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BIOLOGICAL SHIELD EVALUATION OF THE WATER BOILER

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1.

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ABSTRACT

A series of measurements were made to determine the effectiveness of the CR&D Water Boiler Reactor biological shield. Included are data on the concrete and timber primary shields, the thermal column shielding, and a general evaluation of the total shield. The report also includes neutron and gamma flux traverses and emergent gamma energy spectra obtained at various points around the reactor shielding with a three crystal spectrometer.

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AEC, Oak Ridge, Tenn.-W44381

EVALUATION OF THE BIOLOGICAL SHIELDING OF THE WATER BOILER REACTOR

1. INTRODUCTION

The CR&D Water Boiler Reactor consists of a 12-1/2 inch OD by 0.080 inch wall stainless steel sphere containing approximately 700 grams of U-235 in an enriched uranyl sulfate solution of about 14.5 liters volume. The sphere is embedded in the center of a right circular cylinder of graphite five feet in diameter by five feet high, which serves as the reflector. This in turn is covered by a 3/8-inch thick steel tank, which is surrounded by a 0.030 inch thick sheet of cadmium and a five inch layer of lead.

The reactor is situated in a cave constructed on the sides of three-foot thick keyed concrete blocks, measuring seven by twenty by seven feet inside dimensions. The top of the cave is covered by two feet of timber recessed into the cave and another two feet spanning the top, with a one-inch layer of borated paraffin between the two portions.

The reactor and its shielding are located in the CR&D experimental physics building.

The cave contains the entire control and safety rod mechanisms as well as the various components of the closed cycle gas handling system. A continuous flow of air is forced over the sphere to sweep fission product gases and dissociated hydrogen and oxygen from the vicinity of the fuel solution. The hydrogen and oxygen are recombined catalytically, and the resulting water is condensed and returned to the sphere. Fission product gases are circulated continuously and are partially trapped out in a series of filters. Due to the high level of radiation inherent in the gas, and because the gas lines, pump, filters etc., are situated on both sides of the reactor, and are not shielded, a certain time, depending on the operating history, must elapse after operation before personnel may enter the cave.

Exposure facilities include a central exposure tube, or glory hole, 1.1-inch in diameter penetrating the sphere on a diameter and continued out through the reflector, cave, and concrete shield. When not in use the hole through the concrete is plugged with a three foot long steel rod. A maximum thermal neutron flux of 2.1×10^{10} neutrons/per cm^2 per sec exists in the center of the sphere at a power level of 500 watts.

There are eight graphite stringers leading past the sphere which are removable from the south face for sample loading and subsequent irradiation. The eight stringer holes are filled by stepped lead plugs in the cylindrical lead case surrounding the reflector, and by removable hardwood plugs in the concrete shield. The holes are further covered by two hinged lead doors one and one half inches thick.

A horizontal thermal column measuring approximately four by four by three feet penetrates to the north face of the shielding. It is attached to the reflector graphite by a graphite adapter section which penetrates the lead, steel, and cadmium surrounding the reflector in a 20 by 20 inch square. The thermal column face is shielded by four inches of lead contained between 1/2-inch thick steel plates. The sides are shielded by four inches and two inches of lead near the face, and the intervening space between the column and the concrete is packed with borated paraffin.

A vertical thermal column two and one half feet in length by five by five feet square is located on top of the reactor. This column is coupled to the reflector graphite through a 16-inch diameter cylinder penetrating the lead, cadmium and steel. The column contains a 0.030-inch thick cadmium shutter spanning the 16-inch opening. A five foot high by five foot diameter aluminum tank containing distilled water is situated on top of this column, and penetrates the top timber shield. Controls and instrumentation are located in a control room adjacent to the reactor cave.

The above description may be supplemented by consulting references (1), (2), and (3) and Fig. 1. Individual shielding components are treated in greater detail in subsequent sections of this report.

2. EXPERIMENTAL MEASUREMENTS

2.1 General

The CR&D water boiler was originally installed for 100 watt operation. Calculations showed that three feet of concrete would be sufficient for operation at this power, and that the expected radiation level on the surface of the concrete should be approximately tolerance considering both slow and fast neutrons, and gamma rays resulting from capture gamma (n, γ) reactions in the concrete. The use of timber on top of the reactor cave was dictated by the need for low cost shielding. Borated paraffin was inserted here to make this part of the shield more effective, and it was planned to exclude personnel from the top of the reactor during operation. Similarly, it was calculated on the basis of carbon capture gamma rays that the shielding on the face of the horizontal thermal column should be four inches of lead.

After loading to criticality and preliminary operation, it became apparent that the shielding was generally more effective than anticipated. Hence, approval was secured from the Reactor Safequards Committee for an increase in power level. Present operating power is 500 watts.

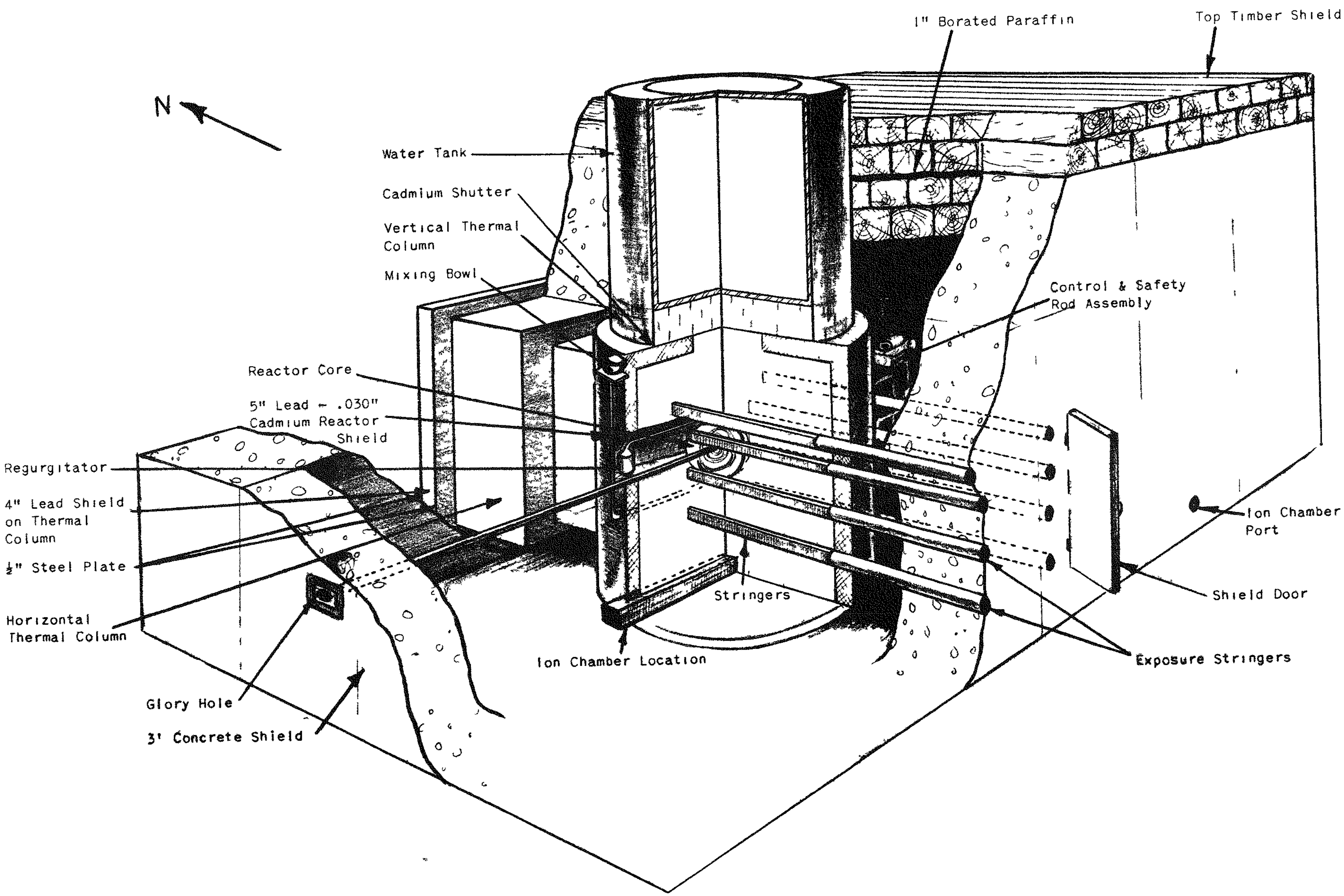

FIG. I - PERSPECTIVE OF REACTOR INSTALLATION

A general radiation survey of the experimental physics building with the reactor operating at 500 watts is shown in Fig. 2. Data are included for slow neutron and gamma intensities. Fast neutron measurements were made with a portable survey type instrument, and in no case did readings exceed half tolerance except on the roof timbers where the maximum level was 1-1/2 times tolerance.

It may be seen that levels average slightly more than tolerance on the surface of the shield except on the top timber, from which personnel are excluded, and in the immediate vicinity of the horizontal thermal column face. Readings were taken at chest height and no significant deviations were encountered above or below this position.

Gamma measurements were made with a Tracerlab "Cutie Pie" monitor. Slow neutron readings were taken with a portable slow neutron survey instrument.

Reference (4) may be consulted for more complete information on the survey methods used. Measurements made on the horizontal thermal column face will be discussed later in this report.

The neutron flux measurements presented in this report were made for the most part by exposing thin indium or gold foils and measuring induced activities by counting them with thin end window Geiger tubes using standard techniques. Saturated activities were computed and corrections applied on an IBM Card Programmed Calculator. Corrections take into account background, coincidence loss, and individual variations between foils. Computation of saturated activity extrapolates and normalizes the activity to infinite exposure time where it is directly proportional to the incident neutron flux (5)

Several gold foils were irradiated in the Oak Ridge Standard Pile and were counted at the CR&D laboratory. All foils were then standardized to an absolute thermal neutron flux as measured by ORNL.

Bare and cadmium covered foils were exposed whenever feasible since thermal activity may be arrived at by the difference in activities. The cadmium ratio, defined as the ratio between bare and cadmium covered activities is a crude measure of the neutron spectrum.

High level gamma traverses discussed later in this report were made using a Stratex chamber manufactured by the Jordan Company.

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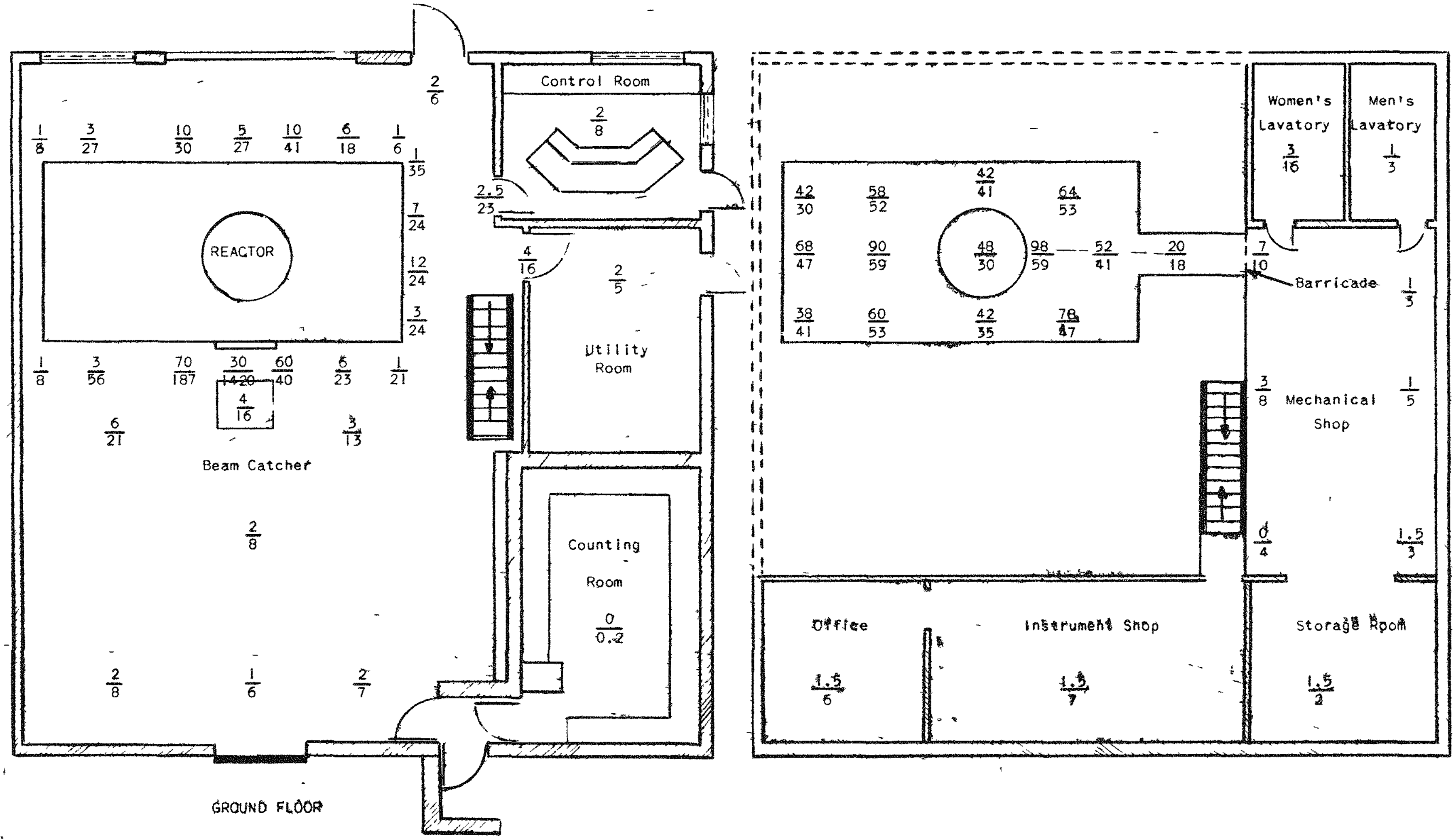

NOTE: Power 500 Watts
Upper Figure is Gamma Level MR/HR
Lower Figure is Thermal Neutron Flux Level N/CM^2/SEC

FIG. 2 - RADIATION SURVEY

2.2 Reactor and Cave Interiors

Figure 3 shows a plot of slow neutron flux versus distance in the glory hole from the center of the sphere to the west edge of the concrete. Flux values were obtained by exposing gold and indium foils.

Attenuation of the neutron flux due to the cadmium surrounding the reflector is seen to be quite significant. Thermal flux in the horizontal thermal column is plotted in this region on the same figure. At the edge of the reflector the flux in the thermal column, which is essentially unperturbed by cadmium, is seen to be about 40 times that in the glory hole.

The flux is very uniform in the glory hole tube leading through the cave. In the first half of the concrete it falls off slowly, but then drops to a relaxation length of about seven centimeters. The rapid drop off in the latter half of the concrete is due to the presence of boron loaded paraffin which was packed around the glory hole tube in a two inch annulus in this region.

Figure 4 describes the cadmium ratio in the glory hole as measured by indium foils as a function of distance. The effect of the cadmium is plainly evident as well as the borated paraffin in the concrete.

A plot of the gamma activity in the glory hole as a function of distance is shown in Fig. 5.

Gold foils were positioned at various points in the cave, and they were exposed by taking the reactor up to 500 watts rapidly and maintaining that power for 15 minutes during the exposure. The reactor was then scrammed, and the foils were removed and counted soon after.

Figure 6 shows relative flux values throughout the cave at 500 watts The average thermal neutron flux in the west end of the cave is about 2×10^6 neutrons per cm^2 per sec, and the average cadmium ratio is about 4 as measured with indium foils.

Eight bare indium foils were suspended from the top timber to the floor on the west side of the cave, and a neutron traverse was measured. A gamma traverse was also taken in the same positions. Results are shown in Fig. 7. The neutron flux is seen to peak about the glory hole tube while the gamma flux peaks somewhat lower, due probably to the gas system components located on the north wall near the floor.

Maximum gamma level in the cave near the gas system components on the west side after several hours operation at 500 watts has been observed to reach about 1500 roentgens per hour.

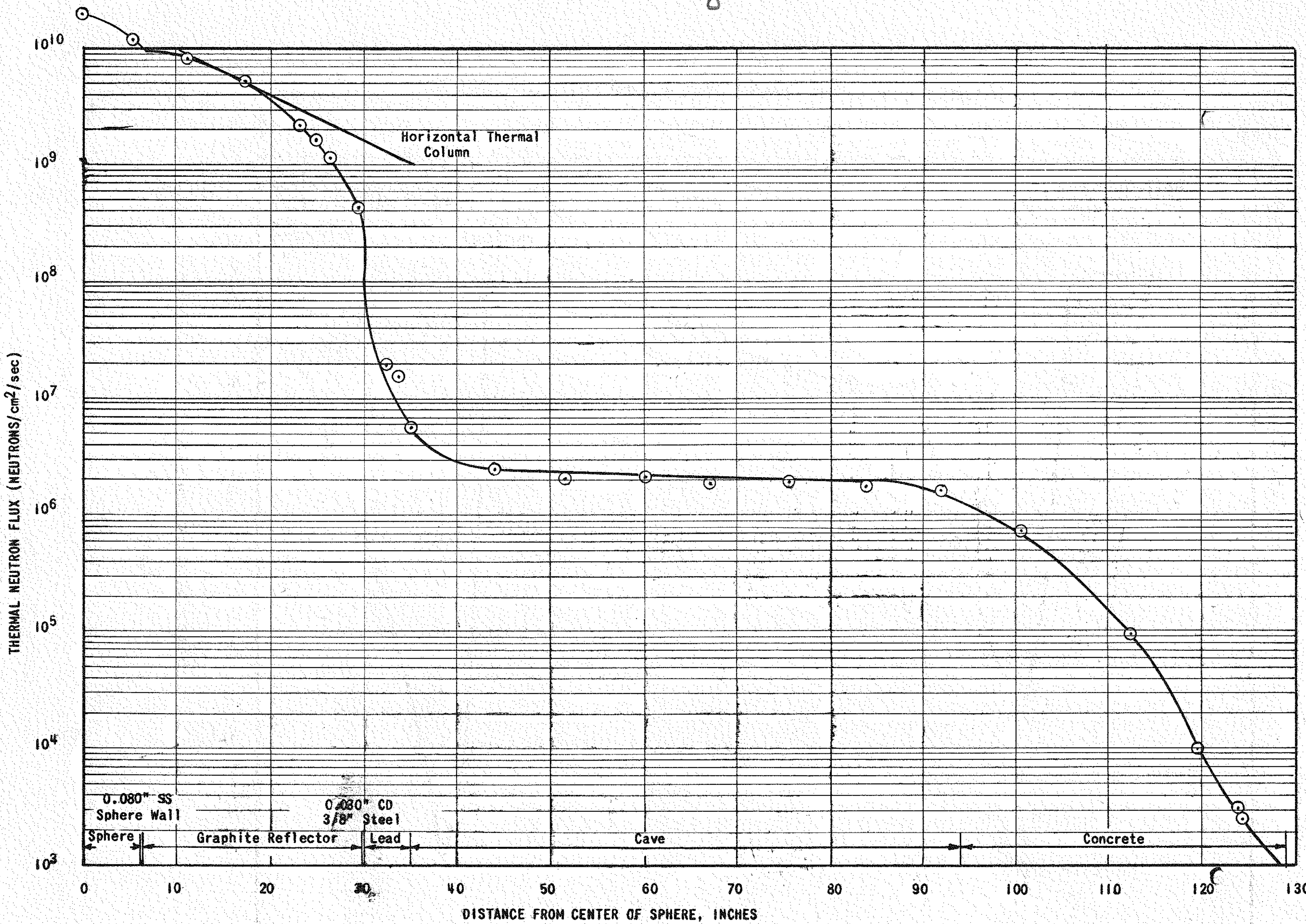

FIG. 3 - SLOW NEUTRON FLUX IN GLORY HOLE

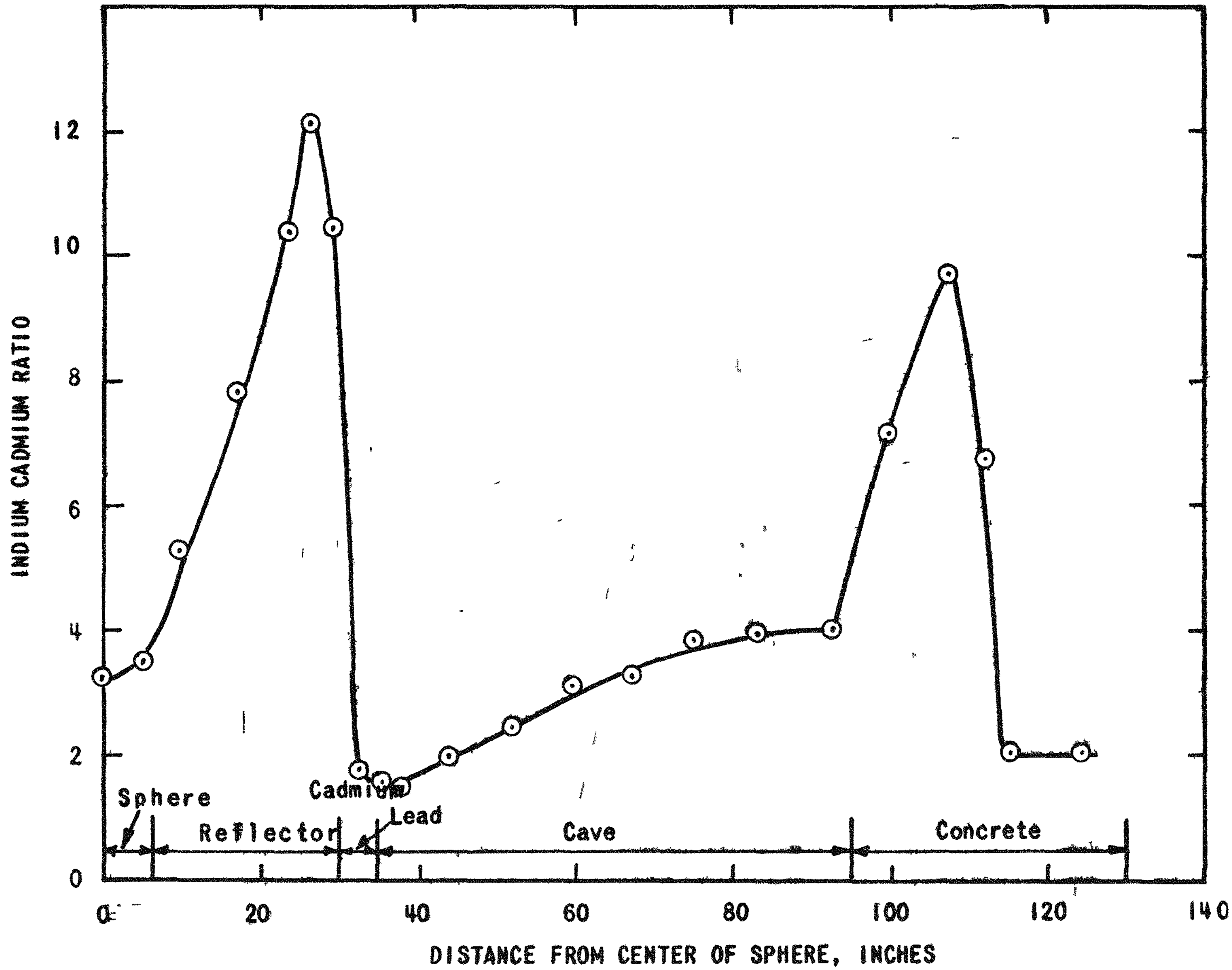

FIG. 4 - CADMIUM RATIO IN GLORY HOLE

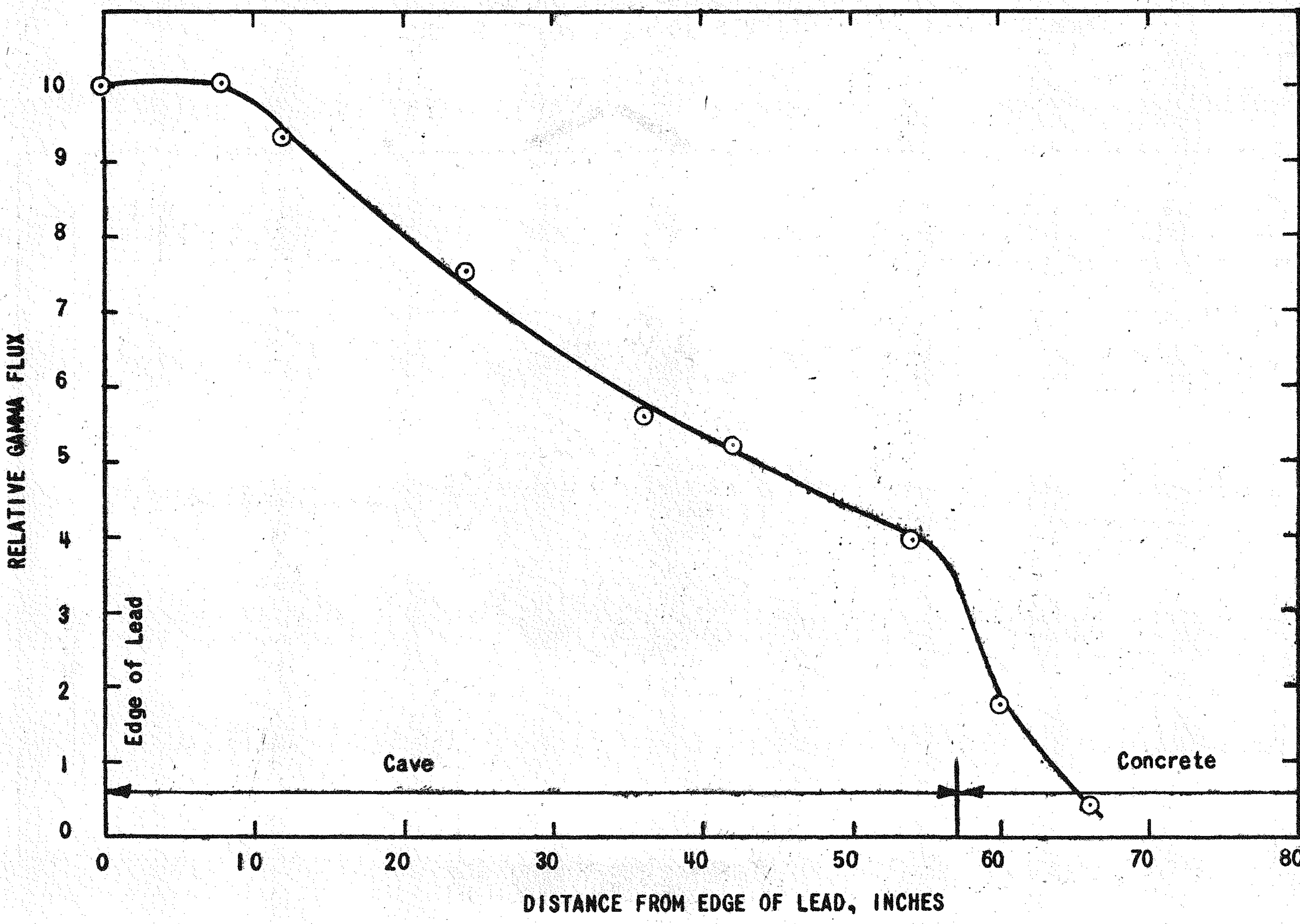

FIG. 5 - RELATIVE GAMMA ACTIVITY IN GLORY HOLE

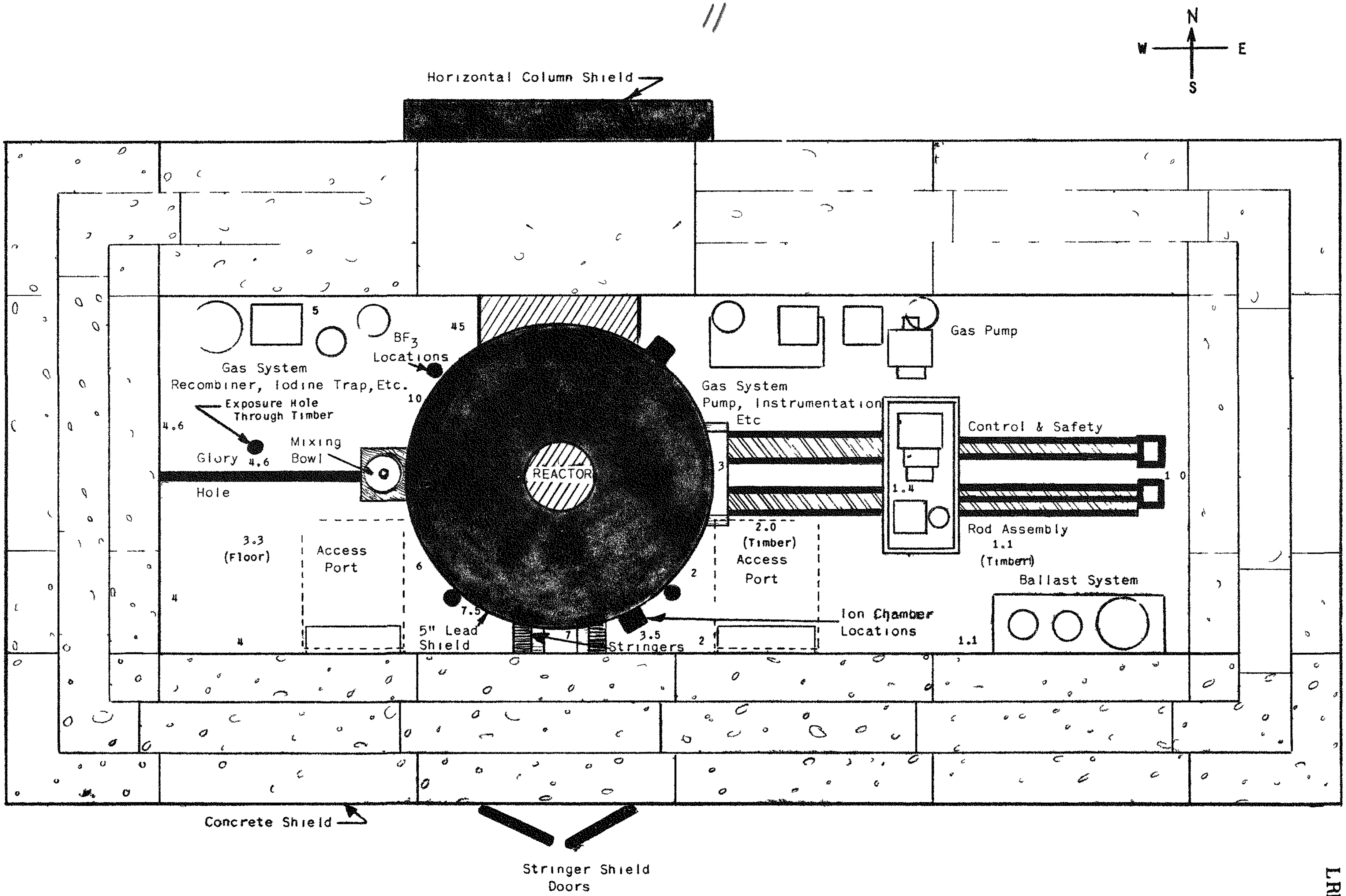

FIG. 6 - TOP VIEW OF REACTOR WITH TIMBER REMOVED
RELATIVE NEUTRON FLUXES IN CAVE

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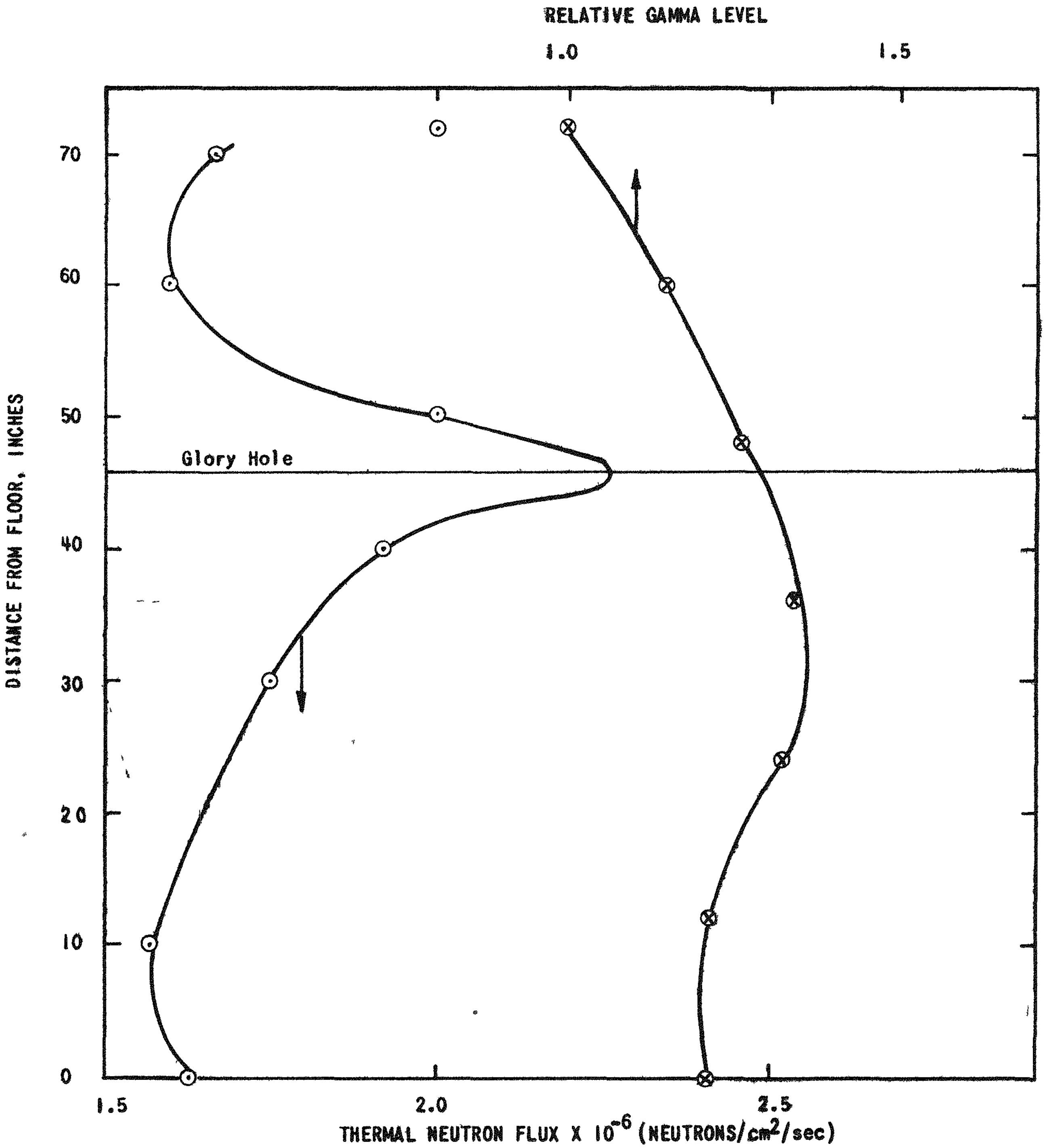

FIG. 7 - NEUTRON AND GAMMA VERTICAL TRAVERSES IN CAVE

2.3 Concrete

As mentioned previously, the reactor is located in a cave constructed of three foot thick ordinary concrete blocks measuring seven feet wide by twenty feet long by seven feet high (inside dimensions). The reactor is nearly centered on the cave width and the outer face of the lead is approximately five feet from the inside west face of the concrete. Fig. 6 shows a top view of the reactor with the timber shielding removed.

The concrete walls are formed of three courses of three foot thick by three foot high concrete blocks, two, three, and five feet in length. The blocks interlock on all four sides as shown in Fig. 6, by means of a four inch high by one foot wide offset center section. Timber and sand were used to fill voids left at the bottom and top.

Photographic film exposed at corners between blocks shows very slight streaming of gamma rays down the cracks.

The reactor and shielding blocks are situated on an eight inch thick reinforced concrete pad laid on the concrete floor.

The cement used in making the blocks was C-150, "High Early Strength Concrete", Type 3, mixed with water and aggregate to a minimum slump of three inches and a maximum of six inches. Lifting hooks were recessed and embedded in each block.

A quantitative spectrographic analysis was made of the concrete. Results are shown in Table I. Mild iron reinforcing rods are located throughout the concrete blocks. The amount of iron present is 1.85 per cent by volume and 5.9 per cent by weight.

A series of calibrated and standardized indium foils was exposed in a concrete cylinder inserted in the concrete shield in one of the stringer positions. The foil block was constructed of the same materials as the shield blocks except that no reinforcing steel was used. Particular attention was paid to obtaining a close fit of the cylinder in the stringer hole, and those concrete cylinders placed between foils during the exposure. Results are plotted in Fig. 8. The relaxation length for thermal neutrons has been calculated from these data to be 7.4 centimeters.

The incident flux on the inside of the concrete was measured to be approximately 6×10^6 thermal neutrons per cm^2 per sec, at 500 watts. On the basis of the above data this value is decreased to about 25 neutrons per cm^2 per sec at the outer face of the shielding, in close agreement with the value as measured by the survey instrument.

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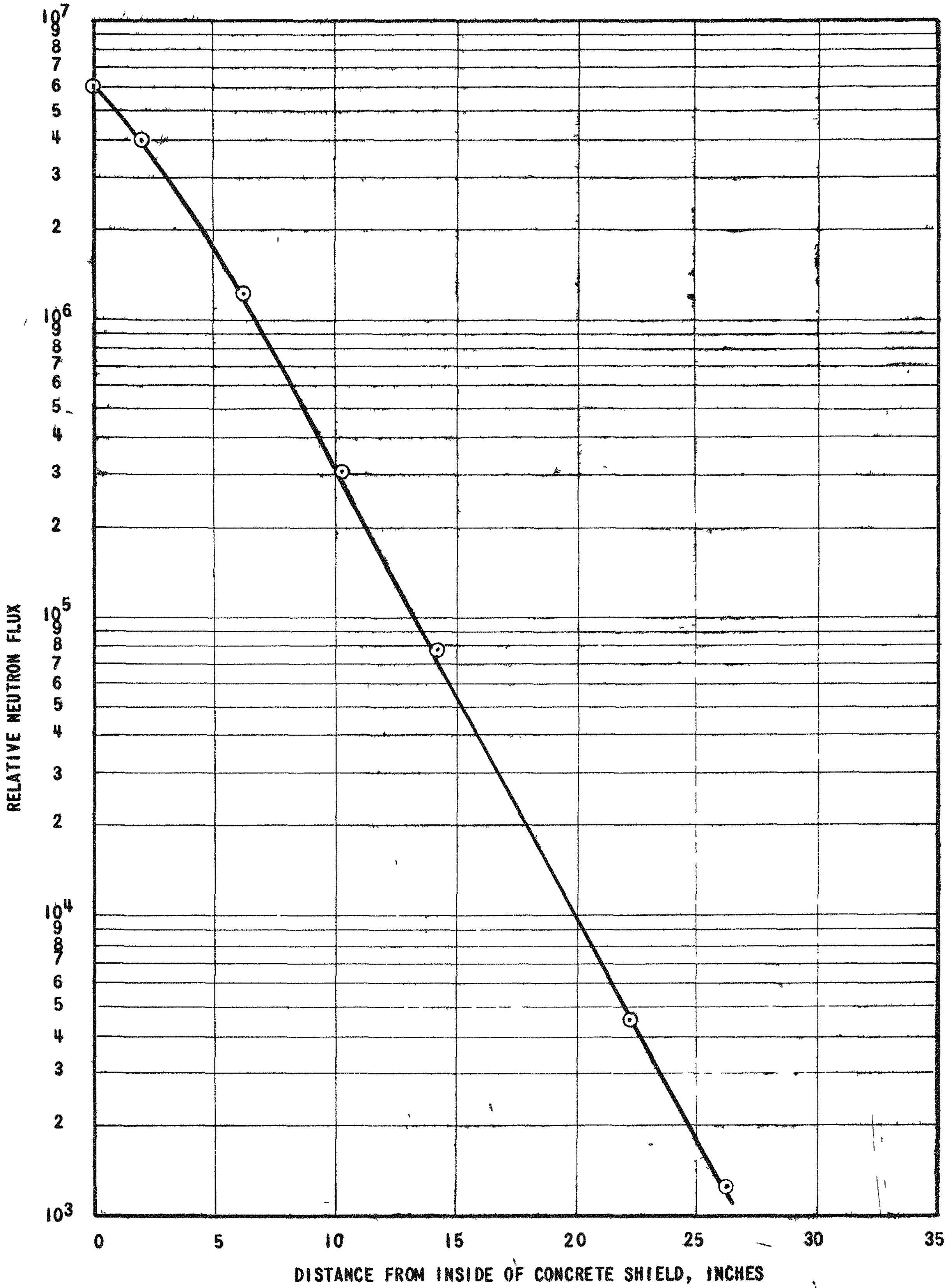

FIG. 8 - NEUTRON TRAVERSE THROUGH CONCRETE

TABLE I

Constituents of Concrete used as Shielding
(Not including reinforcing rods)

Aluminum	3.4 wt per cent
Barium	0.045
Calcium	13.0
Chromium	0.02
Copper	0.003 - 0.03
Iron	3.2
Lead	0.003 - 0.03
Magnesium	1.5
Manganese	0.25
Potassium	0.1 - 1.0
Silicon	38 (Est.)
Sodium	1.15
Titanium	0.18
Vanadium	0.003 - 0.03
Zirconium	0.003 - 0.03
Oxygen	45 (Est.)

A triple coincidence, sodium iodide crystal, pair spectrometer was positioned outside the south side of the shielding at the west end, and the spectrum of gamma rays emergent from the concrete was measured. The spectrometer was modified to act as a Compton spectrometer and measurements were extended to the low energy region. Results are presented in Fig. 9. Hydrogen capture gammas are observable at 2.2 Mev, as well as what is interpreted as the 7-Mev iron capture gamma from the reinforcing steel.

Calibration was established in the pair spectrometer measurements by means of the excited carbon-12 transition gamma of 4.42 Mev and the sodium-24 2.18 Mev gamma. For the low energy Compton measurements the cesium-137 0.66-Mev line was used.

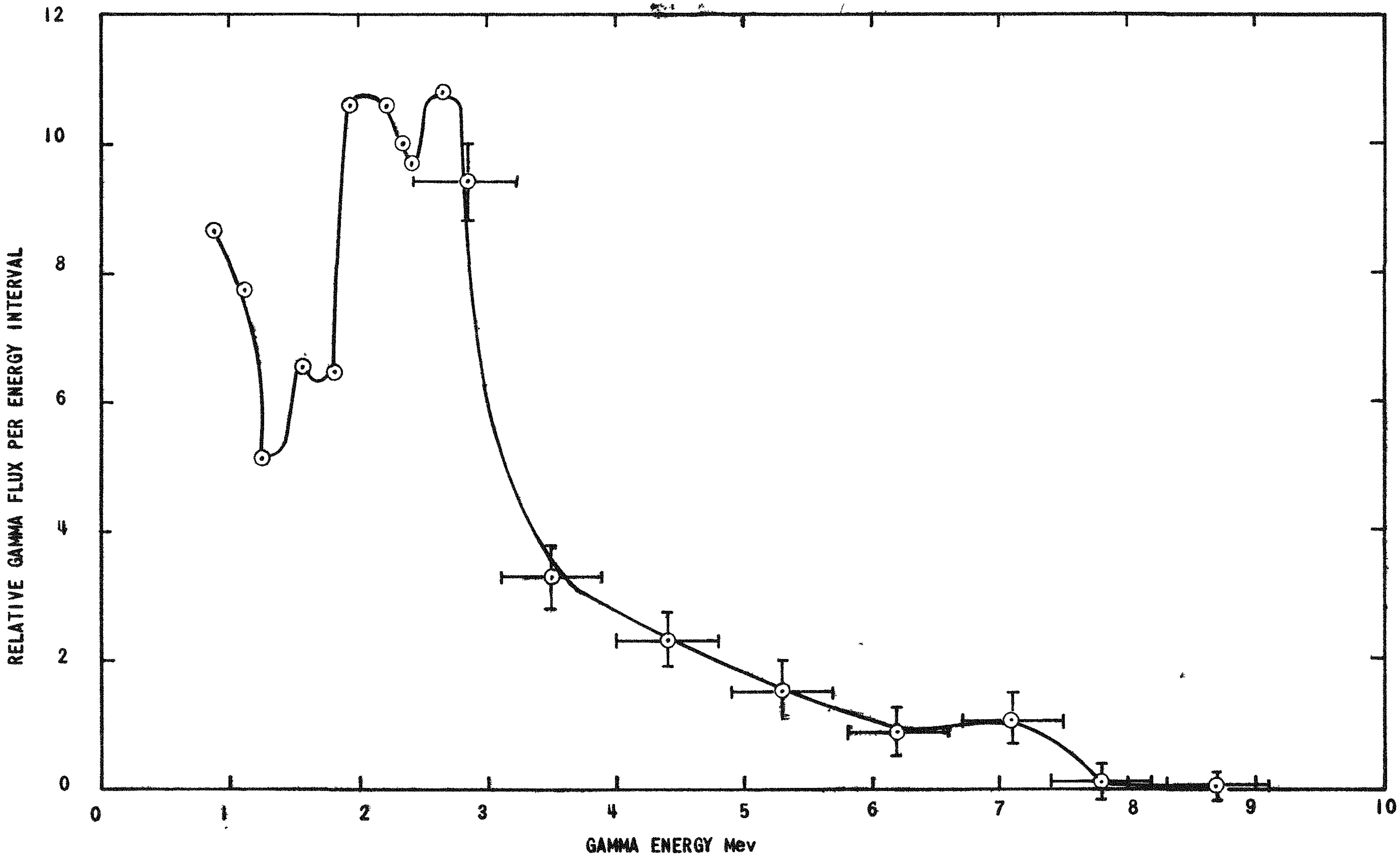

FIG. 9 - GAMMA SPECTRUM FROM CONCRETE

2.4 Top Timber

The top timber shield consists of four staggered layers of nonimal 12 by 12 inch timbers. The bottom two feet are recessed into the cave. A sheet of boron loaded paraffin was placed on top of this. A final two feet of timber completes the shield by spanning the full width of the cave. The wood used was seasoned Douglas Fir. The top timber was cut to surround the water tank on the vertical thermal column, and the corners were filled with packed sand. There are two removable hatches, one on each side of the reactor, to permit access to the reactor components for maintenance.

A two-inch diameter hole was drilled completely through the top timber on the west side. Its location is shown in Fig. 6. A special wooden plug was fabricated from Douglas Fir with slots and inserts for positioning indium foils. Bare and cadmium covered foils were exposed, and the results are plotted in Fig. 10.

The thermal flux is seen to drop off with a relaxation length of 14 centimeters in the first two feet, and three centimeters through and after the borated paraffin layer. The cadmium ratio drops sharply at the boron interface, indicating that a significant number of thermal neutrons are absorbed at this point.

A gamma traverse taken through this hole is plotted in Fig. 11. The gamma flux drops with an initial relaxation length of 28 centimeters increasing to 44 centimeters in the vicinity of the boron.

The pair spectrometer was installed on the top timber shield, and measurements were made of the relative gamma intensity from 1.75 to 2.25 Mev. Results are plotted in Fig. 12, and indicate that hydrogen capture gammas from the wood are very much in evidence.

2.5 Horizontal Thermal Column

Cross sectional views of the horizontal thermal column are shown in Fig. 13. The column is shielded on the sides by four inches of lead extending eight inches into the column, and two inches of lead extending an additional 16 inches inward. The lead and graphite are contained in a box constructed of 1/2-inch thick steel plate. The space between the steel and the concrete is packed with two inches of borated paraffin. The face of the column is covered with four inches of lead contained between 1/2-inch steel plates. The central portion of the shield is removable in four stepped sections to facilitate removing graphite from the column.

A one-inch thick layer of borated paraffin covers the face. In addition, a 0.030-inch sheet of cadmium was installed over the face and an adjustable cadmium shutter was positioned to mask the removable door area.

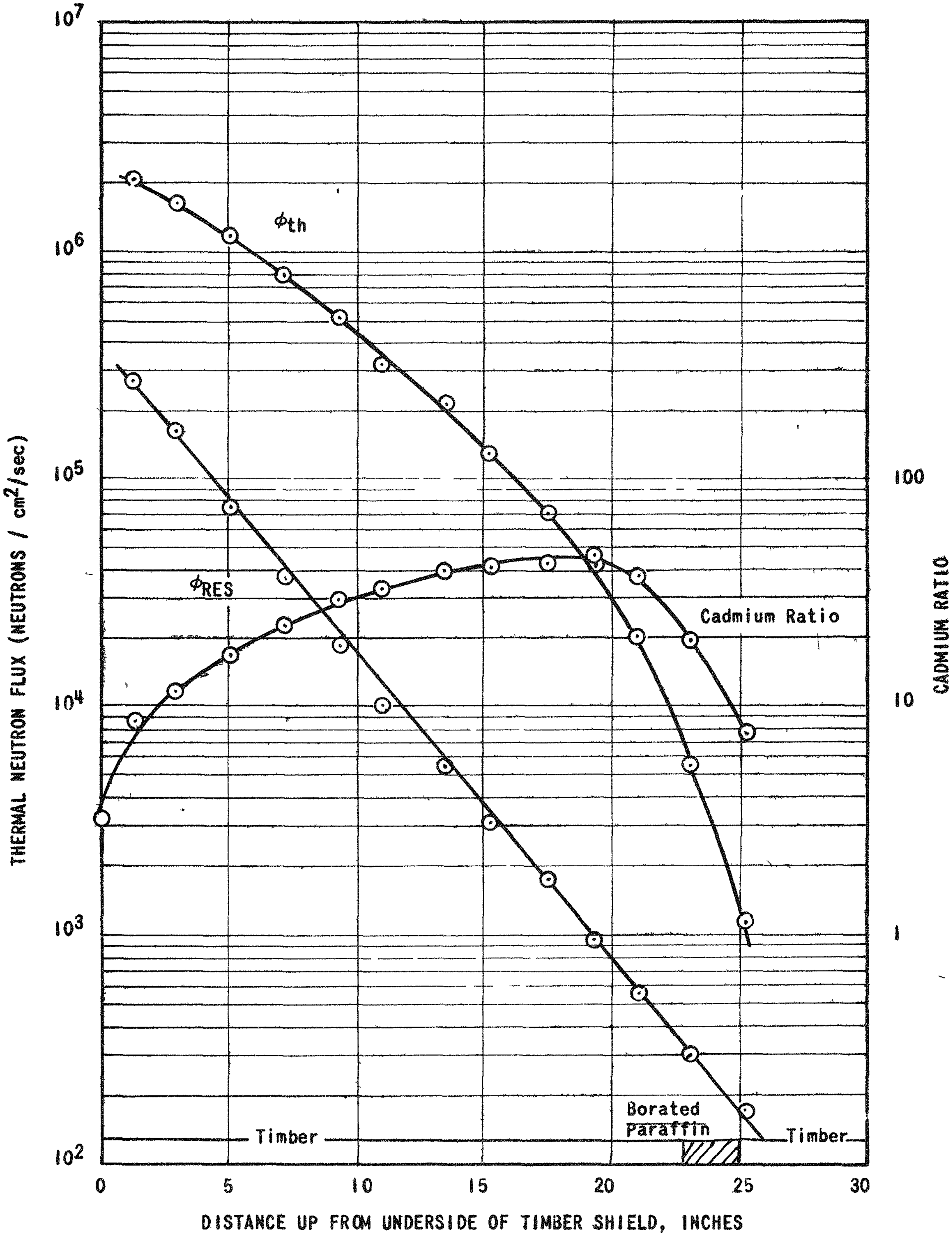

FIG. 10 - NEUTRON TRAVERSE THROUGH TOP TIMBER SHIELD

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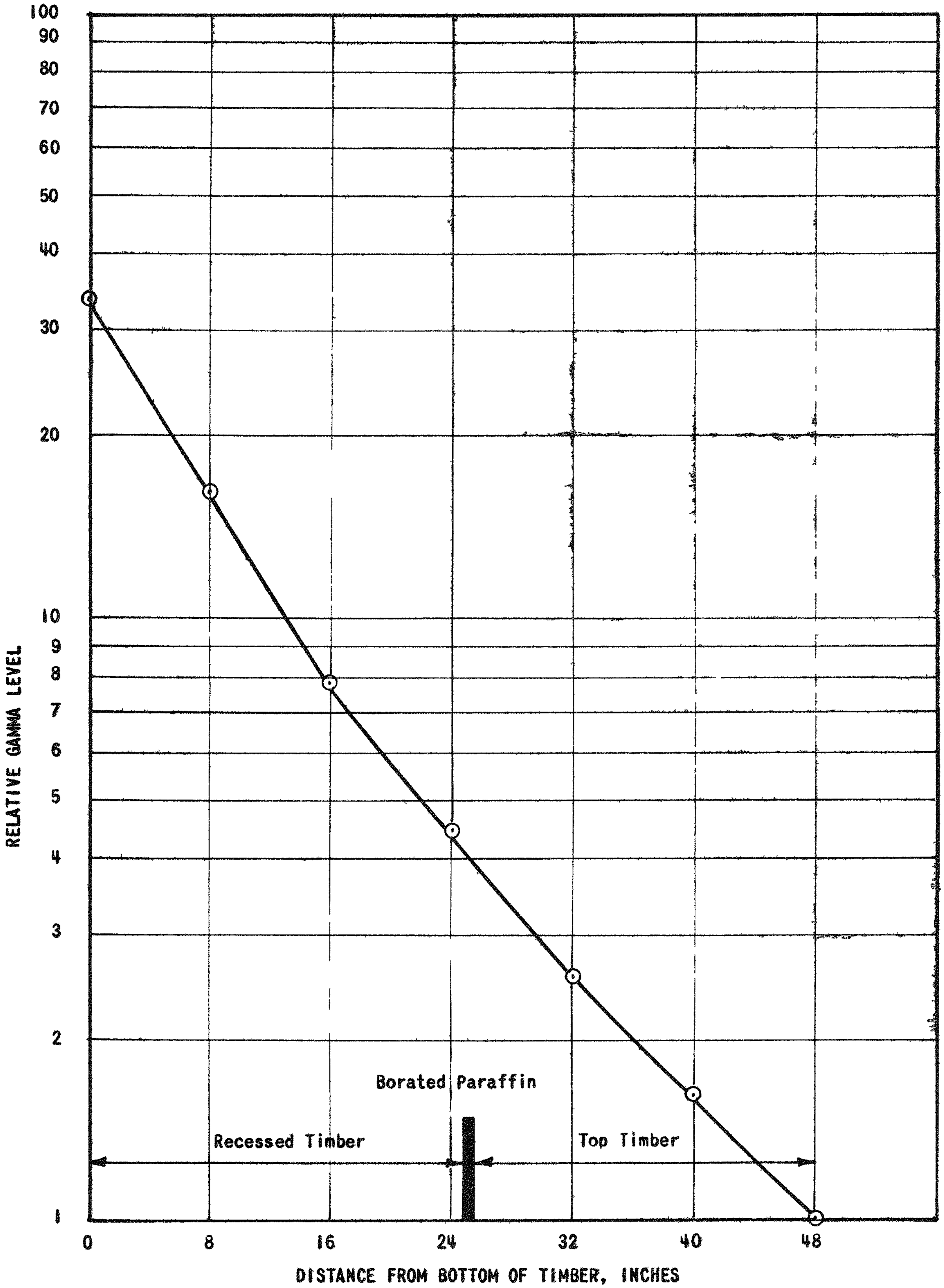

FIG. 11 - GAMMA TRAVERSE THROUGH TOP TIMBER SHIELD

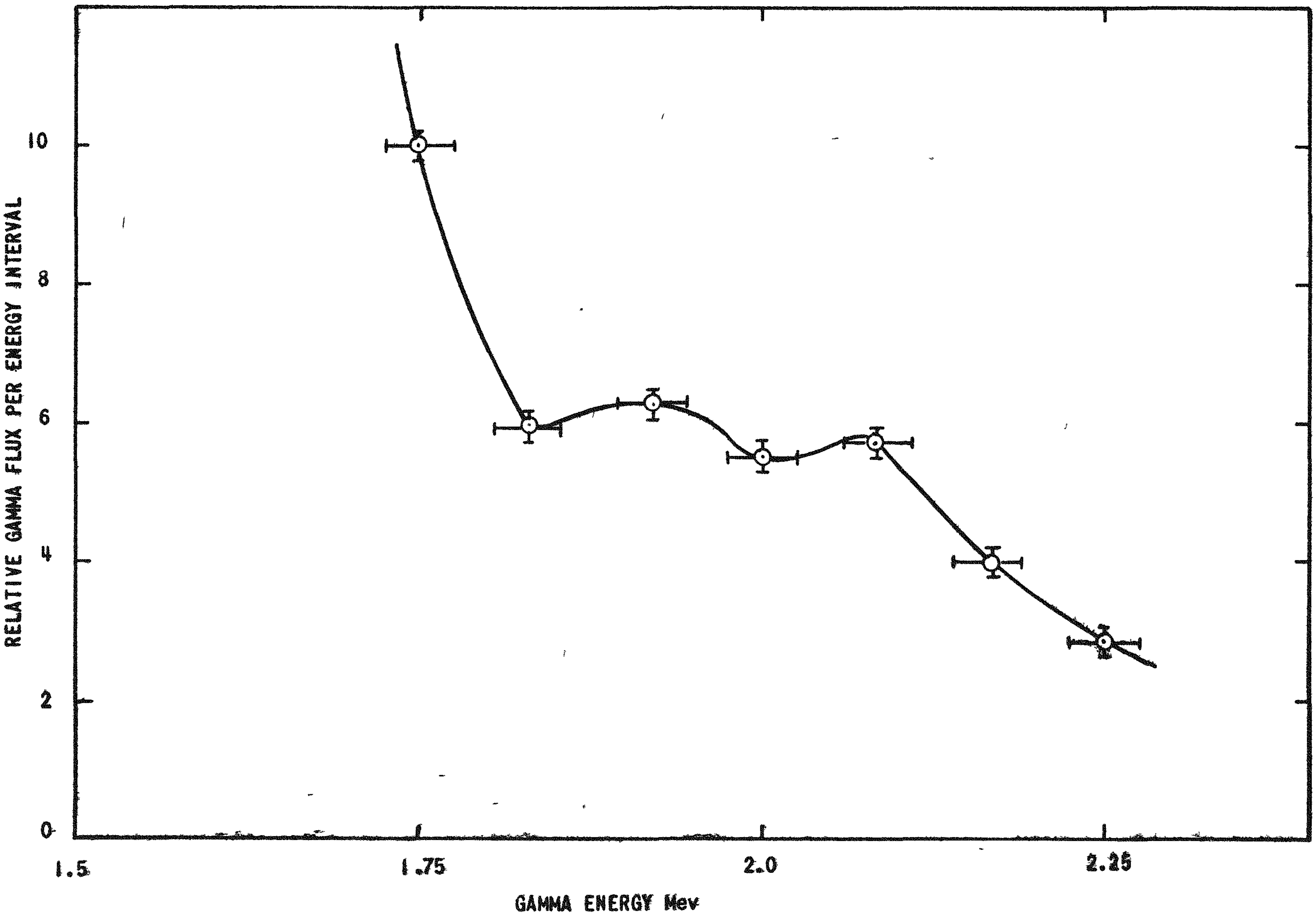

FIG. 12 - GAMMA SPECTRUM FROM TOP TIMBER SHIELD

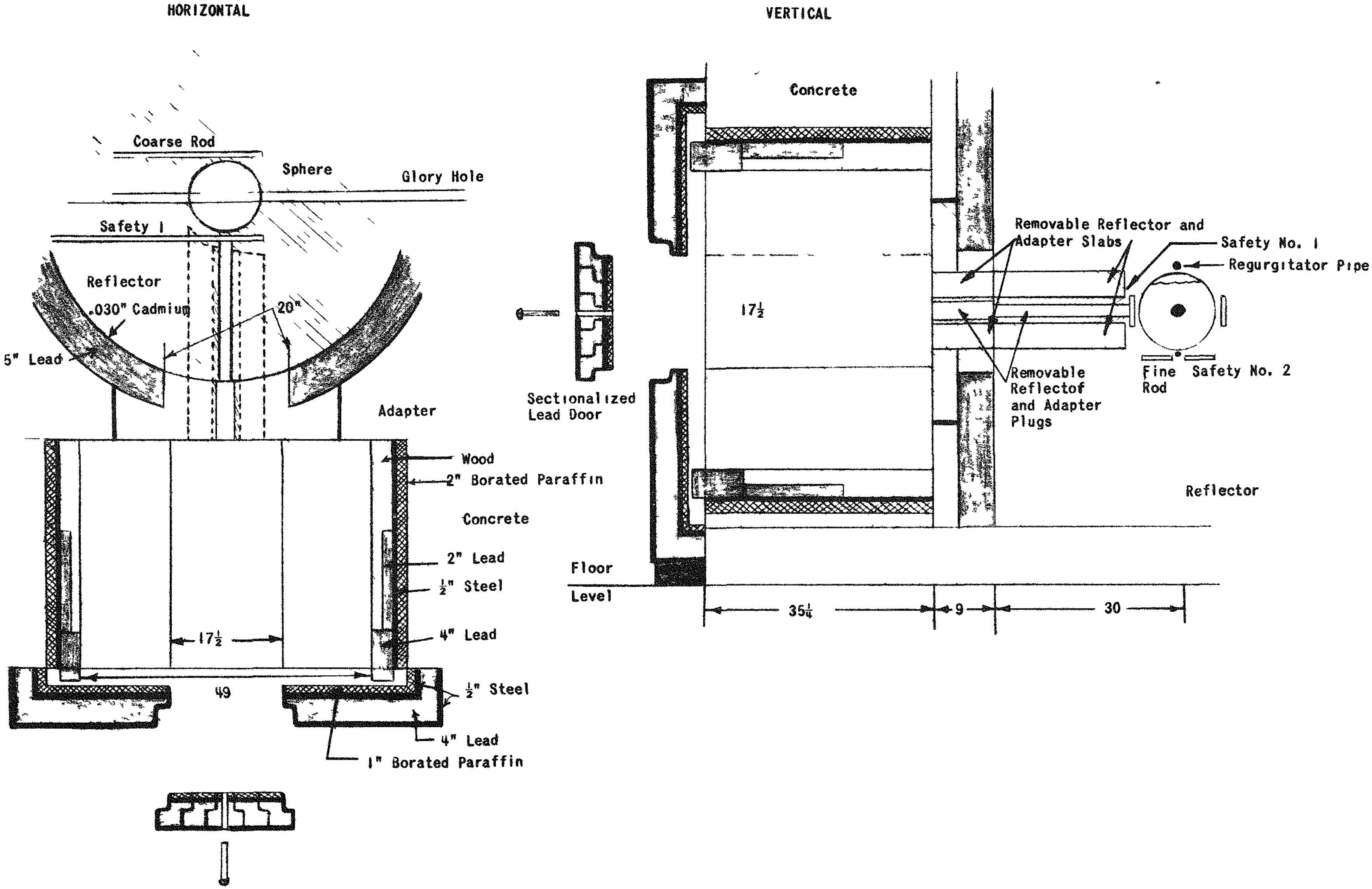

FIG. 13 - SECTIONS THROUGH HORIZONTAL THERMAL COLUMN

The emergent neutron flux on the face of the graphite with all graphite in place is approximately 1.5×10^6 in a cadmium ratio of 950 as measured by indium foils.

The mean gamma level on the face of the removable doors is 20 mr per hour, most of which feeds through the interstices between door sections. Unfortunately, tolerances were not satisfied in the manufacture of the door sections, and cracks up to 1/4-inch wide exist. Shifting the door sections to one side allows the radiation level to rise to a maximum of 35 mr per hour at the cracks.

Levels on the face of the shield proper are below tolerance, except at the removable door sections. At the sides of the column against the concrete, radiation levels rise to a maximum of 70 mr per hour indicating considerable leakage at the corners.

The lead door reduces the neutron flux by approximately a factor of ten. A beam catcher made of paraffin was installed several feet from the door to protect personnel from high flux neutron and gamma beams which occur when graphite is removed and the doors are left open for certain experiments.

The pair spectrometer was set up outside the the thermal column, and the spectrum of emergent gamma rays was scanned from 1.5 to 7 Mev for the following five cases:

a. Bare column
b. Lead door in place
c. Small lead plug removed
d. Cadmium shutter in place
e. Steel plug replacing lead plug.

No prominent lines were visible in this region for any of the five cases considered, the spectrum being a smooth function of energy. Results for one of the runs made on the bare column are shown in Fig. 14.

2.6 Miscellaneous

The stringers were shielded by 1/2-inch of lead for operation at 100 watts. A lead half value layer of 0.5 inches was measured at that time which is equivalent to a mean gamma energy of 1.7 Mev. The radiation level was about 18 mr per hour with the doors open. Upon raising the power to 500 watts, two more half value layers were added, increasing the door thickness to 1-1/2 inches and decreasing the gamma level with the doors closed from 45 to 11 mr per hour.

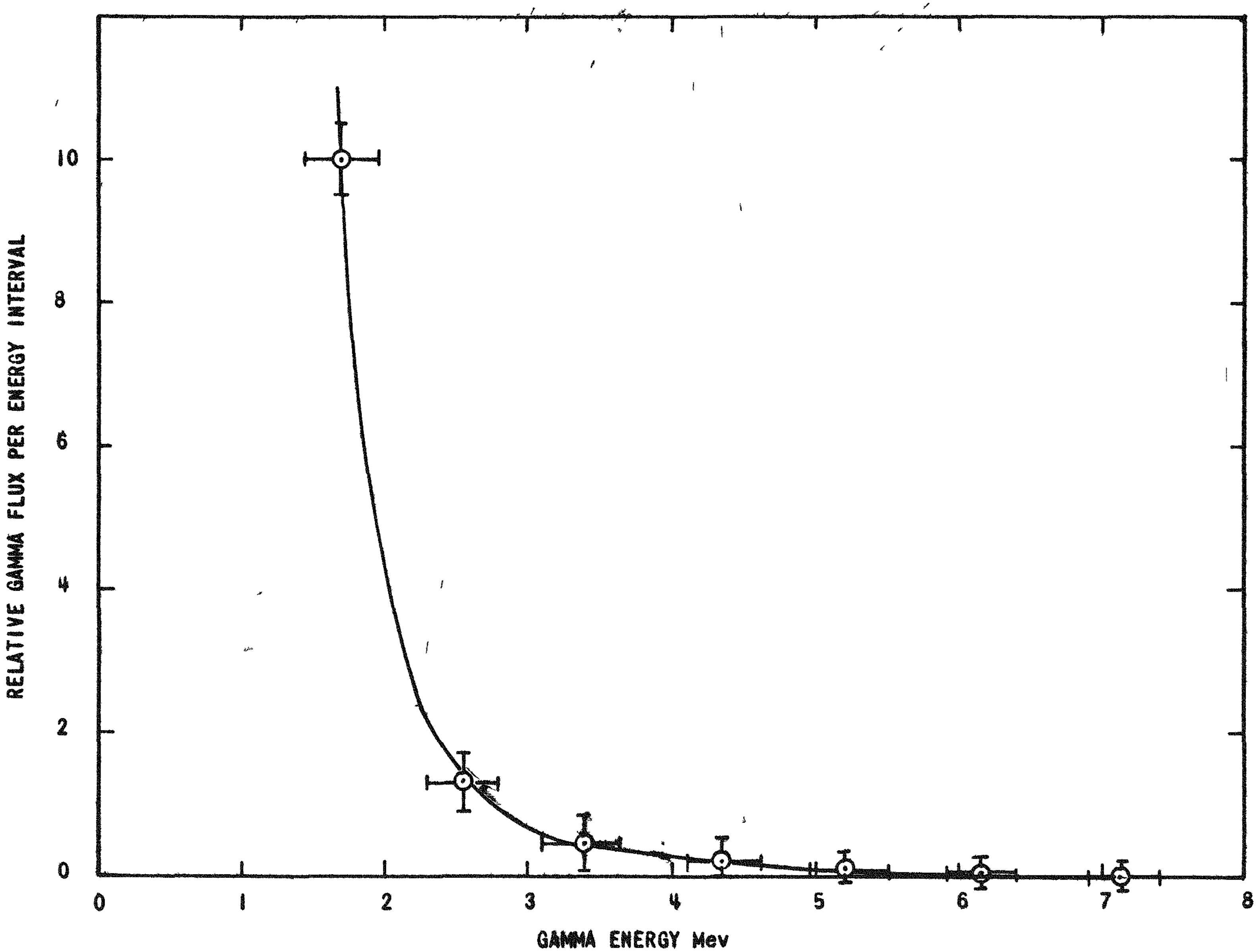

FIG. 14 - GAMMA SPECTRUM FROM HORIZONTAL THERMAL COLUMN

The mean gamma energy of the gas system components was measured in a similar manner by surrounding a gamma monitor tube with lead sleeves. The value found was 0.75 Mev corresponding to a lead half value layer of 0.18 inches. Entry to the cave would be facilitated by shielding the gas system. From these measurements it would take approximately 14 half-value layers or 2.5 inches of lead to shield to twice tolerance for a maximum gamma level of 300 r per hour after shutdown.

Shielding for the vertical thermal column is provided by the water tank in which the thermal neutron diffusion length has been measured as 2.88 centimeters. (3). The cadmium shutter in this column reduces the thermal neutron flux by 40 per cent when closed.

The steel plug filling the glory hole tube reduces the gamma intensity from 40 to 12 mr per hour at 500 watts.

Six-inch diameter ion chamber ports lead obliquely through the concrete near the floor on both north and south sides. They are shielded by inserting hardwood plugs with 1-1/2 inch thick stepped lead covers. The combination reduces the gamma level from 210 mr per hour to background.

3. CONCLUSIONS

In retrospect the shielding for the CR&D reactor appears to be entirely satisfactory for operation up to 500 watts. It also appears that the use of low cost shielding such as borated paraffin and timber is quite practical for a research reactor.

Since the neutron flux in the cave is relatively high, it seems that it might be possible to increase the shielding effectiveness and raise the reactor power by lining the inside walls with cadmium sheets to reduce the incident neutron flux, and thus decrease the capture gammas generated in the concrete.

The costs of the external shield are broken down in the following table:

TABLE II

I.	Concrete Blocks	
	A. Materials, Forming, and Placement	$4100
	B. Special Block (e.g., Stringer Block) and Modifications	3200
II.	Roof Timbers	
	A. Materials, Fabrication, and Erection	3500
III.	Horizontal Column Shield Door	
	A. Materials, Fabrication, and Erection	4550
IV.	Horizontal Column Side Shielding (Lead)	
	A. Materials and Installation	2550
V.	Borated Paraffin	
	A. Materials Only	410

It is hoped that the enclosed data are sufficient to permit calculation and extension to other cases.

4. ACKNOWLEDGEMENTS

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The authors also wish to express their appreciation to R. W. Kenny of the University of California Radiation Laboratory for supplying the spectrometer used in the gamma flux spectrum measurements, and for his advice and help in taking these data.

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