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THERMAL NEUTRON RADIOGRAPHY WITH THE PLUTONIUM RECYCLE CRITICAL FACILITY

J. L. Cason
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June 1970

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THERMAL NEUTRON RADIOGRAPHY WITH THE PLUTONIUM RECYCLE CRITICAL FACILITY

By

J. L. Cason
K. S. Maiwald

Nondestructive Testing Department
Systems and Electronics Division

And

E. P. Lippincott

Reactor Physics Department
Physics and Engineering Division

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RICHLAND, WASHINGTON 99352

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THERMAL NEUTRON RADIOGRAPHY WITH THE PLUTONIUM RECYCLE CRITICAL FACILITY

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ABSTRACT

The feasibility of using the PRCF (Plutonium Recycle Critical Facility) for thermal neutron radiography has been demonstrated. Results include flux measurements and neutron radiographs with both direct and indirect techniques. The PRCF was modified on a temporary basis to provide an internal and external beam of neutrons. Experiments were performed under both conditions which proved the feasibility of producing high quality neutron radiographs of various samples and test pieces. Recommendations and conclusions regarding possible approaches for permanent modification of PRCF are presented.

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THERMAL NEUTRON RADIOGRAPHY WITH THE PLUTONIUM RECYCLE CRITICAL FACILITY

J. L. Cason, K. S. Maiwald and E. P. Lippincott

SUMMARY

The PRCF (Plutonium Recycle Critical Facility) has been evaluated as a facility for performing thermal neutron radiography. The flux measurements and radiographic results indicate that it is well suited for performing high quality neutron radiography.

The study included an evaluation of external and internal neutron beam capabilities. Requirements included obtaining a reasonable thermal flux ($>10^4$ nv) at the object position with the degree of collimation needed for neutron radiography. These two basic factors insure the production of high resolution neutron radiographs in a reasonable period of time.

The permanent modification of such a facility would aid in supporting nondestructive testing (NDT) effort for the AEC at the Hanford Complex. Some areas of support would include quality assurance through neutron radiography of pre- and post-irradiated fuel pins, test capsules and other reactor test assemblies.

As a nondestructive testing method, neutron radiography will serve as a complementary test to X and gamma radiography. In other areas (e.g., irradiated objects) neutron radiography will be the only acceptable method for radiographic examination.

DISCUSSION

NEUTRON RADIOGRAPHY

Neutron radiography like X or gamma radiography provides internal interrogation of an object with penetrating radiation. The image of the attenuated radiation is recorded and provides the needed information for object evaluation. Image characteristics depend upon collimation of incident neutrons, energy state and distribution of neutrons, radiation attenuation in the object and the imaging method. When comparing neutron to X or gamma radiography, emphasis is placed on the difference in the nature of radiation attenuation. This basic difference makes neutron radiography a unique and useful technique. The relative differences for radiation attenuation coefficients, mass absorption and neutron absorption scattering for X-ray and thermal neutrons are given in Figure 1. The high scatter of neutrons by light elements seems to be particularly advantageous as is the ability to discriminate between materials which have similar X-ray absorption coefficients. It should be noted that the random distribution of neutron absorption for the elements is found primarily for thermal neutrons. The cross-sectional differences for fast neutrons tend to diminish, making the use of high energy neutrons less desirable for general radiographic purposes. General examples of neutron radiographic uses are given in Table 1.

IMAGING NEUTRONS

The techniques employed to image neutrons are basically different from those used to image X or gamma rays. X-rays can be imaged directly with a piece of film. At present there is no "film" that images neutrons directly; hence, neutrons must be converted to a type of radiation that is easily imaged. To convert an attenuated neutron beam to a type of radiation that is detectable on film, a converter material must be used. A

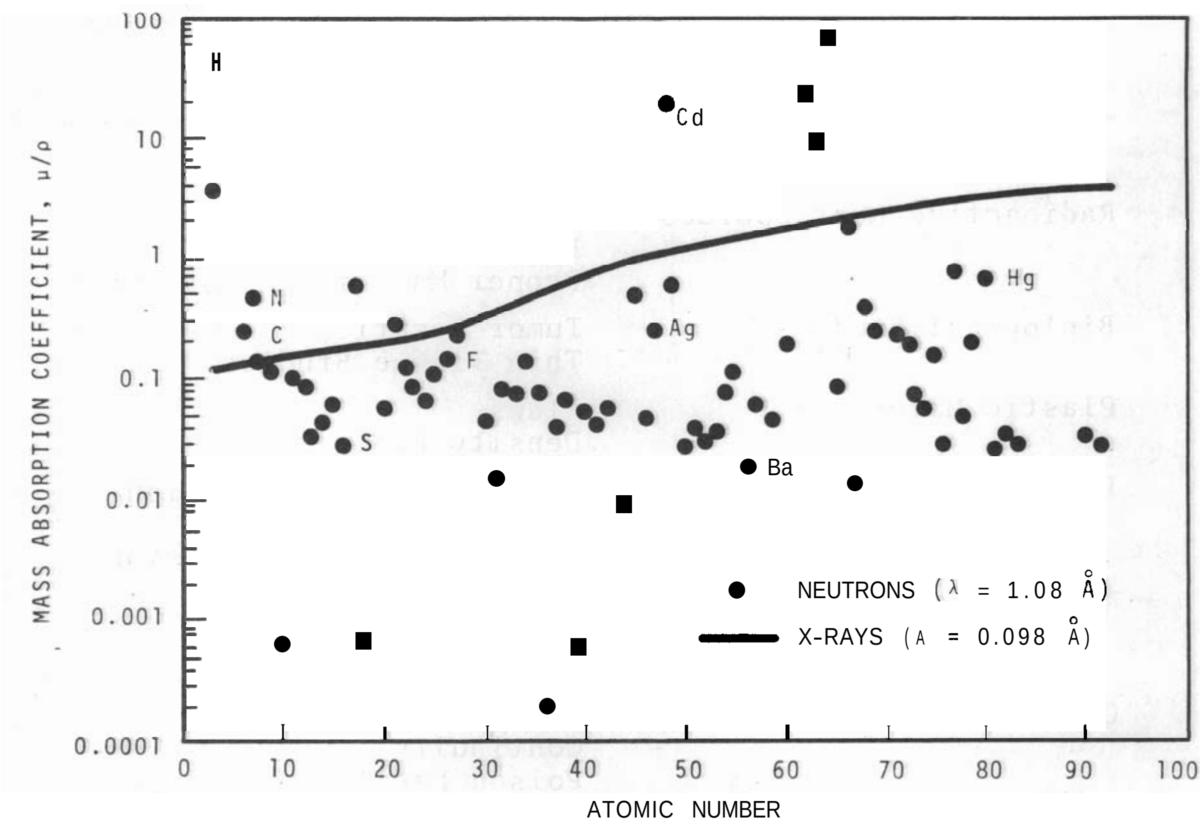

FIGURE 1. Comparison of Thermal Neutrons and X-Rays Absorption for Various Elements

few of these materials are listed in Table 2 and emit either prompt or delayed radiation. The use of prompt and delayed emitter materials results in direct and indirect (transfer) neutron radiographic techniques, respectively. These two cases are illustrated in Figure 2. Both techniques were utilized in the evaluation of the PRCF.

TABLE 1. General Examples of Neutron Radiography Uses

Object	Requirement
General	
Radioactive Heat Sources	Weld Evaluation Element Continuity Proper Material Constituents
Biological Studies	Tumor Location Thin Tissue Studies
Plastic Materials	Flaws Density Evaluation
Physics and Chemistry Basics	Inter-Metallic Diffusion Processes Gaseous - Metal Diffusion Characteristics
Reactor Technology	
Control Rods	Homogeneity Continuity Poison Levels Inclusions and Voids
Fuel Elements	Homogeneity and Enrichment Continuity Poison Levels Inclusions and Voids
Shielding Materials	Homogeneity Continuity Inclusions and Voids
Rocket and Missile Technology	
Rocket Fuel	Crack or Fissures
Rubber Tubing	Continuity
Organic Gaskets	Voids
Explosive Devices	Inclusions
Electronic Components	Material Definition

TABLE 2. **Characteristics of Several Neutron Converter Materials**

Material	Isotope Involved in Reaction	Relative Natural Abundance, %	Cross-Section for Reaction (thermal neutrons, velocity = 2,200 m/sec), barns	Reaction	Half-Life S = sec m = min h = hours d = days
Lithium	Lithium-6	7.52	910	$^{6}Li(n,\alpha)^{3}H$	
Boron	Boron-10	18.8	3,770	$^{10}B(n,\alpha)^{7}Li$	
Rhodium	Rhodium-103	100	12	$^{103}Rh(n)\ ^{104m}Rh$	4.5 m
			140	$^{103}Rh(n)\ ^{104}Rh$	44 s
Silver	Silver-107	51.35	44	$^{107}Ag(n)\ ^{108}Ag$	2.3 m
	Silver-109	48.65	2.8	$^{109}Ag(n)\ ^{110m}Ag$	270 d
			110	$^{109}Ag(n)^{110}Ag$	24.2 s
Cadmium	Cadmium-113	12.26	20,000	$^{113}Cd(n,\gamma)^{114}Cd$	
Indium	Indium-115	95.77	155	$^{115}In(n)^{116m}In$	54.1 m
			52	$^{115}In(n)^{116}In$	13 s
Samarium	Samarium-149	13.8	40,800	$^{149}Sm(n,\gamma)^{150}Sm$	
	Samarium-152	26.8	140	$^{152}Sm(n)^{153}Sm$	47 h
Gadolinium	Gadolinium-155	14.73	61,000	$^{155}Gd(n,\gamma)^{156}Gd$	
	Gadolinium-157	15.68	240,000	$^{157}Gd(n,\gamma)^{158}Gd$	
Dysprosium	Dysprosium-164	28.1	2,000	$^{164}Dy(n)\ ^{165m}Dy$	1.25m
			500	$^{164}Dy(n)^{165}Dy$	140 m
Gold	Gold-197	100	96	$^{197}Au(n)^{198}Au$	2.7 d

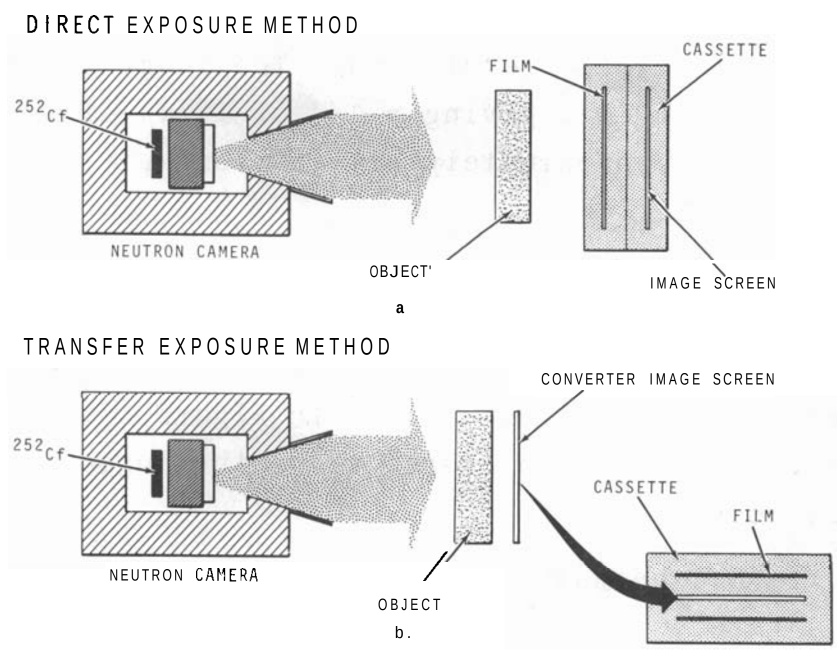

FIGURE 2. **Direct and Transfer Exposure Methods for Neutron Radiography**

FEASIBILITY EXPERIMENTS PRCF

APPARATUS

The PRCF is an experimental reactor designed to operate at maximum power levels of 10 kW with plutonium or uranium fuels and either heavy or light water moderators. The reactor is also designed so that a fuel element which has been irradiated in a power reactor can be transferred to the PRCF for reactor neutronic measurements.

A light-water moderated reactor core made up of UO_2-PuO_2 fuel rods was used for the radiography studies. A cutaway view of the reactor and the cell in which it is located is shown in Figure 3.

The PRCF was modified on a temporary basis to provide an internal beam (Figures 4-6) for indirect radiography and two external beams (Figures 7-11) for direct radiography.

The collimators used were 4-in. diameter aluminum tubes (0.050 in. thick) wrapped with 0.040 in. of sheet cadmium. The external beam tube was evacuated to reduce neutron scatter and provide better image resolution. The length of the internal beam tube was 60 in. giving a ℓ/d of 15:1. The external beam (Case 1) was approximately 210 in. long giving a R/d of approximately 53:1.

The internal beam arrangement illustrated in Figure 4 is shown in photographs in Figures 5 and 6. In Figure 5 the collimator is shown at the neutron input (a) directly above the grid plate on top of the fuel. In Figure 6 the exit end (b) of the collimator is pictured above the support plate for the control rods.

The external beam arrangement, Figure 7, is shown in photographs in Figures 8, 9 and 10. The beam extraction from the top plate which supports the control rods is shown as (a)

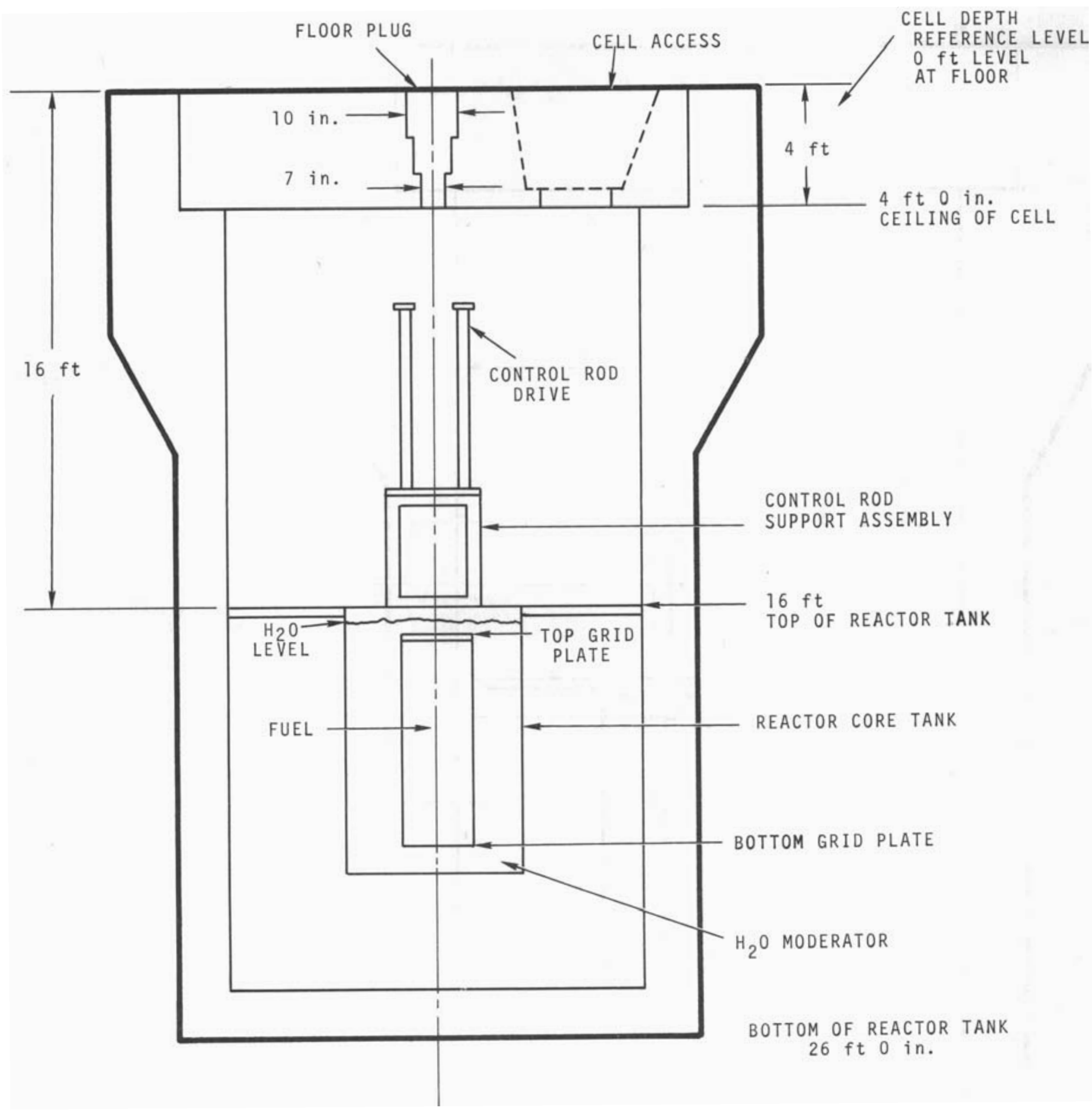

FIGURE 3. PRCF Cell

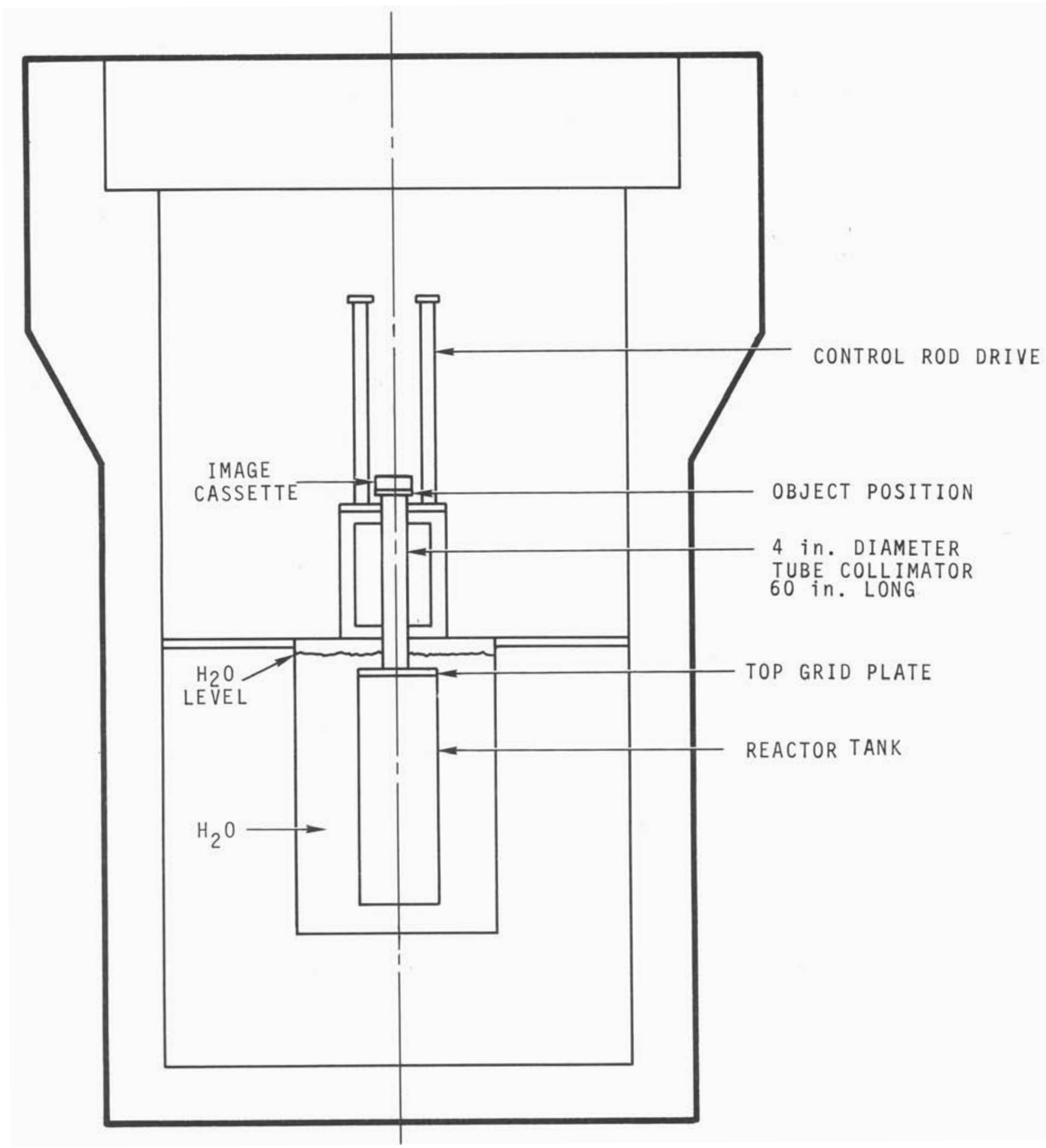

FIGURE 4. Internal Beam Collimator

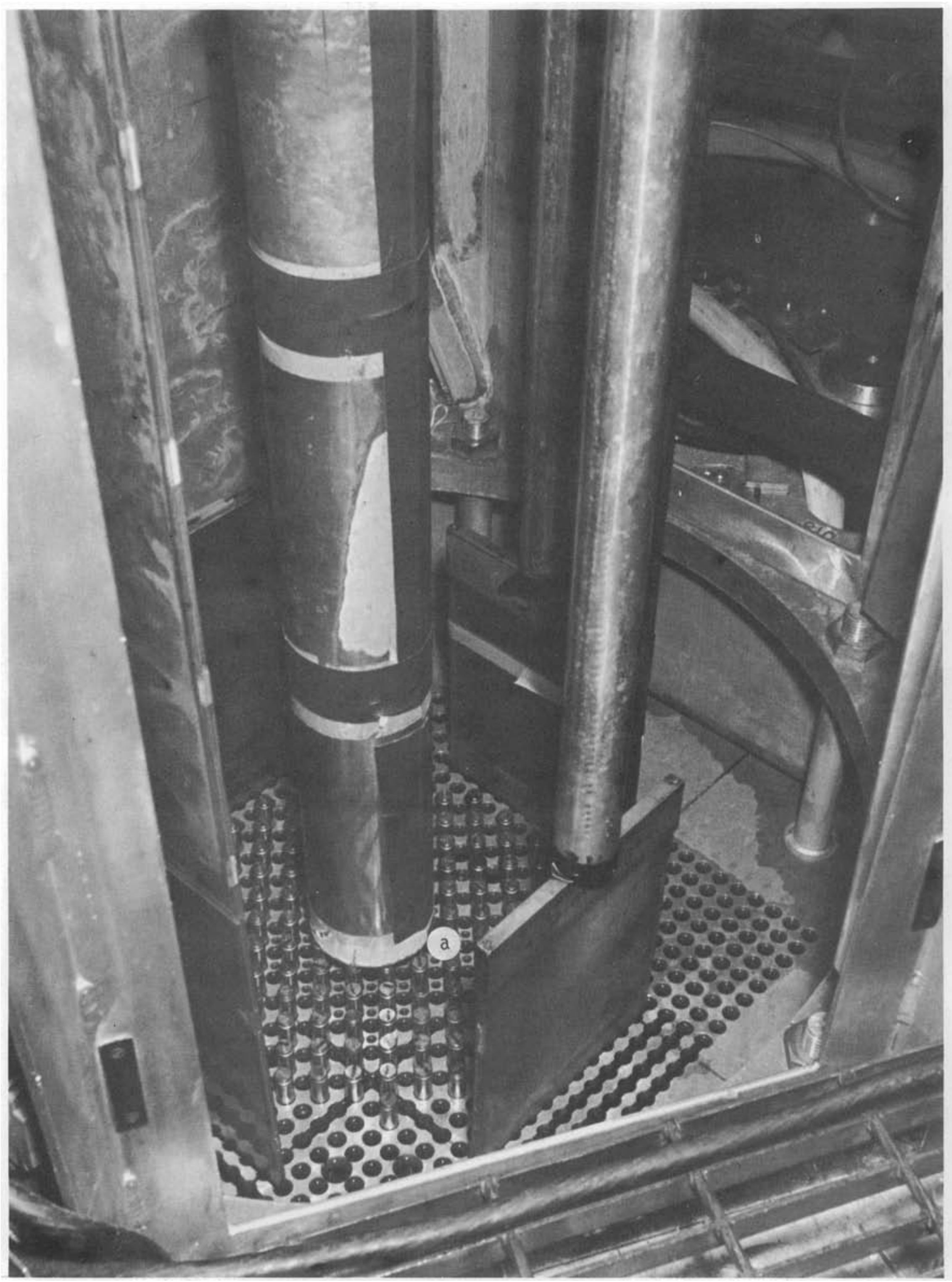

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FIGURE 5. PRCF Internal Beam - View A

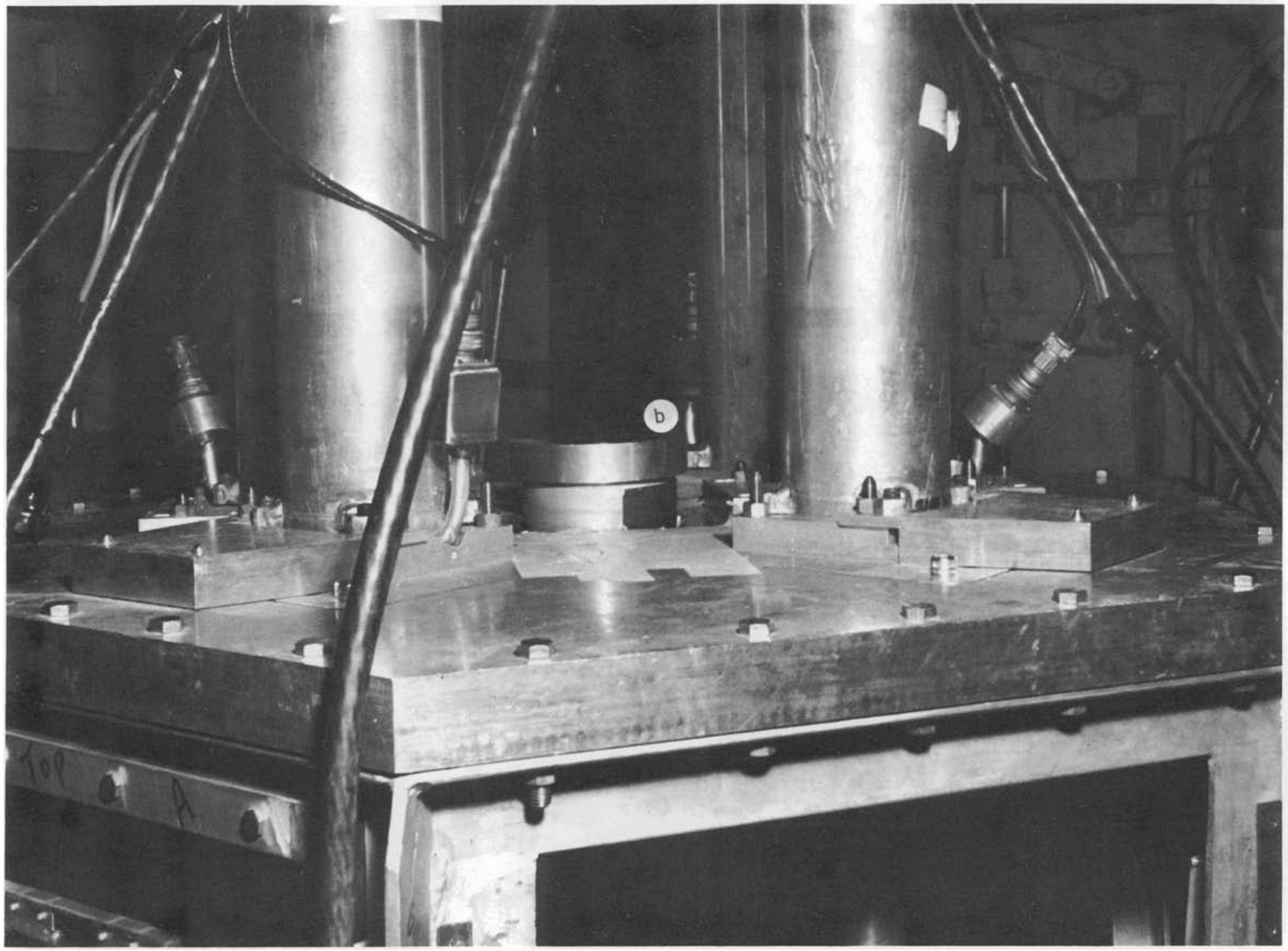

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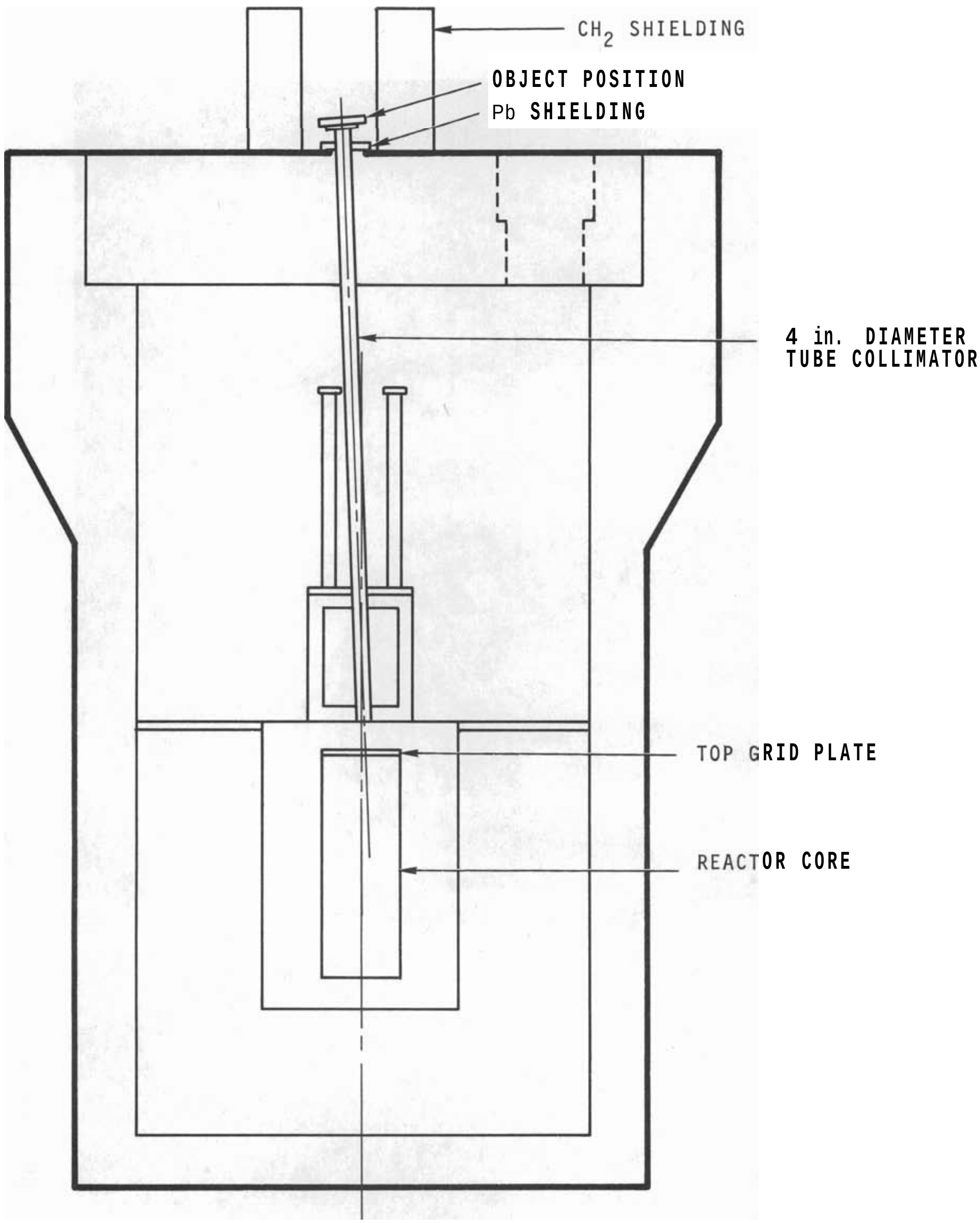
FIGURE 6. PRCF Internal Beam - View B



'FIGURE 7. PRCF, External Beam Modification

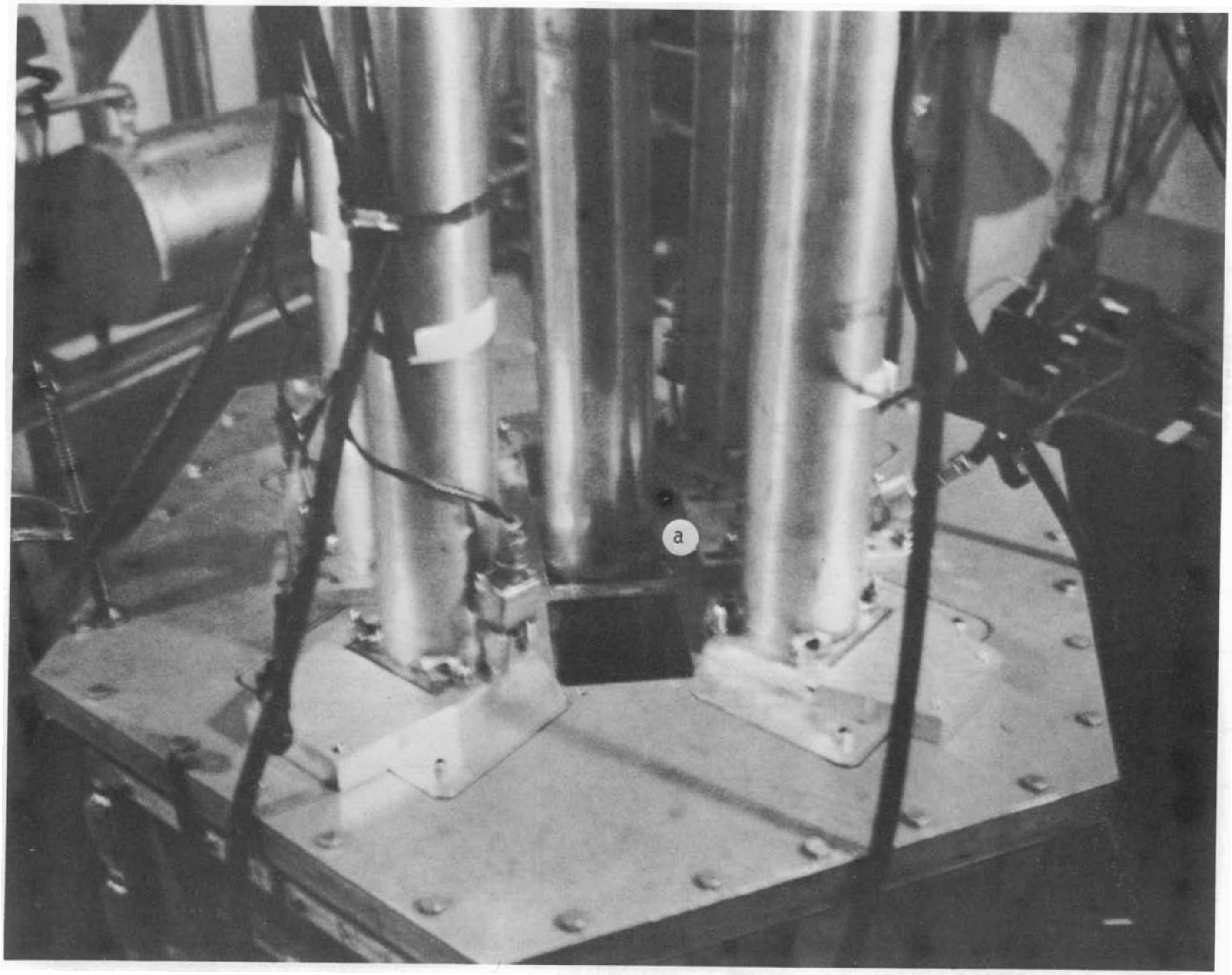


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FIGURE 8 PRCF Ex l Beam - View A

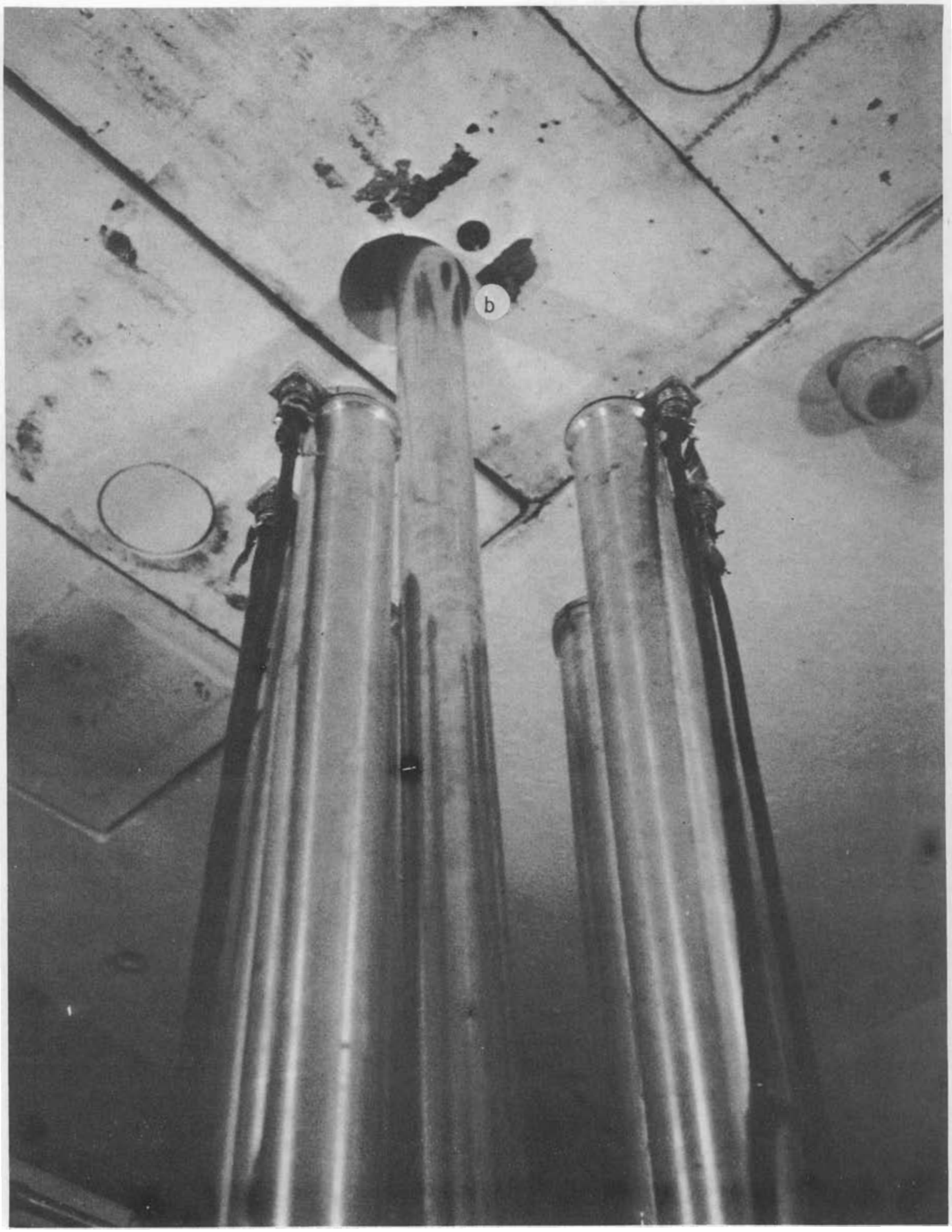

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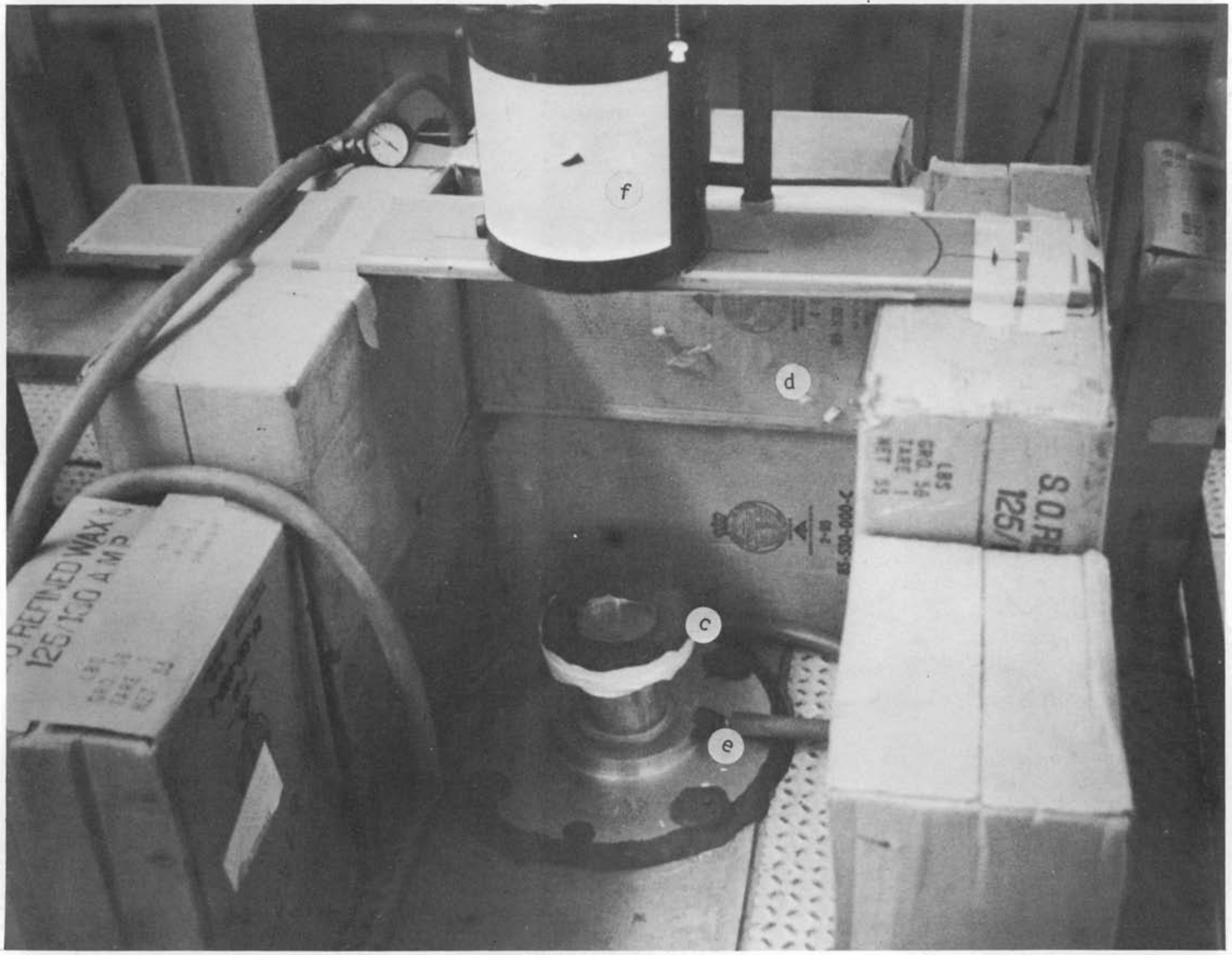
FIGURE 9. PRCF External Beam - View B



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<u>FIGURE 10</u> PRCF External Beam - View C

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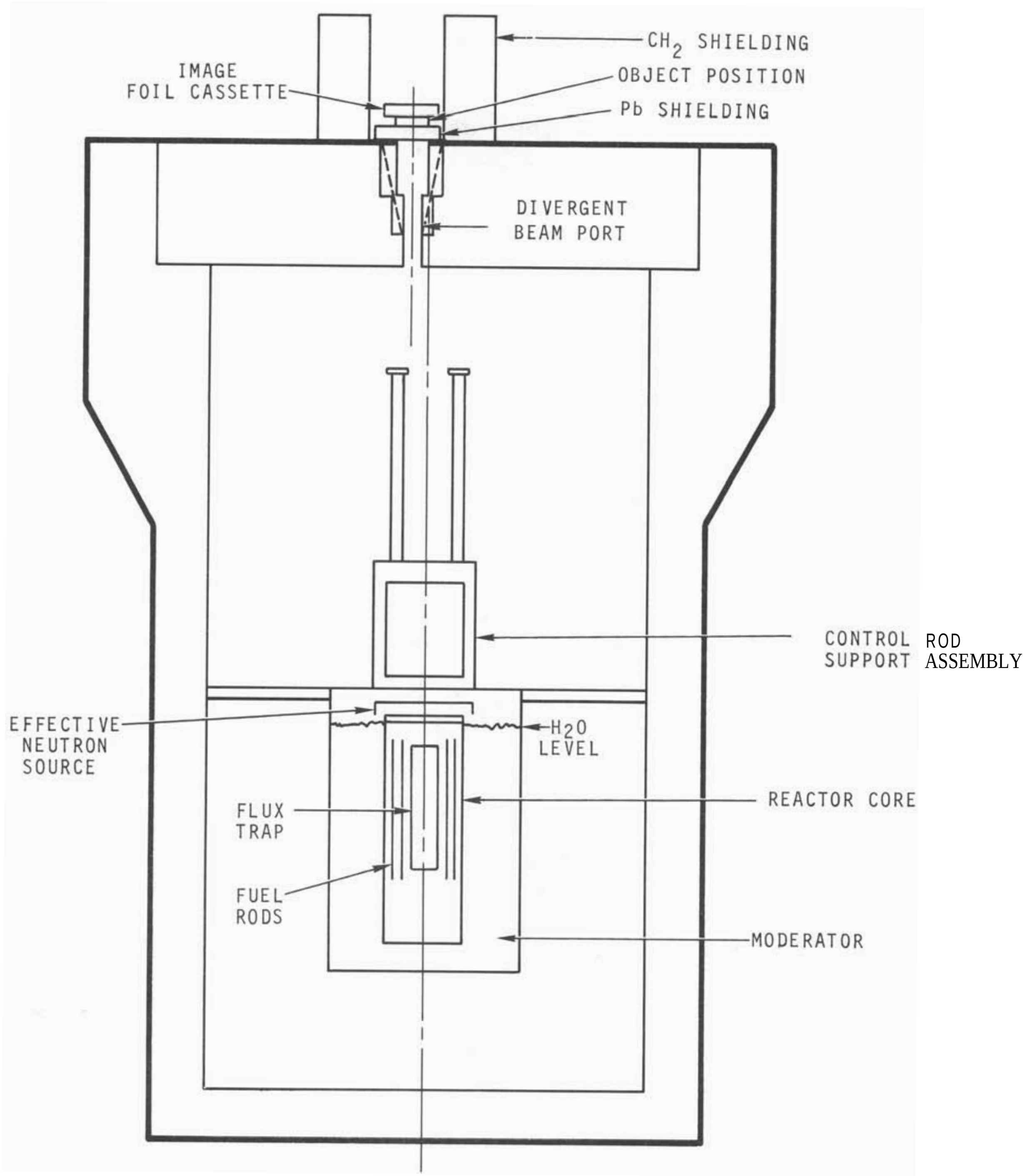


FIGURE 11. **PRCF External Beam - Divergent**

in Figure 8. The beam extraction tube is shown in Figure 9 as it passes through the top of the PRCF cell (b) to the floor above, pictured in Figure 10. The exit end of the beam (c), the biological shielding (d), the vacuum hookup for the collimator (e), and a neutron detecting instrument (f) are shown in Figure 10.

Case 2 was for an air gap between the internal beam exit to the floor plug (a distance of 144 in.). In this case no tube was used and an evaluation of the cutting of another floor plug for an additional beam was determined feasible. A relative value for the collimation can be determined by assuming (in Figure 11) that the lower side of the floor shield plug (a) was the source; thus, in effect, producing a divergent beam with a 7:1 ℓ/d. However, the geometrical resolution capabilities of the beam indicate that the collimator is much better than would be expected with a ℓ/d of 7:1.

EXPERIMENTAL TECHNIQUES

The ability to radiographically image objects in the presence of high gamma is one of the basic requirements for radiography of irradiated objects. Both direct and indirect radiography were performed using the external beam. Because of high gamma background in the cell (>20 R/hr) direct radiography with the internal beam configuration was not possible. Neutron radiography within the PRCF cell with the transfer technique demonstrated the ability of the collimation and image technique for producing neutron radiographs in the presence of high gamma radiation.

EXPERIMENTAL RESULTS

The results of various radiographic techniques that were employed in the evaluation of the PRCF are outlined in Table 3. Listed are: the techniques, the collimator type, image conditions, objects radiographed and radiographic results,

TABLE 3. PRCF Neutron Radiographic Techniques

No.	Technique	Object Radiographed	Results
A	External Collimator-Dysprosium indirect	T-1 Pu fuel pin & Cd shim	Good resolution and definition
1	External Collimator-Dy. indirect	M-16 Ammunition N.R.l Penetrameter	Fair definition, good resolution
2	External Collimator Gd direct 1 1/4 in. Pb filter	M-16 Ammunition N.R.l Penetrameter	Processing error
3	External Collimator-Gd direct 1 1/4 in. Pb filter	M-16 Ammunition N.R.l Penetrameter	Good definition and resolution
4	External Collimator-Dy indirect	M-16 Ammunition N.R.l Penetrameter	Poor definition, fair resolution
5	External Collimator In indirect	M-16 Ammunition N.R.l Penetrameter	Objects moved
6	External Collimator Gd direct 1 1/4 in. Pb filter	M-16 Ammunition N.R.l Penetrameter	Underexposed - good definition
7	External Collimator-Dy indirect	M-16 Ammunition N.R.l Penetrameter	Good definition and resolution
8	External Collimator In indirect	M-16 Ammunition N.R.l Penetrameter	Underexposed
9	Internal Collimator Dy indirect	M-16 Ammunition N.R.l Penetrameter	Overexposed
10	Internal Collimator In indirect	M-16 Ammunition N.R.l Penetrameter	Overexposed
11	External Beam - No collimator Gd direct 2 1/2 in. Pb filter	Lighter - Match book	Fair definition and resolution - high gamma
12	External Beam - No collimator Bd direct 1 1/4 in. Pb filter	Lighter - Match book	Good definition and resolution
13	Internal Collimator-Dy indirect	M-16 Ammunition N.R.l Penetrameter	Overexposed, fair definition High scatter
14	Internal Collimator-Dy indirect	M-16 Ammunition N.R.l Penetrameter	Overexposed, fair definition High scatter

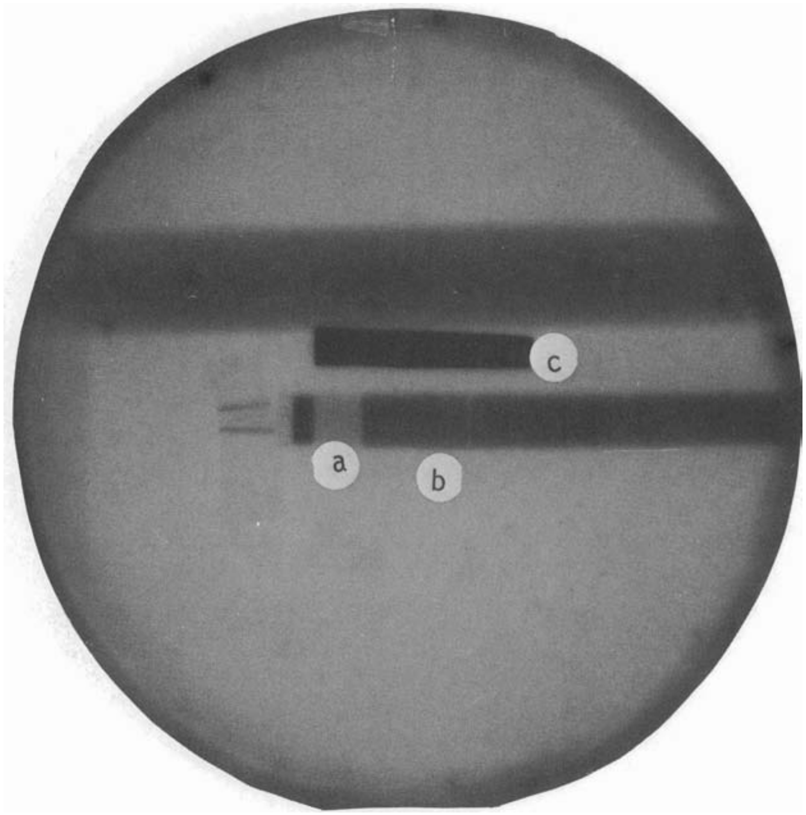
Some of the typical radiographs obtained are presented in Figures 12 through 15. A brief description of the objects is given with each figure. Reproduction of the radiographs has resulted in some loss in quality. Analysis using densitometers allow more quantitative interpretations than could be obtained from the reproductions. The examples are moderate quality neutron radiographs, as would be expected to result from feasibility studies using temporary experimental arrangements. Modifications of a permanent nature would be expected to produce radiographs of a higher degree of resolution. The results demonstrate the feasibility of using the PRCF for thermal neutron radiography for both unirradiated and irradiated samples.

Absolute flux measurements were made using gold foils at the object position for the external beam configuration (Figure 10). Bare and cadmium covered foils were irradiated to give the thermal and epithermal flux. Bare foils were placed at various distances from the center of the beam to estimate the uniformity of the beam over the 4 in. diameter. The results indicate that the beam is uniform to within less than 5%; values of the absolute flux are given in Table 4.

TABLE 4. Absolute Flux Measurements at External Object Position*

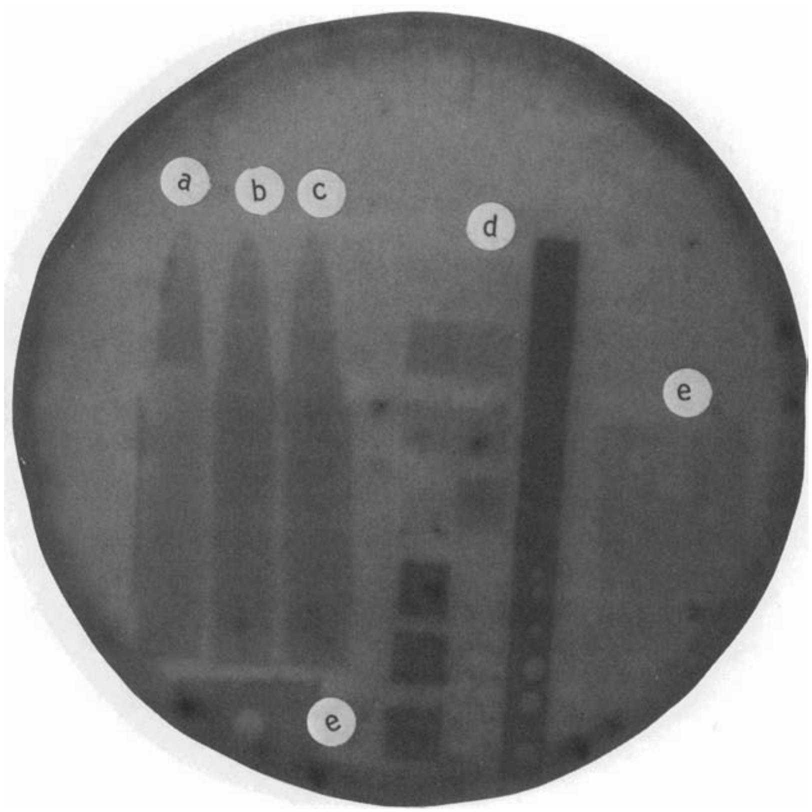
Thermal Flux	7.5×10^4 n/cm^2-sec/kW
Epithermal Flux	1.25×10^4 n/cm^2-sec/lethargy unit/kW

* *As measured by gold foil. The activation of 0.005 in. thick gold foil is 60% by thermal neutrons and 40% by epithermal neutrons.*



T-1 PuO_2 Fuel Pin
a. Natural UO_2 Pellet
b. Swollen PuO_2 Pellet
c. Cadmium Test Piece

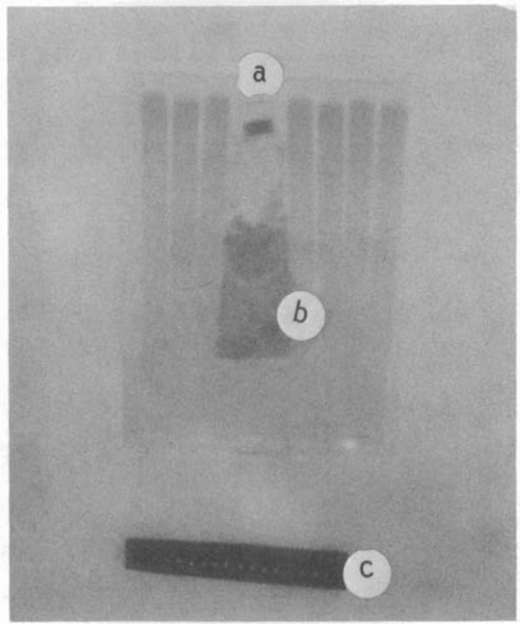
FIGURE 12. Neutron Radiograph of T-1 PuO_2 Fuel Pin Per Technique A, Table 3



M-16 Ammunition

a. Booby-trapped Round
b. Tracer Round
c. Standard Load
d. Special Neutron Radiographic Image Quality Indicator
e. Teflon

FIGURE 13. Neutron Radiograph of M-16 Ammunition Per Technique 7, Table 3



a. Detonator
b. Plastic Explosive
c. Cadmium Test Piece

FIGURE 14. Neutron Radiograph of Match Book Booby-trapped Per Technique 11, Table 3

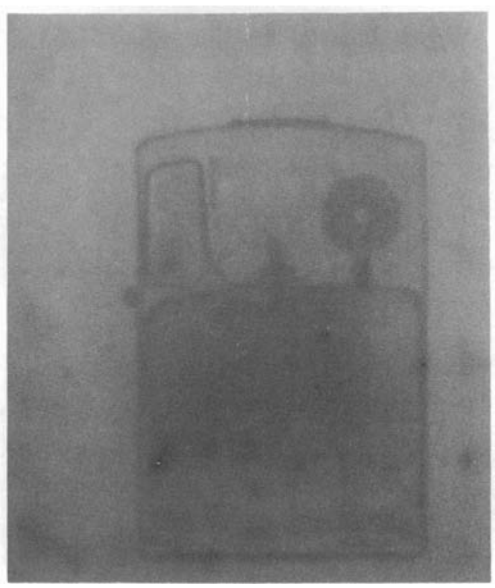


FIGURE 15. Neutron Radiograph of a Lighter Per Technique 12, Table 3

CONCLUSIONS AND RECOMMENDATIONS

This work shows that neutron radiography using the PRCF is practical. The experimental arrangement was sufficient for the feasibility study and provides the basic information needed for the design modification of the PRCF as a neutron radiographic facility.

A description of a design modification of the PRCF for thermal neutron radiography is divided into three basic headings. The first heading includes those items necessary for modification of the basic components of the reactor. These items are necessary whether or not the object to be radiographed is radioactive. The second heading includes requirements for providing radiography of nonirradiated samples. The third heading includes requirements for handling irradiated samples for radiography. Alternate solutions for handling and radiographing irradiated samples are offered. Prior to making any permanent modifications, a design and safety evaluation would be made.

REQUIREMENTS FOR MODIFICATION OF BASIC REACTOR COMPONENTS FOR NEUTRON RADIOGRAPHY

- A study performed to determine the type of fuel and loading to maximize the beam flux.
- Reactor core be arranged so as to provide a central flux trap, thereby increasing the thermal neutron flux available for collimation input at a given power level.
- Control mechanisms relocated or modified to simplify access to reactor fuel.
- A shielded storage designed and constructed for irradiated fuel elements.
- A remote manipulator provided for transferring fuel between shielded storage and reactor.
- A shielded enclosure be constructed outside the cell at floor level that would completely shield the beam output region (i.e., beam catcher). Top view shown in Figure 16.

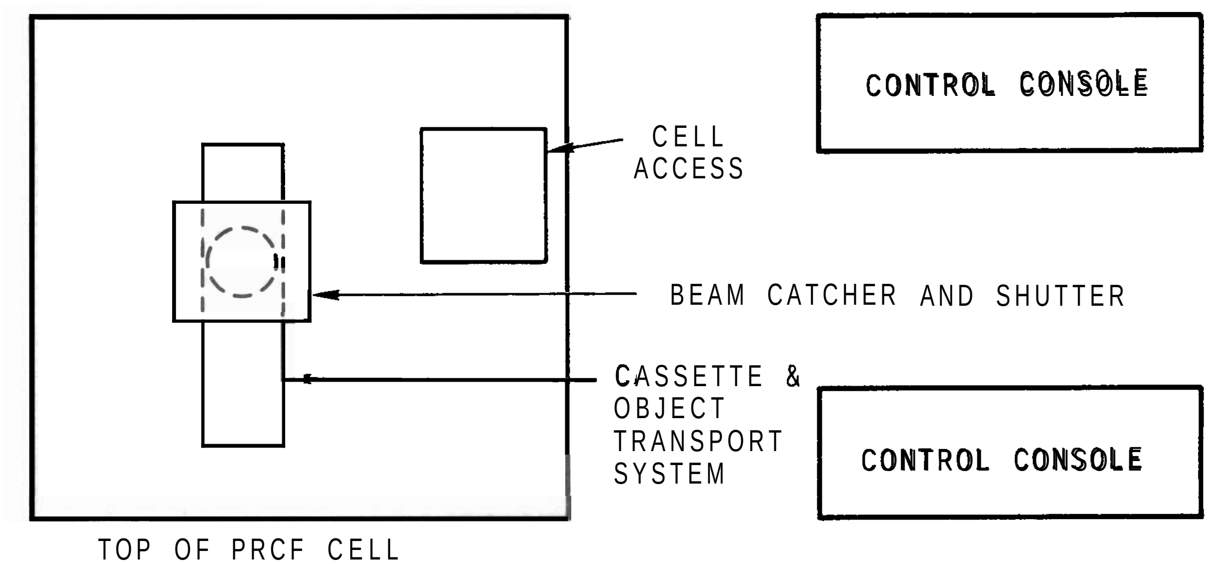


FIGURE 16. PRCF External Cell Modifications **for** Radiography of Unirradiated **Objects**

- Experiments be conducted to determine optimum placing of shutter mechanism for external beam control.
- Divergent collimators be constructed and installed in place of tube type collimators. This would increase area available for radiographic inspection and would improve resolution. These collimators should be lined with a boron-carbide epoxy compound to reduce neutron scatter and gamma emission of collimator walls, thus improving the test system resolution.
- Bismuth filter be used for external neutron beam for reduction of source gammas when using the direct technique.
- Complete flux measurements be made for various collimator systems proposed.
- Neutron radiographic techniques and exposure tables be established for various materials collimator and reactor conditions and for imaging techniques as a function of the flux level.

REQUIREMENTS FOR PROVIDING NEUTRON RADIOGRAPHY OF UNIRRADIATED SAMPLES

The basic requirements for providing an external beam of neutrons would at the same time provide a facility for radiography of unirradiated samples.

- A shielded enclosure be constructed outside the cell at floor level that would completely shield the beam exit region (i.e., beam catcher). Top view is shown in Figure 16.
- Included in the beam catcher would be:
    a. A shutter device for the beam
    b. A slide tray or other transport mechanism for manually positioning the object and image cassette in the beam when the shutter is closed
    c. Radiation warning light for indication of the shutter position and the radiation conditions within the object beam area.

REQUIREMENTS FOR HANDLING IRRADIATED MATERIALS FOR NEUTRON RADIOGRAPHY

- One alternative would be to use the existing cell which houses the PRCF as the enclosure for handling irradiated samples (see Figure 17).
- The other alternative would be the construction of a hot cell facility above the reactor cell roof (control room floor) for the handling of radioactive samples (see Figure 18).
- Another possibility for handling irradiated fuels for radiography would be the modification of the PRTR storage and water transfer basin to include an underwater beam from the PRCF. Neutron radiography would then be performed underwater and additional shielding would not be necessary.
- The first alternative has the following advantages and disadvantages:

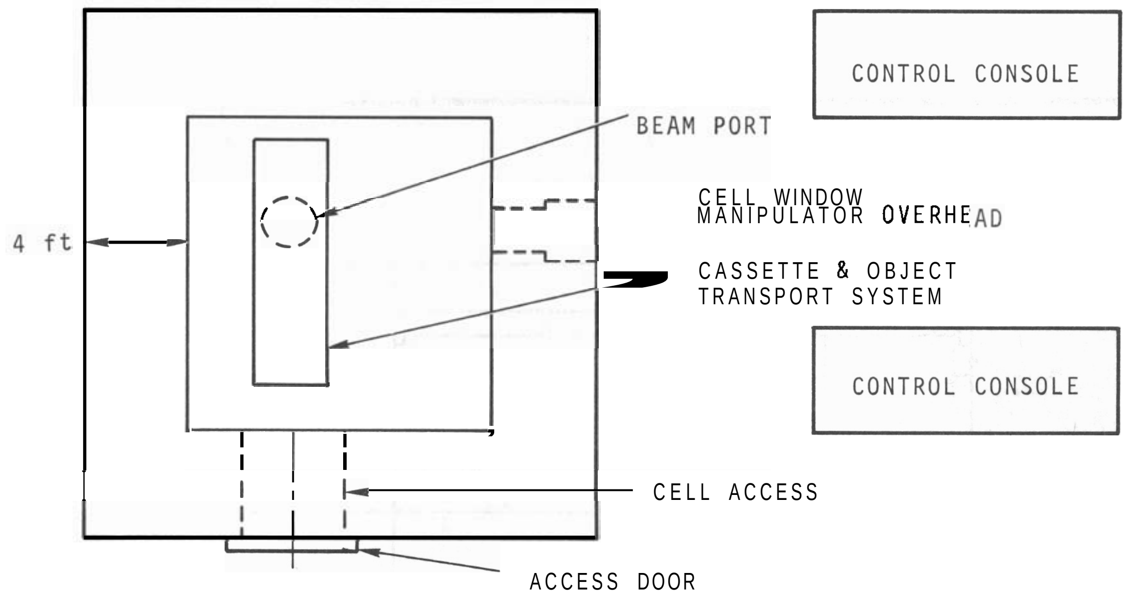


FIGURE 17. External Cell Mocifications for Radiography of Irradiated Objects

Advantages

- Construction of additional shielding would not be necessary.
- Higher flux would be available, thus foil activation times for the transfer image technique would be short.

The feasibility of this technique was not determined under this program; however, the merits of such a system make it worthy of consideration. The handling of irradiated samples could be accomplished using existing PRCF and PRTR basin equipment.

Disadvantages

- High background of scattered neutrons within the cell results in neutron radiographic image degradation.
- Reduced source-to-object distance limits to some extent maximum permissible resolution.

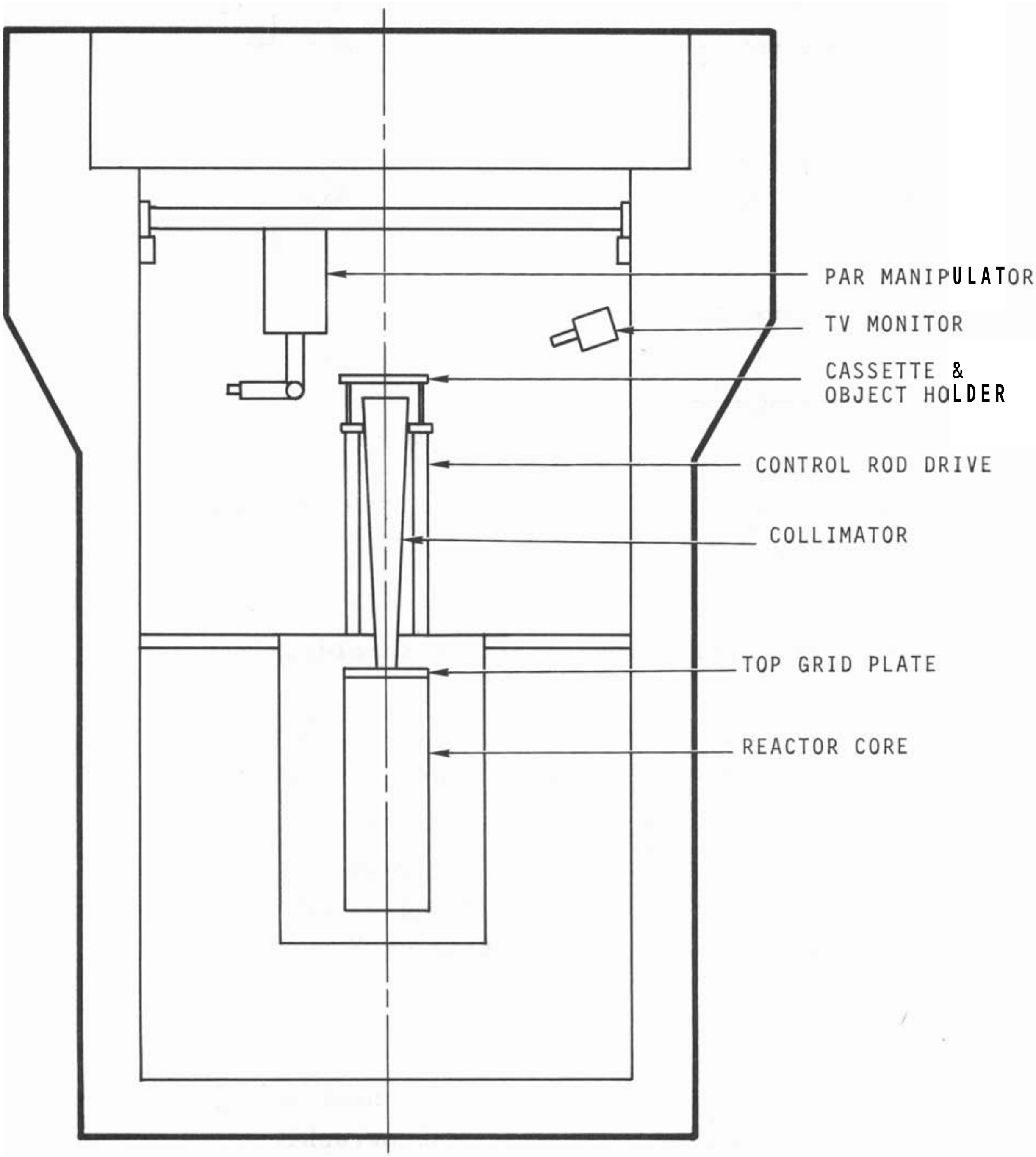


FIGURE 18. Internal Cell Modifications for Radiography of Irradiated Objects

- Handling of irradiated sample remotely within cell would require an extremely complex manipulation system.
- In the event of irradiated sample capsule failure (i.e., Pu fuel) the cell would become contaminated and inhibit any maintenance on the PRCF prior to clean-up.
- Remote viewing of sample for proper alignment and position would have to be a television monitor or similar system. Maintenance on such a system would be difficult until the reactor core was removed because of the high background in the cell when the reactor is shut down.

The second alternative has the following advantages and disadvantages:

Advantages

- Low background of scattered neutrons would result in better radiographic resolution.
- Handling of samples within external hot cell would be easy because of visual contact through a hot cell window and less complex sample transport system.
- In the event of irradiated capsule failure, contamination would not spread to the reactor cell and clean up of a small hot cell would be relatively easy.
- Increased distances from neutron source would provide a system with inherently better geometrical resolution.

Disadvantages

- Substantial shielding (∿4 ft thick) above the PRCF cell would have to be installed adding increased floor load.
- A cask handling platform would have to be added to manipulate the cask to the hot cell wall for transport of the radioactive object.

- Possible relocation of the PRCF control room would be necessary because of the reduction of available space for hot cell installation.

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