INVESTIGATION OF A DIRECT METHOD FOR MEASURING THE RESONANCE ESCAPE PROBABILITY IN THORIUM-WATER LATTICES *

by

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I. INTRODUCTION

The resonance escape probability, p, is one of the factors in the so-called four factor formula that describes a neutron cycle in a nuclear reactor. In a chain reaction which is maintained by thermal neutrons, the energetic (fast) neutrons from fission are slowed down by elastic collisions with the nuclei of a suitable moderator material. During this slowing down process some of the neutrons are removed from the cycle by non-fission interactions with the materials in the assembly. Because the absorption takes place mainly in the sharp nuclear resonances which the absorbing materials exhibit in the intermediate energy range, this parasitic capture of neutrons has been named resonance absorption. Thus, the resonance escape probability is the probability that a fast neutron from fission will escape absorption during the slowing down process. Since p describes merely the non-capture probability during a moderating process, the concept may be applied to a multiplying system (critical reactor or subcritical assembly) as well as to a non-multiplying system (one that does not contain fissionable material).

The experiments to be described utilize a non-multiplying assembly composed of thorium metal as the resonance absorber and water as the moderator.

The analytical determination of p even in a simple homogeneous system requires knowledge of all the cross-sections involved, the shape of the resonances, and a number of assumptions as to the nature of the moderating process. Additional simplifying assumptions are necessary to include resonance scattering. In a heterogeneous assembly the problem is further complicated by the spatial dependence of the neutron flux over a unit cell, the self-shielding of the resonance flux inside a lump, and the mutual shadowing of the lumps, so that more simplifying assumptions have to be applied. If one wishes to avoid the various simplifying assumptions, the Monte Carlo computational method remains the only means for treating the problem.

The importance of experimental methods for determining p directly are therefore obvious, both as check on analytical approaches to the problem and as an independent means for determining this quantity when it is required in the design of a nuclear reactor.

One of the experimental methods for determining p is the "direct method," sometimes referred to also as the "substitution method" when it involves, in addition to the assembly under investigation, another assembly of the same scattering properties but containing no resonance absorbers. In the case of a non-multiplying assembly it may be the only practicable method for measuring p directly. In this method we measure the decrease in the neutron density due to resonance absorption.

To illustrate the principle of the direct method, let us consider a homogeneous moderating medium of infinite extent into which fast neutrons are introduced at a uniform rate, Q per sec, and moderated to a lower energy, E. If there is no absorption, the integral of the slowing down density* over the system equals the number of source neutrons, i.e., $\int q_o(E,\bar{r})d\bar{r} = Q$. If an absorbing material is then uniformly distributed in the medium, the slowing down density will be $q(E,\bar{r})$, and

$$\int q(E,\bar{r})d\bar{r} = p \int q_o(E,\bar{r})d\bar{r} \qquad (1)$$

where p is the resonance escape probability to energy E for the system under investigation.

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* Defined on p. 16.

It may not be necessary to measure the integral of the slowing down density; the value of $q(E,\bar{r})$ at a single point may be all that is required. For a localized source inside a medium of large extent it can be shown on the basis of the continuous slowing down model (Fermi age) (13) that if the initial energy $E_f \gg E$

$$q(E,\bar{r}) = p\ q_o(E,\bar{r}) \qquad (2)$$

where q is the slowing down density at any point in the system under investigation and q_o is the slowing down density in the absence of resonances. Since we cannot "turn-off" the resonance cross-section, we may have to use, in addition to the assembly under investigation, another assembly (substitute assembly) that has exactly the same scattering properties but no resonance absorption. This method was used in the early days of the atomic energy program both in the United States and in the USSR (25).

Using the VPI Cockcroft-Walton accelerator to produce fast neutrons by the D-D reaction, Anthony (1) applied the method to measure p in a non-multiplying homogeneous system with light water. The system under investigation consisted of solutions of thorium nitrate

in different concentrations. The substitute system was solutions of ferric nitrate. In both systems the thermal neutron densities were measured by a BF_3 counter. Anthony inferred from his neutron-density traverses in the thorium nitrate and the ferric nitrate solutions that "the spatial distribution of neutrons was essentially constant" and made this assumption in the analysis of his data and in a derivation of the value of p. The present work is an attempt to extend Anthony's work to a non-multiplying heterogeneous system. As originally planned, the experiment was to be performed with thorium or thorium-oxide pins of different diameters in a number of water-to-metal ratios. But when these materials were not available, Savannah River type hollow slugs of thorium metal of a single size were used. The assembly under investigation consisted of a square lattice made up of these slugs. In the substitute assembly, the thorium was replaced by lead to reproduce the scattering in thorium as closely as possible. In both assemblies the neutron flux was measured at the indium-resonance energy of 1.46 ev by exposing cadmium-covered indium foils.

In a preliminary experiment the Cockcroft-Walton accelerator was used to produce a neutron source, and the

target was placed on the boundary of the assembly as in Anthony's experiment. The initial results indicated, however, that the spatial distribution of the indium-resonance neutrons was not the same in the two assemblies. It was therefore decided to measure the integral of the slowing-down densities according to Eq. 1 and accordingly make changes in the location as well as in the nature of the source. It was found necessary (a) to put the source inside the assembly; (b) to use a fission source to eliminate any possible effect from the anisotropy of an accelerator source. The new source thus consisted of a disc of 5 gms of U-235 exposed to the thermal neutron beam from the VPI reactor. Since it is impractical to actually measure the integral of the indium-resonance flux over the whole assembly, possible anisotropy in the resonance absorption had to be investigated by measuring it along perpendicular traverses, to determine if the ratio of the $r^2 q(r)$ integrals over a traverse is the same in both directions.

This report contains a description of the experiment as well as an evaluation of the direct method for measuring

p for a system like the one under investigation. However, the preliminary experiment using the Cockcroft-Walton accelerator will not be included, although it provided important insight into the problem.

II. LITERATURE REVIEW

Resonance absorption was found to be the most difficult problem in the first attempts to prove the possibility of a chain reaction in a thermal reactor fueled with natural uranium, and an intensive investigation, both theoretical and experimental, of resonance absorption in uranium was initiated as early as 1941. The earliest experiments for measuring resonance absorption for uranium in bulk (i.e., heterogeneous rather than homogeneous) and determine its dependence on shape, size, and temperature were conducted at Princeton University in 1941. These experiments as well as the associated theoretical work are reported by E. Cruetz, H. Jupnik, T. Snyder, and E. P. Wigner in a series of four articles published in 1955 (5). Although the resonance absorber under investigation was natural uranium, the general nature of their results applies not only to uranium but to any other lumped resonance absorber.

In a review paper given in 1956 (24), Wigner compares the results of United States investigations on resonance absorption of uranium in bulk and the results

published by Russian workers. This paper can also serve as a summary of basic methods for measuring resonance escape probability in assemblies fueled with uranium.

Results of measurements of resonance absorption in thorium were reported by Hughes and Eggler (10) in 1945. Their measurements involved thin foils and homogeneous mixtures. Such results are also reported by Macklin and Pomerance (12) in a survey of work done in the United States prior to the first Geneva conference (1955). Work on the resonance absorption of thorium and/or thorium-oxide is reported by Davis (1957) (7), Sher (1957) (21), and Dayton and Pettus (1950) (6).

A comprehensive treatise on resonance absorption in uranium and thorium is presented by Dresner (8) who also gives a comparison of theory and experiment.

Methods for evaluation of p in heterogeneous multiplying assembles can be classified into three main groups:

(a) Activation experiments, where the lattice forms part of a critical reactor. The determination of p depends upon the ability to measure the ratio of resonance to thermal radiative capture in U-238 and requires the

activation of bare and cadmium-covered uranium foils inside the uranium slugs (17).

(b) Analysis of exponential or critical experiments. The infinite multiplication factor of a reactor medium as given by the four factor formula $k = \epsilon p f \eta$, where ϵ is the fast fission factor, f the thermal utilization of the medium, η the number of neutrons produced by an absorption in the fuel, and p the resonance escape probability. p can thus be evaluated if the other three factors and k are known. k can be determined from the buckling, measured by an exponential experiment, and the migration area of the lattice. By one group theory, in a bare critical reactor $k(1 + B^2M^2)^{-1} = 1$. B^2 is the buckling and M^2 the migration area. The above equation gives then k and hence p through the four factor formula above (16).

(c) The direct measurement of p. In this "direct method" the quantity measured is the decrease in the number of neutrons due to capture in the resonance absorber. In addition to the lattice under investigation a similar "substitute" lattice is required that has the same scattering properties but no resonance absorption. Such an experiment was reported by Burgov of USSR in 1955 (4). This work is also reviewed by Wigner (25).

Since the experiment reported by Burgov is pertinent to the subject of this report, some detail will be presented based on Wigner's review paper. The Burgov measurement was made on a lattice of natural uranium rods in heavy water. His experimental arrangement consisted of an array of cadmium-covered uranium rods (1.4 cm in diameter) immersed in a cylindrical vessel (80 cm in diameter and 100 cm high) filled with D_2O. The rods formed a square lattice with a spacing of 5.8 cm. A Ra-Be mixture provided a constant source of neutrons. The density of the neutrons which escaped resonance capture was measured by a BF_3 counter. The uranium rods could be replaced by similar bismuth rods, which were considered to have negligible resonance absorption. The fraction p of neutrons escaping resonance capture by the uranium rods was simply the ratio of the counts of the BF_3 counter with uranium rods present to the similar counts in the assembly with the uranium replaced by bismuth rods. The ratio of the counting rates with uranium rods forming the lattice to the counting rates with the bismuth rods substituted was not entirely independent of the relative position of source and counter. This was attributed to the difference in the scattering properties of uranium

and bismuth. For this reason the distance between source and counter was so chosen that the neutron density would be influenced as little as possible by a slight difference in the slowing-down power of the medium. The condition imposed was that the derivative of the density of neutrons to which the counter is sensitive with respect to their age in the medium should vanish. Using the "Fermi age" formula for the slowing down density, this condition is satisfied for a distance $r = \sqrt{6\tau}$. This distance was, however, determined independently by a separate experiment.

It is obvious that this direct method can be applied to a non-multiplying system, such as thorium, instead of uranium. Furthermore, the fact that the multiplication of source neutrons need not be considered may allow considerable simplification in the experimental arrangement.

Anthony's work (1) is a more recent example of the application of the direct method. Here the system was homogeneous and non-multiplying with H_2O rather than D_2O as the moderator. The basic assumption made was, however, essentially the same; if the two systems have exactly the same scattering properties the ratio of the thermal neutron densities in the two systems is spatially

independent, as has already been mentioned in the introduction. The work that will be reported in this paper is an extension of Anthony's work to an heterogeneous assembly. The systems consisted of an array of thorium metal slugs immersed in H_2O, and utilized a "substitute" assembly of lead slugs.

III. THEORY OF THE EXPERIMENT

The resonance escape probability, p, is defined as the fraction of fast (fission) neutrons that escape capture in resonances when slowing down to thermal energies. In this definition it is assumed that there is no leakage. The lower energy is "thermal energies." For experimental purposes we may set as the lower energy any energy below the resonance region of the material under investigation; it may be set as the cadmium cut-off energy or, as in this experiment, the indium-resonance energy of 1.46 ev and p defined accordingly. The lowest resonance in thorium is at 21.9 ev.

Assuming that both the original and the substitute assemblies extend to infinity and that the substitute material (lead) has no resonance absorption, the resonance escape probability can be defined (see introduction, Chapter I) as

$$p = \frac{\int q(\bar{r})d\bar{r}}{\int q_o(\bar{r})d\bar{r}} \qquad (3)$$

where q and q_o are the slowing down densities at the indium-resonance energy in the thorium and lead assemblies

respectively, and each integration is carried out over the whole assembly.

This operational definition of p raises two questions: (a) the assemblies are of finite extent; (b) it is impractical to integrate q over the whole assembly. Regarding (a), if the system is large enough, the shape of the slowing down density as a function of the distance from the source may be found and extrapolated to infinity (as done in "age" experiments). Referring to question (b), anistropy in the resonance absorption has to be explored to see if the integrals of $q(\bar{r})$ over the whole assembly in Eq. 3 cannot be replaced by integrals of $r^2 q(r)$ along a traverse, extending to infinity.

Another point to be considered is the location of the source. If the source is too close to the edge of the tank, it may affect the measured flux traverse. Measurements by Reier (19) with a Po-Be source in pure water indicated, however, that as little as 3 cm of water between source and tank is enough to assure that the infinite medium flux distribution is obtained on a traverse away from the source. In the present experiment the source was located 5 inches from the wall of the tank for the horizontal traverses and 3-5/16 inches from the

base plate for the vertical traverses. The distance to the other boundary in the direction of the measurement was approximately 17 inches in both cases. This was considered adequate to give the infinite medium distribution.

In Eq. 3, p is defined in terms of the slowing down densities, q, but the quantity measured by the indium detector foils is neutron flux. In a non-absorbing medium q is related to the flux ϕ by (14):

$$q(E) = \xi\Sigma_s(E)\,\phi(E)E \qquad (4)$$

where q(E) is the slowing down density at E (number of neutrons per unit volume per unit time whose energies are changed from some value above E to some value below E), $\xi\Sigma_s$ the slowing down power of the moderator, and $\phi(E)$ the flux per unit energy interval at E.

The activation of a cadmium-covered indium foil can be written as

$$A(\bar{r}) \sim \int_{E_c}^{E_f} \phi(\bar{r},E)\,\Sigma_a^{In}(E)\,dE \qquad (5)$$

where Σ_a^{In} is the effective macroscopic absorption cross-section of the indium foil, E_f the highest (fission) energy, and E_c the cadmium cut-off energy.

From Eq. 4 it follows that

$$A(\bar{r}) \sim \int q(\bar{r},E)\left(\sum_a^{In}(E) / \xi\Sigma_s\right) dE/E \qquad (6)$$

To a first approximation in integrands in Eqs. 5 and 6 are zero except in the vicinity of the indium resonance energy of 1.46 ev. Therefore, q can be taken out of the integrand and Eq. 5 written as

$$A(\bar{r}) \sim \frac{q(\bar{r},\ 1.46\ ev)}{\xi\Sigma_s} \int_{E_c}^{E_f} \sum_a^{In}(E)\ \frac{dE}{E} \qquad (7)$$

or

$$q(\bar{r},\ 1.46\ ev) = kA(\bar{r}) \qquad (8)$$

where k is a constant, since the integrand in Eq. 6 is the same for all foils and $\xi\Sigma_s$ is a function of the scattering properties of the medium only.

Thus, if the two assemblies have the same scattering properties and if there is no anistropy in the resonance absorption in the system under investigation p can be taken as

$$p = \frac{\int_0^{r} r^2 A(r)dr}{\int_0^{\infty} r^2 A_o(r)dr} \qquad (9)$$

where A is the activation of the indium foils in the lattice under investigation (Th) and A_o the activation of the foils in the substitute lattice (Pb).

In a medium which has slight absorption at the indium resonance energy, Eq. 3 should be replaced by the following equation (15):

$$q(E) = \left(\xi\Sigma_s(E) + \gamma\Sigma_a(E)\right)\phi(E) \qquad (10)$$

where $\gamma = 1$ for a pure hydrogen moderator. Eq. 7 should then be corrected accordingly by replacing $\xi\Sigma_s$ by $(\xi\Sigma_s + \gamma\Sigma_a)$. This correction was considered negligible in our case.

In Eq. 8 it is assumed that the cadmium-covered foil captures only neutrons with energies in the vicinity of 1.46 ev. Indium, however, can capture neutrons at other energies, mainly in its higher lying resonances. The neutron energy distribution varies with the distance of the detector foil from the source, and the contribution

of the higher resonances to activation of the foil will, therefore, also vary with source-detector separation. Wade (24) tried to determine this effect experimentally for mixtures of D_2O-H_2O, but assumed it to be negligible in water. This assumption is followed here.

IV. EXPERIMENTAL ARRANGEMENT

The assembly under investigation consisted of a lattice of hollow thorium metal slugs immersed in light water in a cylindrical aluminum tank 22-1/2 inches in diameter. In the substitute lattice the thorium was replaced by lead, which has negligible resonance absorption.

The tank was placed on a dolly in front of the thermal column door of the VPI nuclear reactor (Fig. 3) and a neutron beam from deep within the thermal column passed into the tank through a 1 inch aluminum tube. A fission disc containing approximately 5 gms of U-235 metal mounted at the end of the tube, provided a fission source of neutrons. The fission disc will be referred to subsequently as the "fission source" and the 1-inch aluminum tube as the "source tube." A second disc containing lutetium, which has a resonance structure similar to that of U-235, will be referred to later as the "mock source."

For measuring a horizontal neutron flux traverse, the source tube was positioned in the tank to locate the source in the mid-plane of the lattice about 5 inches from the

wall of the tank. For measuring a vertical flux traverse, another longer source tube located the source on the central axis of the lattice 11-1/4 inches from the wall of the tank and 3-5/16 inches from the base, measured to the center of the source. The general arrangement is shown in Fig. 1.

Primary Source of Neutrons and Collimating System; Monitoring the Primary Source Neutrons

The VPI reactor, the primary source of neutron, has a 5 ft long thermal column closed by a 2 ft concrete door. The thermal column is separated by an additional 12 inches of graphite from the nearest fuel elements (22).

A neutron beam was extracted from deep inside the thermal column by removing part of its central stringer. For measuring the horizontal flux traverses, 40 inches of the central stringer were removed. For the vertical traverses, an additional 10 inches was removed to increase the intensity of the beam, since in this case a higher epithermal content could be tolerated in the beam. The intensity of the thermal neutrons striking the source was about the same in both cases, around 3×10^6 n/cm^2 sec at the full reactor power of 10 kw.

At the exit from the thermal column the beam was defined by a tube 2 inches in diameter inside a 6 inches long collimator filled with borated paraffin that was located in the thermal column door in place of the plug. The end of the 2-inch tube held a 1-inch long lucite bushing that had an inner diameter of 1 inch, so that the source tube would fit into it.

To monitor the primary neutron source and normalize the different runs, a 1/2-inch indium foil was exposed in a fixed geometry inside the north beam-port of the reactor.

Thorium Lattice

The thorium metal available was in the form of Savannah River hollow, aluminum clad, slugs (Mark VII-T). The slugs were 1.207 inch in outer diameter, 0.495 inch in inner diameter, and 6-5/8 inches long, with approximately 0.040 inch thick cladding. The slugs were stacked end to end in groups of three to give a length of about 20 inches, and arranged in a square lattice of 1-9/16 inch spacing, center to center, for a water to thorium volume ratio of 2 to 1 (water to metal ratio 1.45 to 1).

The lattice was mounted on a 3/8-inch aluminum plate on the bottom of the tank and the slugs were held in position by aluminum guide tubes, 7/16 inch in outside diameter and 20-3/4 inches long, which were inserted in a grid of holes drilled in the base plate. A 1/8-inch aluminum plate which was drilled to produce a similar grid was then mounted on the top of the aluminum tubes to give the lattice rigidity. The top plate was cut into a number of sections for easy mounting (Fig. 5). The lattice occupied all the area of the 22-1/2 inch diameter cylindrical tank and contained altogether 444 slugs.

Lead Lattice

The lead slugs were made of "virgin" chemical grade lead that was poured in lengths of 20 inches between two concentric aluminum tubes. Since aluminum tubing of the same outside diameter as the thorium slugs was not commercially available, the lead slugs were made in two sizes, 1-1/4 and 1-1/8 inch outside diameter and arranged in the lattice in the ratio 2 to 1 (one 1-1/8 inch slug to two 1-1/4 inch slugs) to give the same water to metal ratio

as in the thorium lattice. The inner aluminum guide tubes were of 5/8-inch outside diameter and had a 0.065-inch thick wall to give an inner diameter of 0.0495 inch, exactly as in the thorium. The wall thickness of the outer tubes was 0.035 inch. The trace elements in the lead and the elements alloyed in the aluminum tubing are given in Tables (A-1) and (A-2).

The lead slugs were held in position in the lattice in the same way as the thorium slugs, by the same base and top plates and the same 7/16 inch aluminum guide tubes (Fig. 6).

A number of slugs in each lattice were machined for the passage of the source tube.

Source Tubes, Fission Source, and Mock Source

The source tubes, 1 inch in outside diameter, were made in two lengths. The shorter tube, which was used for measuring horizontal flux traverses, penetrated 4-3/4 inches inside the tank, at a height of 10 inches above the base plate of the lattice. The longer tube, which was used for measuring vertical traverses,

penetrated 11 inches inside the tank, at a height of 3-5/16 inches above the base plate. The end of each tube was closed by a thin aluminum disc soldered in place. The walls of the tubes were covered with 0.020 inch thick cadmium. The sources were similarly covered with cadmium on the sides and on the face towards the assembly. The purpose of the cadmium was to shield the fission source from in-system thermal neutrons, so that it would be affected only by neutrons coming directly from the beam.

The fission source was a disc of U-235, 0.900 inch in diameter made up of 25 one-mil foils; the total weight was 5 gms. It was contained in a double walled cylindrical aluminum box that was made water-tight by sealing with epoxy cement.

The mock source was made of 4.3 gms of lutetium oxide powder compressed into a thin disc and enclosed and sealed in an aluminum box identical with that of the fission source. The sources were attached to the end of the source tube by a thin coat of vaseline and could thus be easily attached, removed, and interchanged. A rim about 1/32 inch deep and 1 inch in inside diameter around the face of the source prevented any lateral

movement of the source. The source tubes and sources are shown in Fig. 4. They can also be seen in Figs. 5 and 6.

Foil Holders and Cadmium Covers (Boxes)

For measuring flux traverses (at the indium-resonance energy of 1.46 ev) cadmium-covered indium foils were positioned in the lattice by means of foil holders made of lucite, which has scattering properties similar to those of water. The foil holders were designed to minimize the amount of foreign material introduced into the lattice including lucite.

For a horizontal traverse, two kinds of foil holders were used. One contained 1-inch foils and positioned them on a line along the axis of the source tube in the water gaps between the slugs with the plane of the foils perpendicular to the direction of measurement. The spacing of the slugs in the square lattice allowed only one kind of spacing for these foils, that of the lattice itself, i.e., in steps of 4.0 cm. The foils could thus be positioned only at distances of 4, 8, 12, etc., cm from the source. Altogether eight such foils were used for a traverse, positioned 4 to 32 cm from the source. The

other foil holder positioned 1/2 inch foils with their planes along the direction of measurement. In this position the foils could be spaced arbitrarily and foil recesses were cut to accommodate six foils at a spacing of 2 cm from center to center and at distances of 2 to 12 cm from source to center of foil.

For a vertical traverse, the foil holder was made to contain 3/4 inch foils and position them in the water gap above the source with their planes perpendicular to the direction of measurement (axis of the lattice). Here the spacing could be arbitrary, and the nine foils used for such a traverse had a spacing beginning at the source of 3 cm for the first four foils and 4 cm for the remainder. The foil holders can be seen in Figs. 5 and 6.

The cadmium covers were 0.030 inch thick, except the covers for the 1/2 inch foils, which for technical reasons were made 0.020 inch thick. All the covers were designed to prevent any forward-backward movement of the foil within the box.

The cadmium boxes were held in position in the recesses of the foil holders by means of aluminum or lucite rings. The boxes were made water-tight by applying a little vaseline along their rims.

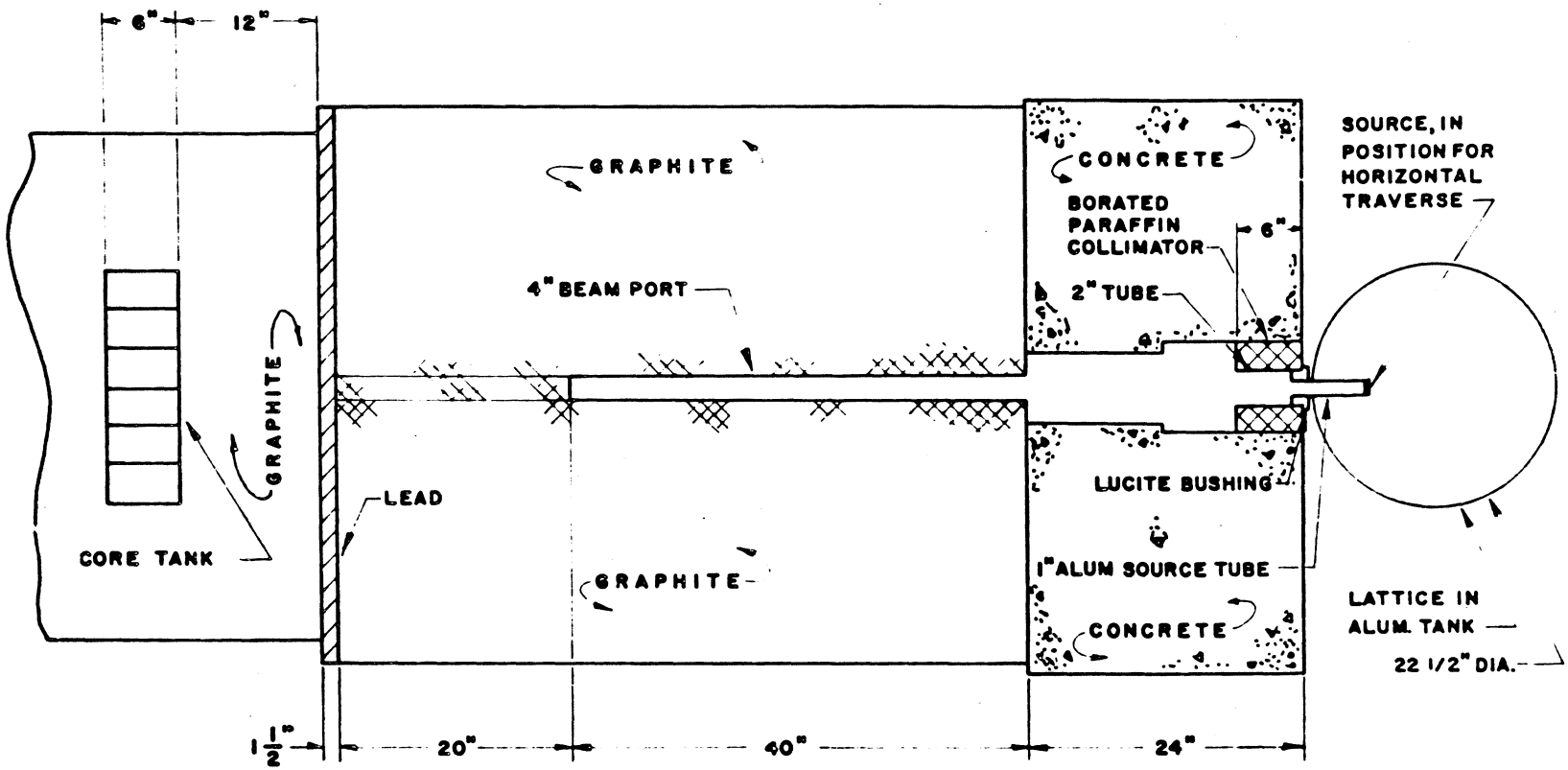

FIG. 1 PLAN OF EXPERIMENTAL ASSEMBLY

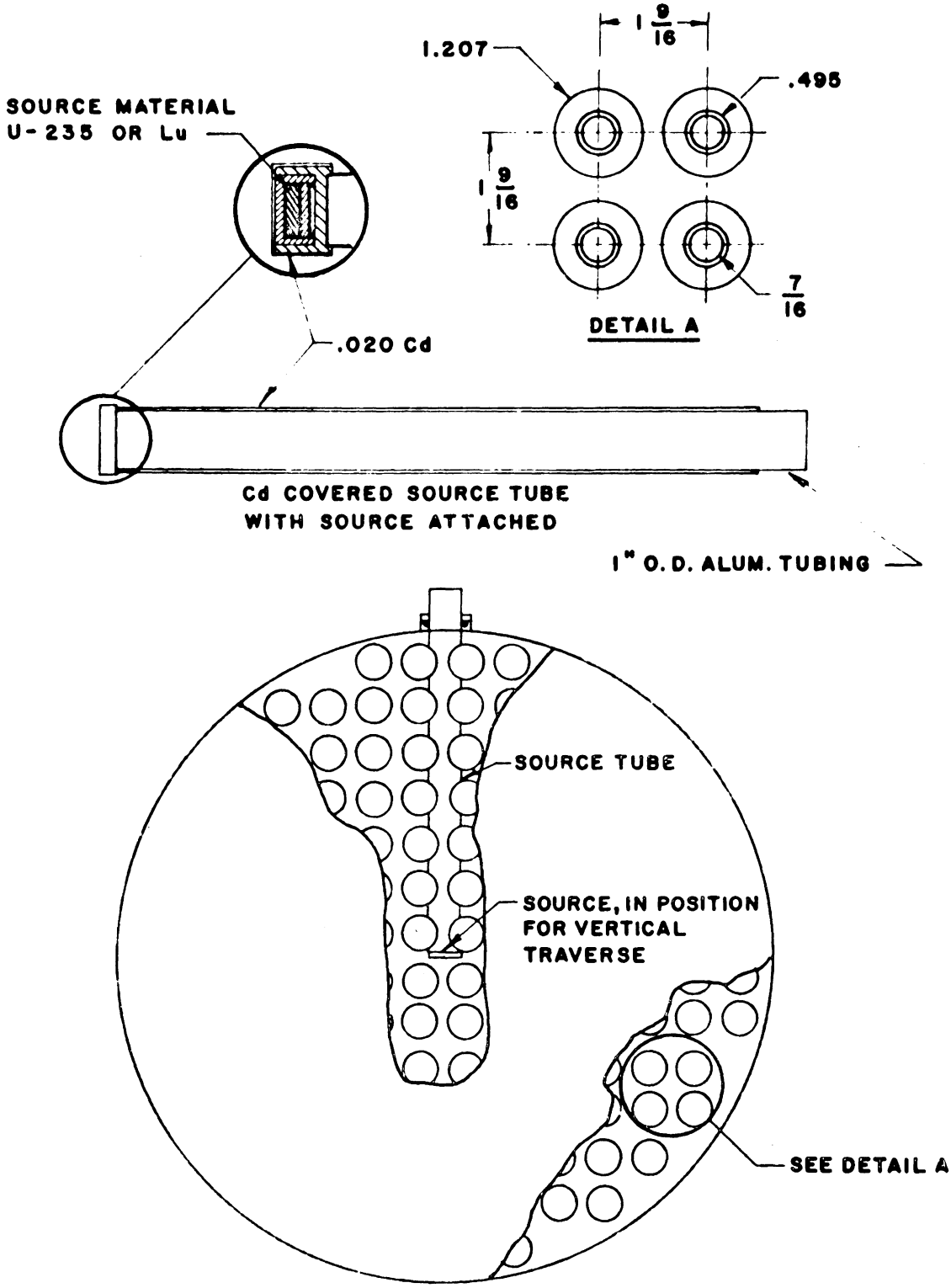

FIG. 2 SKETCH OF LATTICE & SOURCE TUBE IN ALUM. TANK

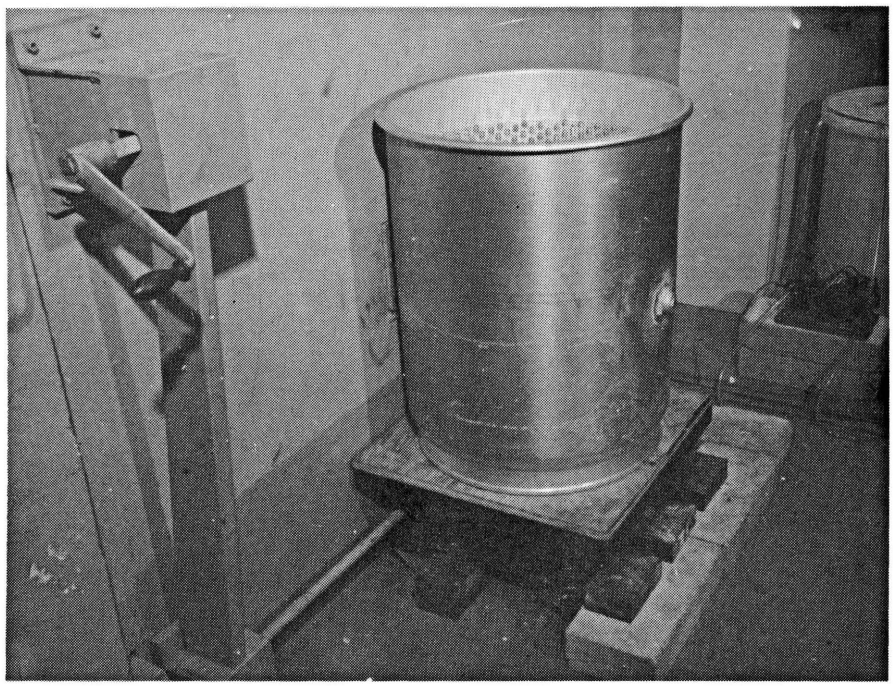

FIG. 3. ALUMINUM TANK WITH LATTICE AT DOOR OF THERMAL COLUMN

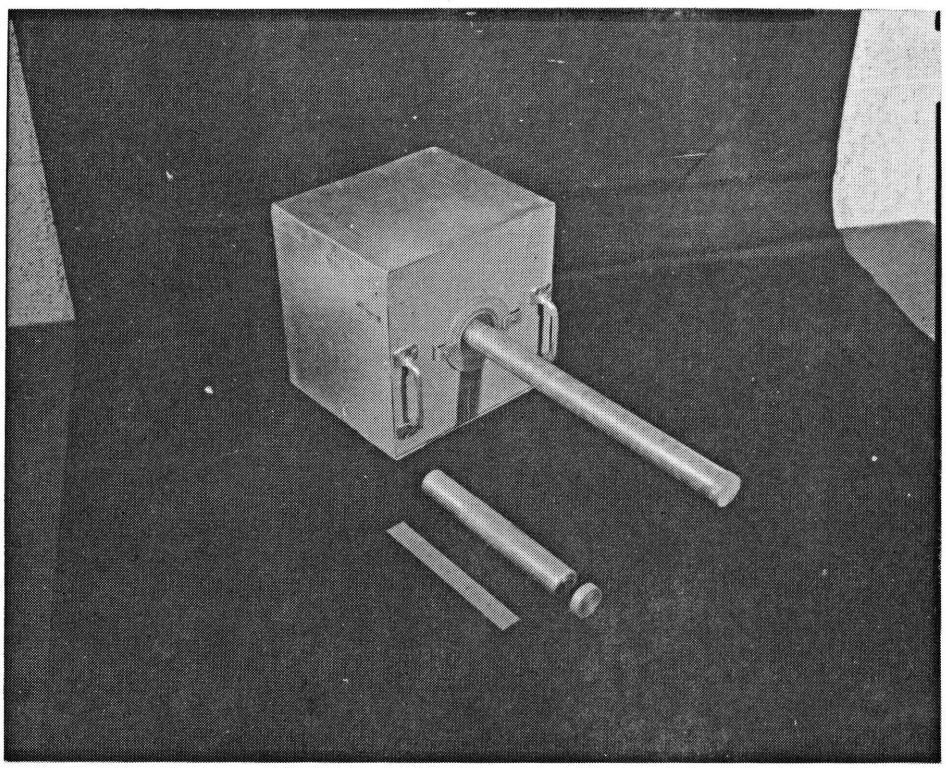

FIG. 4. BORATED PARAFFIN COLLIMATOR, SOURCE TUBES AND SOURCES

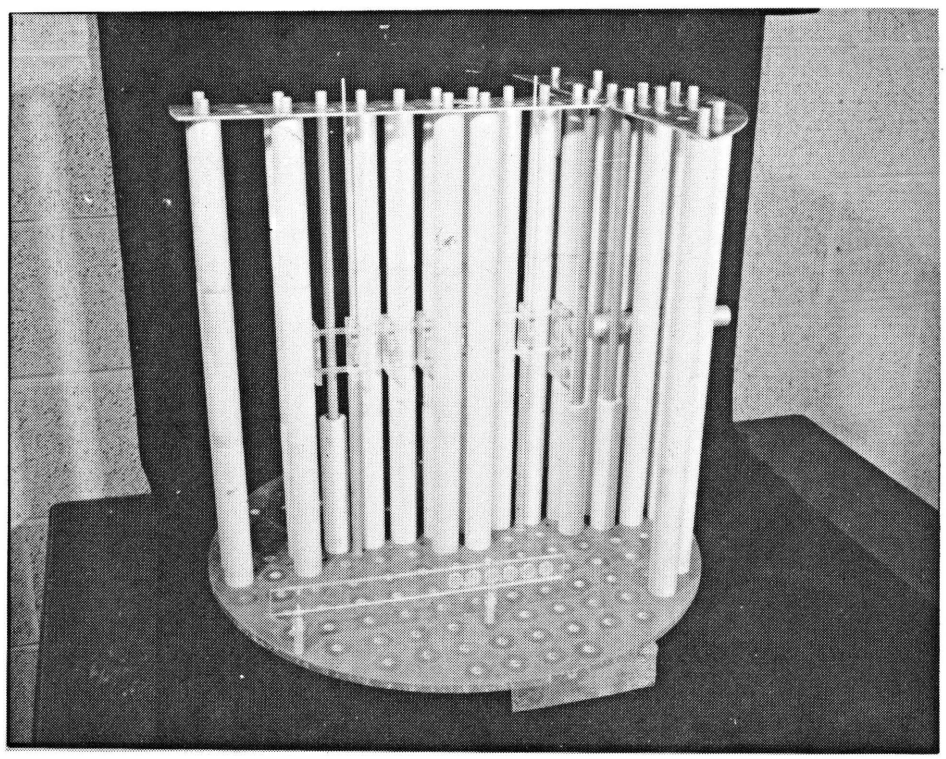

FIG. 5. INSIDE VIEW OF THORIUM LATTICE WITH SOURCE TUBE, SOURCE AND FOIL HOLDERS IN POSITION FOR HORIZONTAL TRAVERSE

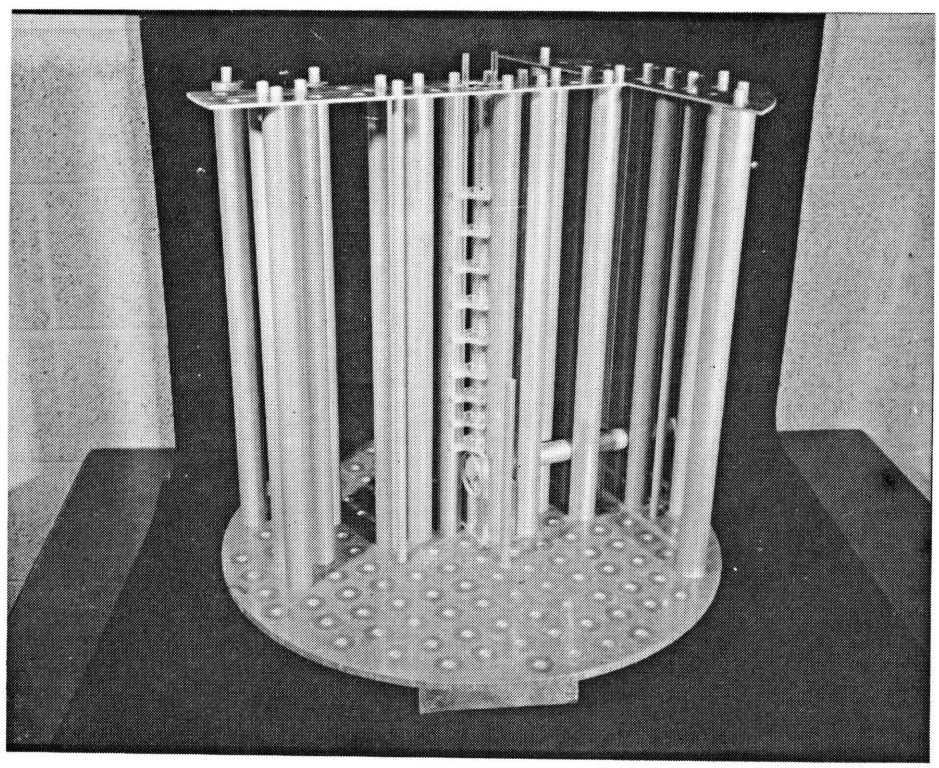

FIG. 6. INSIDE VIEW OF LEAD LATTICE WITH SOURCE TUBE, SOURCE AND FOIL HOLDER IN POSITION FOR VERTICAL TRAVERSE

All the indium foils used were 5 mils thick (100 mg/cm^2).

Counting Equipment

The counting equipment consisted of two Packard gas flow proportional counters with micromil windows and two Nuclear-Chicago Ultrascalers Model 192A. PR-gas (90 percent argon, 10 percent methane) was used and the working voltage was around 2400 volts.

V. EXPERIMENTAL PROCEDURE

Measuring a flux traverse in any one lattice involved two series of irradiations, one with the fission source, the other with the mock source. Irradiation with the mock source is required in order to correct the activation produced by the fission source irradiation for the activation by non-source neutrons, i.e., primary source epithermal neutrons that penetrate the assembly. Some of these neutrons will be scattered by the uranium in the fission source or captured in its resonances. The mock source should, therefore, contain a material that has a resonance structure similar to that of U-235. Lutetium in the form of lutetium oxide powder was selected (20), since it has a resonance structure somewhat similar to that of the uranium it replaces (11).

A foil traverse was generally divided into two sets of alternating foils (foils 1, 3, 5, 7, ... in one set, 2, 4, 6, 8, ... in the other), and each set was irradiated separately to prevent any depression of the indium-resonance flux by the adjacent foils. The two runs were normalized through the activation of the monitor foil.

A flux traverse thus involved the following steps: Positioning and irradiation of one set of foils with one of the sources, say the mock source, and the removal and counting of the foils at the end of the irradiation. The same was later repeated with the other set of foils. The sources were then interchanged, i.e., the mock source replaced by the fission source, and the same steps repeated. These four runs together give the experimental data for a single flux traverse. Each run was repeated at least once for statistical accuracy.

When a flux traverse measurement had been finished, the thorium slugs in the lattice were replaced by the lead slugs and the procedure repeated. The thorium and lead runs were normalized to the intensity of the fission source by the activation of the monitor foil.

The foils were all counted in the same fixed geometry. Each foil was counted on both sides and the sum of the two counting rates corrected for waiting time and counting time was taken after normalization as the "relative activation." The minimum waiting time was 10 minutes to allow the decay of the indium 13 sec activity.

The same foils were used repeatedly, in the mock source and fission source irradiation and in the two

lattices (thorium and lead). The foils were checked periodically for build-up of long lived residual activities, and though some was found, it was negligible. All irradiations were made at the full reactor power of 10 kw for 2-1/2 hours to 85 percent of the saturated activity.

The measured traverses extended to only 32 cm from the source, since at the maximum power of 10 kw enough activation for counting could not be produced further away from the source.

In the fission source irradiation at least 10,000 counts were obtained from each side of the first seven foils and between 7000 and 5000 for the other foils. In the mock source irradiations the number of counts ranged from 10,000 for the foil nearest to the source to about 2000 for the foil farthest away from the source. This lower number of counts was considered adequate, since the mock source activation contributed only from 3 to 15 percent to the total (fission source) activation.

The stability of the counters was checked frequently with a standard source, and it was found that the counting rates obtained were reliable only within 2 percent.

VI. RESULTS

The activation measurements are presented in Figs. 7 to 14. Where the difference between repeated runs is large enough to be seen on the graph, both values are shown; where the difference is too small for graphical representation, the value shown is the average of the runs.

After subtracting mock-source activation from fission-source activation, the values obtained were corrected for the finite size of the foils and the source, in the case of the horizontal traverses, and for the finite size of the foils alone, in the case of the vertical traverses. This correction is discussed in Appendix B and the appropriate formulae given there.

In the horizontal traverses the 1-inch and the 1/2-inch foil measurements were normalized at point 4 = 8 cm, and for expediency in drawing the graphs, the relative activation at point 5 = 4 cm in the lead lattice was arbitrarily set as 50,000 cpm (actual value 77,500 cpm).

Tables I and II list the corrected experimental values of the relative activation and their products

TABLE I

RESULTS OF ACTIVATION MEASUREMENTS

HORIZONTAL TRAVERSES

r, cm	A, cpm	$Ar^2 \times 10^{-3}$
	(a) Lead Lattice	
2	62,200	249
4	50,000	800
6	36,000	1296
8	24,000	1536
10	15,300	1530
12	9,860	1420
16	3,990	1021
20	1,630	652
24	680	392
28	300	235
32	135	138
	(b) Thorium Lattice	
2	60,000	240
4	48,000	768
6	34,700	1249
8	22,500	1440
10	14,150	1415
12	8,900	1282
16	3,450	883
20	1,350	540
24	554	319
28	244	191
32	107	110

TABLE II

RESULTS OF ACTIVATION MEASUREMENTS

VERTICAL TRAVERSES

r, cm	A, cmp	$Ar^2 \times 10^{-3}$
	(a) Lead Lattice	
3	60,500	545
6	38,400	1382
9	21,000	1701
12	11,000	1584
16	4,520	1157
20	1,905	762
24	820	472
28	365	286
32	170	174
	(b) Thorium Lattice	
3	57,800	520
6	36,300	1307
9	19,600	1507
12	10,000	1440
16	3,940	1010
20	1,560	624
24	647	373
28	290	227
32	130	133

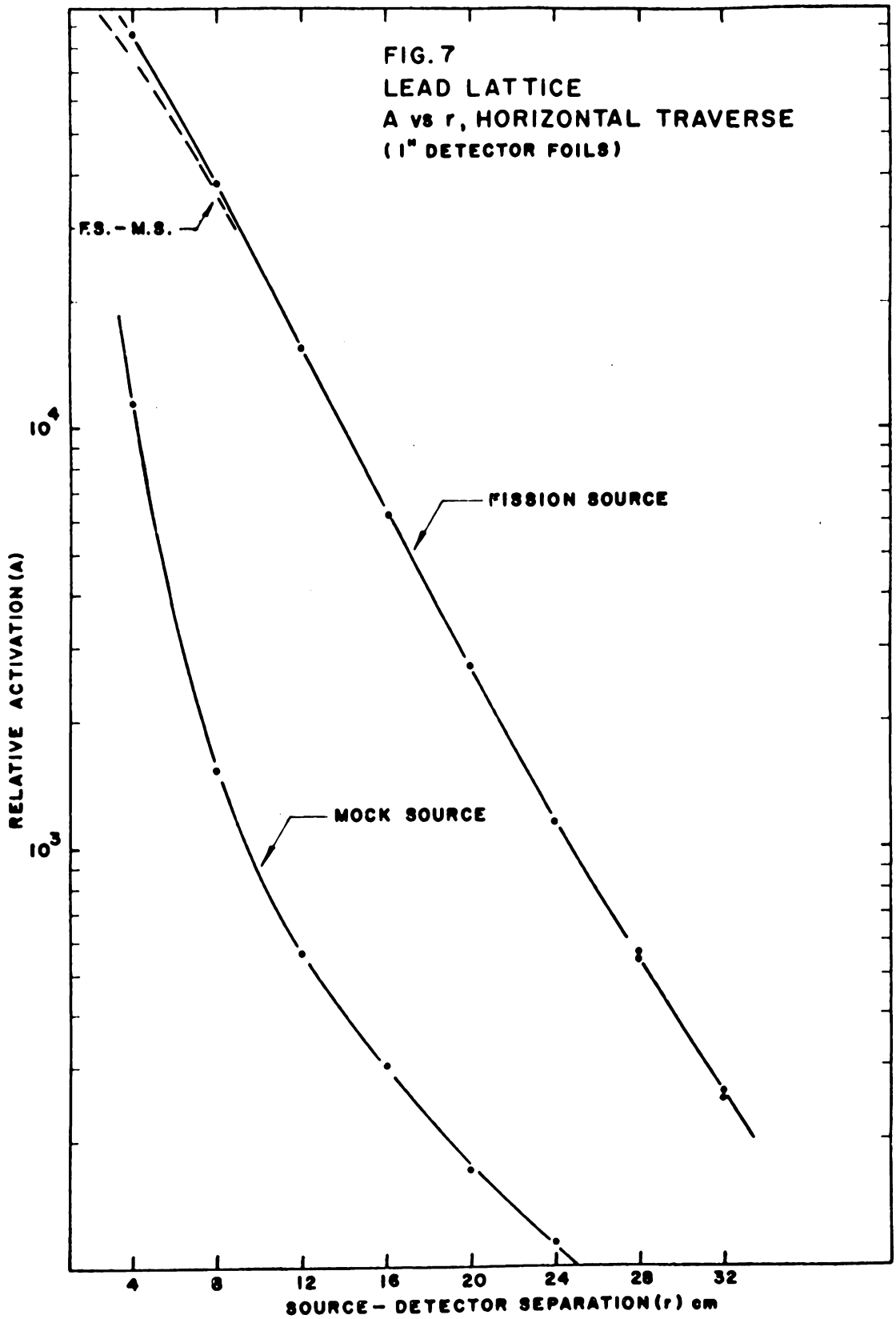
FIG. 7
LEAD LATTICE
A vs r, HORIZONTAL TRAVERSE
(1" DETECTOR FOILS)
F.S. - M.S.
FISSION SOURCE
MOCK SOURCE
RELATIVE ACTIVATION (A)
10^4
10^3
4
8
12
16
20
24
28
32
SOURCE - DETECTOR SEPARATION (r) cm

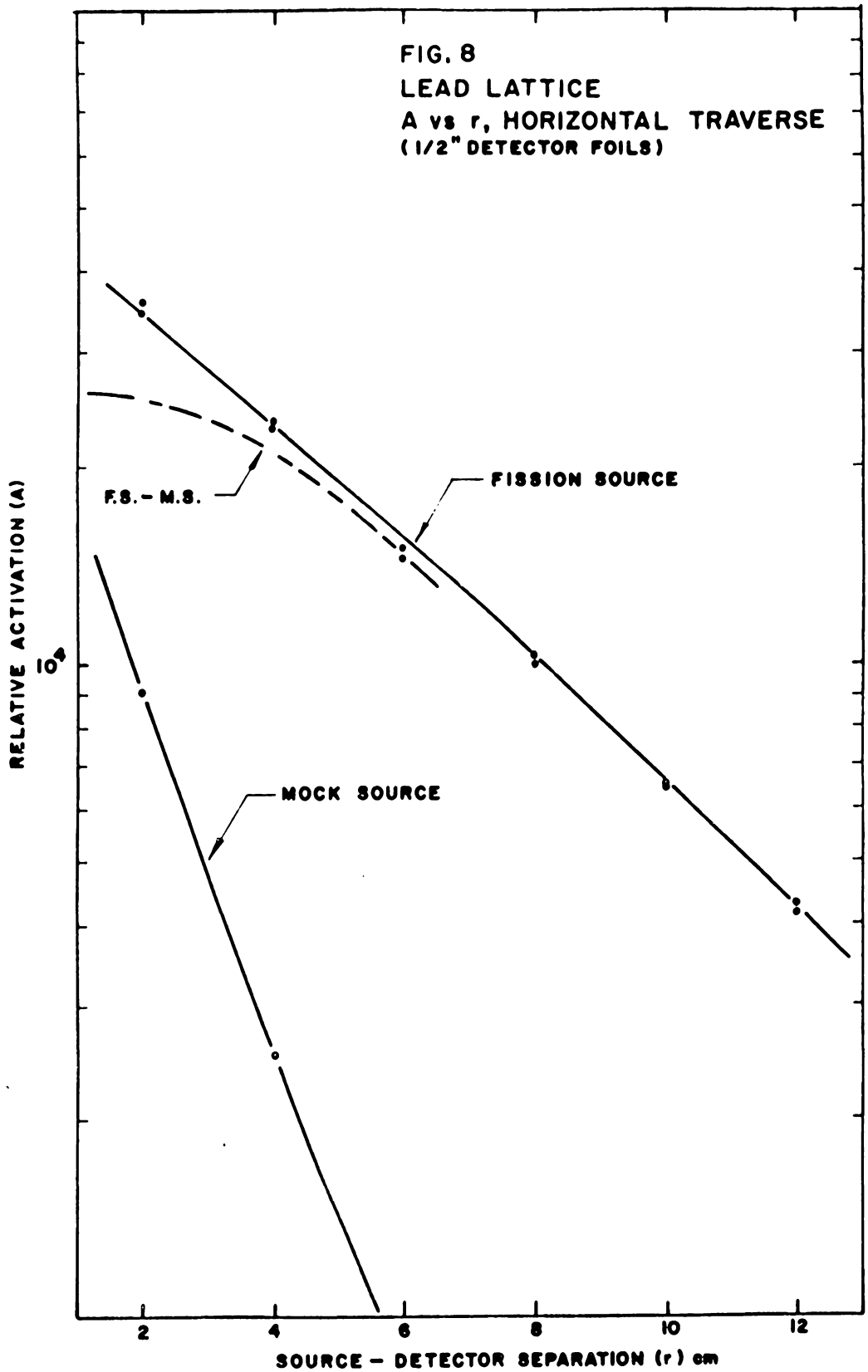
FIG. 8
LEAD LATTICE
A vs r, HORIZONTAL TRAVERSE
(1/2" DETECTOR FOILS)
RELATIVE ACTIVATION (A)
10^4
F.S. - M.S.
FISSION SOURCE
MOCK SOURCE
2
4
6
8
10
12
SOURCE - DETECTOR SEPARATION (r) cm

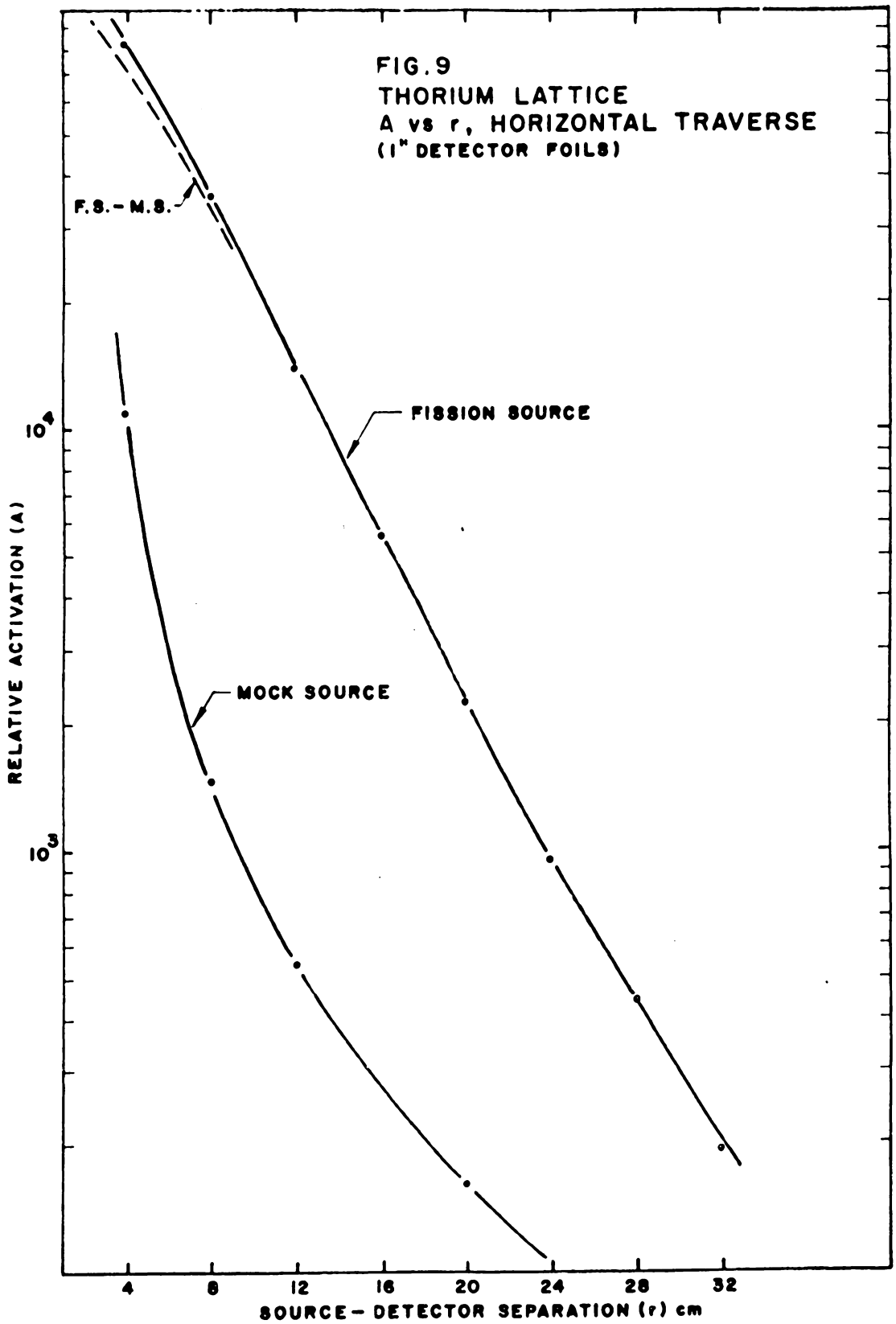
FIG. 9
THORIUM LATTICE
A vs r, HORIZONTAL TRAVERSE
(1" DETECTOR FOILS)
F.S. - M.S.
FISSION SOURCE
MOCK SOURCE
RELATIVE ACTIVATION (A)
10^4
10^3
4
8
12
16
20
24
28
32
SOURCE - DETECTOR SEPARATION (r) cm

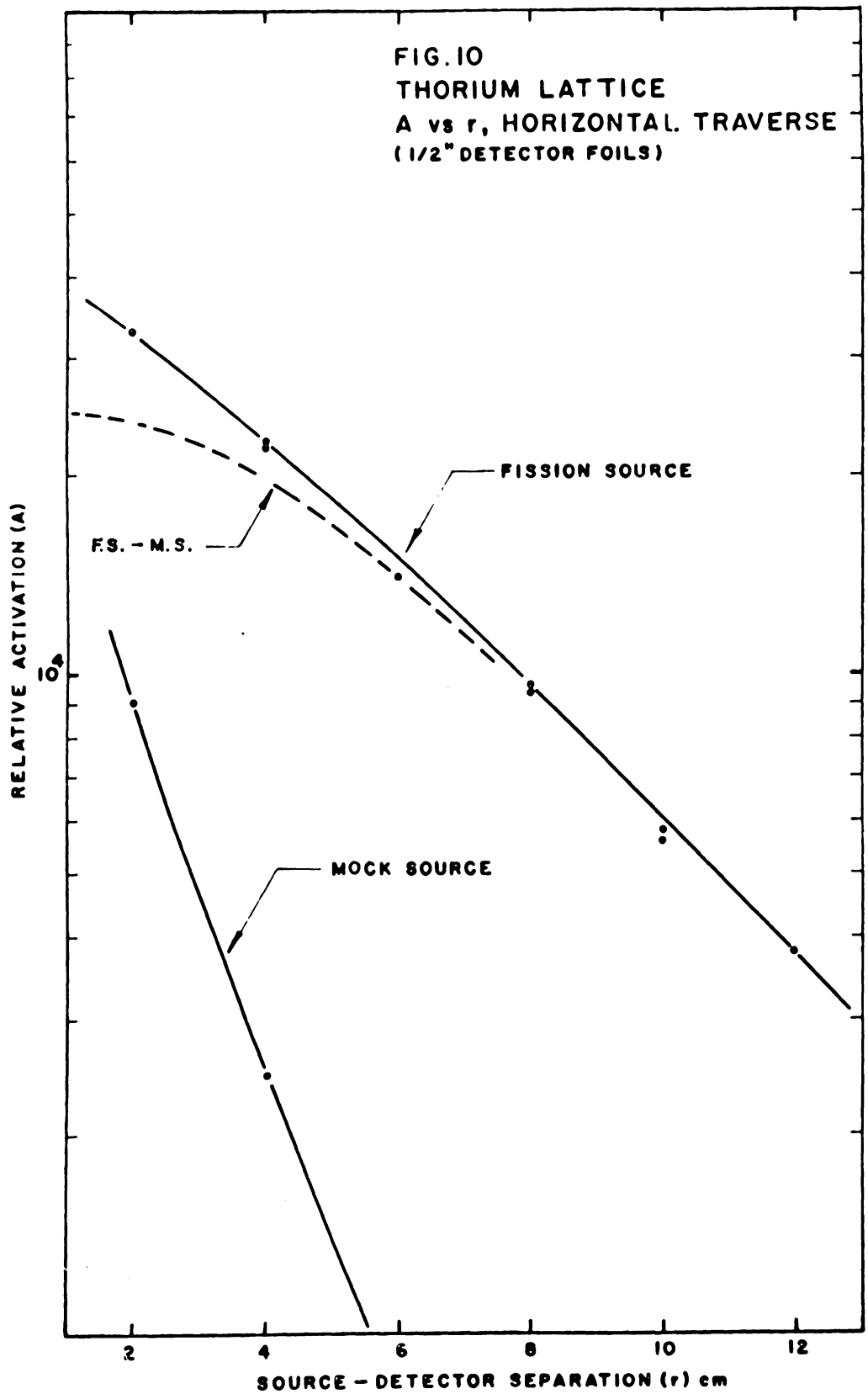
FIG. 10
THORIUM LATTICE
A vs r, HORIZONTAL TRAVERSE
(1/2" DETECTOR FOILS)
FISSION SOURCE
F.S. - M.S.
MOCK SOURCE
RELATIVE ACTIVATION (A)
10
2
4
6
8
10
12
SOURCE - DETECTOR SEPARATION (r) cm

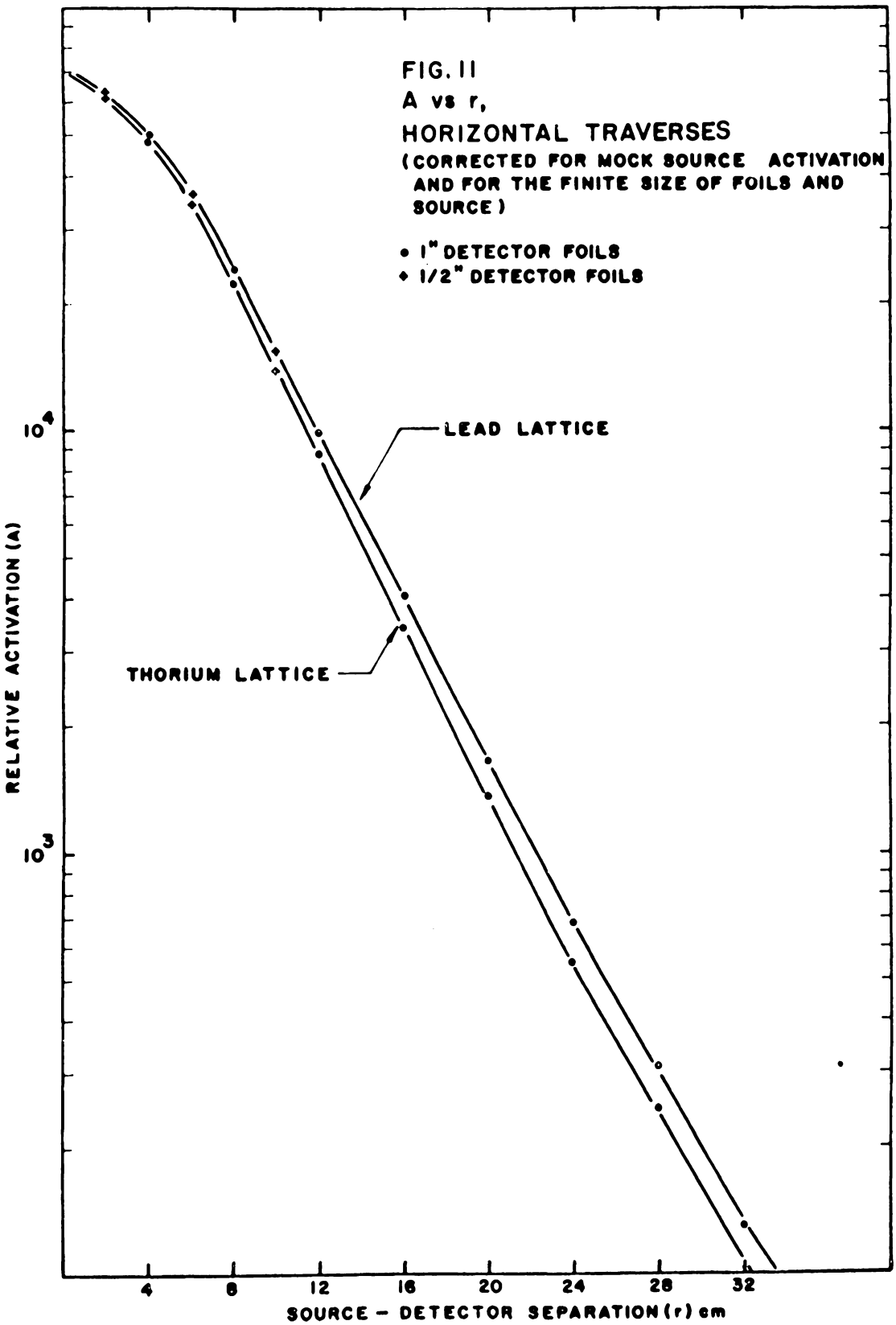
FIG. 11
A vs r,
HORIZONTAL TRAVERSES
(CORRECTED FOR MOCK SOURCE ACTIVATION AND FOR THE FINITE SIZE OF FOILS AND SOURCE)
• 1" DETECTOR FOILS
♦ 1/2" DETECTOR FOILS
LEAD LATTICE
THORIUM LATTICE
RELATIVE ACTIVATION (A)
10^4
10^3
4
8
12
16
20
24
28
32
SOURCE - DETECTOR SEPARATION (r) cm

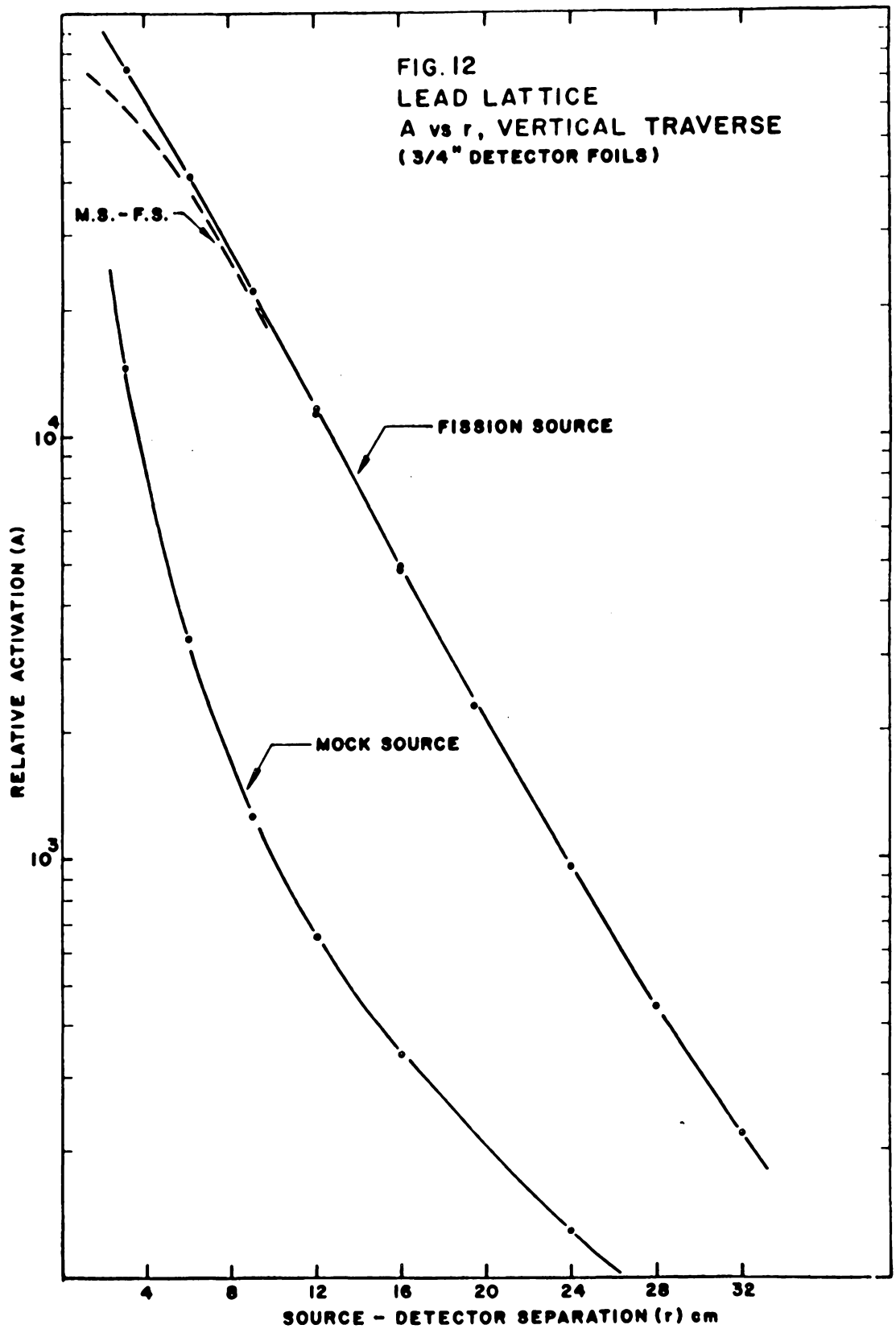
FIG. 12
LEAD LATTICE
A vs r, VERTICAL TRAVERSE
(3/4" DETECTOR FOILS)
M.S. - F.S.
FISSION SOURCE
MOCK SOURCE
RELATIVE ACTIVATION (A)
10^4
10^3
4
8
12
16
20
24
28
32
SOURCE - DETECTOR SEPARATION (r) cm

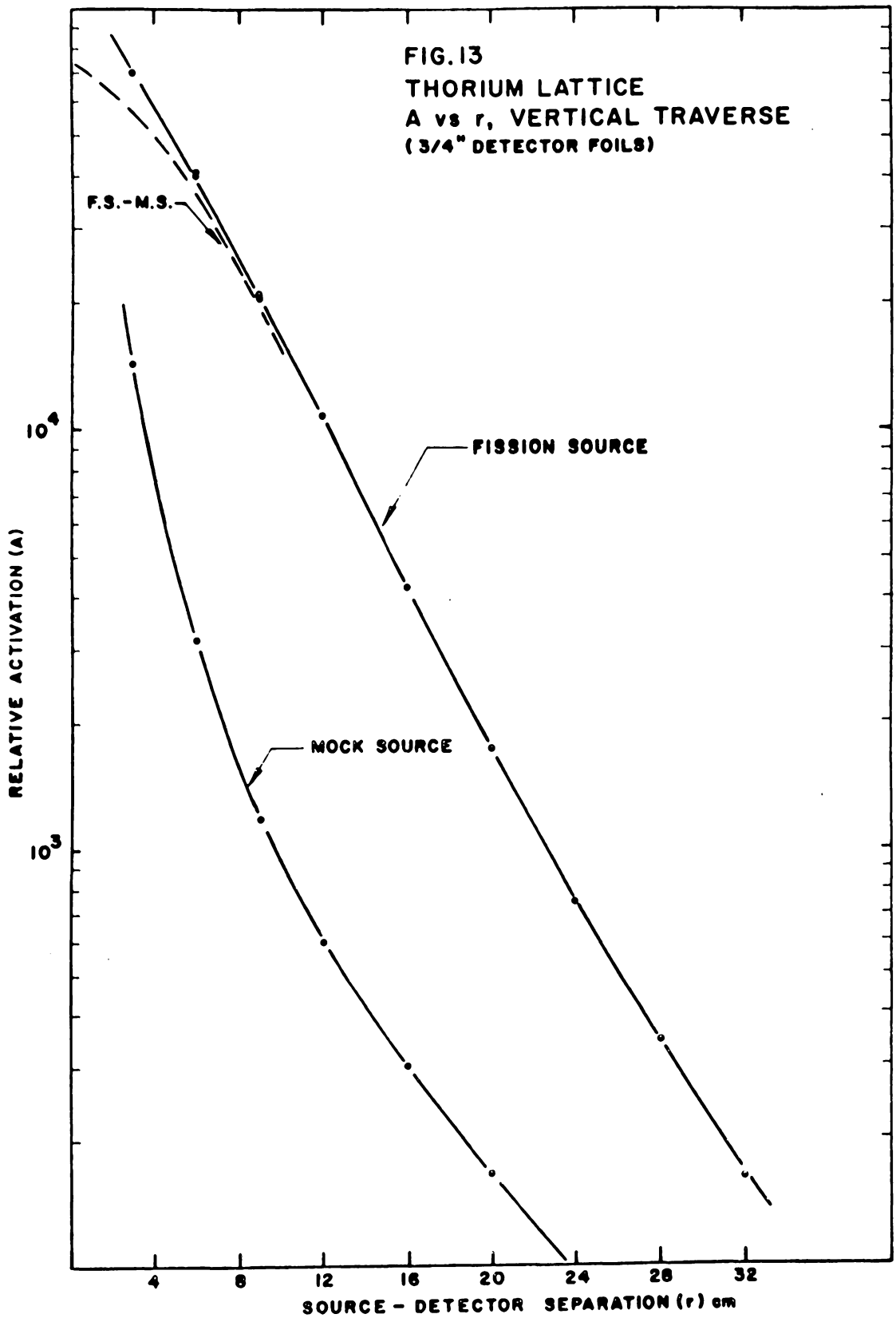
FIG. 13
THORIUM LATTICE
A vs r, VERTICAL TRAVERSE
(3/4" DETECTOR FOILS)
F.S.-M.S.
FISSION SOURCE
MOCK SOURCE
RELATIVE ACTIVATION (A)
10^4
10^3
4
8
12
16
20
24
28
32
SOURCE - DETECTOR SEPARATION (r) cm

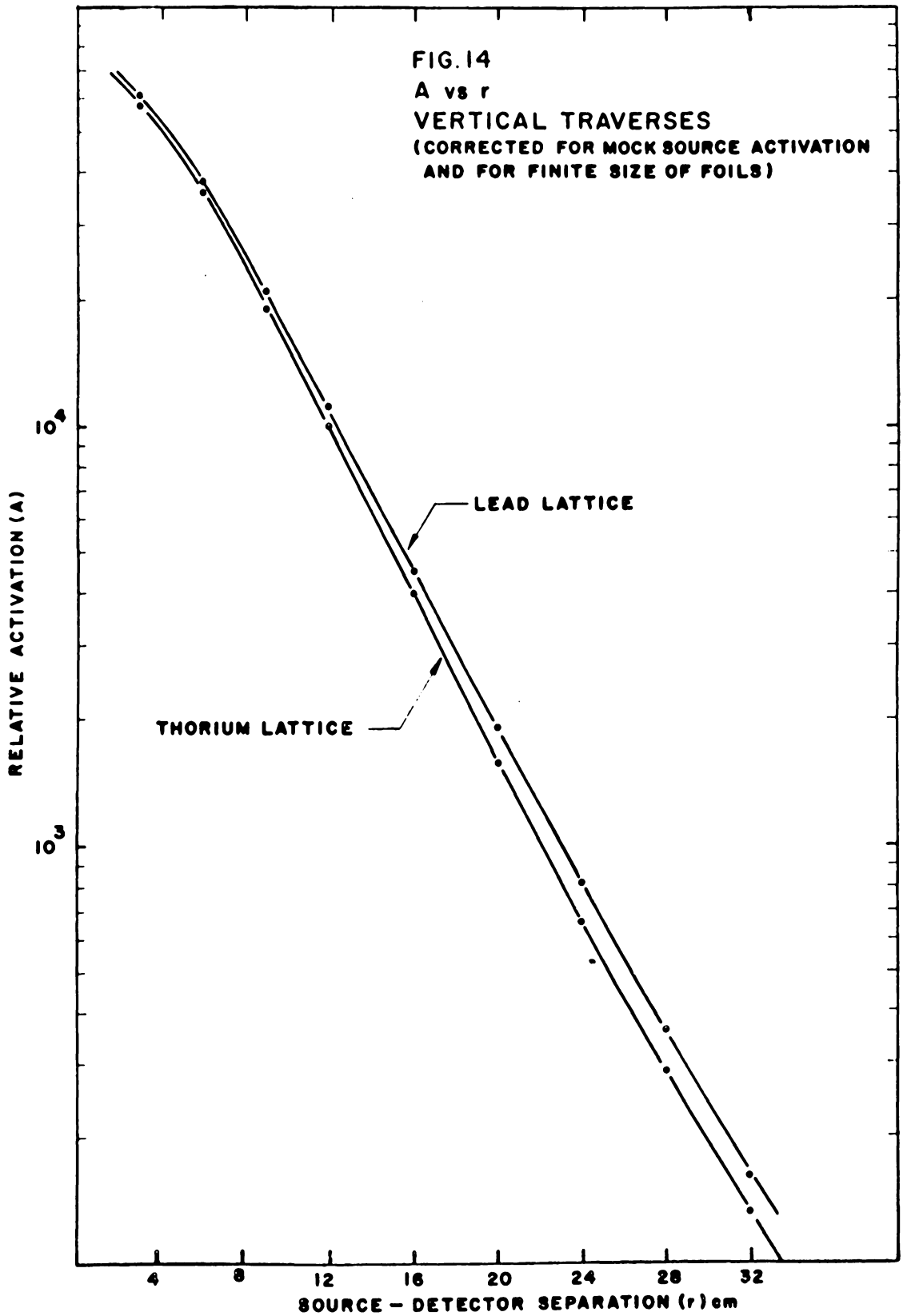
FIG. 14
A vs r
VERTICAL TRAVERSES
(CORRECTED FOR MOCK SOURCE ACTIVATION AND FOR FINITE SIZE OF FOILS)
LEAD LATTICE
THORIUM LATTICE
RELATIVE ACTIVATION (A)
10^4
10^3
4
8
12
16
20
24
28
32
SOURCE – DETECTOR SEPARATION (r) cm

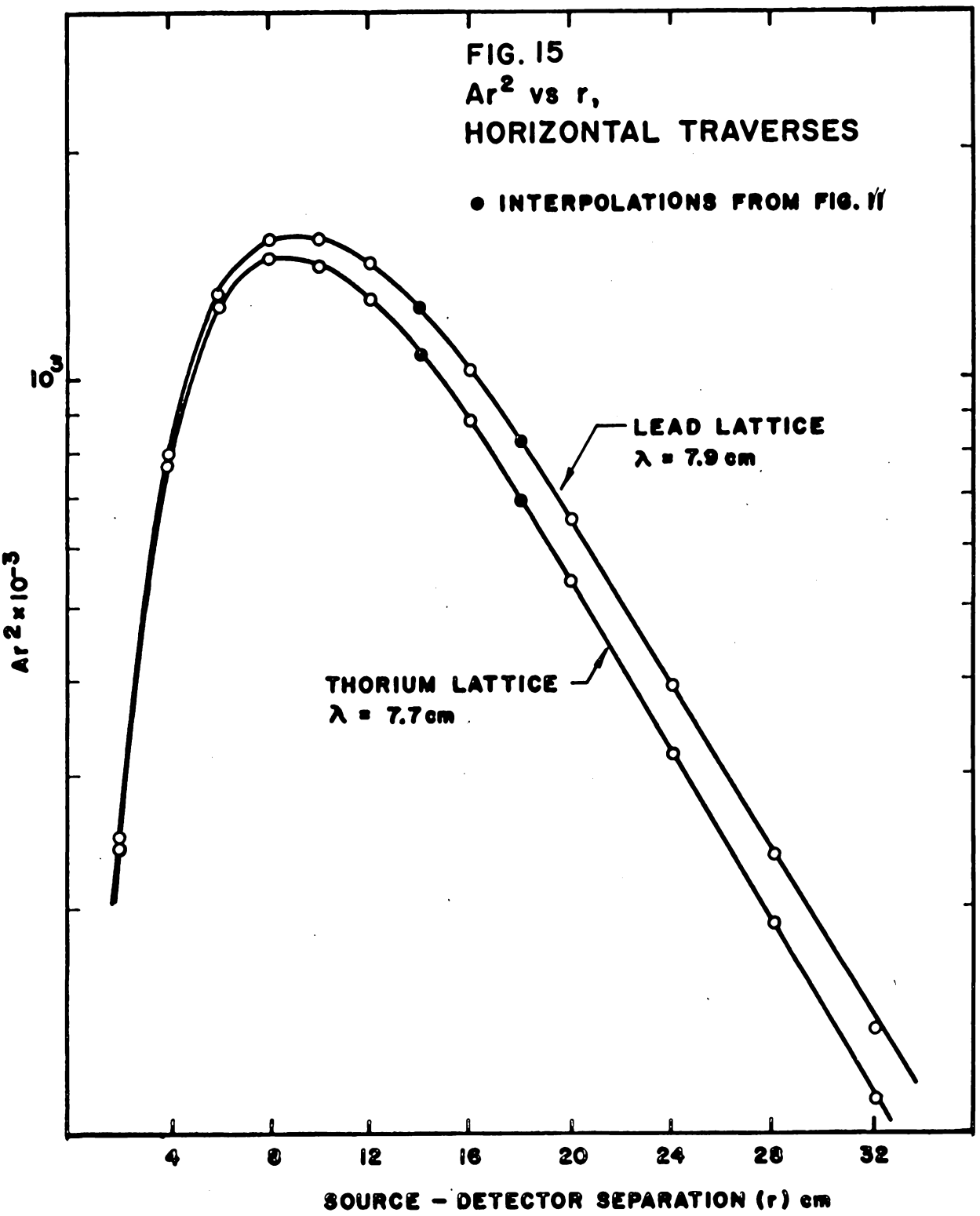
FIG. 15
Ar² vs r,
HORIZONTAL TRAVERSES
● INTERPOLATIONS FROM FIG. 11
LEAD LATTICE
λ = 7.9 cm
THORIUM LATTICE
λ = 7.7 cm
Ar² x 10⁻³
10³
4
8
12
16
20
24
28
32
SOURCE - DETECTOR SEPARATION (r) cm

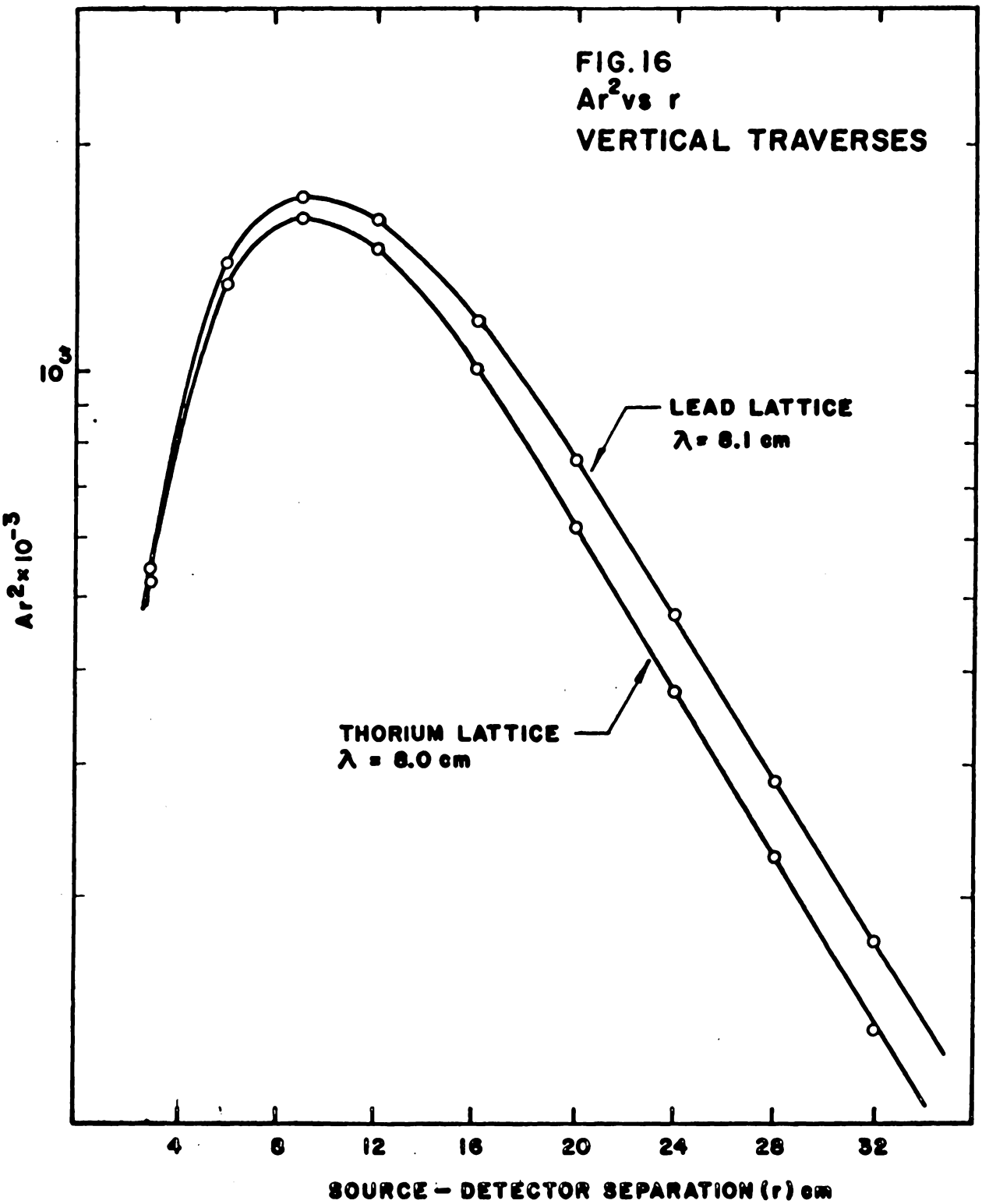
FIG. 16
Ar^2 vs r
VERTICAL TRAVERSES
10^3
$Ar^2 \times 10^{-3}$
LEAD LATTICE
λ = 8.1 cm
THORIUM LATTICE
λ = 8.0 cm
4
8
12
16
20
24
28
32
SOURCE – DETECTOR SEPARATION (r) cm

with r^2 (i.e., Ar^2). The same data are presented in Figs. 15 and 16, which give the curves of Ar^2 vs r for the horizontal and for the vertical traverses. It was assumed that for values of r greater than some value r_1, to be determined from the curves (about 20 cm in our cases) the points in the semi-log representation lie on a straight line, i.e., that A(r) can be represented by $C \exp(-r/\lambda)/r^2$ (3,19,20), where $-\lambda$ is the inverse of the slope of the curve and has the dimension of length (cm); C is a constant. It can be seen from Figs. 15 and 16 that this assumption is justified.

Integration was performed in two parts. The curved portion of Ar^2 vs r up to r_1 was integrated numerically (Simpson's rule); the points were read from the smooth curve every 2 cm. From r_1 to infinity the curve was integrated analytically using the relationship $A \sim \exp(-r/\lambda)/r^2$. This portion turns out to be λA_1, where A_1 is the value of A at r_1. The extrapolated portion beyond the last measured point constitutes between 4 and 5 percent of the total. The final results are given in Table III.

As seen in Table III, p as measured by a horizontal traverse in the lattice is lower by about 1 percent than

TABLE III

FINAL RESULTS OF ACTIVATION MEASUREMENTS

Lattice	$\lambda_\perp$ cm	$\lambda_\parallel$ cm	$\tau_\perp$ cm^2	$\tau_\parallel$ cm^2
Thorium	7.7 ± 0.15	8.0 ± 0.16	44 ± 2	46 ± 2
Lead	7.9 ± 0.15	8.1 ± 0.16	47 ± 2	49 ± 2

$-\lambda$ = inverse of slope of tail of Ar^2 vs r curve

τ = age to indium-resonance energy

$\perp$ = direction of measurement perpendicular to slugs

$\parallel$ = direction of measurement parallel to slugs

Resonance Escape Probability

$p_\perp$ = 0.877 ± 0.017

$p_\parallel$ = 0.886 ± 0.017

Average = 0.88 ± 0.015

p as measured by a vertical traverse. The difference is, however, within the experimental error. It seems therefore reasonable to take the average of the two values as giving the value of p for the lattice.

The data also yield the "age" to indium-resonance energy of fission neutrons in the lead and thorium lattices. In the lead lattice it is 47 ± 2 cm^2 as measured perpendicular to the slugs and 49 ± 2 cm^2 as measured parallel to the slugs. In the thorium lattice it is 44 ± 2 cm^2 as measured perpendicular to the slugs and 46 ± 2 cm^2 as measured parallel to the slugs. The "age" to indium-resonance energy for the fission neutrons is thus greater when measured in a direction parallel to the slugs than when measured in the perpendicular direction. This result is in agreement with theory (18), but disagrees with other reported measurements. Barkov et al. (2) who measured "age" in natural uranium-light water lattices found no anisotropy. He found that the indium-resonance neutron distribution in a plane through the source was the same when measured along different traverses, and the values for the "age" when measured parallel and perpendicular to the rods agreed within the experimental error. Roberts and Pettus (20) measured

"age" in ThO_2-D_2O-H_2O lattices and found that in the ThO_2-H_2O lattice the perpendicular age was somewhat larger than the parallel age, though here again the difference was within the experimental error.

VII. CONCLUSIONS

As seen in Figs. 11 and 14 the spatial distribution of the indium-resonance neutrons in the thorium lattice is not the same as in the lead lattice. The ratio of the foil activities in the two lattices varies from approximately 0.96 at 4 cm from the source to approximately 0.80 at 28 cm from the source. This means that absorption decreases the ratio of the neutrons far removed from the source to the neutrons near the source for a hydrogenous moderator, as predicted by theory (23). From the difference in the shape of the indium-resonance neutron distribution in the two lattices it is evident that the simple method, good for heavy moderators, of measuring the slowing down density at one point (Eq. 2), or averaging it over a few points, is not applicable here, and the problem must be approached through Eqs. 1 and 3, as done in this experiment.

The difference in the results for p as obtained by the two traverses (horizontal and vertical) is within the experimental error. It may therefore be concluded that measuring many traverses to provide an integration over

the whole assembly is unnecessary, and the integration along one traverse gives the true value of p.

We thus say as a conclusion that the direct method used here is a practical method, provided the right pure materials can be obtained for the substitution lattice. Impurities with resonances can be particularly undesirable, such as the antimony often added to harden lead alloys.

The measured value of p holds only for the source geometry used in this experiment. It is believed, however, that for such a close-packed lattice the effective source of first collision neutrons will approach a distributed source and yield a value of p very close to that for a distributed source.

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APPENDIX A

TABLE A-1

PERCENT OF ALLOYING ELEMENTS IN THE ALUMINUM TUBING USED (61S)

Copper	-	0.25
Silicon	-	0.6
Magnesium	-	1.0
Chromium	-	0.25

TABLE A-2

PERCENT OF TRACE ELEMENTS IN VIRGIN ST. JOSEPH CHEMICAL LEAD

Silver - 0.02 (max), 0.002 (min)

Copper - 0.08 (max), 0.04 (min)

Arsenic, Anthimony, Tin - 0.002

Zinc - 0.001 (max)

Iron - 0.002 (max)

Bismuth - 0.005 (max)

APPENDIX B

Correction of Foil Activities for Finite Size of Source and Detector Foils

In Eq. 9 it is assumed that both a point source and point detectors are utilized. To account for the finite size of the source and the foils, corrections must be applied to the measured activities of the indium foils. Such corrections have been published previously (9,24).

For a plane circular source of diameter d_s and a plane detector foil of diameter d_f the first order correction for the activity of the foils is

$$A(r) - A_m(r) = - \frac{d_s^2 + d_f^2}{16r} \frac{dA}{dr} \qquad \text{(B-1)}$$

where $A_m(r)$ is the measured activity and $A(r)$ is the activity induced by a point source in a point detector at r. dA/dr was taken to be the slope of the experimental curve A vs r, since the correction was small.

Eq. (B-1) is applicable when the planes of the source and the foils are perpendicular to the direction of the measurement. If the planes of the foils lie along the

direction of the measurements, as was the case with the 1/2-inch foils in the horizontal traverses, the correction becomes

$$A(r) - A_m(r) = \left(\frac{d_s^2}{16} + \frac{d_f^2}{32} \right) \frac{dA}{dr} \qquad \text{(B-2)}$$

This equation was derived following (9).

ABSTRACT

A direct method for measuring the resonance escape probability, p, in thorium-water lattices was experimentally examined. The system under investigation consisted of a square, close-packed, lattice of hollow aluminum clad thorium metal slugs (1.207 inch O.D., 0.495 inch I.D.) in water, spaced to give a water to thorium ratio of 2 to 1 by volume (water to metal 1.45 to 1). A substitute lattice, in which the thorium was replaced by lead, was also used to give the same scattering properties as thorium but no resonance capture. The neutron source consisted of a fission plate made of a disc of U-235 (0.900 inch in diameter, 5 mgs in weight) mounted at the end of a Cd-covered aluminum tube which conducted a beam of neutrons from inside the thermal column of the VPI reactor into the lattice. Cd-covered indium foils were used to measure flux traverses in two perpendicular directions, parallel to the slugs (denoted by $\parallel$) and perpendicular to the slugs (denoted by $\perp$). The curves of Ar^2 vs r, where A is the normalized relative activation of the foils, corrected for activation by epithermal neutrons from the primary source (reactor),

were integrated to infinity and the ratio of the integrals in the thorium and lead lattices yielded p. It was found that $p_{\perp}$ and $p_{\parallel}$ differed by only one percent, which was within the experimental error. It was therefore concluded that there was no anistropy in the resonance absorption and the average of the two values, 0.88 ± 0.015, was taken as the value of p for the lattice.

The experiment yielded also the age τ to indium resonance energy:

In thorium lattice, $\tau_{\perp} = 44 \pm 2$ cm^2, $\tau_{\parallel} = 46 \pm 2$ cm^2

In lead lattice, $\tau_{\perp} = 47 \pm 2$ cm^2, $\tau_{\parallel} = 49 \pm 2$ cm^2