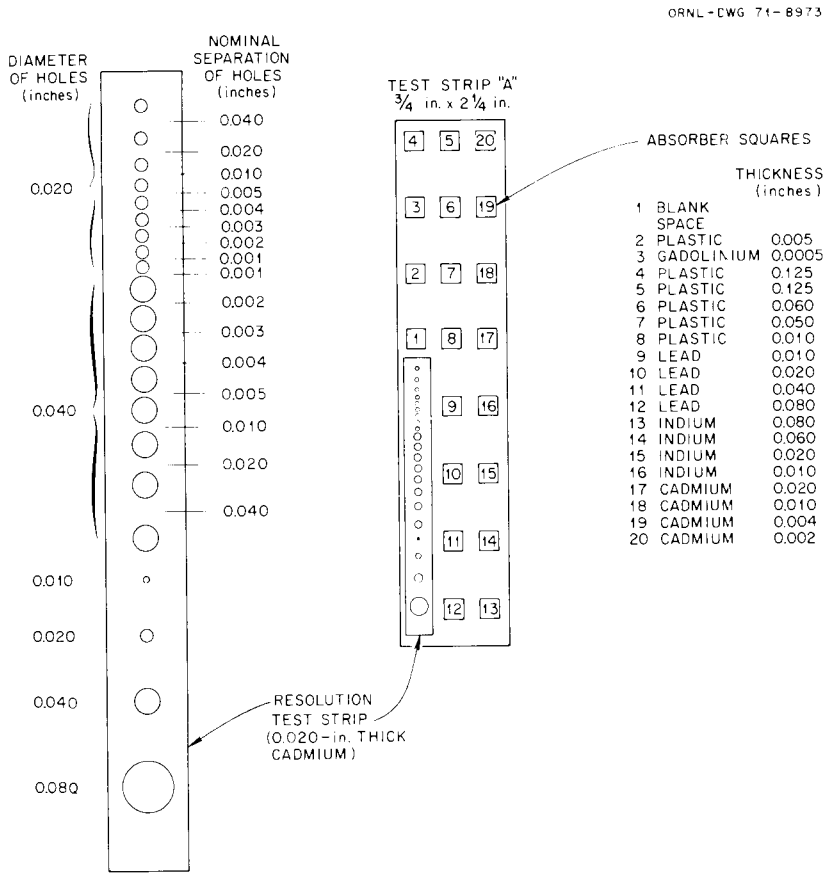

Fig. 15. Test Strip A on Plate No. 1.

wires of various diameters and a series of holes in a 0.020-in.-thick cadmium sheet (see Fig. 16). However, the IQI available to us had the test strip B on only Plate Nos. 3 through 8. These A and B strips can be used to obtain additional data on the neutron spectrum and unsharpness of the facility. In addition, the relative gamma content of the beam could be determined if the direct exposure techniques were used. However, with about 10^8 R/hr gamma intensity at the aperture of the collimator, we necessarily used the transfer method.

A print of the radiograph (made with the 0.3-in. aperture) of the IQI is shown in Fig. 17. On the original radiograph, all 13 plastic wires from 0.100 to 0.003 in. diam that were 2 9/16 in. from the indium foil and mounted on Plate No. 8 were visible. The holes in the cadmium strip on test strip B on Plate No. 7 were clearly resolved but were

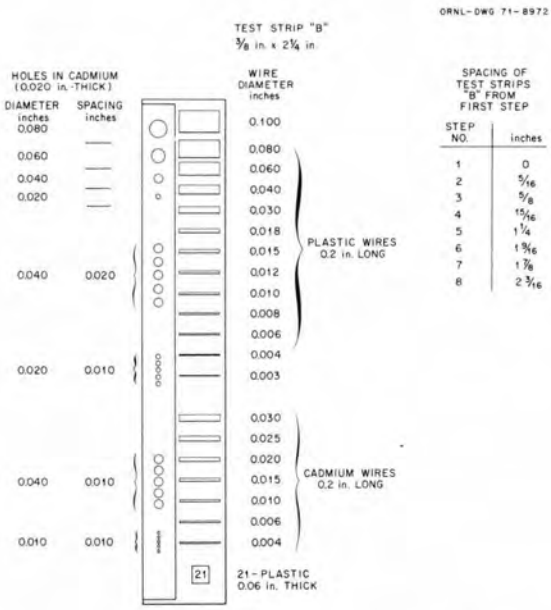

Fig. 16. Test Strip B on Plate Nos. 1–8.

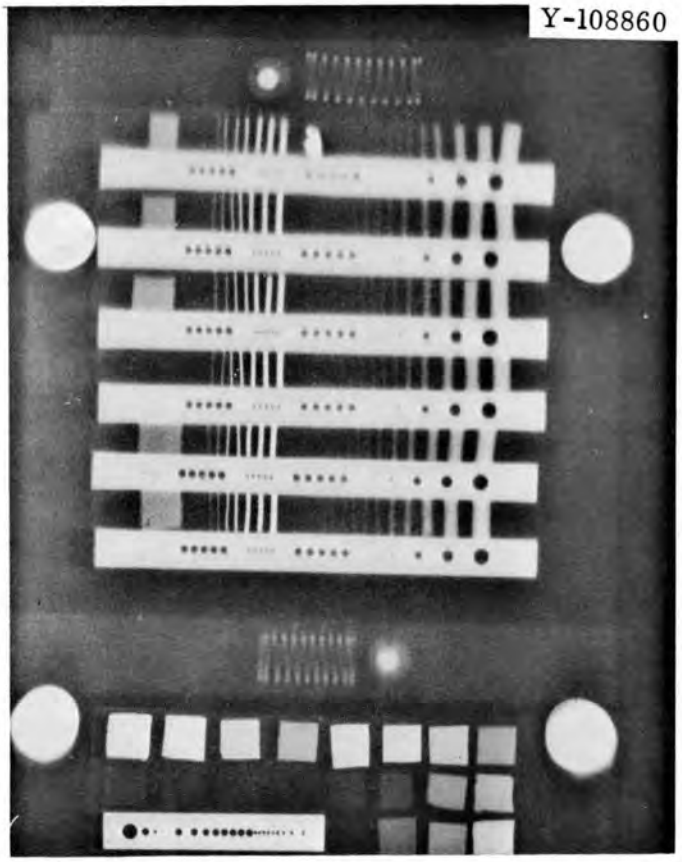

Fig. 17. Neutron Radiograph of System Image Quality Indicator.

somewhat distorted on Plate No. 8. All of the holes and spacing on test strip A (3/8 in. from indium foil) on Plate No. 1 were resolved. The smallest separation between holes was only 0.001 in.

The capability of the system to reproduce fine detail was best demonstrated by imaging the 0.003-in.-diam × 0.2-in.-long plastic wire on test strip B Plate No. 8 (2 9/16 in. from the foil) of the IQI.

APPLICATIONS

This facility has been successfully used to examine various capsules both before and after periods of irradiation. The types of capsules radiographed have consisted of UN, UO_2, and $(U,Pu)O_2$ reactor fuel in the form of metal-clad pellets or Sphere-Pac beds, and carbon-coated UO_2 and $(U,Th)O_2$ particles in graphite fuel sticks. Thermocouples and other instrumentation with inlet and outlet gas purge lines are also present and surround the fuel pins. The fuel pins are usually surrounded by NaK and enclosed in double wall stainless steel containers. The radiographs have shown changes in lengths of the fuel material as well as bowing of a graphite tube, used to support fuel sticks in a capsule, that occurred during irradiation.

Instrumented Capsule Containing Carbon-Coated UO_2 and $(U,Th)O_2$ Particles in Bonded Graphite Sticks

Figure 18 shows a photographic reproduction of a neutron radiograph of experiment HRB-1 (ref. 6) that was irradiated in the High Flux Isotope Reactor. This experiment contained carbon-coated particles of UO_2 and $(U,Th)O_2$ bonded together into fuel sticks and supported in a segmented tube of needle-coke graphite. The radiograph illustrates the bowing of the graphite tube (see center portion of Fig. 18) that occurred during irradiation. Some detail was lost in the photographic reproduction,

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[6] J. H. Coobs et al., "Irradiation on HTGR Fuel and Fuel Elements," GCRP Semiann. Progr. Rept. March 31, 1970, ORNL-4589, pp. 22–36.

Photo 100093R

Fig. 18. Neutron Radiograph of HFIR Experiment HRB-1.

but the change in length of the graphite tube as well as positions of all thermocouples and fueled specimens were easily confirmed on the radiograph. This transfer from the activated indium foil was on Type M film.

Instrumented Capsule Containing UO_2 Pellets

The basic design of the capsule for irradiation testing of uranium nitride as modified for clad UO_2 pellets is shown in Fig. 19. Each of the three fuel pins have two thermocouples at their axial midplane and four sets of two thermocouples each are located at the same axial position in the Zircaloy-2 calorimeter or outer containment. Since these capsules are very complex, highly instrumented, and expensive to build, it is essential to verify the proper location of various components prior to operation of this capsule in the reactor. We are using neutron radiography for this verification and will use the preirradiation neutron radiographs to compare with radiographs made at selected intervals during the 10,000 hr irradiation test.

Figure 20 is a photographic reproduction of the preirradiation neutron radiograph of Capsule UN-6. On the original radiograph the pellet interfaces and the various capsule components could be located.

Uninstrumented Capsules Containing Sol-Gel-Derived $(U,Pu)O_2$ Fuels

A series of uninstrumented capsules have been irradiated in the Engineering Test Reactor

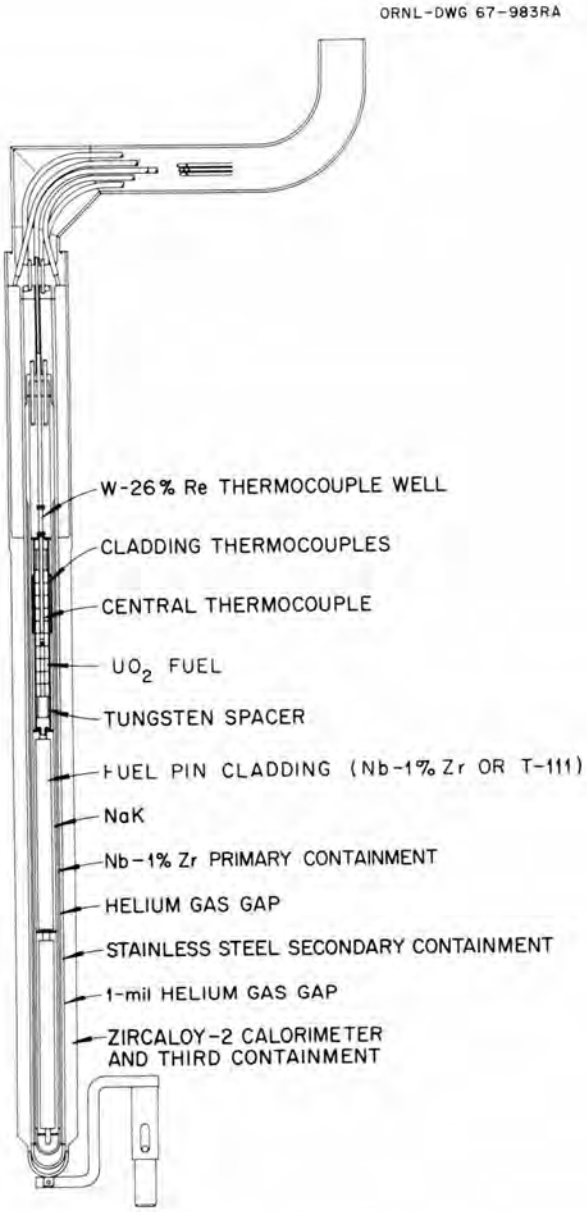

Fig. 19. Design of Capsule UN-6 Containing Clad UO_2 Pellets Shown in Neutron Radiograph, Fig. 20.

Fig. 20. Neutron Radiograph of Capsule UN-6.

(ETR) to evaluate the performance of sol-gel-derived $(U,Pu)O_2$ fuels fabricated by the Sphere-Pac process.[7] These 1/2-in.-diam stainless steel capsules contain four fuel pins mounted in tandem and centered in the NaK heat transfer medium by spiders threaded into the end caps. Each pin is 7.5 in. long. The pin cladding is made from 0.250-in.-diam type 304 stainless steel tubing with a 0.010 in. wall thickness. The pins contain a 3.1-in.-long bed of $(U\text{–}15\%\ Pu)O_2$ with a 0.25-in.-long low-density ThO_2 insulator pellet on each end and a gas plenum filled with Fiberfrax wool.

Figure 21 shows the postirradiation neutron radiograph of two pins removed from one of these test capsules. Because of the flux distribution in the ETR, both the linear heat rate and the burnup vary along each

[7]R. B. Fitts, A. R. Olsen, and J. Komatsu, "Sphere-Pac Fabrication of Sol-Gel Nuclear Fuels," Am. Ceram. Soc. Bull. 47(9), 844 (1968).

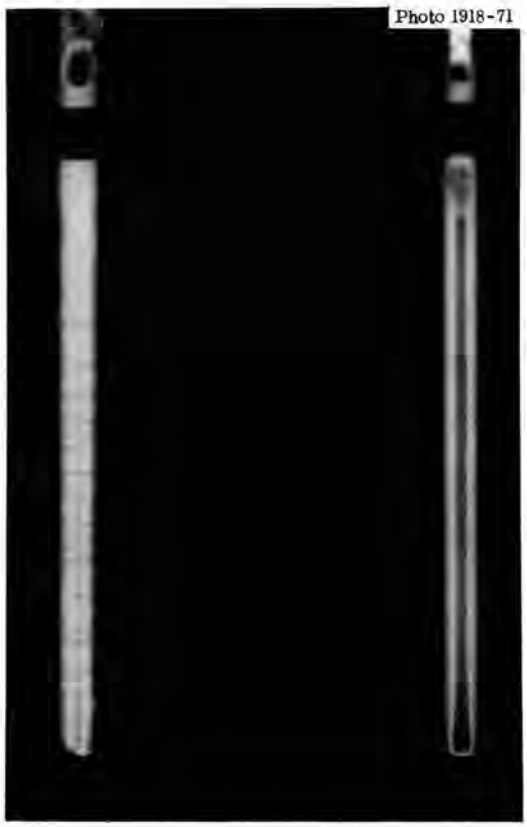

Fig. 21. Neutron Radiograph of Irradiated Capsules Containing $(U,Pu)O_2$.

pin and from pin to pin. The pin on the left in this figure operated at a peak linear heat rate of approximately 14 kW/ft to a burnup of 100,000 MWd/tonne of U + Pu (10% FIMA) while the pin on the right operated at about 11 kW/ft to a peak burnup of about 80,000 MWd/tonne of U + Pu (8% FIMA).

The postirradiation neutron radiographs show in-reactor fuel sintering and densification of the Sphere-Pac fuel beds with the development of a central void and a decrease in bed length. The diameter of this center void varies with the localized heat rate. Flux peaking at the ends of the fuel columns, with the consequent increase in local fission rates, causes the void enlargements in these regions. The radiographs also show cracking of the densified fuel beds due to thermal cycling. The neutron radiographs are also used to select sections for metallographic examination.

Biological Specimen

A neutron radiograph of a frog is shown in Fig. 22. The detail of the muscle structure in the legs can be seen rather well. The usual interference of the bones encountered in x radiography is noticeably absent.

SUMMARY

A facility has been described for making neutron radiographs 4 × 20 in. with the capability of handling objects up to 10 ft long by sequential exposures. The high thermal flux of 1.7×10^8 neutrons cm^{-2} sec^{-1} allows the use of small apertures and large ratios (270 to 1000) of collimator length to aperture size to achieve high resolution with relatively short exposure and transfer times. The high resolution capability was demonstrated by resolving 0.010-in.-diam holes with 0.010-in. spacing in cadmium sheet (see Fig. 16) located 2 1/4 in. from the detector foil and the 0.003-in.-diam plastic wire located 2 9/16 in. from the detector.

We have successfully evaluated fueled capsules of metal clad UN, UO_2, and $(U,Pu)O_2$ pellets and carbon-coated UO_2 and $(U,Th)O_2$ particles

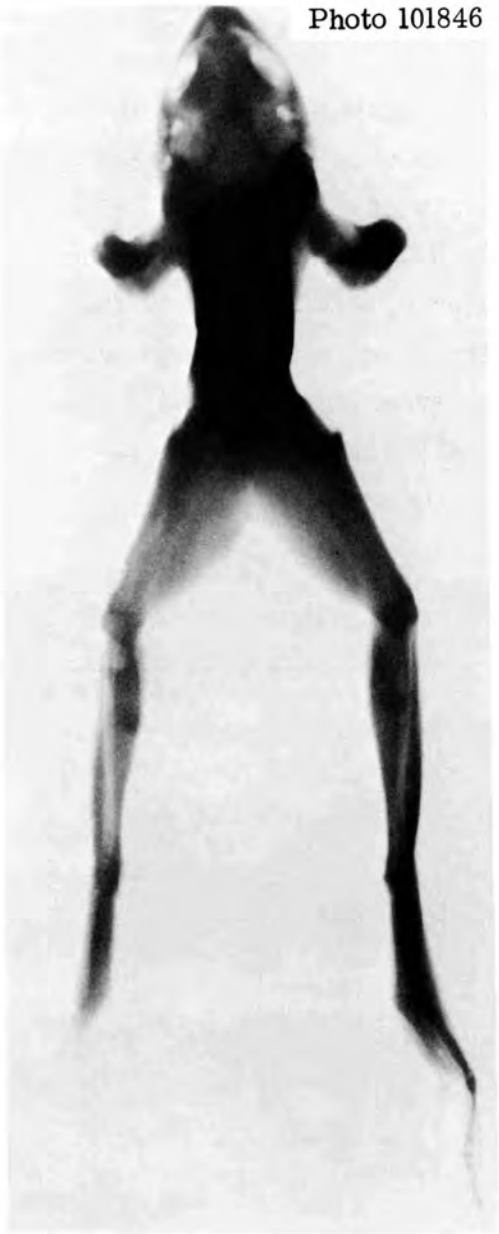

Fig. 22. Neutron Radiograph of a Frog.

in both the preirradiation and postirradiation condition. In addition, the versatility of the system was shown by the detail in the radiograph of a frog.

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