RADIOTRACER STUDIES ON RAPID SAND FILTRATION

Annual Progress Report

on

OWRR Project B-008-GA and

Georgia Tech Project E-600-701, jointly,

covering period June 1, 1966 to June 30, 1967

by

G. G. Eichholz and T. F. Craft

Nuclear Sciences Division, Engineering Experiment Station,

and School of Nuclear Engineering

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GEORGIA INSTITUTE OF TECHNOLOGY

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Table of Contents

List of Tables

List of Figures

Introduction

Rapid sand filtration is a very important process in the purification of water. Through widespread use over many years, the practical aspects of filter operation have been highly refined, but no satisfactory fundamental theory has yet been developed.

Virtually all filter design to date has been based on empirical deduction from observations. The resulting design "recipes" are used interchangeably with little regard for the characteristics of the water to be filtered. This seems to indicate that either the action of the filter is independent of the nature of the influent or that in many cases the filters must have been grossly overdesigned. Until such time as the basic mechanism is more fully understood, any improvements will likely be incremental.

There are a number of variables involved in rapid sand filtration, and they may be placed in one of three general categories: (1) hydraulic factors, (2) physical-chemical parameters of the porous bed, or (3) influent characteristics. Many individual factors have been studied, and the inter-relationships of a number of these have been reported. Although a number of theories have been advanced,[1] it is evident that no single theory so far developed can explain the available experimental data. Without invoking scientific principles yet unknown, it seems likely that a combination of chemical and physical laws are involved, but additional information is required to ascertain the relative importance of the mechanisms so far proposed and to assist in the formulation of a definitive theory.

Little attention has been focused on the distribution of particle sizes deposited at different depths within a filter. Such information appears use-

ful due to the wide range of particle sizes found in natural waters. Eliassen[2] reported some data on particle sizes at different depths in an experimental filter, but he was working with an iron floc which consisted for the most part of particles much larger than the minimum size that a sand filter will remove.

A technique involving radiotracers was used by Stanley[3] in a study of some of the variables of sand filtration. The floc particles employed were passed through an orifice so that reproducible sizes could be obtained. He did not report any actual particle sizes, but he concluded that the size of the particles affects penetration. Other parameters considered included the concentration of iron, pH, ion concentration, sand particle size, and rate of flow. The movement of deposited solids within the sand was also briefly studied. The present work aims to extend the use of radioactive tracers in elucidating these factors. This has been done through the use of labeled particles of various kinds, which were entrained in the water flow through a pilot-scale filter bed.

There are two experimental approaches to the determination of the relation between particle size and the ultimate position of deposit. One might either use a wide range in size of suspended particulates and determine the resulting distribution at different levels, or use a narrow range of particle sizes and measure simply the gross deposit at each level. So far, the second approach has been used in the present project, utilizing various particle size fractions up to 105 μ diameter, but work based on the first approach is also under consideration.

The immediate goal has been to determine the amount of material of a given size that is deposited in the porous medium as a function of bed characteristics, time, and position in the filter. Experimental equipment for

this purpose has been designed, constructed, and evaluated; and considerable data have been collected.

Since this presentation is of the nature of a progress report, many of the tests reported are incomplete. The purpose of this report is to summarize work to date and to serve as a rallying point for projected research.

Description of the Method Employed

A sand filter has been constructed and set up to permit easy variation of flow rates, sampling of the sand at different depths, and collection of influent and effluent samples. As nearly as feasible, the laboratory-scale equipment was designed to simulate utility operations. Under such conditions, any findings may be more directly applicable than would be the case with highly idealized conditions.

The porous media used at first consisted of screened fractions of sand; these will be later replaced with sand of a wider size distribution such as is commonly employed in full-scale operations. It is proposed that Anthrafilt and other media be investigated later; some preliminary work has already been done with the Anthrafilt.

It is planned that the behavior of different types of particles be compared, but the initial series has for the most part been confined to studies of ground vermiculite. This material was chosen primarily because of its relatively high cation exchange capacity. Particle sizes are separated by screening. The major short-coming of the screening process is the contamination of a given fraction with smaller size particles. Wet screening has offered some advantages, but greatest efficiency would be achieved only with the addition of a dispersing agent. The effect of any such agent on the surface properties of the particulates is unknown, but it may affect subsequent behavior in the porous medium. As the number of variables should be kept as small as possible, no dispersant has yet been used.

To study filter performance, particles of known size are labeled with a radioisotope so that the point of deposition of these particles may be determined with a collimated Geiger-Müller tube. Cesium-137 has been chosen for

labeling of the vermiculite particles. This isotope is known to have a high adsorption affinity for most minerals and is frequently used in the determination of ion exchange capacities of various substances. Its use in the present project is quite convenient due to its ready availability and long (30 year) half life. With a half life of this length, the rate of disintegration is essentially constant for the periods of time with which these experiments are concerned; therefore, no decay correction is needed.

Iodine-131 has been found to have little affinity for stream sediments[4] and has been used in experiments where minimum retention on particles or porous medium was desired. The eight-day half life of this isotope is shorter than preferred; but, of the isotopes available, it seemed best suited for this purpose.

Constructional Details of the Equipment

Several filter systems were constructed to provide a means for testing representative filter beds. It was decided to work with filters about one square foot in area with beds of 10-12 inches in depth. Adequate water depth above the bed was found necessary to provide sufficient water pressure to ensure rapid flow through the bed. An adequate supply of wash water was also required. Flow rates comparable to the standard rate of two gallons per square foot per minute had to be handled, and a transparent window seemed desirable for visual observation of the filter bed. These considerations governed the actual design of the filter systems.

The first two systems have been installed in the Dangerous Reactions Laboratory of the Chemical Engineering-Ceramic Engineering Building; the third one, which required a larger water supply, was set up in the Unit Operations Laboratory of the same building, by kind permission of Dr. H. V. Grubb, Director, School of Chemical Engineering.

Three filter systems have been constructed, all in the same general pattern. Details of construction are shown in Fig. 1, and pictures of the completed units are shown in Figs. 2 and 3. Filter No. 1 has an overall height of four feet, while both No. 2 and No. 3 are eight feet tall; in other respects they are identical. Exterior grade 3/4 inch fir plywood was used for the first two; the third was built of marine grade 3/4 inch fir plywood. Brass or cadmium-plated wood screws were used to fasten them together. No. 1 and No. 2 were assembled first and then sealant was applied to the joints. This procedure was not very satisfactory, so on No. 3, butyl rubber caulking was applied to the mating surfaces prior to assembly.

To prevent possible channeling of flow between the sand and the filter

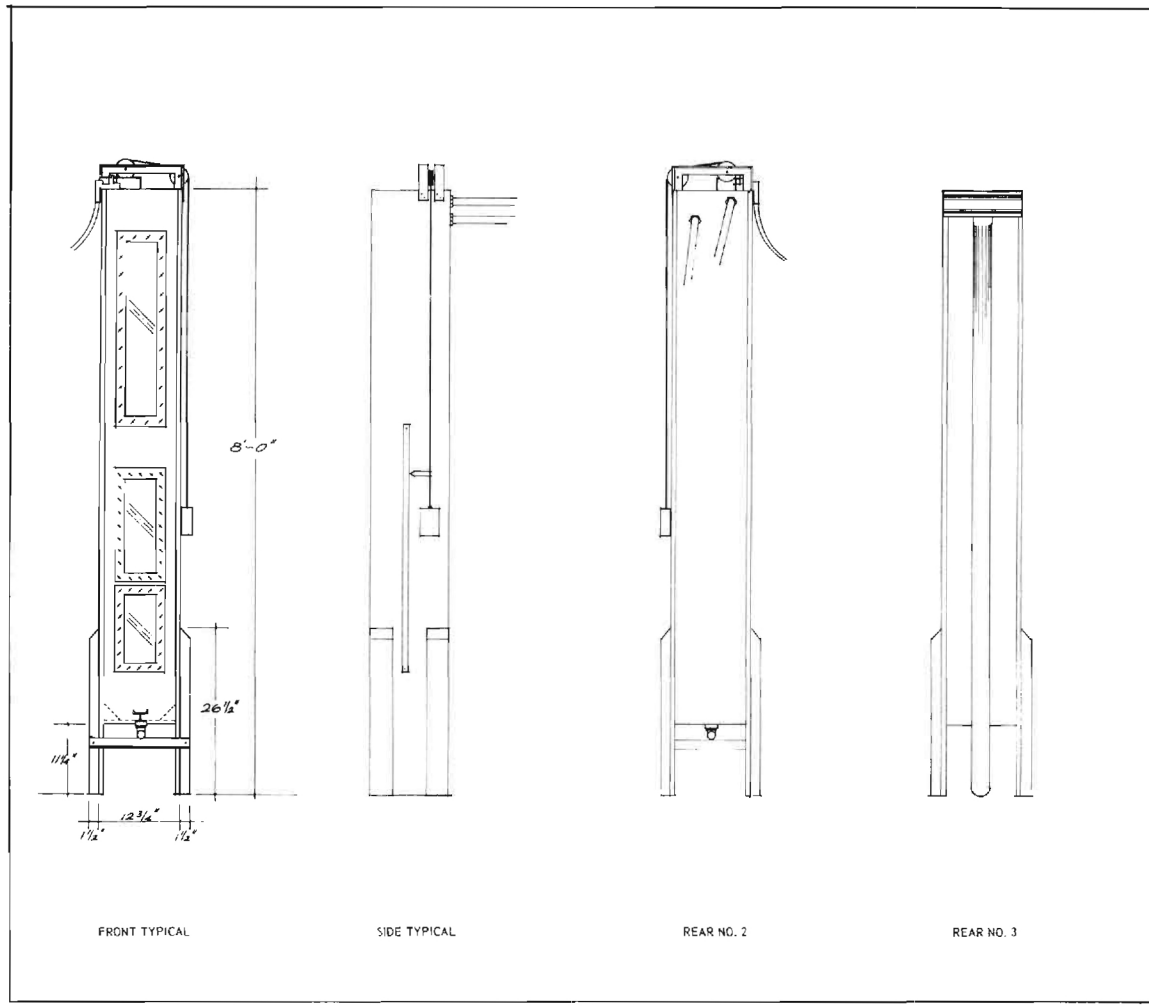

Fig. 1. Details of Filter Construction

Fig. 2. Filter No. 2

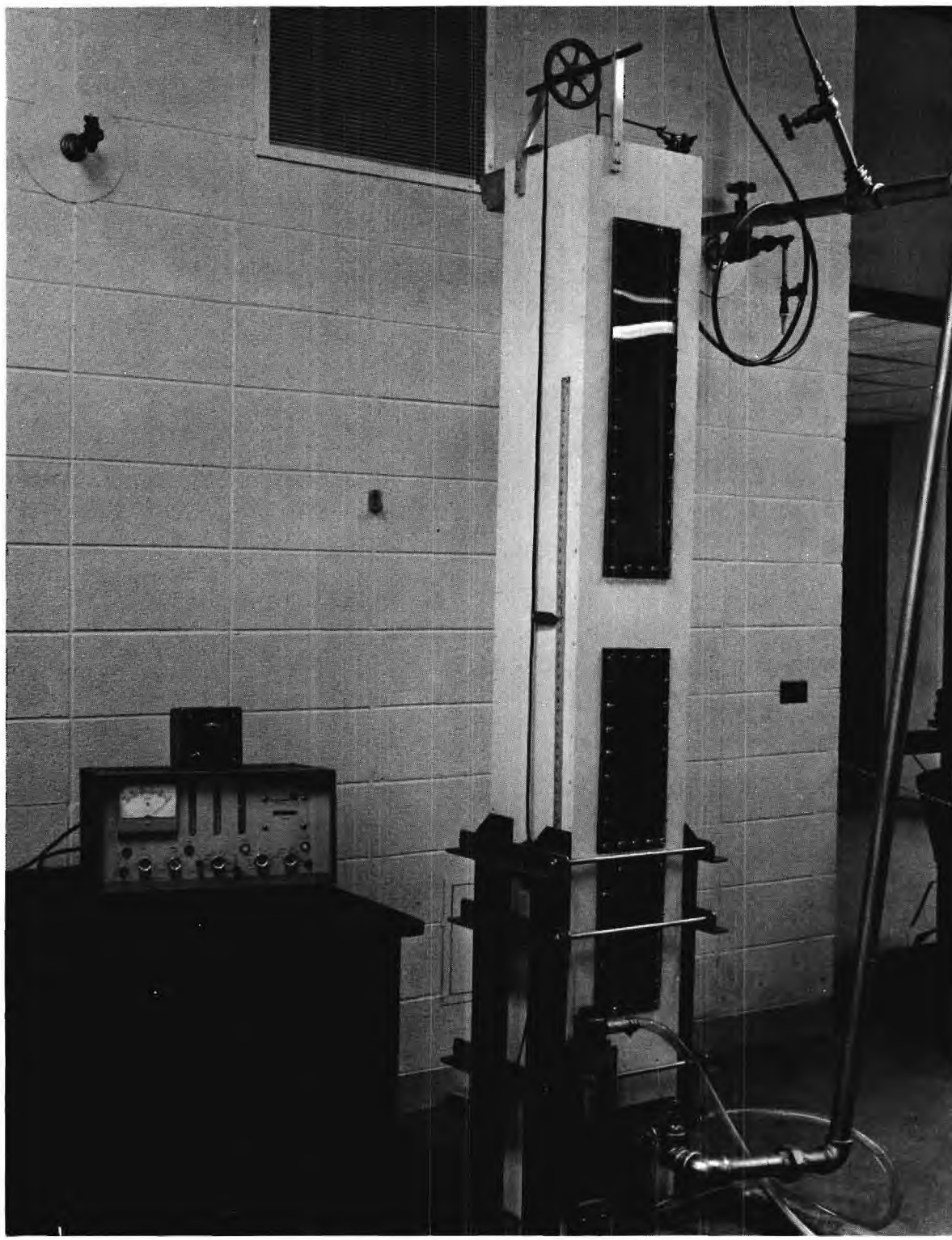

Fig. 3. Filter No. 3

walls, butyl rubber foam, 1/8 inch thick, was used as a lining material and was applied with contact cement. It was also folded over the edges of the observation openings and, with the addition of small pieces for the corners, formed the gaskets for the Plexiglas windows. The cells of the foam rubber are non-interconnecting, and it was thought that this would provide an additional barrier against possible leakage. In spite of this lining, some leakage still occurred. The actual point or points of penetration were never located, but slight leakage was apparent almost from the beginning and was annoyingly difficult to stop, at least in filter No. 1.

Filter No. 2, with its greater depth and consequently greater water pressure at the bottom, presented increased leakage problems. Several different sealing materials were tried, but leakage was not completely stopped until most of the inside of the box had been treated with several liberal applications of melted roofing tar. No leaks have developed in the eight subsequent months of operation. Leakage problems with filter No. 3 were minor, and they were solved by using three heavy angle-iron clamps around the outside, as may be seen in Fig. 3.

The plumbing arrangements provided for water flow inlets and outlets at the top and bottom of the boxes as shown in Fig. 4. For the steady filtration operation, water was introduced through a toilet-type constant level float valve. This type of valve has performed very well, and in spite of occasional fluctuations in the pressure of the water supply, no appreciable changes in flow rate have been observed.

Water outlets at the top of the boxes were necessary for the exit of wash water. In filter No. 1, a single one inch diameter bulkhead fitting was used to penetrate the back wall of the filter near the top. By attaching a short inverted length of tubing inside the box and a long piece on the out-

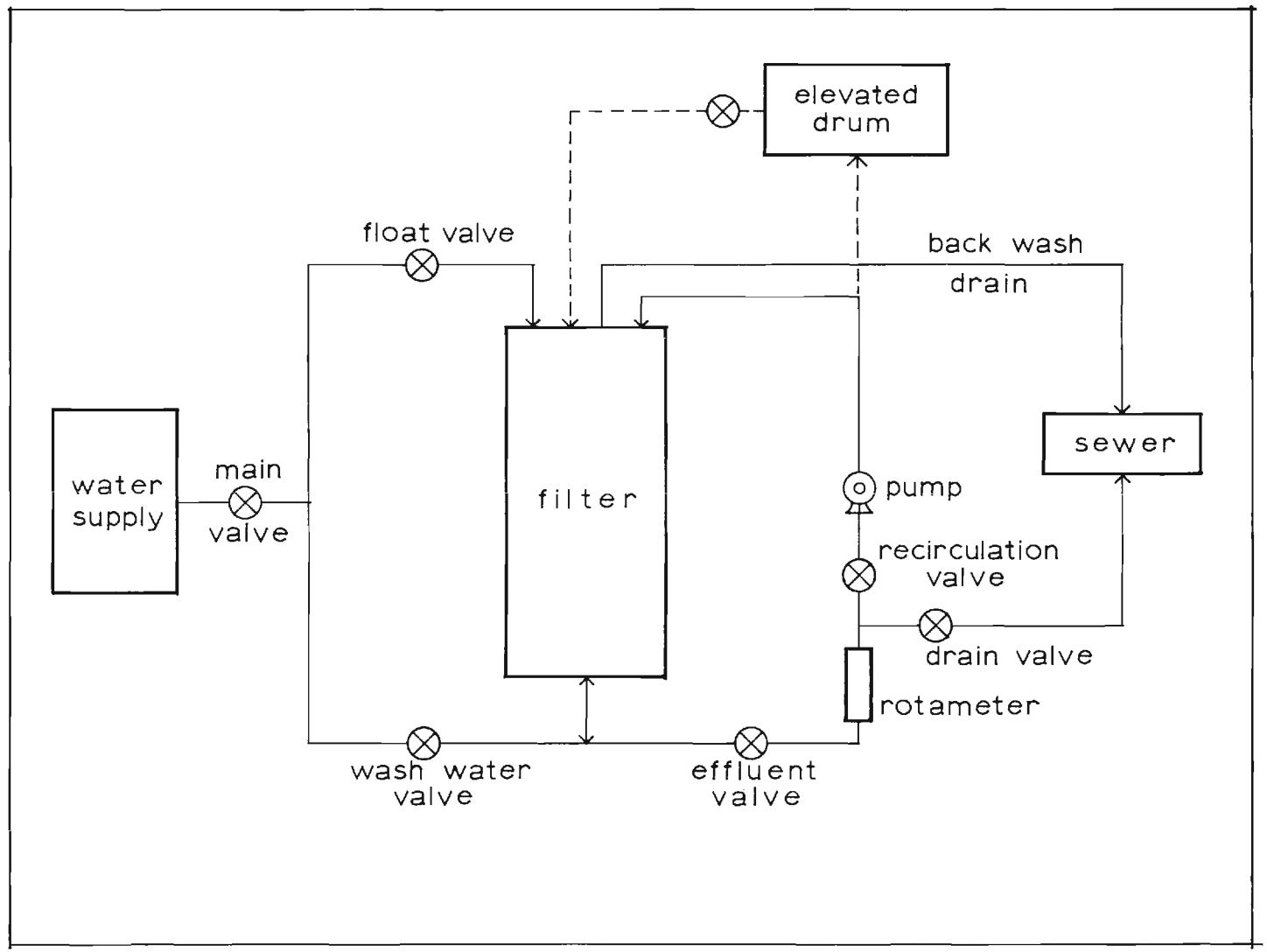

Fig. 4. Schematic Diagram of Apparatus

side, a siphon could be created that was ample for the flow involved, but there was little freeboard left at full flow. In filter No. 2, the wash water was brought to the filter more directly, resulting in a higher possible flow rate. Therefore, two drain openings were provided. These were located at different levels in the filter wall so that the upper might serve as an overflow when the capacity of the lower was exceeded. These were arranged to provide more freeboard than in the first installation. The wash water from both of these filters was drained into a laboratory sink.

Number 3 was designed with a greatly increased flow in mind, and the upper outlet consisted of a short section of galvanized gutter attached to the box. Both the box and the adjacent side of the gutter were notched out and provide what is actually an overflow weir. The gutter is emptied through a 3 inch galvanized downspout which conducts the flow into a subfloor level drainage channel.

In all filters, a single opening in the center of the bottom serves both as the effluent exit during filtration and the wash water entrance during the backwash cycle. To prevent pieces of the bed support from entering this opening, the end was protected with either a heavy metal mesh (filter No. 2) or by heavy brass wires crossed over the opening (Nos. 1 and 3). The filter effluent was normally directed into a floor-level drain, but a pump, valves, and an elevated 55 gallon galvanized drum were installed to provide recirculation and/or retention as desired, especially for radioactive fluids.

The rate of filtration was controlled by the effluent valve and measured by use of a glass tube rotameter. The instrument used on No. 2 had a range of 0.5 to 3.5 gpm, while the one for No. 3 was graduated from 0.5 to 5.5 gpm. These rotameters were checked by volumetric measurement of the flow passing through in a definite period of time. While extreme precision was not at-

tempted, all measured volumes were in agreement with the indicated markings.

Immediately following completion of filter No. 1, it was packed with 40-60 mesh sand and put into operation for a preliminary evaluation of its performance. It was noticed that, after running for an hour or more at a flow rate of two gallons per square foot per minute, air bubbles began to form in and on the sand. This effect became very pronounced during prolonged runs and was probably due to the combination of high head loss across the bed and low total head above the sand. Such a condition is known as "air binding" and is occasionally encountered in commercial filters. Attempts to alter the hydraulic situation were not successful, so filter No. 2 was built much deeper to provide more head above the sand. Later, experimentation involving the shallow filter with an Anthrafilt bed of considerably larger particle size, showed a similar tendency to air binding, and no further runs with filter No. 1 are contemplated at present.

Experimental Details

a. Bed Characteristics

The sand support arrangement was essentially the same in all cases. An initial trial was made using several progressively smaller sizes of granite gravel in accordance with commercial practice, but the large pieces required in the first layer were so irregular that pronounced channeling of flow occurred during backwash. This condition likely exists in full-scale filters, but such local variations are of no consequence there when the total area of the filter is considered. In a laboratory-scale filter, this irregularity was considered intolerable, so this arrangement was changed.

Porcelain spheres of graduated size were not readily available; through the cooperation of the School of Ceramic Engineering, a high-fire porcelain body was prepared, formed by hand into spheres of appropriate size, and fired under suitable conditions. Three sizes of spheres were produced with nominal diameters of 1-1/4, 1, and 3/4 inches.

These spheres were packed into the bottom of the filter in layers, beginning with the largest size. These were covered with a layer of 5/8 inch diameter glass toy marbles. Quartz pebbles were ground in a roller mill and screened into three fractions, which were placed over the layer of marbles; the sand was then placed on the layer of smallest size. This configuration has been found to be very satisfactory and stable during repeated filtrations.

The sand used as the filtration medium in the first series of experiments was a white, small-grained silica sand, supplied by the Pennsylvania Glass Company, Columbia, South Carolina. The sieve analysis of the material as received is shown in Fig. 5. This was carefully screened on standard Tyler screens and the -40 + 60 mesh fraction retained.

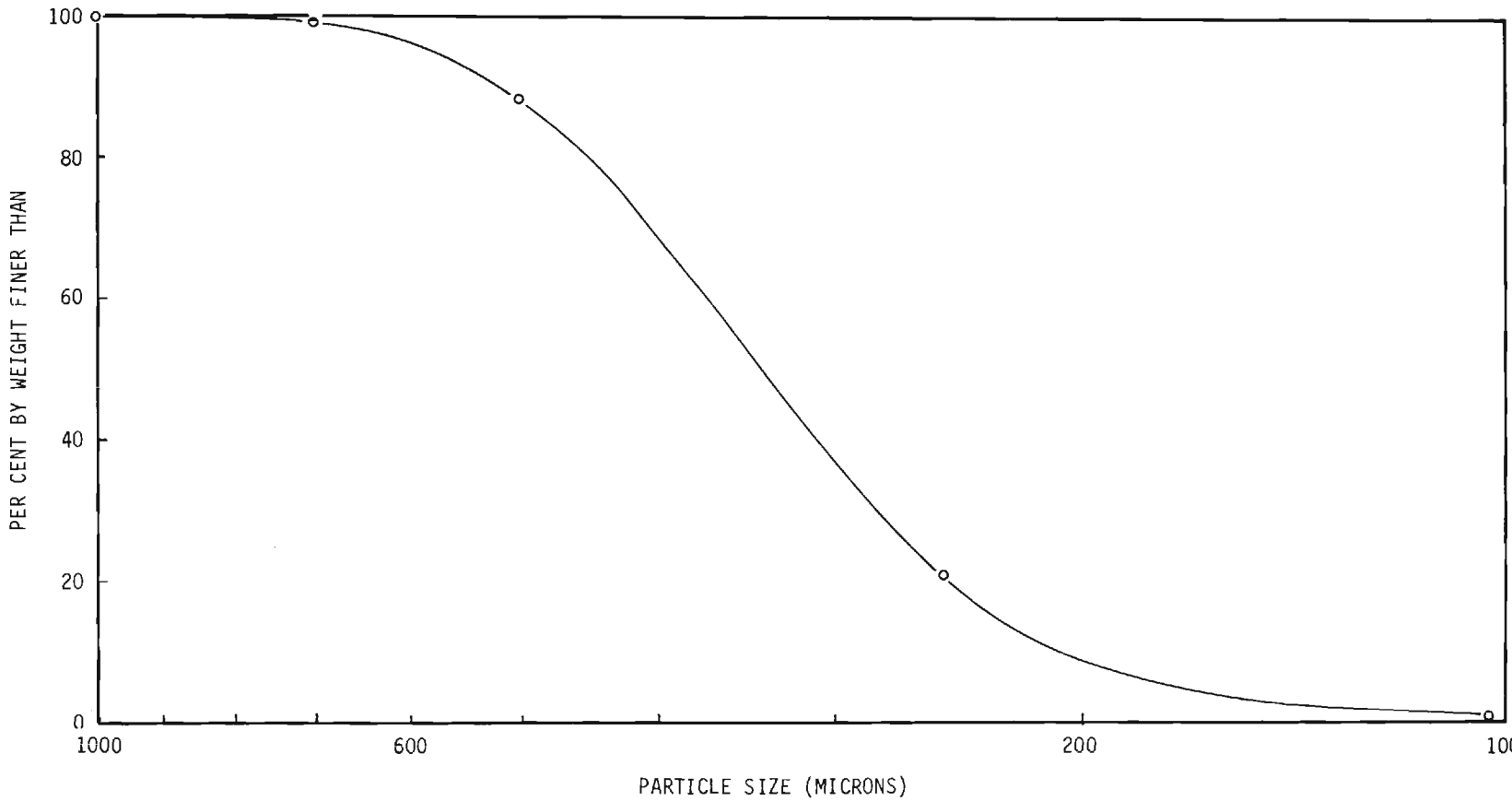

Fig. 5. Particle Size Distribution of South Carolina Sand

For purposes of calculation, it was assumed that the sand bed consisted of spheres 250 microns in diameter. Such spheres in a close packed arrangement would allow passage of particles with a maximum diameter of 38 microns. This is not a very precise approximation due to the angularity of the particles and the range of sizes present. The effective pore diameter is probably smaller, even though the measured porosity of the bed was found to be about 45%, as compared to a theoretical value of about 25% for close packed spheres.

The second series of experiments will involve -20 + 30 mesh sand. As little material of this size is present in the South Carolina sand, other material was obtained. The Atlanta Water Works supplied sand that had previously been used in a rapid sand filter at the Hemphill Treatment Plant. The exact history of this sand is not known, but it was initially put into water filtration service in 1926. It continued in use until either 1941 or 1948, at which time it was removed to make room for surface wash equipment. Since removal, it had been stored on the ground beneath the sand filters. A sieve analysis of this sand was made and the resulting curve is shown in Fig. 6. The -20 + 30 mesh fraction of this material was removed by hand screening and will be used as the initial medium in filter No. 3.

Calculated on the same basis as above, the -20 + 30 mesh sand should allow passage of particles about 91 microns in diameter.

The water supply enters the laboratory through a 3/4 inch pipe which furnished an adequate volume for backwashing of the -40 + 60 mesh sand; it was used for the first two filters and was sufficient to produce a 100% expansion of the sand bed. Even at maximum flow, the support gravel remained undisturbed.

This water supply was inadequate to properly backwash larger bed materials, so the third filter was installed in another location with ready

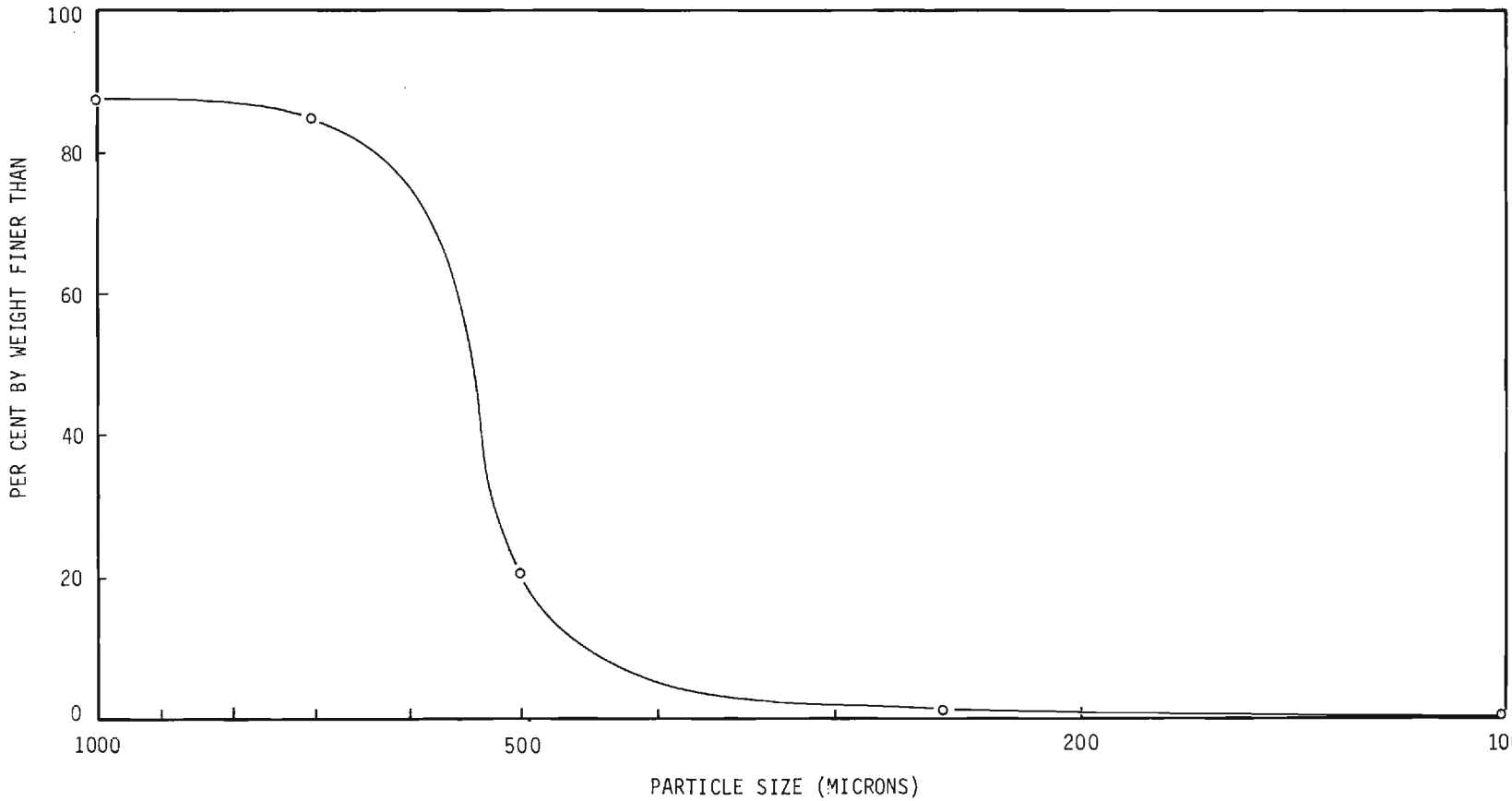

Fig. 6. Particle Size Distribution of Atlanta Water Works Sand

access to a 1-1/4 inch copper line about 3 feet long, feeding from a 4-1/2 inch cast iron conduit. Even with the head losses brought about by several 90° bends and an additional 15 feet of connecting pipe, this supply appears more than adequate. Care is necessary during backwash operations to avoid disturbing the bed support material. Flow of wash water through this box is currently limited only by the configuration of the drain, and, if ever desirable, the drain capacity could be increased considerably with only minor modifications.

Most efficient washing of sand is reported to occur at a bed expansion of about 60%. Under such conditions, the sand grains are in rapid random motion and particulate matter trapped by the filter is flushed out. The cleansing of the sand is greatly facilitated by the contact of the grains with each other. This is apparently a mechanical action and simply involves knocking or scraping off any adhering particles. The amount of water used for backwash is an important variable in commercial water filtration, but is of little concern for our purposes; backwash periods of 20 to 30 minutes were normally used. In a few cases, where more effective cleansing of the bed material was desirable, a dilute hydrochloric acid solution was circulated.

At the conclusion of backwash, the sand settles into a metastable configuration of greater depth than will exist after filtration has proceeded for a time. Therefore, in order to have a fixed, reproducible compaction of sand, the regular procedure involved striking the outside of the filter box with a rubber mallet as the sand was settling. This rapidly produced a more stable configuration that did not change even during prolonged filtration runs. The sand was returned each time to the same indicated position on the counter level scale, so that the degree of compaction was considered constant during the entire period of operation.

b. Turbidity Measurements

Turbidity measurement was considered as an auxiliary means of monitoring filter action, and a series of experiments was performed to determine the feasibility of this method. The Hellige turbidimeter is a standard instrument for turbidity measurement in the laboratories of water production plants, and its use was investigated in detail. The instrument consists essentially of an optical comparison system through which the operator visually determines the relative brightness of two zones in the field of observation. The results obtained are determined to a large degree by the skill, judgment, and experience of the operator.

These experiments utilized an air-floated kaolin, "Pioneer," supplied by Georgia Kaolin Company, Elizabeth, N. J. A typical analysis of this clay as reported by the producer is given in Table I.

Table I. Typical Analysis of Pioneer Clays

Free moisture	1.01%	Titanium dioxide	1.54%
Combined water	13.38	Calcium oxide	0.25
Silicon dioxide (combined)	45.34	Magnesium oxide	0.22
Aluminum oxide	37.29	Sodium oxide	0.35
Iron oxide	0.61	Potassium oxide	0.10

Typical particle size distribution:

Equivalent spherical diameter

cumulative percent	under 10	microns	86%
	5	"	73%
	2	"	54%
	1	"	38%
	0.5	"	22%
	0.2	"	6%

A particle size distribution determination was made of the clay actually utilized in these experiments and was found to coincide almost exactly with the values reported by the supplier. The distribution is shown in Fig. 7.

A slurry was prepared by rapidly stirring Pioneer clay into tap water. Portions of this slurry were added to the filter in varying amounts and at different rates. Subsequently, the effluent was sampled repeatedly and the turbidity of the samples measured. The rate and amount of slurry added were varied in different experiments, and different flow rates through the filter were investigated. When appreciable turbidity was present, readings could be made without difficulty in a consistent, reproducible manner, with little difference between operators. The situation was less satisfactory at turbidities below a few parts per million, and small changes became impossible to detect reliably.

There was poor correlation between the experimental variables and the measured effluent turbidity, particularly at the low levels which are of primary concern at this time. The desired measurements are, therefore, considered to be beyond the capability of this instrument, and its use will be reserved for possible later operations that involve higher turbidity levels.

c. Radiation Detectors

In order to follow the movement of the radioactive tracer, two sets of radiation detection equipment have been used. For measurements involving solid and liquid samples removed from the filter, a two-inch NaI (Tl) well-crystal scintillator was used in conjunction with a Nuclear Chicago Model 186 scaler. Plastic vials were used to hold the samples, and, in cases where liquids were involved, the outside of the vials was carefully washed and dried to avoid possible contamination of the detector.

The second type of measurement involved observation of the movement of

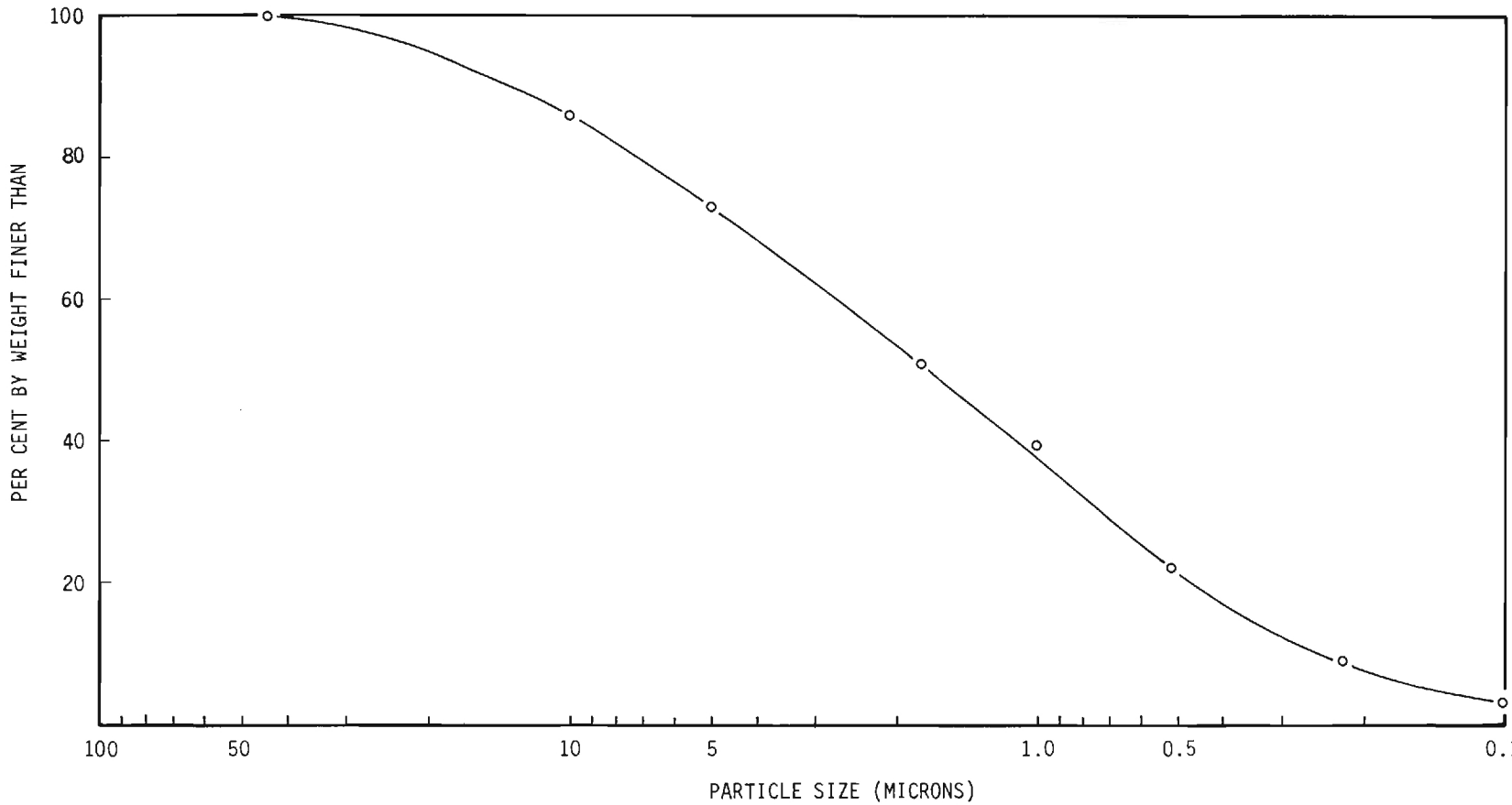

Fig. 7. Particle Size Distribution of Pioneer Clay

radioactively labeled particles inside the filter. A shielded Geiger-Müller tube (Victoreen Thyrode type 1B85) connected to a second Nuclear Chicago Model 186 or 8775 scaler was used for this purpose. The shielded tube was suspended inside a plastic pipe which extended from the filter bed support to a point three inches above the top of the filter box. In filter No. 2, the layout of the plumbing necessitated that the pipe be located slightly off center. In No. 3, the detector guide pipe was centered in the box.

The first shield was fabricated from sheet lead and was suspended from the coaxial cable. The second shield was made much thicker to provide better horizontal collimation. It was machined from a solid piece of lead and was much heavier than the first due to the increase in wall thickness. A separate wire rope was used to carry the weight of this shield. Dimensions of these shields are shown in Fig. 8. In both cases, the support cable was passed over one or two pulleys and counterbalanced by a suitable weight on the outside of the filter (see Fig. 1). A metal pointer was attached to the cable, and a scale was placed on the side of the filter. With this arrangement, the vertical position of the shield could be easily determined and changed at will.

A portable survey instrument was also available for surveillance of the general area and for determination of the environmental level of activity near the radioisotopes used for particle labeling. The quantity of radioisotope required depended on the sensitivity of the detector tube as collimated, and hence primarily on the G-M tube shield that was to be used. The thicker shield required about 48 μC of Cs-137 or I-131 to produce a count rate high enough for satisfactory statistics with counting periods of one minute duration at the beginning of a run. As the indicated activity diminished, longer counting periods (2-5 minutes) were used. When the thinner

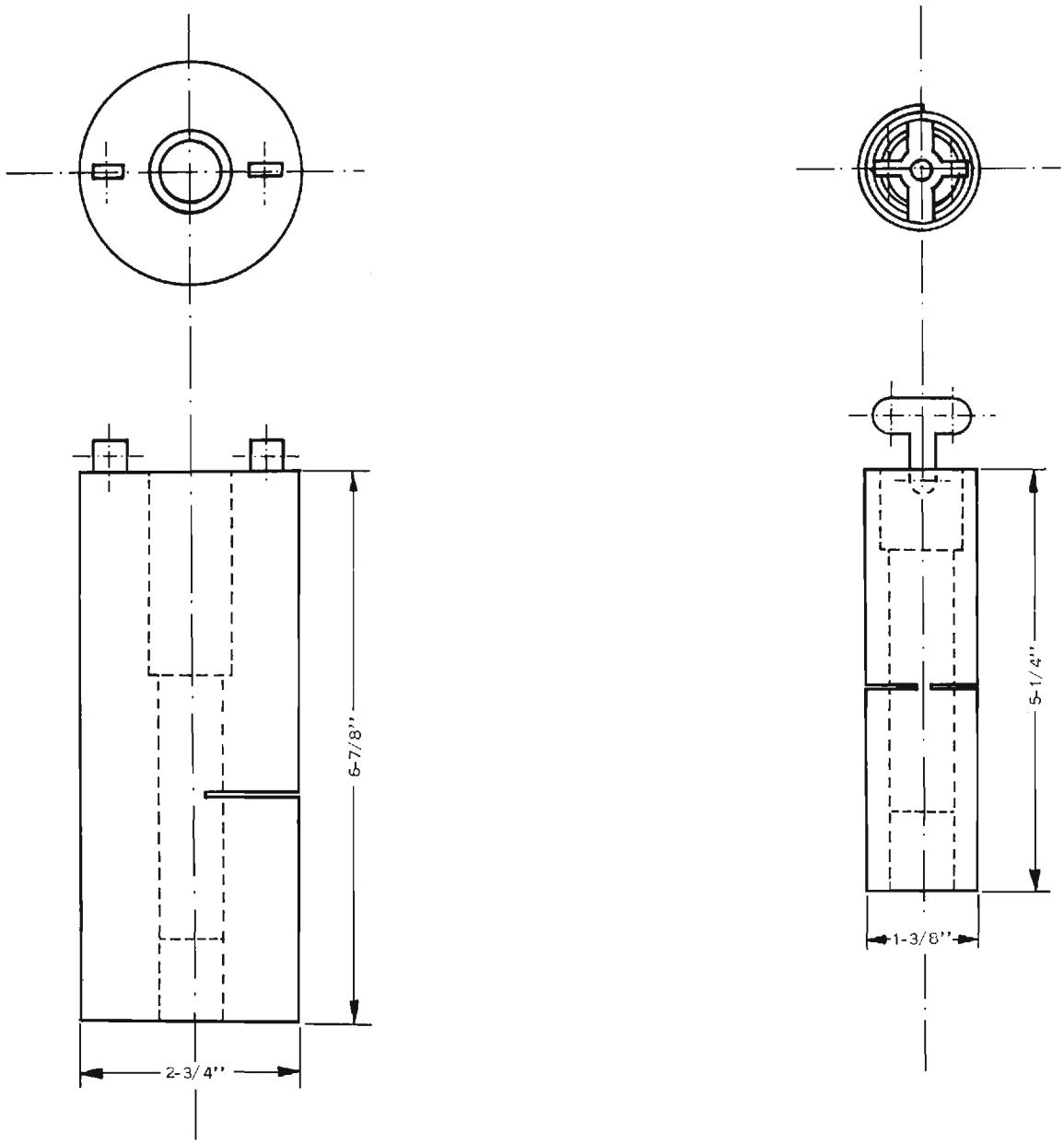

Fig. 8. Lead Shields

shield was used, comparable statistics could be obtained with about 10 μC of activity.

d. Test Materials

The particulate material used in most of the experiments was vermiculite. The first runs involved vermiculite from Transvaal, South Africa, but lack of a sufficient quantity for extended experimentation and the doubtful supply situation prompted a change to a more readily available material.

The Zonolite Division, W. R. Grace & Co., Atlanta, Georgia, subsequently furnished a generous quantity of a domestic material. This was designated as crude vermiculite, ore grade #3, and was mined at Kearney, South Carolina. As received, it consisted of flakes about 2-4 mm in diameter, plus an appreciable amount of fines. The first step in preparation for use consisted of washing it thoroughly under the tap and then on a sieve to remove extraneous dirt and most of the fines. After drying at 100°C, it was reduced by ball milling. To prevent an excessive portion from being ground too finely, it was necessary to mill only a few minutes and then screen out the smaller particles, returning the larger particles for further milling.

The ground vermiculite was then dry screened, to separate it into the desired size ranges. The dry screening process does not produce a very sharply defined particle size range. Examination under a microscope showed that each fraction contained a large number of particles smaller than the desired size. At this stage, a given fraction would consist largely of the indicated screen size when considered on a weight basis, but would contain a greater number of smaller sized particles. Wet screening improved the situation considerably, but it was difficult to remove the smaller particles from the surface of the larger effectively. The addition of a dispersing agent would assist the de-agglomeration process, but since the effect of the added

surfactant on the filtration process was not known, this procedure was ruled out.

The best procedure devised to date consists of stirring the particles rapidly in tap water, allowing them to stand for a few minutes, and decanting most of the water. After several repetitions of this procedure, the stirring is discontinued and dispersion in an ultrasonic bath is substituted. Many repetitions are necessary to produce a sample that will settle rapidly out of the liquid leaving the water unclouded.

Pioneer clay was used in a number of experiments where a wide range of particle sizes was desired. (See Fig. 7 for particle size distribution.) Another material with a wide size range was the fraction of the ground vermiculite that had passed through a 325 mesh screen. This material is referred to as "micron" vermiculite and has a particle size distribution as shown in Fig. 9.

The particles were labeled with a radioisotope tracer by the following procedure. Five grams of the particles are weighed into a beaker and stirred with a few hundred ml of tap water. The radioisotope tracer solution is pipetted into this slurry. This is stirred for an hour or more, allowed to settle for a few minutes, and the liquid poured off. The particles are then washed several times with tap water and finally dispersed in a little water for ease in transferring into the filter. When the micron vermiculite is used, sorption is very high, and the washing procedure is omitted.

e. Test Procedure

Preliminary experiments were performed to determine qualitatively the behavior of the filter and associated equipment, and to find the best experimental techniques. A 100 ml sample of Chattahoochee River water with a measured turbidity of 2500 A.P.H.A. turbidity units was treated with Cs-137

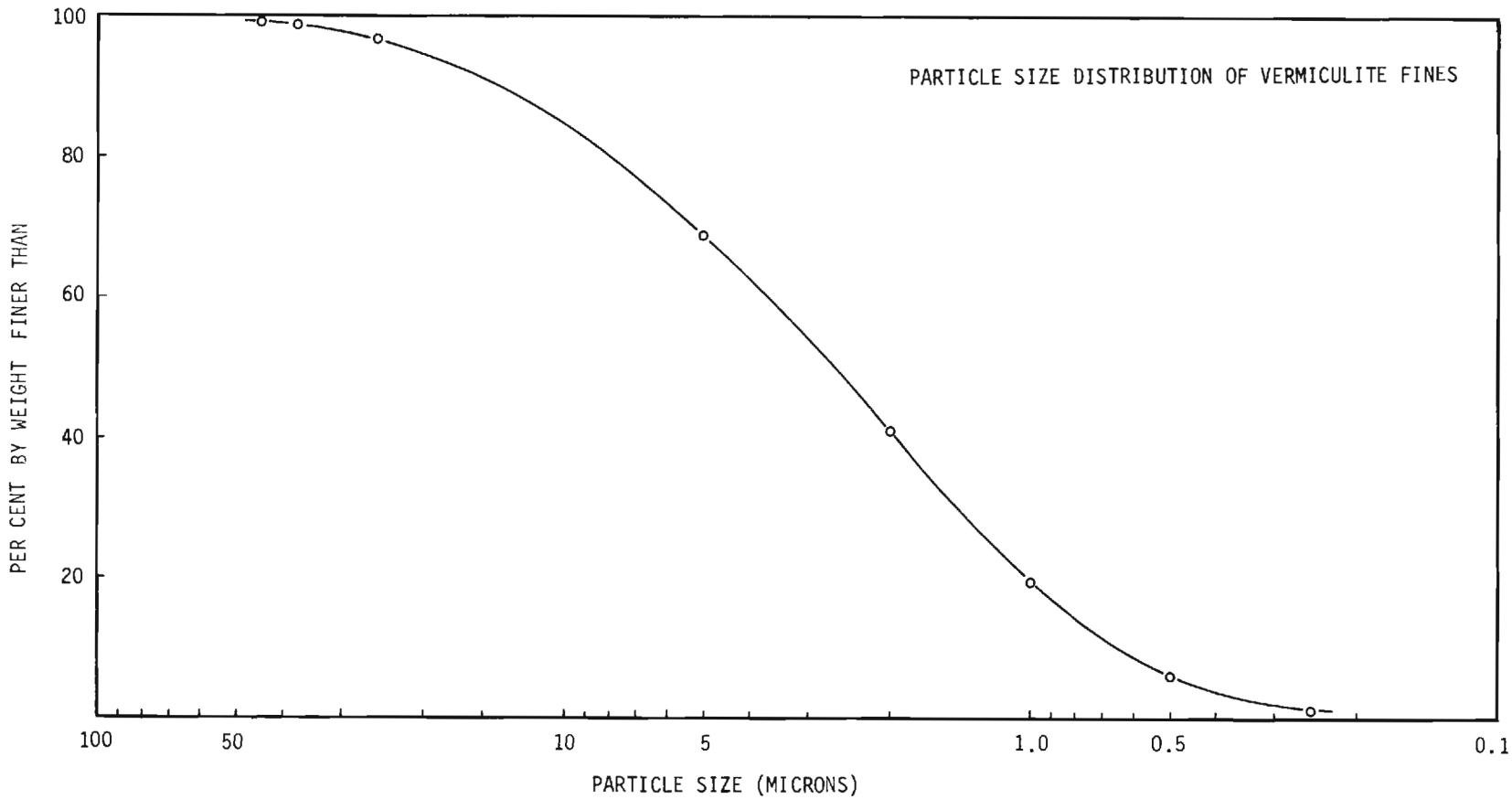

Fig. 9. Particle Size Distribution of Micron Vermiculite

solution. The mixture was stirred to allow equilibration, and the majority of the cesium remaining in solution was removed by centrifuging, decanting, and redispersing in tap water with an ultrasonic generator. After several repetitions of this washing cycle, the sediment was dispersed in about 200 ml of water and added to the filter system through which tap water was flowing at the rate of two gallons per square foot per minute.

The effluent was sampled at frequent intervals, and the activity was measured with the scintillation detector. Only the sample taken at fifteen minutes following addition was found to be above background, although the low total amount of activity and the high dilution may well have obscured other possibilities.

The filter was then drained and the sand was cored with a metal tube. Samples representing each inch of filter depth were dried, thoroughly mixed, and counted on the well crystal. The results were as follows:

1st inch	562 net cpm
2nd inch	58 net cpm
3rd inch	47 net cpm

A more detailed examination of the vertical pattern of activity distribution within the sand was made through the use of more Chattahoochee River sediment labeled with Cs-137. The labeled material was put into the filter, filtration continued for 1-1/2 hours, the filter drained, and sand samples removed from several locations. The samples from each quarter-inch depth were combined, dried, mixed, and counted. The entire procedure was then repeated, carrying the sampling procedure to a depth of two inches. The plotted results gave an essentially exponential curve shown in Fig. 10, which is characteristic of removals reported in the literature.[3,5,6]

These results are in agreement with the well-known effect that in a

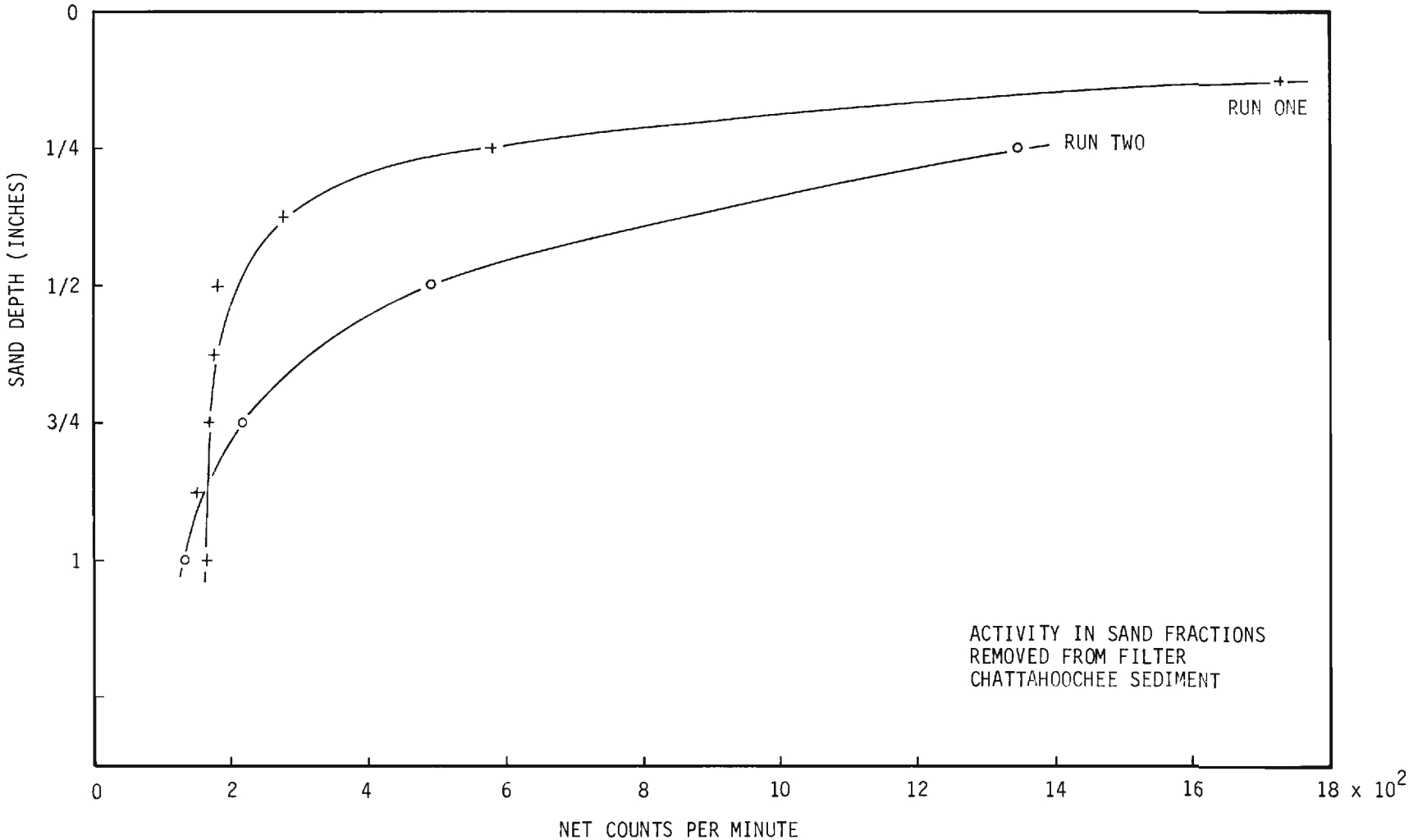

Fig. 10. Activity Distribution in 40-60 Mesh Sand

clean filter bed most of the removal of particles occurs in the top layers. The presence of activity in the effluent suggests some soluble activity remains with the particles and passes rapidly through the filter.

The uniformity of activity deposition across the filter was ascertained by removing sand samples at fourteen different points. In the one inch surface layer, there was more variation than desirable, with five counts outside the 95% confidence level, but this is to be attributed more to inadequacies in the sampling technique and the low specific activity involved rather than actual variations. The consistency of the results was found to be similar in the lower levels, and there was no obvious correlation between results at different depths for a given point. Later experiments have involved higher activity levels, with correspondingly better statistics.

This method of activity determination, by removing and counting sand samples, is a means of obtaining definite values for a certain level by eliminating the influence of any activity in the contiguous layers. This method does require a great deal of time as the flow has to be stopped and the filter drained before the samples can be obtained. The most serious drawback is that there is no means for recommencing filtration, so each run must be terminated by the sampling procedure.

To avoid some of these difficulties, a different technique was devised. This consisted of measuring the horizontal activity of a given bed layer by means of a moveable shielded Geiger tube. The tube was shielded with lead and a narrow slit was made near the center of the sensitive portion of the tube. With this arrangement, activity can be measured without disturbing the sand or the flow conditions.

The standard procedure that evolved is as follows:

1. Backwash filter 20-30 minutes.

2. Compact sand by striking box.

3. Begin filtration and adjust flow rate.

4. Measure radiation background at various levels in the bed and in the water above the bed.

5. Start timer and simultaneously pour labeled particles into filter.

6. Stop flow and timer simultaneously, and determine count rate at various levels. [Alternately, make measurements with flow and timer continuing.]

7. Recommence flow for next time interval.

f. Counter Geometry

In comparing count rates at different levels, it is necessary that geometrical correction factors be included to offset the effect of varying self-absorption and contribution from neighboring layers and the discontinuity existing at the water-sand interface, for all distances from the interface, for the establishment of effective counter geometries.

These correction factors were determined in two separate experiments utilizing different isotopes. In the first experiment, the detector inside its plastic guide tube was lowered into a uniformly mixed solution of cesium-137. Readings were taken at numerous levels below the liquid surface and in the air above it. This resulted in a calibration with reference to the air-liquid interface.

Iodine-131 was used in the second experiment as it had been found to contaminate the sand to a lesser degree than dissolved cesium-137. The sand bed was filled with iodine-131 solution which was recirculated for a prolonged period in order to assure uniform dispersion of activity throughout the entire bed. The liquid level was then adjusted to coincide with the surface of the sand, and a series of readings above and below the sand surface was taken. The sand was then carefully covered with water containing no added

radioactive material, and the measurements repeated.

The results of these experiments are shown in Fig. 11. If any mixing occurred at the interface during the iodine-131 experiment, it may be considered negligible, as the agreement between runs was quite good. It should be noted that the count rate in the water was lower than in the air due to the greater attenuation of the radiation by the water. The actual correction factors calculated from these data are listed in Table II.

Table II. Geometrical Count Correction Factors
1B85 Geiger Tube

Level	Interface		
Inches below sand surface	Air - Cs-137 solution[+]	Water - I-131 solution[*]	Air - I-131 solution[*]
0	2.70	2.69	1.97
1	1.69	1.75	1.44
2	1.29	1.35	1.08
3	1.17	1.16	1.06
4	1.08	1.00	1.00
5	1.03	1.00	1.00

[+]With original lead shield

[*]With heavier lead shield

g. Anthracite Filter Medium

A common assumption concerning filter behavior is its dependence on the granular particles comprising the porous medium. Size, density, packing arrangement, and porosity are no doubt all involved, but the chemical and physical characteristics of the surface of the particles seem to be of great-

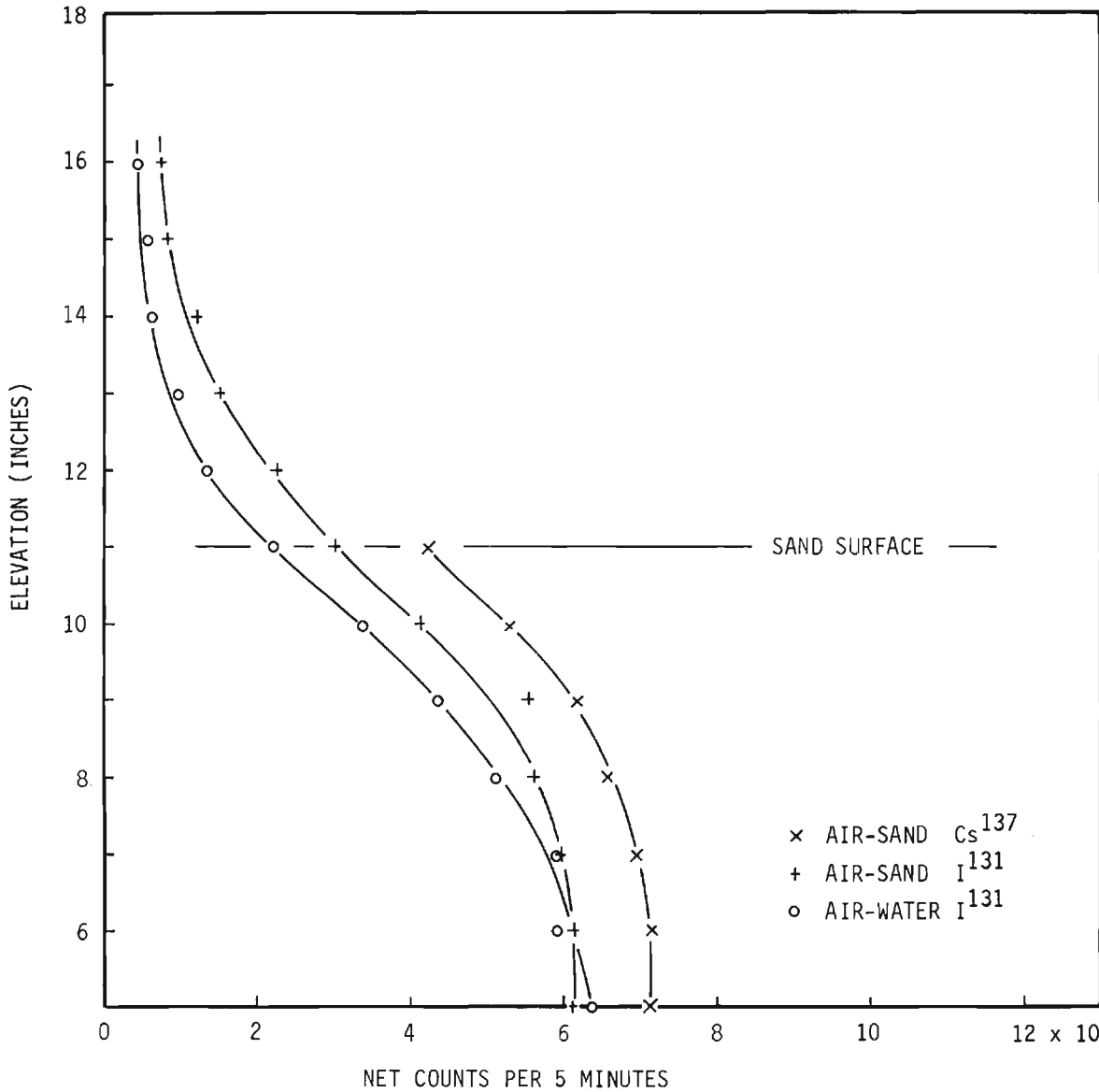

Fig. 11. Geometrical Correction Factor Calibrations

est importance.[7] Without two different materials of the same size and shape characteristics, it is difficult to ascertain quantitatively the effect of these parameters. It seemed advisable, therefore, to study the behavior when a medium other than sand was used.

In commercial operations, the second most frequently used granular material is anthracite.[8] The particle sizes normally utilized are larger than sand particles, but at present the differences in effectiveness between sand and anthracite seem largely subjective. It was, therefore, decided that a filter bed of anthracite would be studied.

The Palmer Filter Equipment Company supplied samples of their anthracite filter medium trade-marked "Anthrafilt." It is prepared from a Pennsylvania anthracite selected and cleaned to have a minimum ash content. It is then screened and classified hydraulically to yield sizes appropriate for filtration.

The smallest size Anthrafilt available is designated "No. 1" and has an effective size of 0.60-0.80 mm and a uniformity coefficient of 1.75. As this is considerably larger than the sand initially used, it was ground and screened to produce a 40-60 mesh fraction, which is the same as the sand used in the initial series of experiments.

Carbon is widely used as an adsorbent in many processes, and before risking severe contamination of an appreciable amount of the screened product, small portions were used to determine the effects that might be encountered.

After stirring a small amount of Anthrafilt with a thin slurry of Cs-137 labeled particles, it was found that a considerable amount of activity appeared on the Anthrafilt and could not be removed by washing. This situation led to an evaluation of the use of I-131 instead of Cs-137 for labeling particles. Information on the relative absorption of I-131 and Cs-137 on an-

thracite was developed during these preliminary tests concerning the feasibility of using Anthrafilt as a filter medium.

A 1.5 gram sample of 88-105 μ vermiculite was stirred for two hours with Cs-137 solution, and another sample was treated in the same manner with I-131 solution. In each case, the particulate matter was then washed repeatedly by stirring with tap water and decanting.

The particles were stirred 30 minutes with 10 grams of washed Anthrafilt #1 in about 500 ml of water. The mixture was then allowed to stand approximately 70 hours. A sample of the supernatant was removed, the Anthrafilt washed free of visible vermiculite particles, and 5 ml portions of both the supernatant and the Anthrafilt were counted.

Table III. Isotope Sorption by Anthrafilt

Sample	Cs-137	I-131
Final wash water	565	157
Supernatant	6,050	5,946
Anthrafilt	267,427	16,412

Under the conditions of this experiment, the activities of the wash waters were very similar, and the final count rates of the supernatants were essentially identical. Under equilibrium conditions, however, the Anthrafilt had sorbed almost 17 times more Cs-137 activity than I-131 activity. Actual values are shown above in Table III.

In another experiment, the affinity of the Anthrafilt for the I-131 was quantitatively determined. A 40 gram sample of washed Anthrafilt #1 was put into a beaker containing about 500 ml of water. Iodine-131 was added, the

mixture stirred for an hour and allowed to stand overnight. The supernatant was decanted and the activity of a sample of the Anthrafilt was determined with the well crystal counter. The Anthrafilt was then washed by vigorous stirring with tap water, allowing it to stand several minutes, and decanting the supernatant. The activity of the Anthrafilt was measured several times, and the results are shown in Table IV.

Table IV. Activity of Anthrafilt Exposed to I-131 (counts per min)

Before Addition of I-131	135
After addition of I-131	3,508
After 4 wash cycles	1,830
After 7 wash cycles	1,189
After 10 wash cycles	606

It has been found nearly impossible to remove Cs-137 activity from Anthrafilt to any appreciable degree; the figures in Table IV show that I-131 can be removed, albeit with many washings. This observation is important as contamination of the bed by the radioisotope tracer needs to be minimized as much as practical. It is concluded that I-131 is, therefore, the preferable tracer for particles to be filtered in Anthrafilt beds, so that if contamination does occur, it will not be necessary to discard the entire bed.

In view of these findings, there is doubt as to whether the activity that eventually appears on the granular material results from soluble ions present all along with the labeled particles or comes from the accumulation of ions originally held but subsequently released by the labeled particles. Regardless of the mechanism, for a meaningful evaluation, the tracer must not be transferred to the granular bed particles.

Experimental Results

Many data have been collected showing the activity in the filter as a function of time and position under different conditions. The major variables so far have been flow rate and size of the suspended particles. As indicated previously, the labeled particles of specified size were added to the filter and the count rate at various levels determined subsequently. A flow rate of two gallons per square foot per minute was chosen to coincide with the most frequently quoted rate of filtration in commercial operations. An arbitrary choice was made of a rate half this value for purposes of comparison.

The number of levels within the filter at which observations of activity were made was varied, depending on the requirements of the particular experiment. The usual number was nine, with one of them four inches above the surface of the bed, one at the bed surface, and the balance at various levels within the bed. It generally required slightly in excess of ten minutes to make a series of nine observations. During the early stages of a run, the activity change was quite rapid, and values were needed for accumulated flow time of 5, 10, 20, 30, 45, 60, 90, and 120 minutes. It was, therefore, necessary to stop the flow at the designated time, make the series of observations, and then recommence the flow. After an accumulated flow time of more than two hours, the rate of change was quite low, and flow was continued while observations were made.

The periods of flow interruption were kept as short as possible, to minimize settling of the particles without simultaneous flow. The inverse relationship of size and settling rate made the settling effect completely negligible when the smallest particle size material was used. With larger particles, the effect is obviously present to a greater extent; however, in

one instance with 53-62 μ particles, where flow was stopped for 45 minutes, only a small effect was observable at the sand surface, and none at a depth of three inches.

The possibility of increasing the activity by adding more of the radioisotope was considered, but the possible increase in statistical precision was concomitant with neither the (slight) radiological health problems that would be encountered nor the unavoidable increase in background. An alternative would have been to place a detector at each level so that simultaneous readings could be made, but the costs and complexities involved put this out of the question. It is quite doubtful that any increase in precision is necessary in view of the other experimental uncertainties that are present.

a. Flow Conditions in Supernatant

The pattern of movement within the supernatant water can be observed quite readily when particulate matter is added. The hydrodynamic force of the influent causes considerable turbulence and a portion of the particulates is forced downward rapidly and in random fashion. Visual inspection indicates that plug flow does not occur, and the persistence of inhomogeneous distribution of the particles throughout the water reveals a lack of complete mixing. A partial-mix flow model, therefore, most likely describes the observed conditions prevailing in the water above the surface of the bed.

b. Time Dependence of Retention

The experimental results have been analyzed in several ways, one of which shows the relationship between accumulated flow time and total activity in the filter bed. The integrated net activity at a given time was calculated by subtracting the background count from the observed count at each level, multiplying the result by the geometrical correction factor corresponding to the level under consideration, and summing the answers for all levels; typical results are shown in Fig. 12.

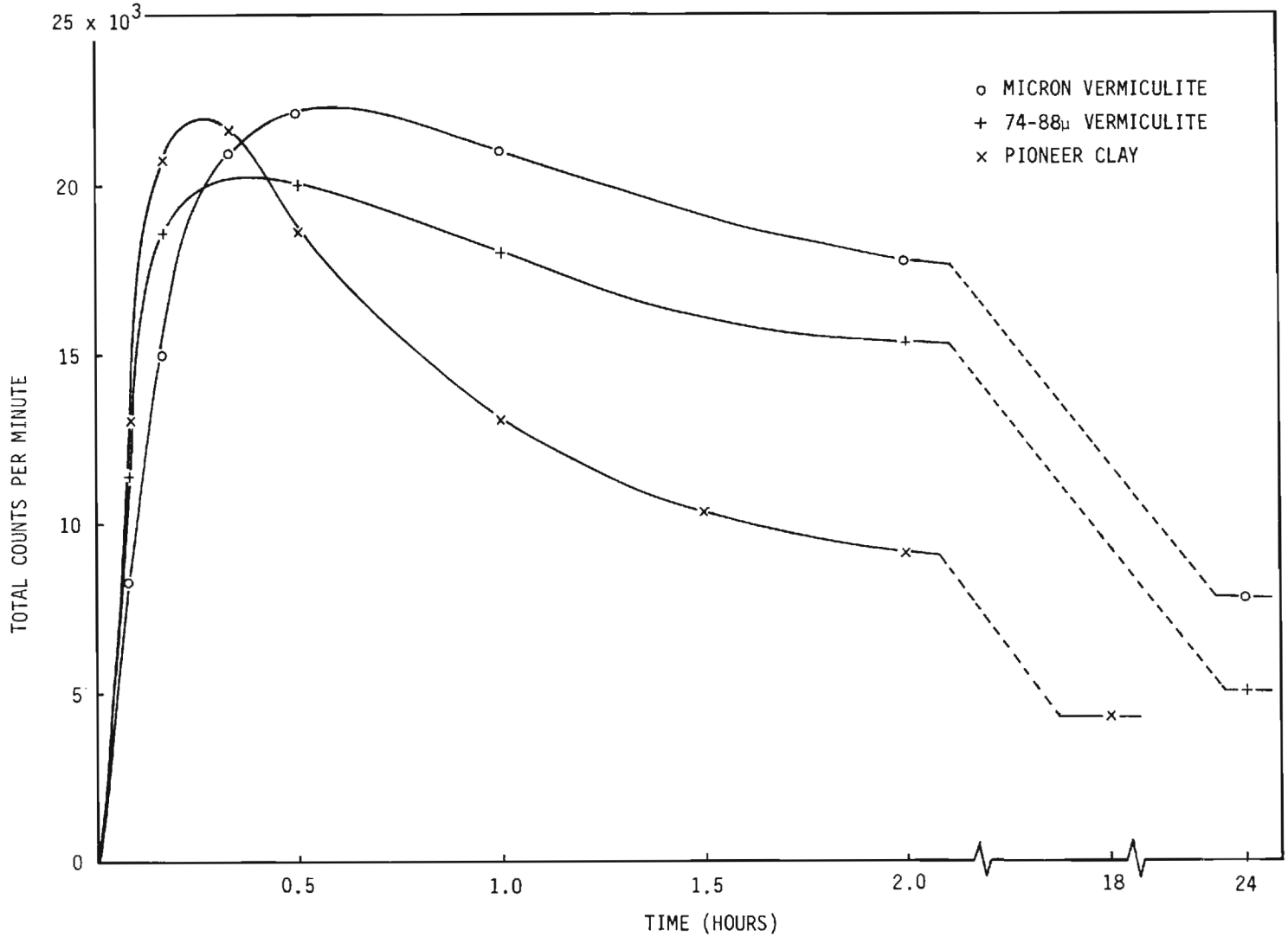

Fig. 12. Relationship of Total Activity to Filtration Time

There was appreciable variation in the details from different runs, but the general features were quite similar. During the early part of a run, the activity increased at a very rapid rate until a peak was reached. Decrease in activity then followed at a much lower rate. The initial rapid increase is probably due to a combination of two effects--the settling of particles through the water, and the net downward motion of the water.

The shape of the peak and the time of its attainment exhibited considerable variation. The time intervals between measurements were large enough to leave some doubt as to the precise time at which the maximum activity was attained, but this is probably of secondary importance and, in any event, the relative values may be considered reliable. Experimental results are summarized in Table V. In two instances shown in this table, the time of maximum activity was not well defined. In one case the total was the same at 20 and 30 minutes; in the other, totals at 30 and 120 minutes were identical.

The shape of the observed peak appears to be a function of flow rate and particle size; high flows and larger particles generally produce an earlier, more sharply defined peak. No quantitative correlation between flow rate and time of maximum was obvious; the type of variation encountered is exemplified by Fig. 13. Later experimentation resulted in more clearly separated particle size fractions which produced very sharp peaks particularly at diameters above 63 μ. The broader peaks seem to indicate a wider range of particle size, so data of this type make possible a crude evaluation of the degree of size separation that has been achieved.

It was found that the time of the highest single point occurred 20 minutes or more after the addition of the particles, with 30 minutes the most frequent. The time was as long as 120 minutes in two cases, both of which were observed during runs at the lower flow rate. The estimate of the time of maximum ac-

Table V. Time of Maximum Total Activity in 40-60 Mesh Sand

Particle size range (μ)	Time of highest single point (min)	Estimated time of maximum (min)	Nominal flow gpm/ft^2
74-88	30	28	2.0
62-74	120	120	1.0
53-62	30	---*	2.0
53-62	60	55	1.0
44-53	20=30	27	2.0
44-53	30	30	1.0
< 37	30	37	1.0
< 37	90	90	1.0
< 37†	30=120	75	1.0
< 37†	60	60	1.0
clay	20	15	2.0
clay	30	27	2.0
clay	30	30	1.0
clay	30	30	1.0
dissolved	15	15	2.0

*No 20 min reading taken; not possible to make any meaningful estimate.

†Heavier shield.

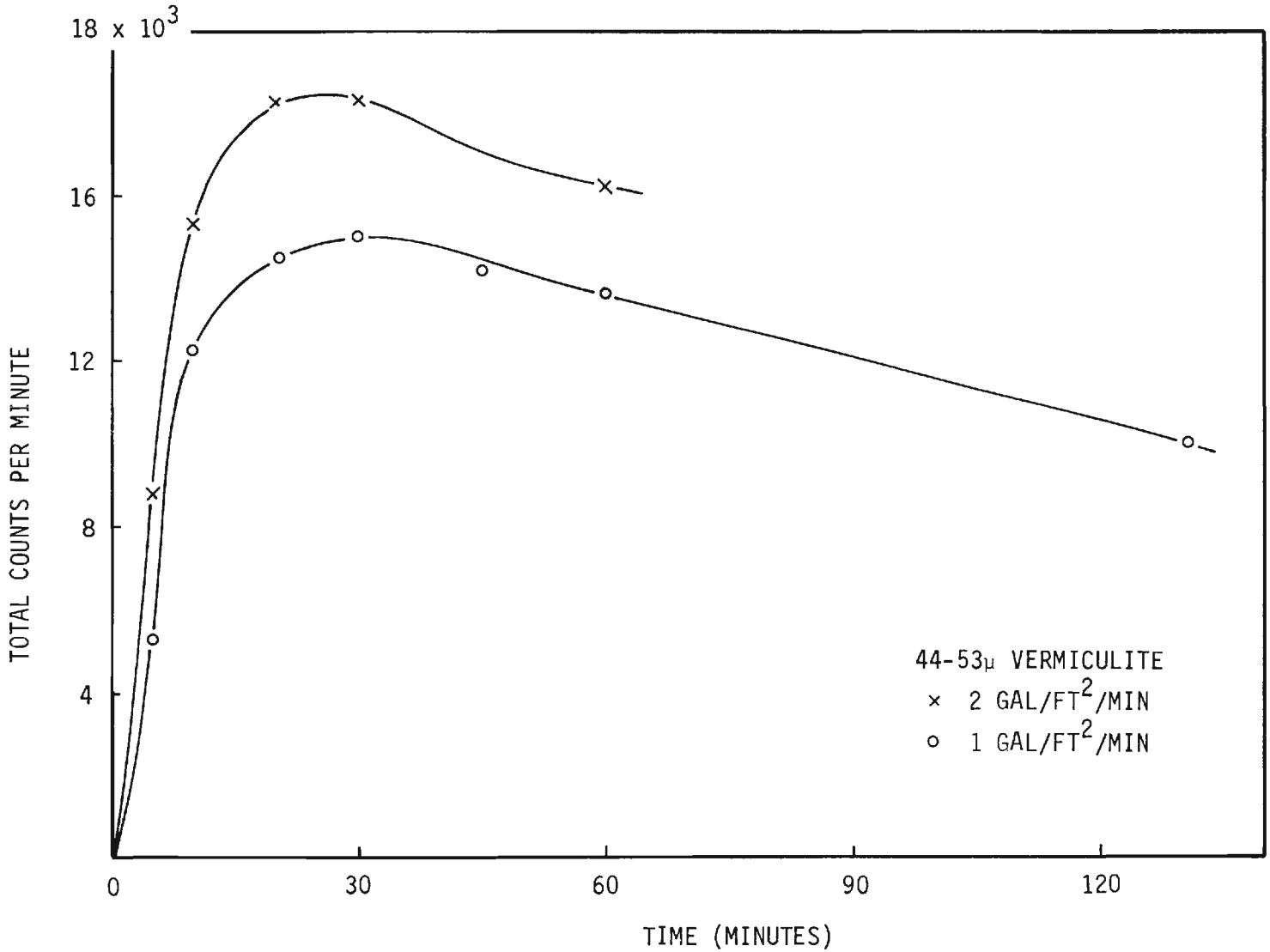

Fig. 13. Relationship of Total Activity to Filtration Time: 44-53 μ Vermiculite

tivity usually fell within the range of 27 to 60 minutes.

In one experiment, Cs-137 was stirred into a small amount of water and added directly to the supernatant; no particulate matter was added. The behavior of this dissolved activity was not vastly different from that of particulate matter, as is evident from Fig. 14. Maximum activity occurred at fifteen minutes; the peak was sharp, the decline of activity rapid, and there was no prolonged retention typical of particles. No readings were taken between 110 minutes and 18 hours, but at 18 hours the activity was essentially at the background level and at the 24 hour observation was indistinguishable from background.

The shape of the slope of decreasing activity seems to follow an exponential curve for a time after the peak is reached; the decrease thereafter is at a very slow rate. This effect may be explained on the basis of passage of some particulate matter and/or dissolved activity through the filter followed by a very slow removal of Cs-137 tracer from the retained labeled particles by the water flowing through the filter. The presence of soluble activity in the effluent was determined by use of an ion exchange resin, which was heat-sealed in a large tea bag and placed in the drain outlet.

A quantitative arrangement to collect all soluble activity was not attempted, but after a few hours of flow an appreciable count was observed on the resin by means of the scintillation detector. Under the prevailing conditions, there appeared to be little possibility that this was due to particulate matter, but the resin was nevertheless thoroughly washed prior to counting so as to avoid any ambiguity in the interpretation.

There is other evidence to suggest that a very mobile slug of activity passes through the filter at the same rate as the water. Fig. 15 relates activity to time at various levels within the sand. As in the case of the total

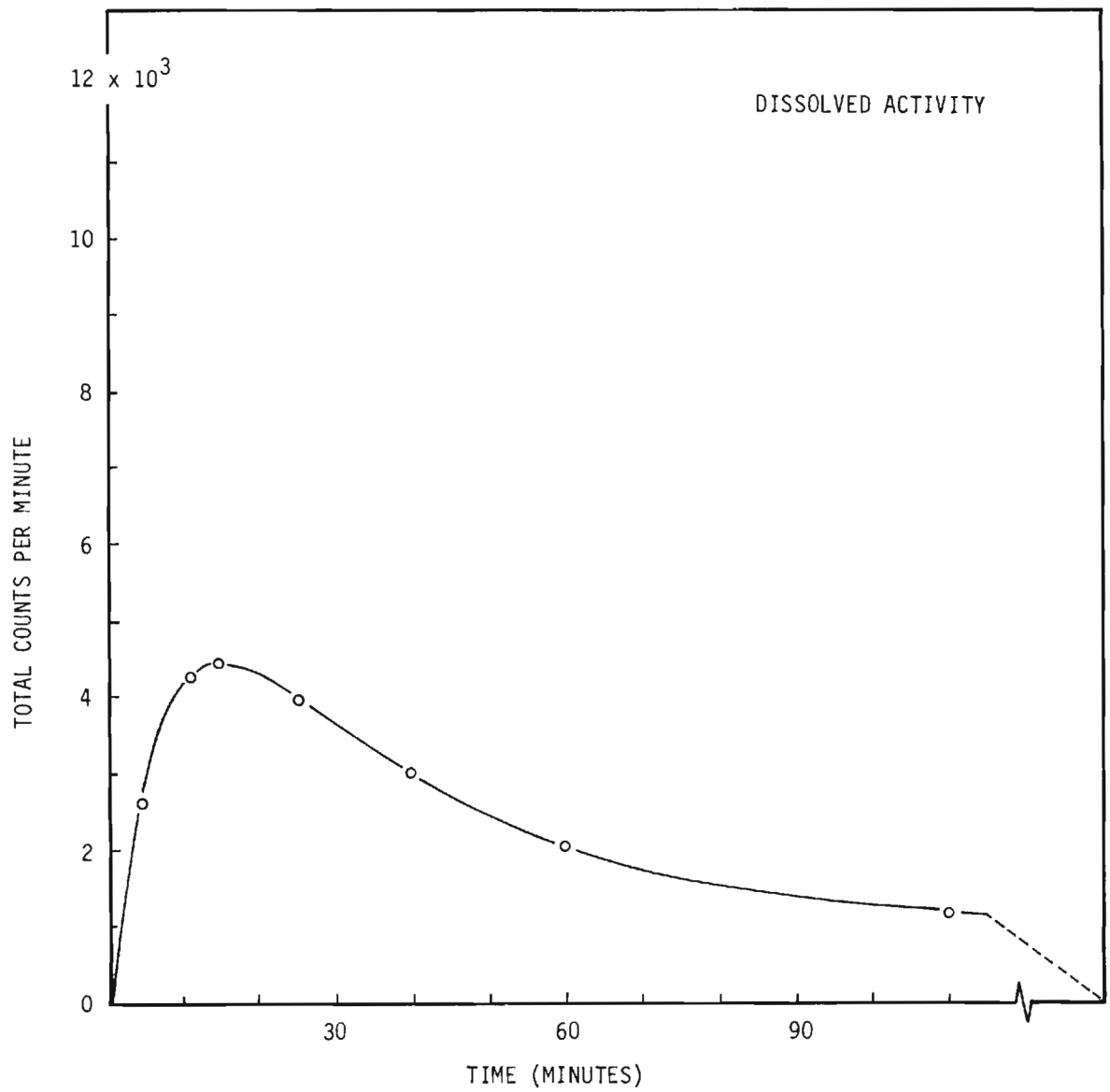

Fig. 14. Variation of Dissolved Activity with Filtration Time

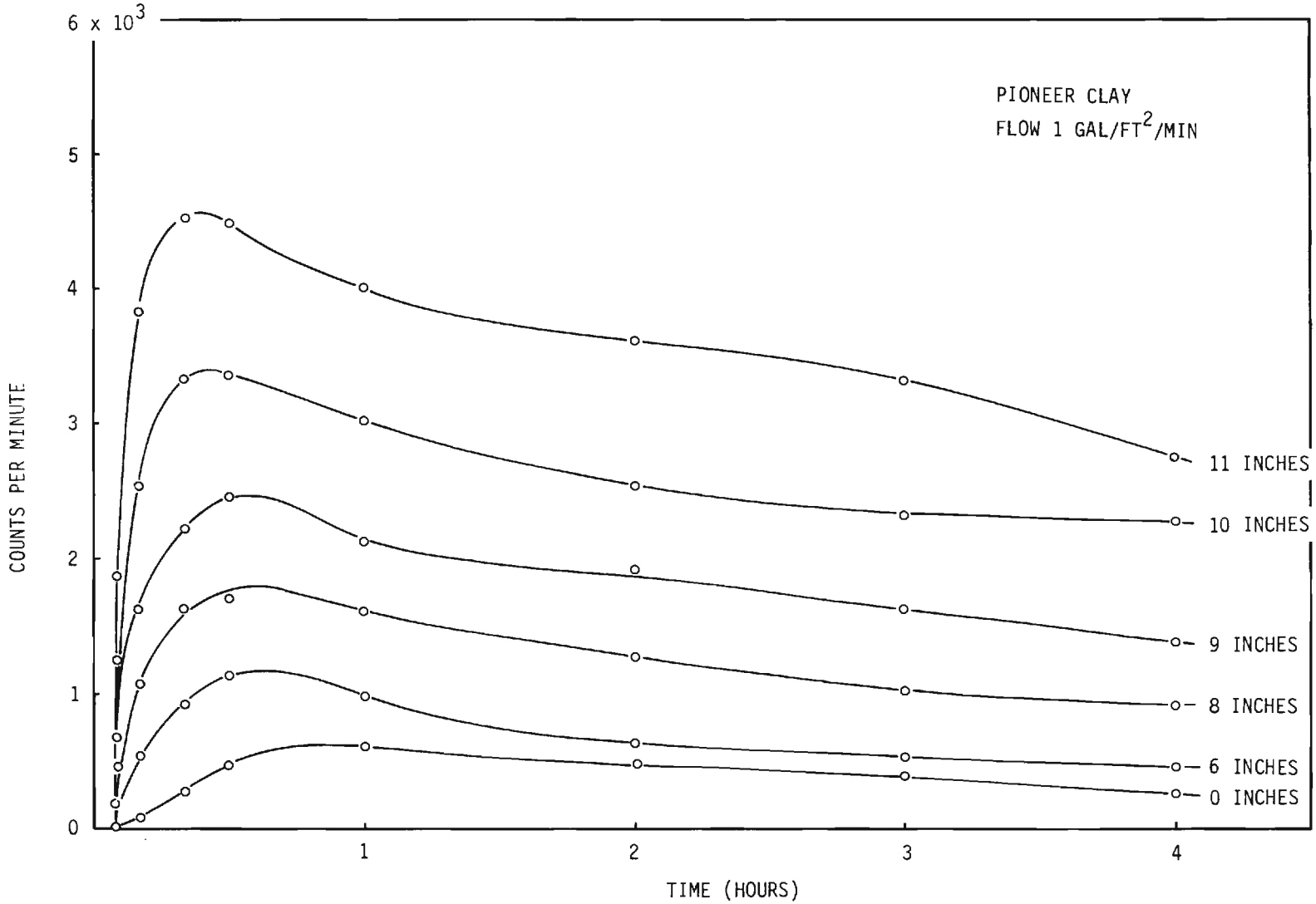

Fig. 15. Time-Activity Relationship at Various Levels in Sand

activity calculations, these data were calculated for net counts, corrected for geometry. It may readily be seen that the time of maximum activity varies with the depth of the layer under consideration. The maximum is reached first at the sand surface, and progressively later at the greater depths.

Once a layer of supernatant liquid has entered the interstices of the bed, it is not subject to the turbulent mixing conditions existing in the water above the bed. A given layer may, therefore, maintain some degree of identity in passing through the bed. The successive peaking at each layer might, therefore, result simply from a slug of soluble activity, perhaps accompanied by particulates, moving through without great vertical dilution. This explanation becomes even more logical when the rate of movement is considered. Using a porosity value of 45% and the conversion factor of 7.48 gallons per cubic foot, the calculated velocity of water through the bed is 0.3 inch per minute at an overflow rate of one gallon per square foot. From Fig. 15, the peak is seen to move eleven inches in about 35 minutes, which agrees quite well with the calculated transit time of 37 minutes.

Later experiments were performed using labeled vermiculite samples that had been subjected to a more rigorous size separation procedure. Most of these tests were carried out with the larger size ranges in order to accentuate any differences.

A sample of 74-88 μ vermiculite was washed by stirring vigorously in tap water, allowing the slurry to stand a few moments, and decanting the supernatant. After repeating this procedure several times, the particles settled very rapidly leaving the water unclouded. A run using this material produced a maximum at 12 minutes as compared to 27-28 minutes reported in Table II.

Ultrasound was later used in the particle washing procedure and this

shortened the preparation time considerably. It appears that more material is lost when ultrasound is used, but this is probably due to de-agglomeration of masses resistant to stirring. One run using 88-105 μ material prepared by this method was found to produce maximum total activity in the filter at 10 minutes. Qualitatively, an early maximum was to be expected due to the large particle sizes and freedom from smaller, more slowly moving bits.

A comparison of results between no washing and ultrasound washing is displayed in Fig. 16. It should be noted that the higher flow rate was used with the washed material. This, of course, would tend to produce an earlier maximum, but would not explain the shift from 50 to 10 minutes. Experiments such as this emphasized the desirability of using particulates with very narrow size ranges, and more attention will be devoted to this in the future.

c. Depth Distribution of Activity

The second major type of analysis consisted of plotting net counts corrected for geometry as a function of position in the sand. This approach furnishes a more realistic view of the pattern of deposition at various intervals. A typical series of curves is shown in Fig. 17. It may be seen that maximum activity is recorded at the surface of the sand with progressively less activity at the lower levels.

As would be expected from the graphs already presented, activity at a given level builds up to a maximum and then decreases. The curves representing different times exhibit the same general shape throughout a run, although their position with respect to the ordinate changes. This change is a function of the amount of radiotracer present and suggests that the pattern of penetration is determined quite early, and subsequent events transpire uniformly within the sand. An alternative explanation is possible, however. The same pattern might result from a single thin layer of activity on the

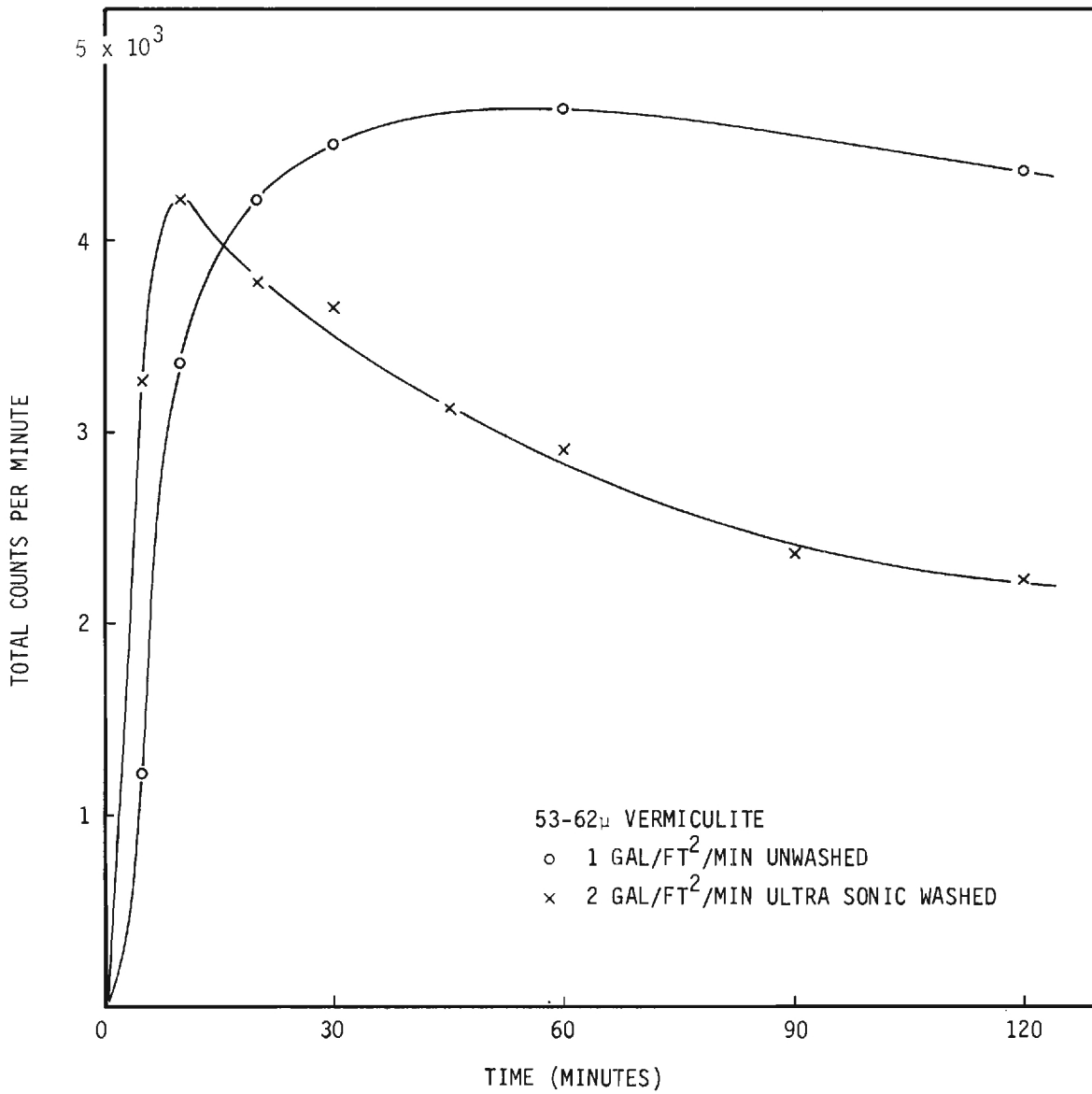

Fig. 16. Comparison of Unwashed and Ultrasonically Washed Vermiculite

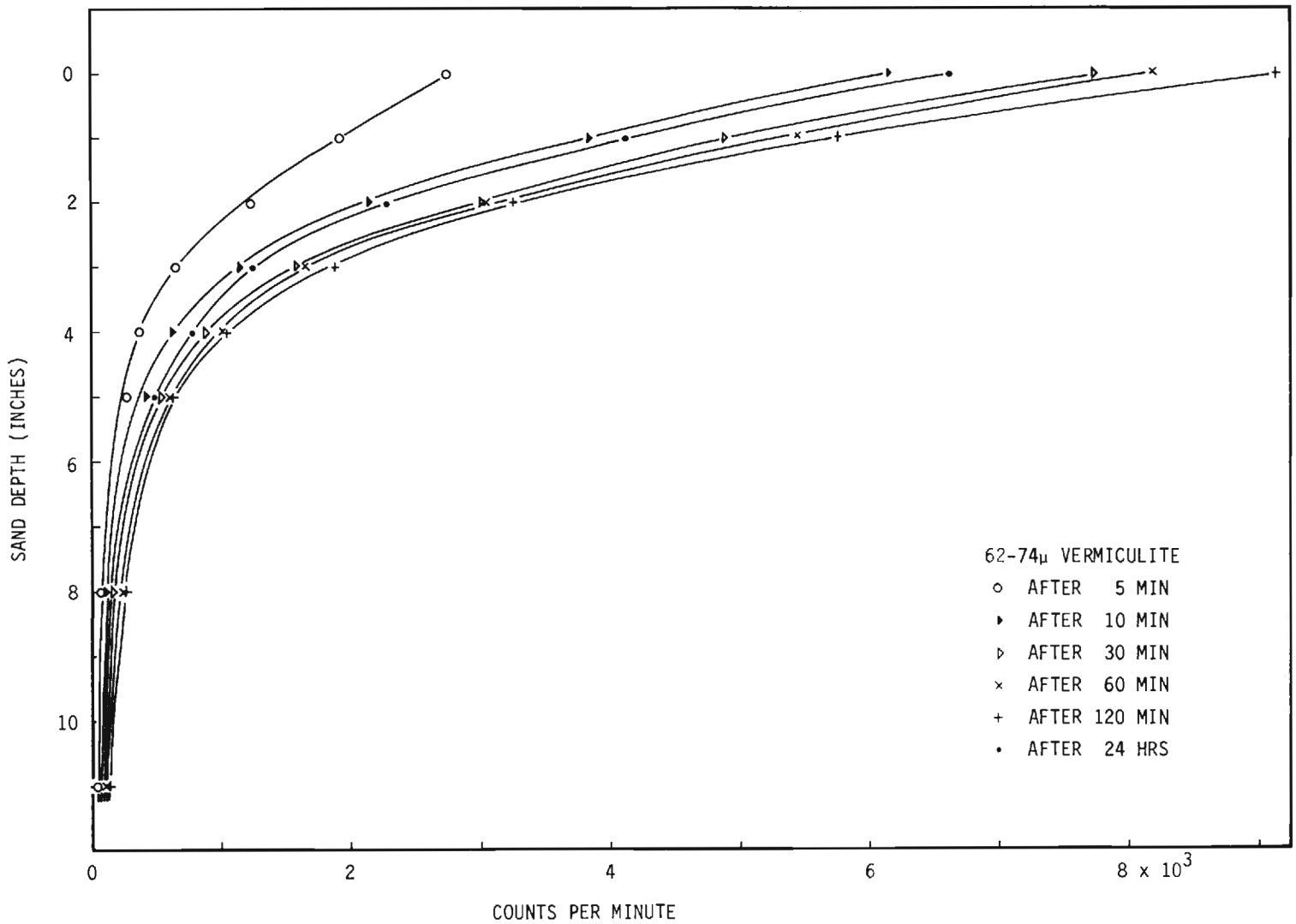

Fig. 17. Distribution of Activity with Time: 62-74 μ Vermiculite

surface, the apparent activity at lower levels being due to attenuation of the radiation by the intervening sand and water. It was found, however, that calculations based on this concept do not agree with the observational data, although there is some uncertainty as to the buildup factors that should be used.

In the case of Fig. 17, the nominal size of the particles is much larger (62-74 μ) than the calculated size of the openings in the sand (38 μ). It is, therefore, concluded that the largest portion of the particulate matter is retained at the sand surface, but some penetration due to the smaller particles does occur.

The shape of the curve is a function of penetration, which is a function of particle size. With ultrasonically washed 53-62 μ vermiculite (see Fig. 18), the portion of the curves representing the top four inches of sand was slightly concave upward, whereas the corresponding portion of the 62-75 μ plot was concave downward.

There is even more contrast when these curves are compared with the plot for micron vermiculite which is shown in Fig. 19. The small particles result in an activity level at one inch depth very nearly the same as at the surface. Activities at these levels, after some fluctuation, became equal at 60 minutes, and thereafter the second level remains higher. The actual geometry-corrected counts are given in Table VI.

Behavior of this sort seems to be due to an initial deposition rising to a maximum at 30 minutes and remaining fairly constant until 60 minutes. Thereafter, the finer particles deposited in the uppermost zone are transported deeper into the sand with the result that the maximum activity is eventually found at the two inch depth.

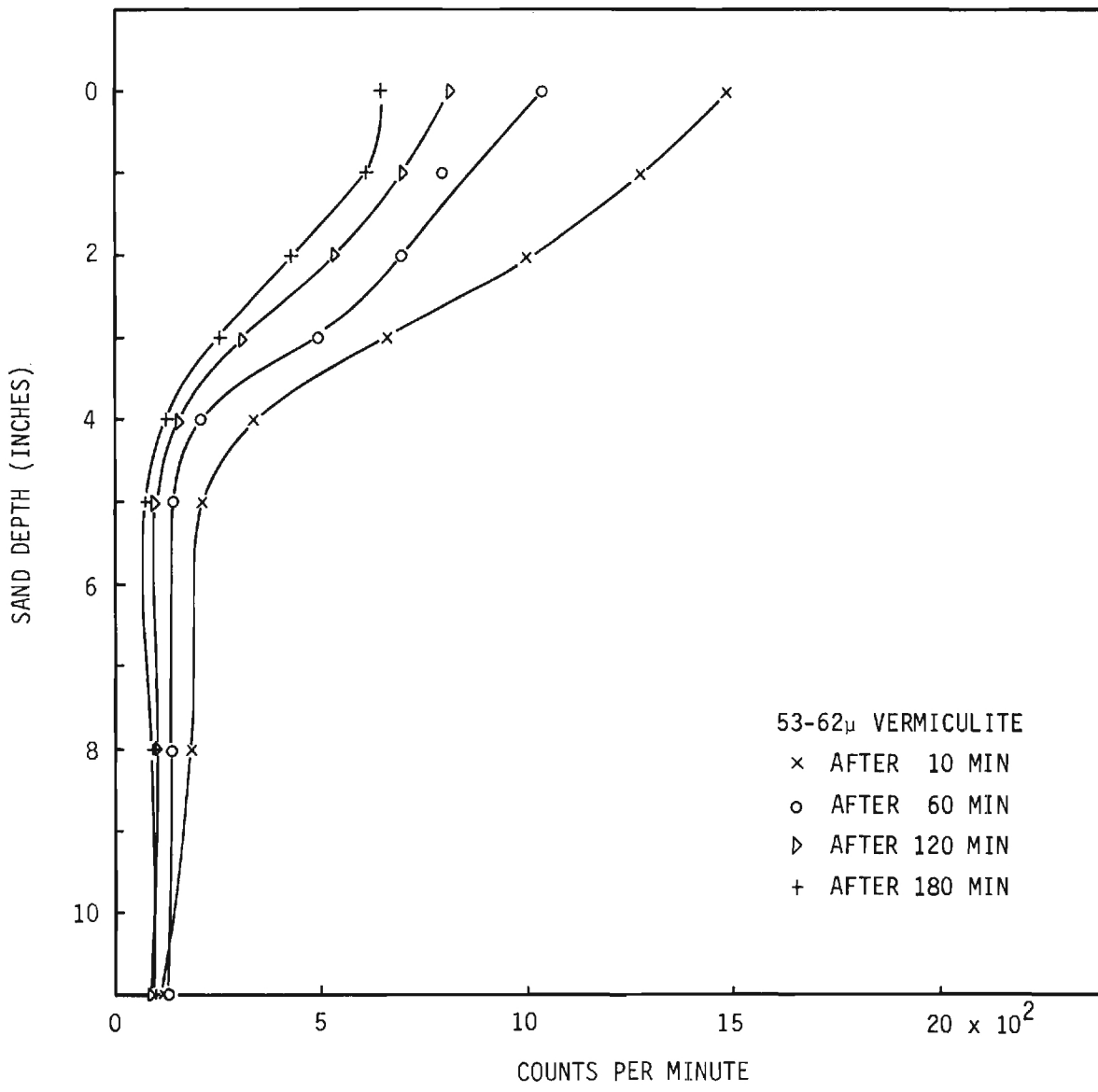

Fig. 18. Distribution of Activity with Time: 53-62 μ Vermiculite

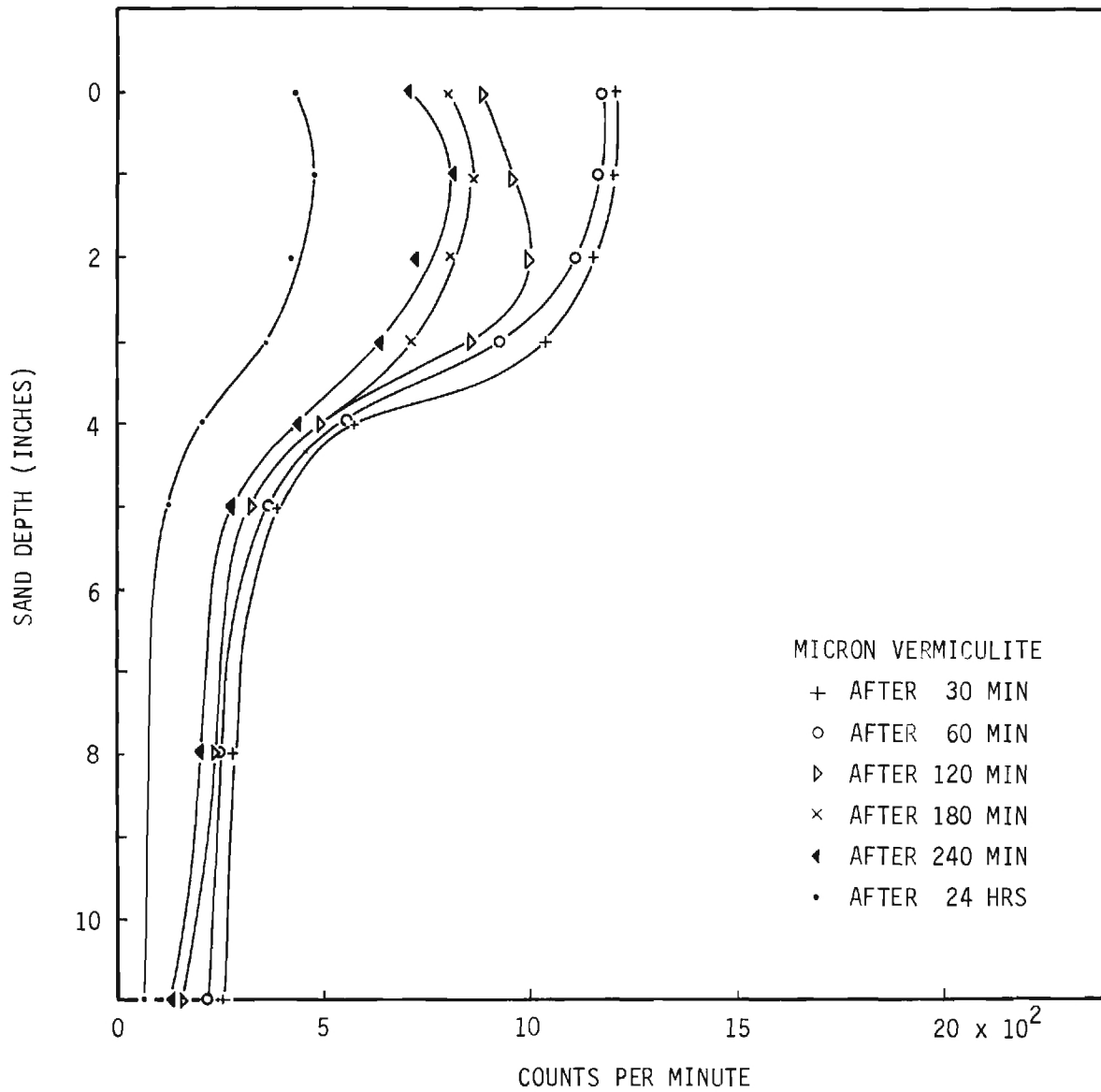

Fig. 19. Distribution of Activity with Time: Micron Vermiculite

Table VI. Micron Vermiculite Run

Position/Time	5 min	10 min	20 min	30 min	45 min	60 min	90 min	120 min	180 min	240 min	24 hr
Sand surface	1072	1131	1193	1199	1123	1177	1012	888	802	705	429
1" depth	801	1004	1158	1164	1224	1178	1026	953	867	806	477

There is no very satisfactory explanation at present for the observation that the point of maximum activity subsequently rises from the two inch to the one inch depth and remains for the duration of the run at the one inch level as shown in Fig. 19. (A somewhat similar tendency was observed with 88-105 μ vermiculite as shown in Fig. 20.) Repetition of this experiment is planned with an increased amount of tracer activity in order to improve the statistics of the counting.

The pattern of penetration and deposition of particles seems to be more easily studied with the activity versus depth type of plot. Data obtained earlier by removing and counting samples of the sand correlate in a qualitative fashion with these curves, but it seems desirable to establish a more quantitative connection. It is expected that appreciable attention will be devoted to this point in the next phase of investigation.

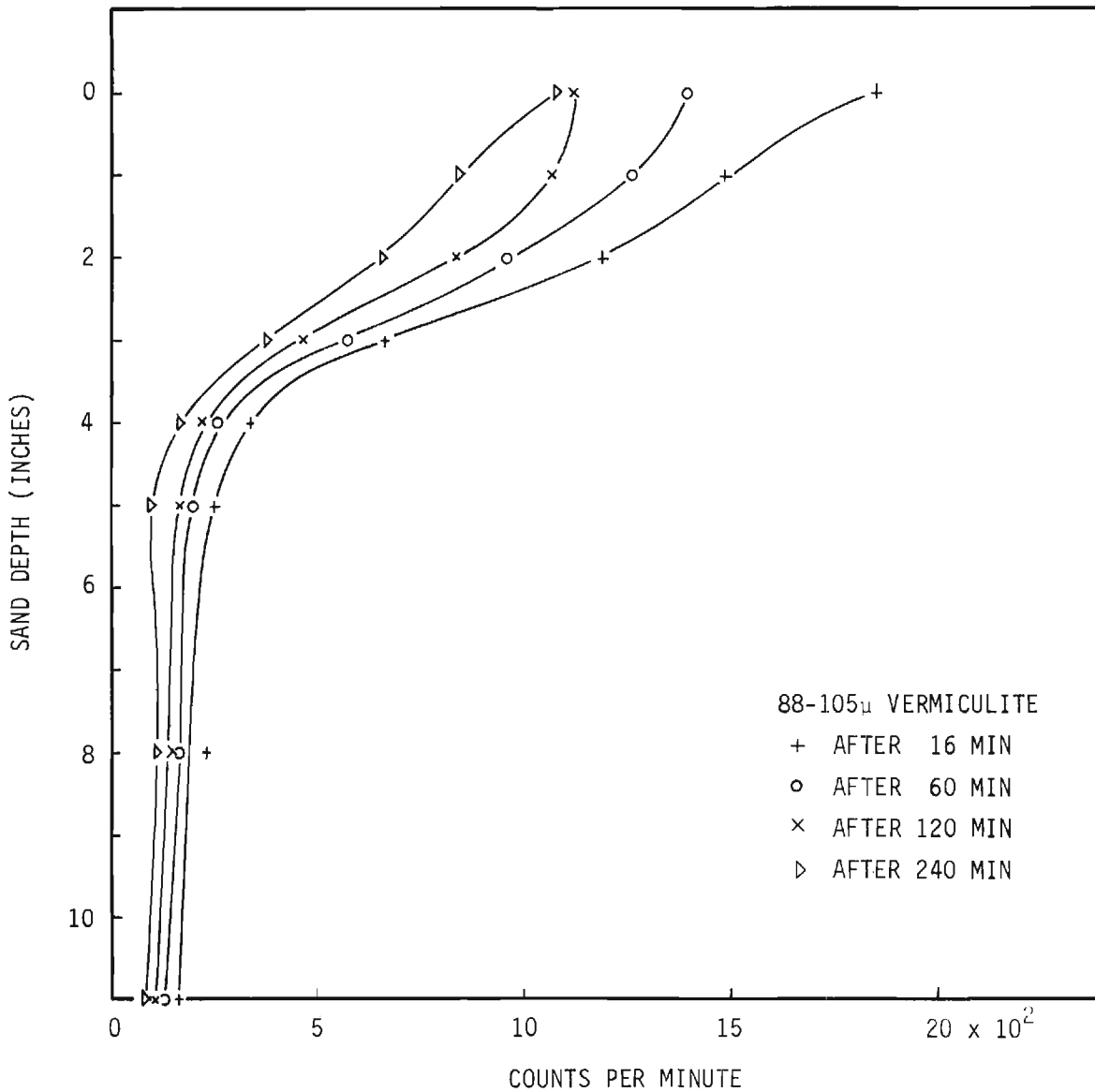

Fig. 20. Distribution of Activity with Time: 88-105 μ Vermiculite

Summary

During the period covered by this report, the planning, procurement, and construction phases have been completed. The major items of instrumentation required so far have been received and put into operation. Tentative decisions were made on the design of equipment and later adjusted as construction progressed. Due to small changes in the plumbing arrangements, filter No. 3 can be operated more easily than the previous filters; the same design would be used again should it become necessary to build additional filters.

No major problems developed during the preliminary experimental stages, although the usual number of minor difficulties appeared and were overcome. The experimental method has received considerable evaluation and it is believed to be reliable.

Many experimental results have been obtained; with few exceptions, they have been found consistent and reproducible. These data have been subjected to preliminary analysis as described above, but a further more meaningful analysis should be possible with the additional experimental evidence expected to be collected in the next few months. At this stage some qualitative conclusions only can be drawn regarding the movement of dissolved ions and labeled particles of varying sizes through the filter bed. It is evident that both adsorption and desorption processes occur and determine the kinetics of particle motion.

Retention of dissolved ions and labeled particles has been determined as a function of time. When fine particles are involved, the relationship depends on the size of the particles, but the result is similar even when only dissolved ions are present indicating that surface adsorption is a major controlling mechanism. Observations at various levels in the filter reveal

the presence of a front of activity that passes through the filter medium following addition of activity to the filter influent.

The pattern of deposition of particles within the filter medium has been observed for a number of different particle sizes. We have observed that this relationship depends on the particle size, although the exact nature of the dependence is obscure.

A difference in the pattern of movement at two different flow rates has been observed, but information concerning more divergent rates is required.

Future Plans

The major uncertainty involved has been in the size of the particles used. The ultrasonic washing procedure has produced more uniform size fractions, but more work directed toward size separations is clearly indicated. More experiments involving a very wide range of particle sizes are also planned. These should be helpful in the present approach, but perhaps even more so when size distributions at various levels are later determined.

It is planned that other sizes and materials be used as the filter medium. Filter No. 3 has been filled with 20-30 mesh sand and will be used in a series of experiments paralleling those which have involved the 40-60 mesh sand. The further use of Anthrafilt as a filter medium is planned, although contamination of the bed by the isotope tracer is a factor requiring careful consideration.

With this additional experimental information, it is believed that further elucidation of the relationship between suspended particles and depth of penetration into filters will be possible.

Acknowledgments

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Staff

The following professional staff has been employed on this project:

Geoffrey G. Eichholz	Principal Investigator	May 1, 1966-Present
T. F. Craft	Research Chemist	May 1, 1966-Present
Joe K. Cochran, Jr.	Instructor, Ceramic Engr.	Oct. 1, 1966-Present

The following student assistants worked on this project on a part-time basis:

Charles Spriggs	Student Assistant	Feb. 13, 1967-Present
Bobby Soekardiman	Student Assistant	Sept. 23, 1966-Present

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Radiotracer Studies on Rapid Sand Filtration

Completion Report

on

OWRR Project B-008-GA and

Georgia Tech Project E-600-701, jointly

covering the Period June 1, 1966 to October 31, 1967

by

G. G. Eichholz and T. F. Craft

Nuclear Sciences Division, Engineering Experiment Station

and School of Nuclear Engineering

Georgia Institute of Technology

Atlanta, Georgia

April, 1968

Introduction

Rapid sand filtration is an important process in the purification of water with common application in municipal purification plants and related uses in the treatment and disposal of waste waters containing radioactive contamination or other pollution of industrial origin.

A detailed research program aiming to determine some of the operational parameters of such filters by the use of radioactive tracers was started in June, 1966 as part of the water-related research program of the Nuclear Sciences Division. The project was set up as a matching-fund project under the auspices of the Water Resources Center; the federal support was designated by Project No. B-2524 (EES Project B-325) and the matching state support by Project No. E-600-701. With the approval of the Office of Water Resources Research, Dept. of the Interior, this work is being continued for a further three-year period. That continuation project has been designated as Project No. B-2550 (EES Project B-327) for the federal portion and Project No. E-600-705 for the state portion. The present report is intended to summarize work completed or in progress up to the end of October, 1967 as funded through the first stage projects.

The work done under the joint project during the first year, through June 30, 1967, has been described in a detailed Annual Report, a copy of which is appended. To avoid unnecessary duplication, that report is assumed to be an adequate introduction to the aims and procedure of the project. This briefer report, therefore, attempts merely to update that report and to review the work done up to the end of the first project at the end of October, 1967. Since the work has been continued since along essentially the same lines, it will be appreciated that this report will not contain any scientific results or conclusions at this stage. It is planned, however, to prepare a brief paper summarizing the method used and some results of practical interest for early publication.

The work during the summer of 1967 was devoted primarily to two aspects of the investigation: a) development of a method for encapsulating the tracer isotope inside the tagged particles, and b) automation of the detec-

tor scan of the filter bed and the associated data recording. The latter portion of the project benefited greatly from the assistance and technical competence of Mr. Heinrich Geuppert, an exchange student from Stuttgart, Germany.

Particle Labeling

One of the major areas of interest is to follow the movement of sized particles through the filter bed and to determine the kinetics of the filtration processes. To this end, vermiculite particles were labeled with radioactive cesium-137 by immersion in a radioactive solution. The particles acquired the radioactive label essentially by an ion exchange process and were introduced into the filter system after being washed briefly to remove non-adhering cesium tracer. In the course of several tracer experiments, it was observed that, after reaching a maximum, the total activity in the filter decreased due either to passage of the labeled particles through the filter or due to loss of some of the radioisotope tracer from the particles. It was found experimentally that the second alternative was definitely occurring, although the filter effluent never revealed a detectable amount of dissolved activity when checked continuously with a Geiger counter or when batch samples were placed in the well scintillation detector. Appreciable activity was accumulated, however, by passing the effluent through a layer of cation exchange resin.

Analysis of activity profiles in the filter bed would be simplified by eliminating this variable, so calcining of the vermiculite particles was investigated as a means of fixing the tracer. The sized vermiculite particles were labeled in the usual fashion by stirring in a Cs^{137} solution. After decanting most of the solution and washing a few times with water, the remaining moisture was evaporated under a heat lamp, and the dry labeled vermiculite particles were heated in a furnace. It was quickly determined that heating to an indicated temperature of less than 1850°F had no effect on the tenacity with which the isotope was held, and that temperatures in excess of about 2300°F fused the particles into a single mass. Between these limiting temperatures, it is possible however to obtain a product only lightly fused and which can be readily broken apart

with a spatula. The necessary temperature range for each particle size fraction is rather sharply defined and conditions must be controlled carefully to obtain consistent results.

After calcining and trituration, the particles were rescreened to ensure uniform size fractions. One filtration run was made using calcined particles. During the first few minutes of flow, the activity increased to a maximum in typical fashion, but thereafter remained essentially constant. Filtration was continued for more than ten days without diminution of the activity levels. Subsequent runs have confirmed that calcination around 2200°F locks in the cesium-137 activity quite satisfactorily in vermiculite particles and even prolonged rapid water flow does not elute the activity.

Automatic Counting System

In view of the many parameters involved in the experimental system, such as bed materials, bed particle size, suspended particle size, flow rate, size uniformity, etc., it is anticipated that a great many runs will have to be carried out involving the determination of activity profiles through the bed by measuring count rates at one-inch intervals from the bed surface down. Since this routine operation of data taking is both simple and time consuming, it was decided to automate this process as much as possible.

An Omni/Guard Low Background Counting System manufactured by Tracerlab, Inc., Waltham, Mass., was available and some of its components were adapted to meet the specific requirements. The scaler unit includes an anti-coincidence circuit, detector power supply, scaler, and timer. Also utilized was the Tracer/Matic Printing Timer.

The coaxial cable supporting the counterbalanced shielded Geiger tube passes over a programming drum, whose position and movement can be precisely controlled. The drum is positively locked in each position by a solenoid-operated plunger so that the selected levels are reproducible. On command, the plunger releases the drum which is then rotated by a reversible gear motor to the next desired position. Control of these positions is by microswitches which are operated by pins in the drum.

When the drum locks into position, a signal starts the count determination by the scaler which also furnishes the high voltage to the Geiger tube. At the end of the counting interval, the number of counts detected is recorded automatically on the printer. An index number indicating the Geiger tube position is also recorded along with the length of the counting interval. After these numerals have been printed, the drum is actuated, the Geiger tube is repositioned, and the next level is counted. Following the complete scan, the tube is returned to an initial starting position and the water valve is opened. A clock-timer is incorporated into the circuit which permits water flow between counting sequences of any desired multiple of 15 minutes.

An overall view of the filter showing the automatic equipment in position is shown in Figure 1, and closeup views of the programming drum and control unit are shown in Figures 2 and 3. Figure 4 is a schematic diagram of the positioner control unit. This system has been put to routine use and, considering the complexity of the system, it has given very satisfactory service.

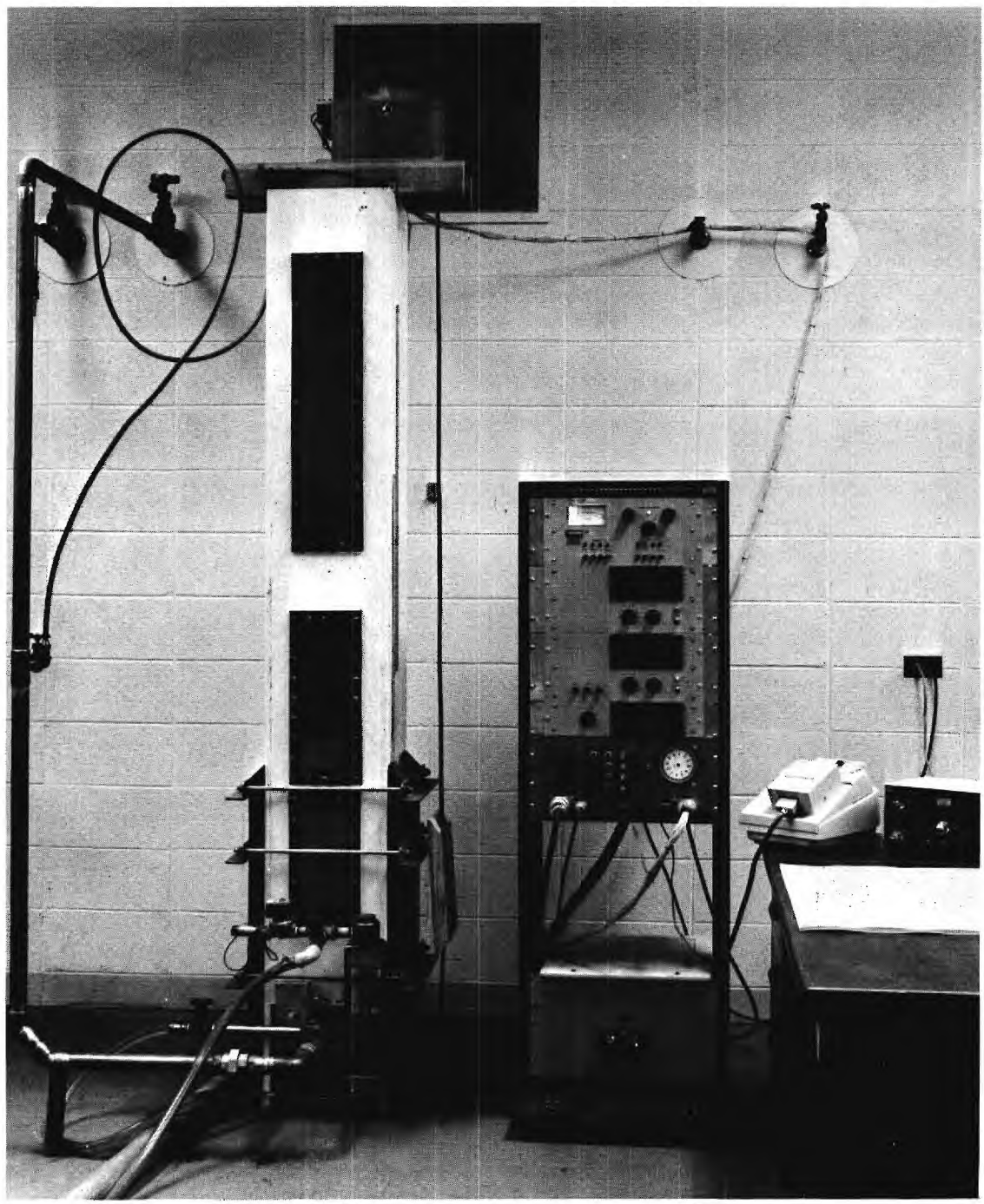


Fig. 1 View of Filter No. 2 and Automatic Counting System
The programming drum is seen in position on top of the filter box.

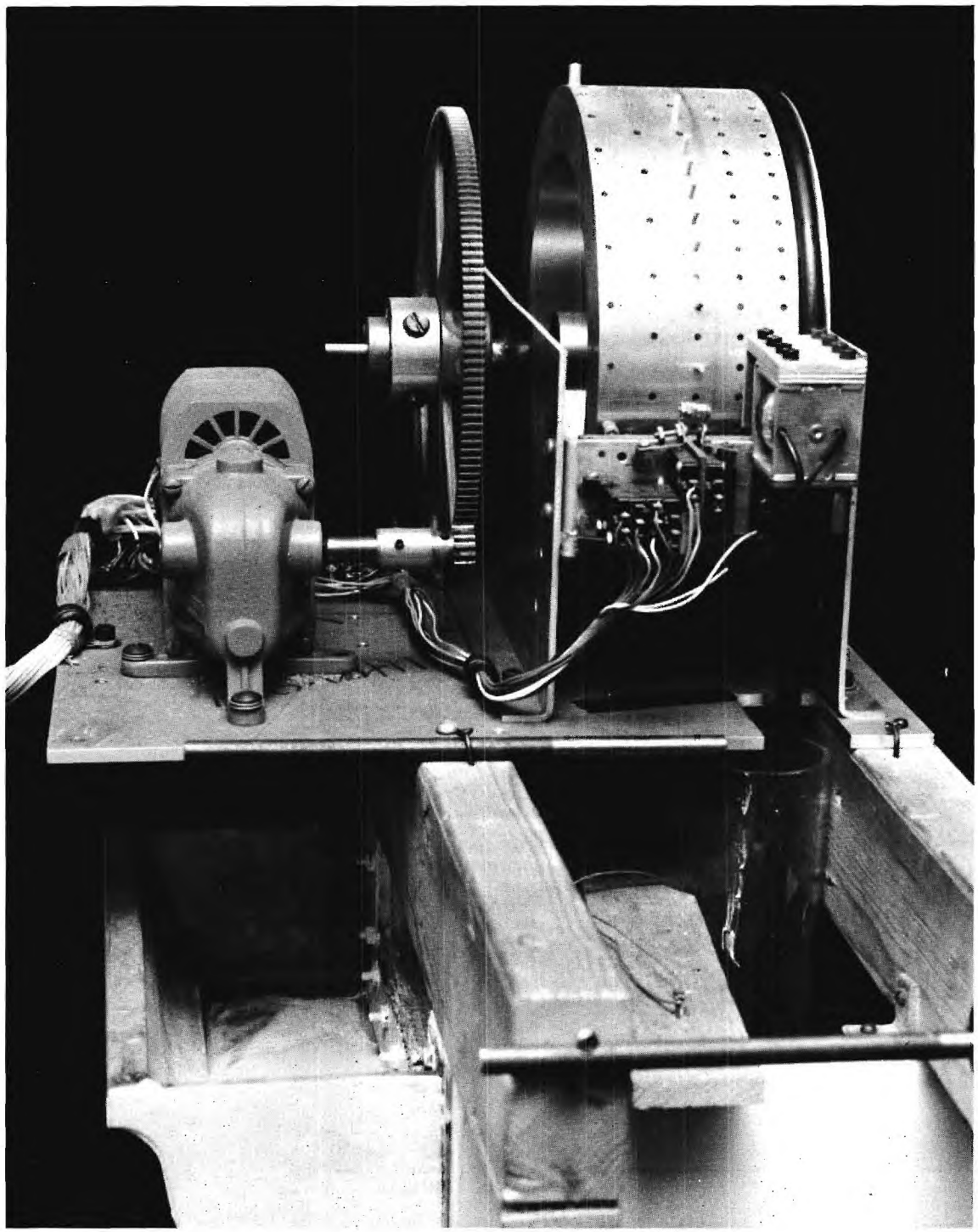


Fig. 2 Closeup view of the Programming Drum
The reversible gear motor is at left. The aluminum pins in the drum can be positioned to select any chosen combination of counter positions.

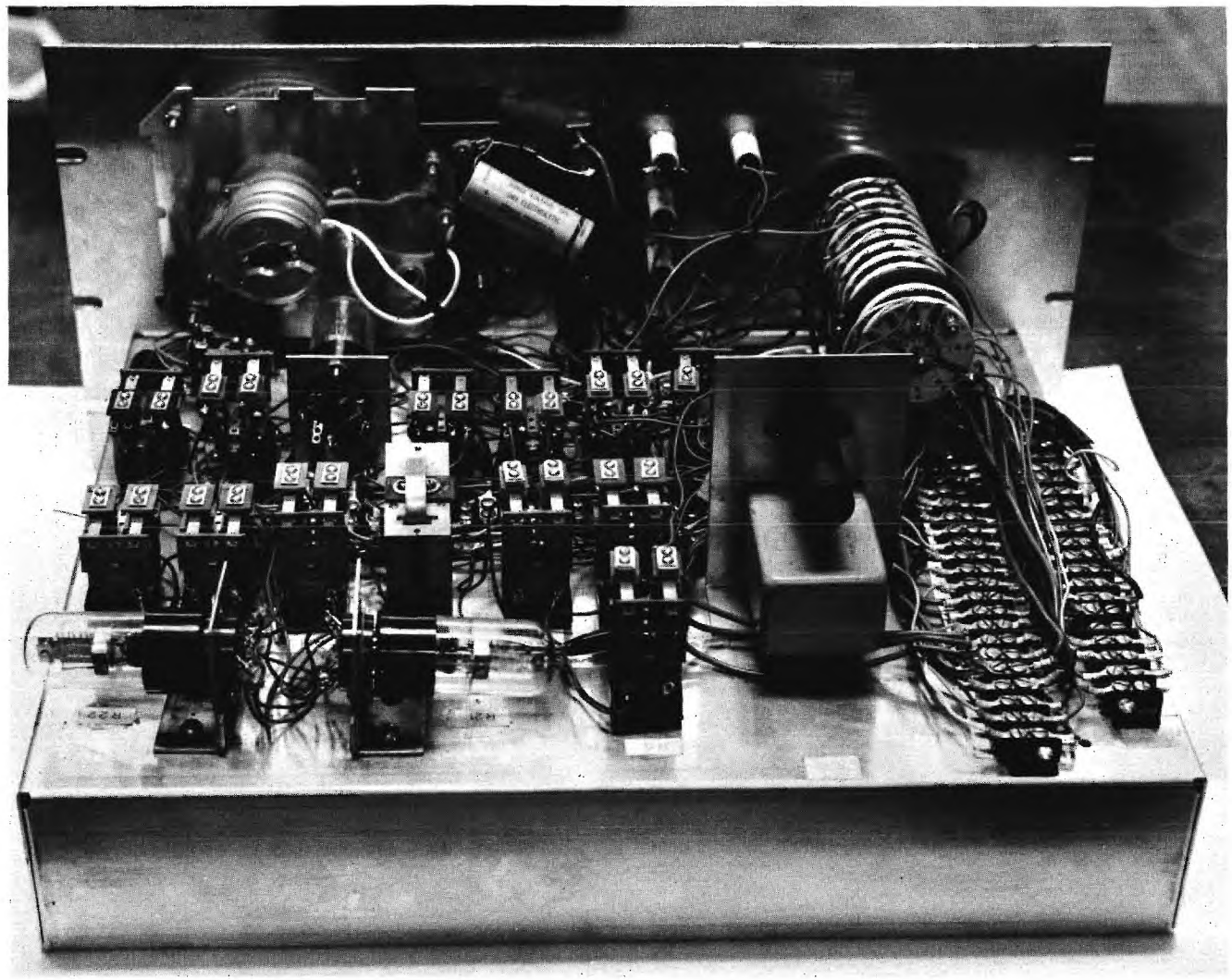
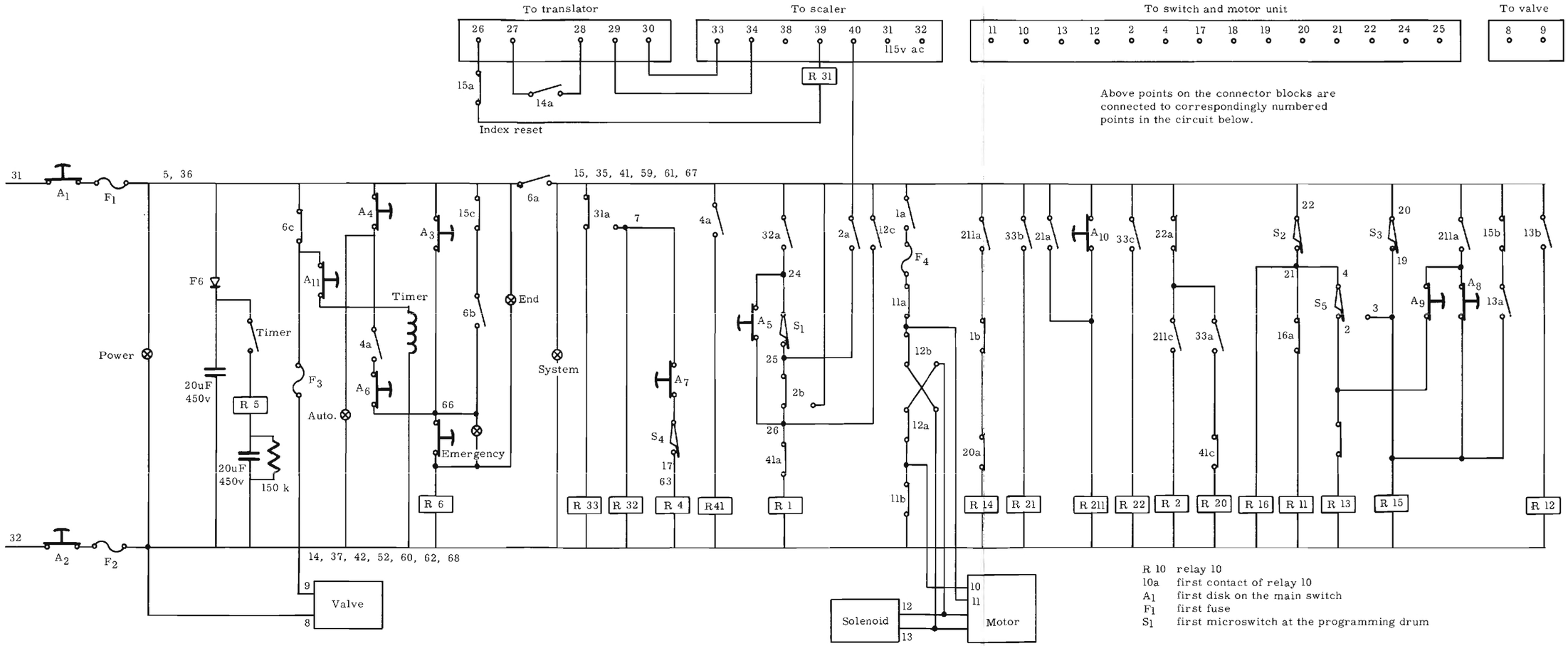


Fig. 3 Backview of Positioner Control Unit



R 10 relay 10
10a first contact of relay 10
A_1 first disk on the main switch
F_1 first fuse
S_1 first microswitch at the programming drum

Final Report

RADIOTRACER STUDIES ON RAPID SAND FILTRATION

By T. F. Craft and Geoffrey G. Eichholz

OWRR Project No. B-020-GA
and EES Project E-600-705, jointly

June 1970

Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
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The work on which this report is based was supported by the Nuclear and and Biological Sciences Division, Engineering Experiment Station, and the School of Nuclear Engineering, Georgia Institute of Technology, and by the Department of the Interior, Office of Water Resources Research, as authorized under the Water Resources Research Act of 1964 (P.L. 88-379). The project was administered through the Water Resources Center of the Georgia Institute of Technology under provisions of P. L. 88-379.

ENGINEERING EXPERIMENT STATION
in cooperation with
ENVIRONMENTAL RESOURCES CENTER

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

PREFACE

The research on which this report is based is a continuation of work performed under OWRR Project B-008-GA, which was initiated in May 1966 and completed in December 1967.

This project was set up as a matching fund project under the auspices of the Georgia Institute of Technology Water Resources Center;* the federal support was designated as Project No. B-2550 (EES Project B-327) and the matching support by the State of Georgia as Project No. E-600-705.

Part of this work was comprised in the doctoral thesis of T. F. Craft which covers also some of the more theoretical aspects of this field that are not dealt with in any detail in this report. That thesis was issued as a Water Resources Center Report WRC-0469 in August 1969.

Thanks are due to Dr. H. V. Grubb and Dr. G. L. Bridger of the School of Chemical Engineering for their hospitality during all laboratory operations of this project. We are also grateful to the Atlanta Water Works (Mr. Paul Weir, director) for their assistance and cooperation; particularly to Mr. Richard R. Smith, Superintendent of the Hemphill Water Treatment Plant for his support and encouragement. The Nuclear and Biological Sciences Division of the Engineering Experiment Station provided financial and logistical support.

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*Since March 1970, Environmental Resources Center.

SUMMARY

Both the theoretical and practical aspects of rapid sand filtration have been investigated. A radiotracer technique made it possible to measure accumulations of suspended matter in porous filter beds. Filter coefficients were calculated and were useful in determining the mechanisms involved when suspended particles are trapped by a porous medium, such as sand or anthracite.

The experimental evidence shows that three major actions occur. These are physical hindrance, interstitial sieving, and the physico-chemical van der Waals and double layer forces. The particular mechanism by which a given particle is trapped in a porous medium is determined primarily by the size of the particle. There is a gradual transition between applicable mechanisms; more than one force may be influencing a particle, but their relative effectiveness depends on the particle size.

The effectiveness of anthracite and normally graded, reverse graded, and uniform sand was evaluated in a series of long filter runs. From the standpoint of head loss, anthracite plus sand or anthracite alone are superior. Other media in order of decreasing effectiveness are reverse-graded sand, uniform sand, and normally-graded sand. When all factors are considered, it is concluded that anthracite plus sand is the best choice.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Concluded)

INTRODUCTION

Filtration is an essential part of water treatment procedures that begin with a turbid water and produce as the end product a clear, sparkling effluent. Filters themselves take various forms and today may utilize one or more of a variety of media, but essentially they consist of a large container supporting a porous medium through which the water to be filtered passes, usually in the downward direction, and usually under the force of gravity alone. The traditional filter medium has been sand and it is still present in the vast majority of filters in use today.

Rapid sand filters have been in use for more than a century and their design and operation are highly developed. However, it has only been in recent years that much attention has been directed to the fundamental principles that cause suspended particles to be removed from a moving liquid during passage through a porous medium.

Virtually all filter design until quite recently has been based on empirical deduction from observations. The resulting design "recipes" have been used interchangeably with little regard for the characteristics of the water to be filtered. This seems to indicate that either the action of the filter is independent of the nature of the influent or that in many cases the filters must have been grossly overdesigned. Until such time as the basic mechanism is more fully understood, any improvements will likely be incremental.

There are a number of variables involved in rapid sand filtration, and they may be placed in one of three general categories: (1) hydraulic factors, (2) physical-chemical parameters of the porous bed, or (3) characteristics of the influent. Many individual factors have been studied, and the inter-

relationships of a number of these have been reported. Although a number of theories have been advanced,[1] it is evident that no single theory so far developed can explain the available experimental data. Without invoking scientific principles yet unknown, it seems likely that a combination of chemical and physical laws are involved, but additional information is required to ascertain the relative importance of the mechanisms so far proposed and to assist in the formulation of a definitive theory.

A major parameter of interest is the distribution of particle sizes deposited at different depths within a filter. Information on this variable appears particularly useful because there is no apparent a priori reason why all particle sizes should behave in identical fashion. If different size particles are affected by different forces, it would simplify matters to consider these influences separately. Eliassen[2] has reported some data on deposition of different particle sizes at different depths in an experimental filter, but he was working with an iron floc which consisted for the most part of particles much larger than the minimum size that a sand filter will remove.

A technique involving radiotracers was used by Stanley[3] in a study of some of the variables of sand filtration. The floc particles employed were passed through an orifice so that reproducible sizes could be obtained. He did not report any actual particle sizes, but he concluded that the size of the particles affects penetration. Other parameters considered included the concentration of iron, pH, ion concentration, sand particle size, and rate of flow. The present work was also intended to elucidate some of these factors. This has been done through the use of labeled particles, which were entrained in the water flow through a pilot-scale filter bed.

There are two experimental approaches to the determination of the relation between particle size and the ultimate location of deposit. One might

either use a wide range in size of suspended particulates and determine the resulting distribution at different levels, or use a narrow range of particle sizes and measure simply the gross deposit at each level. Primarily the second approach has been used in the present project, utilizing various particle size fractions up to 105 μ diameter.

A major goal of the laboratory phase of this work has been to determine the amount of material of a given size that is deposited in the porous medium as a function of bed characteristics, flow time, and position in the filter. A radiotracer technique was chosen for obtaining this information because data on particle deposition could be obtained during filtration without physically disturbing either the filter medium or the flow passing through it. This is a great advantage over the alternate procedure of removing at intervals samples of the bed and/or the flowing water. Excellent laboratory facilities for the utilization of radioisotopes were available and the authors had had previous experience with radioisotopes. In the second phase of these studies, conducted at the Atlanta Water Works, long filter runs were undertaken using actual, prefilter water. Information was obtained by measuring loss of head as a function of time at various elevations within the filter bed.

The primary purpose of this project was the investigation of the basic mechanism of filtration. The second phase was involved with the practical aspects of filtration as encountered under commercial conditions, as a way of evaluating some of the factors that arose during the work in the first phase. Special equipment required for this study was designed and constructed. The resulting data were used in the development of a theoretical interpretation to explain the action of rapid sand filters.

EQUIPMENT AND PROCEDURES

Most of the laboratory studies employed a special filter designed to be wide enough to minimize wall effects and yet small enough to handle available water flow. The laboratory-scale filter used in the radiotracer work had a bed surface area of about one square foot. It was constructed in the conventional manner with arrangements for water to flow either up or down for backwashing or filtration, respectively. A vertical plastic tube, sealed at the bottom, was positioned inside the center of the filter. The lower end of the tube was anchored above the bottom of the filter, and the upper end extended well above the highest attainable water level.

A small Geiger-Müller tube was suspended inside a lead shield which fit snugly inside the plastic tube. The lead shield had a narrow horizontal slit through which the G-M tube could detect radioactive material located in a plane at the same elevation as the slit. A drawing of this shield is shown in Fig. 1. The shield and G-M tube were suspended from a coaxial cable which could be raised and lowered to position the shield slit at desired depths in the filter. An automatic device was constructed to control the positioning of the shield and the operation of the counting and recording system. A general view of the filter with the positioning control and automatic counting system is shown in Fig. 2 and constructional details of the complete system are given elsewhere.[4,5]

Filtration runs were performed in the following manner. The filter was backwashed and the medium compacted to a standard level. The tracer particles containing radioactivity were poured into the top of the filter while the water was flowing in the filtration mode. After allowing sufficient time for the particles to be deposited, the radioactivity at and below the surface of the filter bed was measured. This was accomplished by positioning the slit

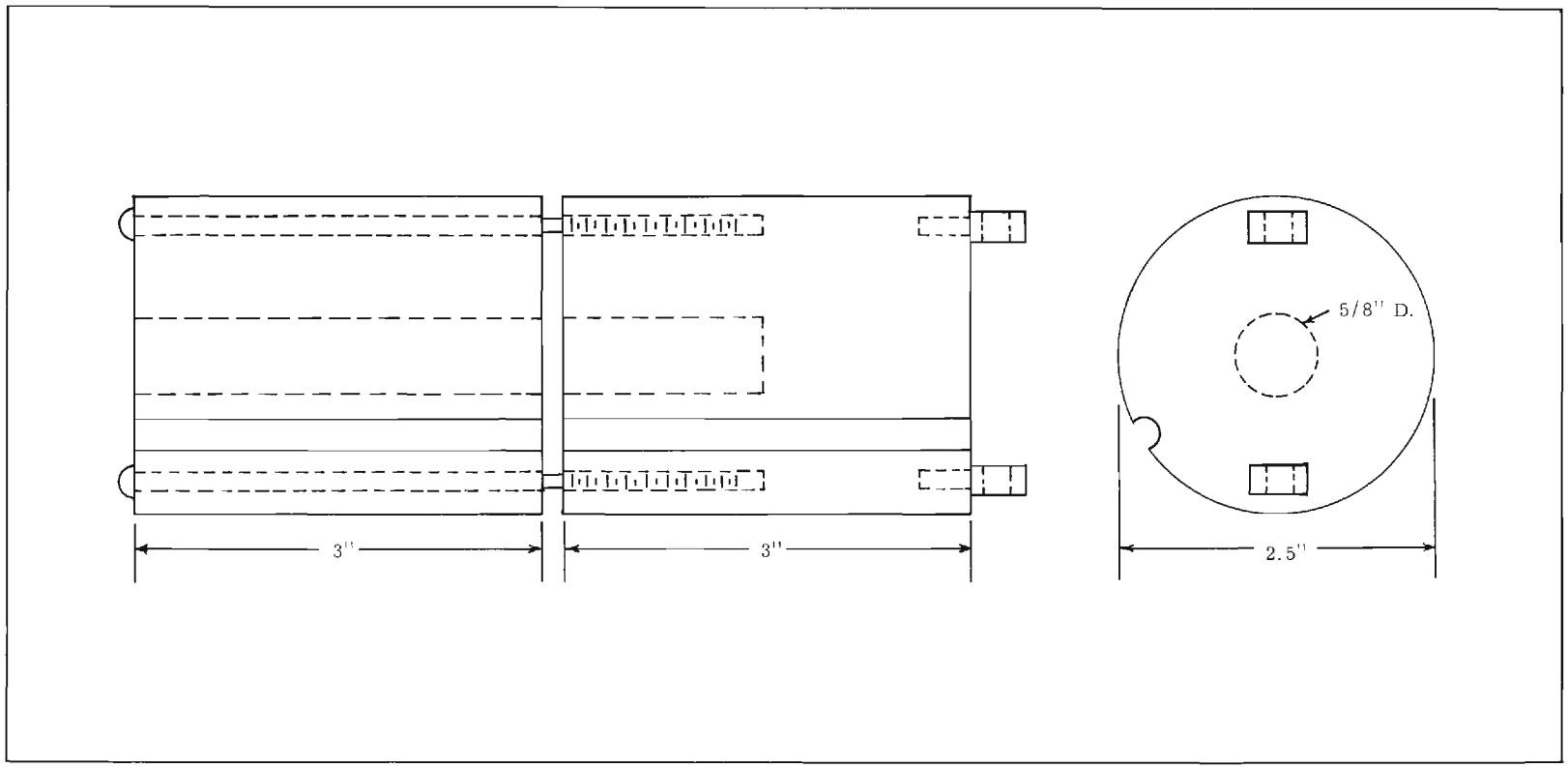

Figure 1. Details of Lead Shield for Geiger Tube

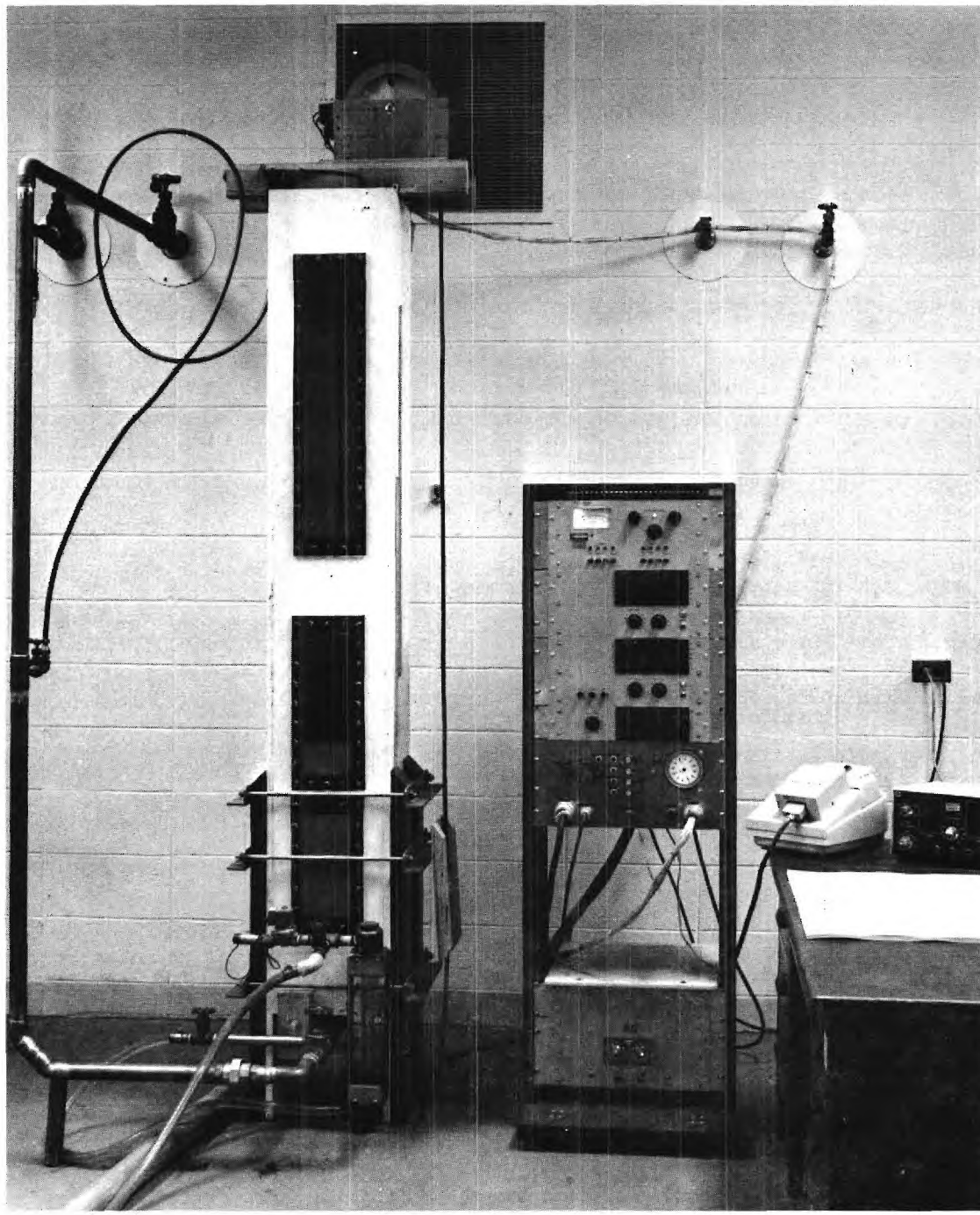

Figure 2. View of Filter and Automatic Counting System

in the lead shield at the elevation of interest and counting with the G-M tube for a definite length of time. This was repeated at all levels desired, producing a profile of activity and consequently indicating a profile of particle deposition.

The second phase of test work was primarily concerned with the effect of different filter media and different filter configurations using actual, pre-treated water. Since this work was done at the Atlanta Water Works, it was considered inadvisable to use radioactive tracers for this phase. For this reason, filter performance had to be evaluated by means of the more primitive method of measuring head losses.

The filter apparatus used for head loss studies consisted of two plastic tubes with spaced taps attached to piezometers. In these tests it was of interest to evaluate the effect of reverse-grading of a non-uniform filter medium and this necessitated a design capable of producing such a configuration of the medium. This was achieved by washing the bed in the normal manner, then placing a wire screen on top of the medium and inverting the entire filter. The filter was filled completely with water during the inversion, so a filter size small enough for manipulation by a single individual had to be chosen. A second filter that remained in fixed position was included so that direct comparison of results was possible.

The photograph (Fig. 3) shows the apparatus arranged for simultaneous flow through both filters. The filter tube on the left is the fixed tube. For backwashing, the valves at the top and bottom of the filter shown in the center of the mounting panel were closed and the tubes disconnected. The flexible leads to the piezometers were long enough to permit this tube to be inverted onto the brackets shown at the right of the panel. The tubes were reconnected, the supporting screen was removed, and backwash carried out in

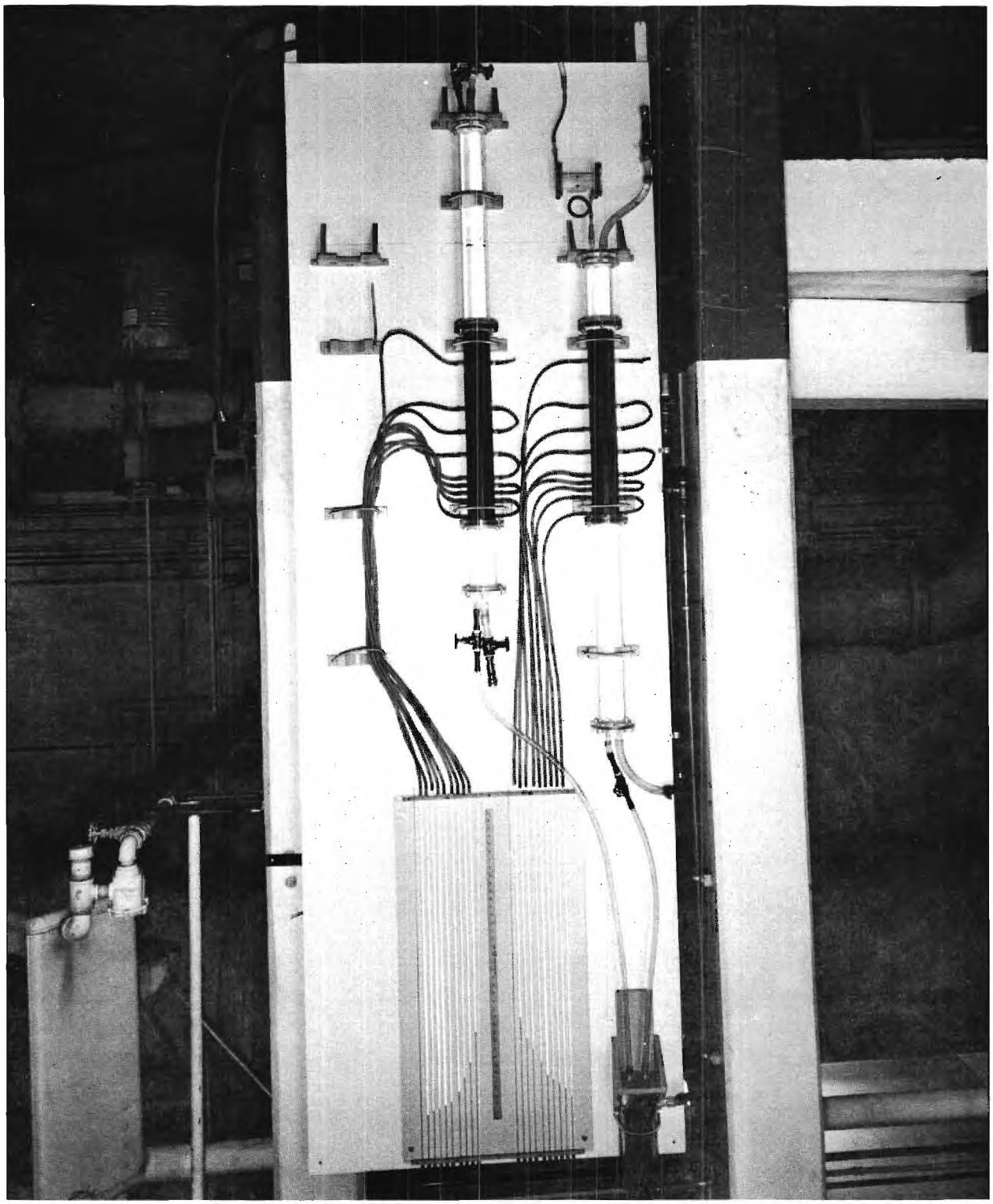

Figure 3. Test Filters Installed at Atlanta Water Works

the normal manner. After backwashing the procedure was reversed to prepare for the next run.

The materials used as filter media were sand and anthracite. A clean white silica sand furnished by the Pennsylvania Glass Sand Corp., Atlanta, Georgia was screened to obtain the desired mesh size ranges for the uniform sands. Non-uniform sand, when used in Phase 2, was filter sand obtained from the Atlanta Water Works. The ground anthracite was supplied by the Palmer Filter Equipment Company, Erie, Pennsylvania under their trade name "Anthrafilt." Details of the properties and preparations of these materials have been previously given.(6)

The suspended matter used in the radiotracer experiments consisted of vermiculite supplied by the Zonolite Company, Atlanta, Georgia. The preparation procedure began with an initial screening. Radioactive labeling was then done by slurrying the particles in a solution of cesium-137 chloride for an hour or more and allowing the mixture to soak overnight. The supernatant was then decanted and the particles were then calcined by heating in a furnace to a temperature of 2050°F. After crushing fused oversized particles and again screening, the sized fractions were ready for use. In this manner, particles were prepared that did not lose their radioisotcpe label even after long exposure to flowing water. At no time was any loss of activity from the particles ever noticed, nor could any leached out activity be detected in effluent that passed over them. The precise procedure necessary to produce these particles has been described earlier.(6)

EXPERIMENTAL RESULTS

Phase 1

Determination of Filter Coefficients

The filter coefficient, λ, was chosen as the parameter of filter efficiency. It is defined by the equation $C = C_o e^{-\lambda L}$, where C_o is the concentration at any depth L within the bed. Values of λ were calculated from the relative number of counts observed at the surface and at a depth of one inch. These two points were used because in every case they revealed the highest count rates, giving numbers that were most reliable statistically. Also, the difference in λ due to different particle sizes is most pronounced when λ is calculated for the top inch of the filter bed. On the other hand, it becomes important to eliminate oversize particles as much as possible from the feed.

Typical net counts at the surface were in the range of 1000 to 2500 per 10 minutes. For convenient comparison, the results of each run were all normalized to a uniform 1200 counts at the surface level. Table 1 lists experimental results for sand and anthracite filter beds. In this summary of normalized data one can see that there is less fluctuation in the values for the one inch depth than for other depths measured. The trend of the data at other levels is in general accord with that at the one inch depth though a few values appear out of place. Table 2 summarizes the λ values calculated from the data of Table 1. A number of runs were repeated in order to ascertain reproducibility of results and to verify an occasional seemingly anomalous result. In general, such doubtful results could be traced to failure of the automatic positioning drum to lock at the desired bed elevation.

Another series of filter runs was made using 30-40 mesh sand. The objective was to determine the effect of flow rate on filter coefficient. The

Table 1. Summary of Observed Data for Constant Flow Rate*

Bed Depth (in.)	Particle Size (μ)									
	1-3	-25	25-37	37-44	44-53	53-63	63-74	74-88	88-105	105 +
Series I: 20-30 Mesh Sand										
0	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200
1	1187	879	743	705	682	662	640	611	596	587
2	886	462	348	340	355	299	280	268	245	255
3	648	218	143	145	175	130	125	122	106	85
4	488	103	74	75	84	54	52	45	50	63
5	380	51	21	23	39	33	22	39	20	14
7	252	---	---	---	---	6	---	---	---	16
9	182	---	---	---	---	0	---	---	7	11
Series II: 40-60 Mesh Sand										
0	1200	1200	1200	1200	1200	1200	1200	1200		
1	1128	692	583	607	584	587	635	552		
2	740	340	235	193	241	256	283	238		
3	441	170	73	104	101	113	104	108		
4	270	104	29	73	57	106	57	41		
5	159	64	---	42	30	61	29	20		
7	70	24	---	35	16	30	14	17		
9	18	26	---	39	12	57	30	---		

*Counts per 10 minutes normalized to 1200 at the bed surface.

Table 1. Summary of Observed Data for Constant Flow Rate (Concluded)

Bed Depth (in.)	Particle Size (μ)								
	1-3	-25	25-37	37-44	44-53	53-63	63-74	74-88	88-105
Series III: 14-20 Mesh Sand									
0	1200	1200	1200	1200	1200	1200	1200	1200	1200
1	1612	1260	949	966	789	737	676	656	674
2	1532	950	506	552	365	514	285	283	298
3	1318	597	244	256	165	247	140	133	125
4	1134	369	120	128	77	205	84	59	62
5	920	222	63	58	40	161	60	28	46
7	659	93	29	12	10	156	44	16	23
9	509	62	23	9	8	166	42	17	13
Series IV: Anthrafilt No. 1									
0	1200	1200	1200	1200	1200	1200	1200	1200	1200
1	1451	984	877	827	774	752	733	726	732
2	1198	586	467	440	376	356	320	332	336
3	923	309	225	207	181	161	164	197	161
4	714	164	109	121	92	60	64	67	71
5	589	86	48	59	47	45	27	70	20
7	368	---	---	12	11	9	---	---	4
9	291	2	5	13	3	---	13	---	---

Table 2. Filter Coefficients (λ) at 2 gal/ft^2/min

Particle Size (μ)	40-60 Mesh Sand	20-30 Mesh Sand	14-20 Mesh Sand	Anthrafilt No. 1
1-3	0.06	0.01	-0.31	-0.19
0-25	0.55	0.31	-0.05	0.20
25-37	0.72	0.48	0.23	0.31
37-44	0.68	0.53	0.30	0.37
44-53	0.72	0.56	0.42	0.44
53-63	0.71	0.60	0.49	0.47
63-74	0.64	0.63	0.57	0.49
74-88	0.78	0.68	0.60	0.50
88-105	--	0.72	0.57	0.49
> 105	--	0.71	--	--

normalized data are presented in Table 3 and the calculated filter coefficients are given in Table 4. The coefficients for the 4 gal/ft^2/min were less reproducible than those obtained at lower flow rates. This may have been due in part to the presence in the water of small amounts of iron oxide-hydroxide that seemingly came from the supply main. It was manifested by a slight brownish stain that formed slowly at the sand surface and gradually penetrated into the sand. With this possible accumulation of material to alter the efficiency of the bed, timing was considered critical.

During previous runs at lower flow rates the timing was never varied much, but in the high rate runs the elapsed time between completion of backwash and introduction of tracer particles was allowed to vary no more than five minutes. Once the particulates had been deposited in the medium, the subsequent deposition of other material was of no consequence.

The statistics of the results were investigated through calculation of deviations in λ due to fluctuations in the observed number of counts at each point. The standard deviation of $e^{-\lambda}$ was calculated from the equation

$$\sigma_{e^{-\lambda}} = \frac{C_1}{C_0} \sqrt{\left(\frac{\sigma_1}{\sqrt{n_1}\ C_1}\right)^2 + \left(\frac{\sigma_0}{\sqrt{n_0}\ C_0}\right)^2}$$

where C_0 is the number of counts observed at the surface of the filter matrix, C_1 is the number of counts observed at the one inch depth in the filter matrix, σ_0 and σ_1 are the standard deviations in C_0 and C_1; n_0 and n_1 are the number of observations of C_0 and C_1, respectively. The effect on λ of this statistical variability in $e^{-\lambda}$ was first added to and then subtracted from the $e^{-\lambda}$ value to yield a lower and an upper limit of $e^{-\lambda}$. The difference in λ values corresponding to these limits is, therefore, the range of two standard deviations in λ and for most filter runs fell within the range 0.02-0.05.

Table 3. Summary of Observed Data for 30-40 Mesh Sand

Bed Depth (in.)	Particle Size (μ)								
	1-3	-25	25-37	37-44	44-53	53-63	63-74	74-88	88-105
				0.5 gal/ft^2/min					
0	1200	1200	1200	1200	1200	1200	1200	1200	
1	810	601	531	510	530	530	535	525	
2	461	263	215	217	210	222	244	102	
3	216	114	104	201	93	104	99	82	
4	191	49	42	105	44	65	53	41	
5	137	36	20	0	13	30	19	28	
7	104	16	13	0	2	25	7	14	
9	50	12	4	0	3	10	9	0	
				2.0 gal/ft^2/min					
0	1200	1200	1200	1200	1200	1200	1200	1200	1200
1	1239	991	827	753	706	678	627	623	636
2	851	574	442	408	330	302	294	300	284
3	679	295	214	192	144	129	130	125	125
4	530	204	78	96	75	65	56	47	42
5	339	70	38	44	25	42	40	26	5
7	256	25	0	37	0	12	9	5	0
9	60	10	0	18	0	2	0	0	0
				4.0 gal/ft^2/min					
0			1200	1200	1200	1200	1200	1200	
1			1071	1008	784	701	597	589	
2			817	713	422	319	251	261	
3			589	512	222	170	129	106	
4			413	348	117	78	57	50	
5			386	222	78	39	30	10	
7			283	156	21	21	20	2	
9			245	71	0	0	7	0	

Table 4. Filter Coefficients (λ) for 30-40 Mesh Sand

Particle Size (μ)	Flow Rate (gal/ft^2/min)		
	0.5	2.0	4.0
1-3	0.375	-0.07	----
-25	0.690	0.18	----
25-37	0.815	0.37	0.11
37-44	0.825	0.47	0.17
44-53	0.820	0.53	0.42
53-63	0.815	0.58	0.54
63-74	0.805	0.65	0.69
74-88	0.825	0.66	0.71
88-105	-----	0.63	----

Many runs were duplicated and the corresponding calculated λ values usually differed by no more than 0.04, which is within the calculated expectation of variability. Uncertainties of this order of magnitude are not particularly significant in determining relationships such as those described here.

Summary of Radiotracer Filtration Runs at Constant Flow Rate

The calculated values of the filter coefficient were plotted against the arithmetic mean of the particle diameters, and the results are shown in Figures 4-8. The theoretical implications of these curves have been previously discussed in detail[6] but briefly the interpretation is as follows. Examining Figure 5, as a typical example, the curve may be divided into three sections, each due to a different predominating mode of capture of suspended particles by the porous medium.

That portion of the curve for particles with diameters larger than about 90 μ is essentially flat and is due to retention of the previously suspended particles on the surface. This occurs where the suspended particles are larger than the openings in the sand. When smaller suspended particles are involved, here in the range of about 60 μ to 30 μ, penetration of the porous bed becomes progressively easier, and the filter efficiency decreases linearly. In this range of particle sizes, the major capture mechanism is considered to be mechanical interstitial sieving.

For particles of diameter less than 30 μ the relationship is no longer linear. While particle capture continues to occur, it is at a much lower efficiency. It is believed that these small particles are influenced largely by van der Waals and double-layer forces and not by purely mechanical forces of interference. These physico-chemical forces are relatively less effective, and filtration depending on them is less efficient than that where other forces are involved.

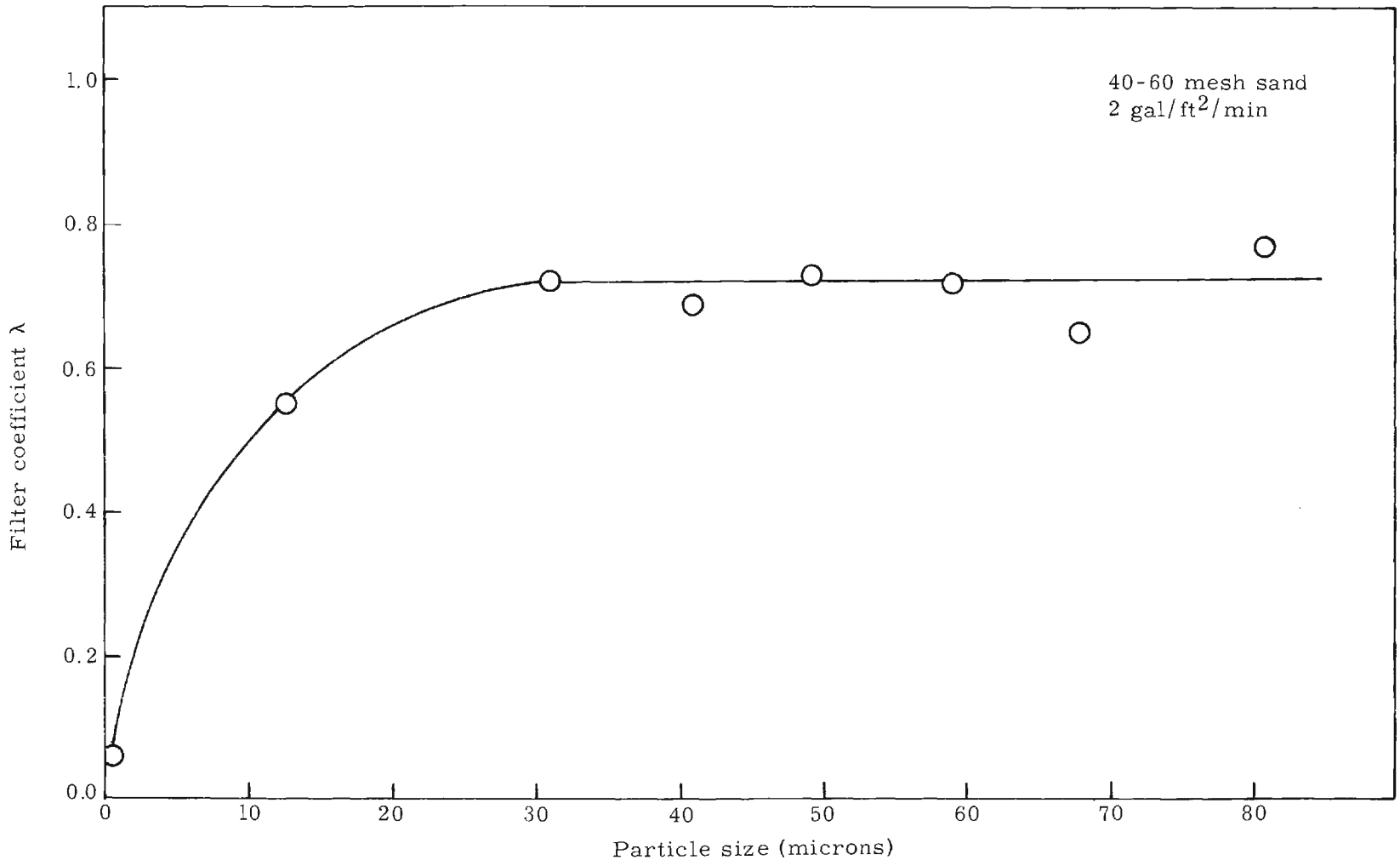

Figure 4. Filter Coefficients for Vermiculite Particles in 40-60 Mesh Sand

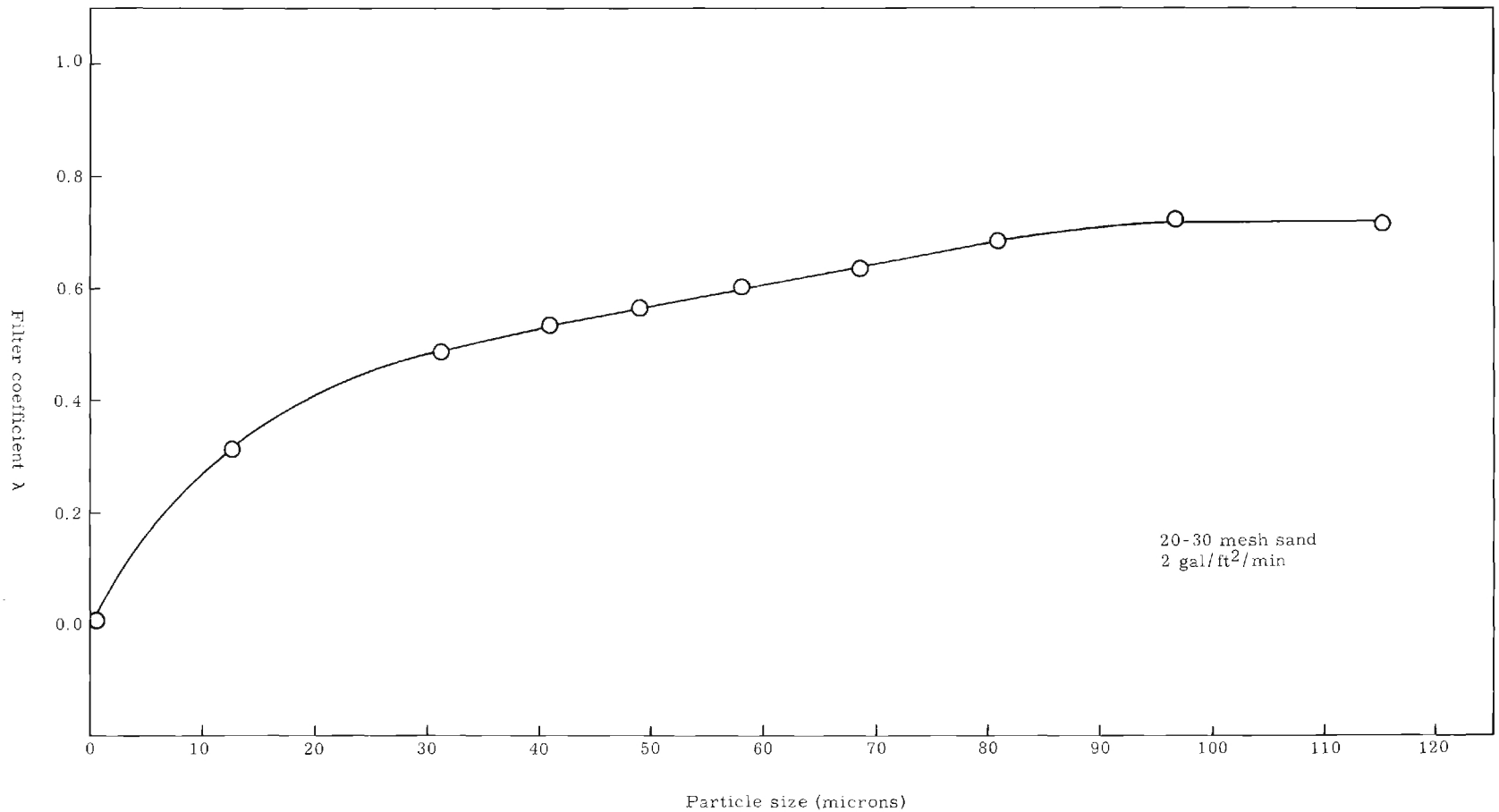

Figure 5. Filter Coefficients for Vermiculite Particles in 20-30 Mesh Sand

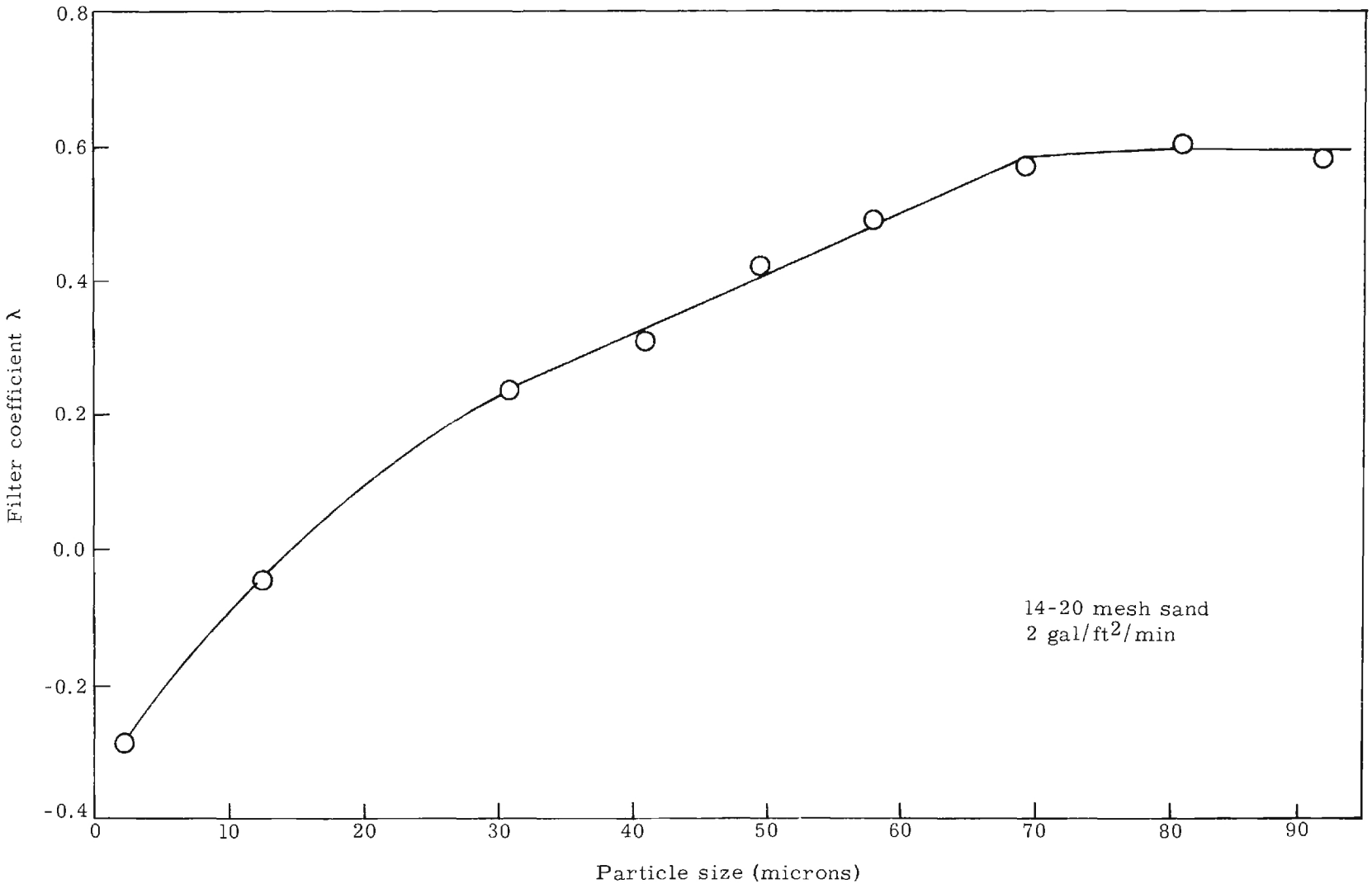

Figure 6. Filter Coefficients for Vermiculite Particles in 14-20 Mesh Sand

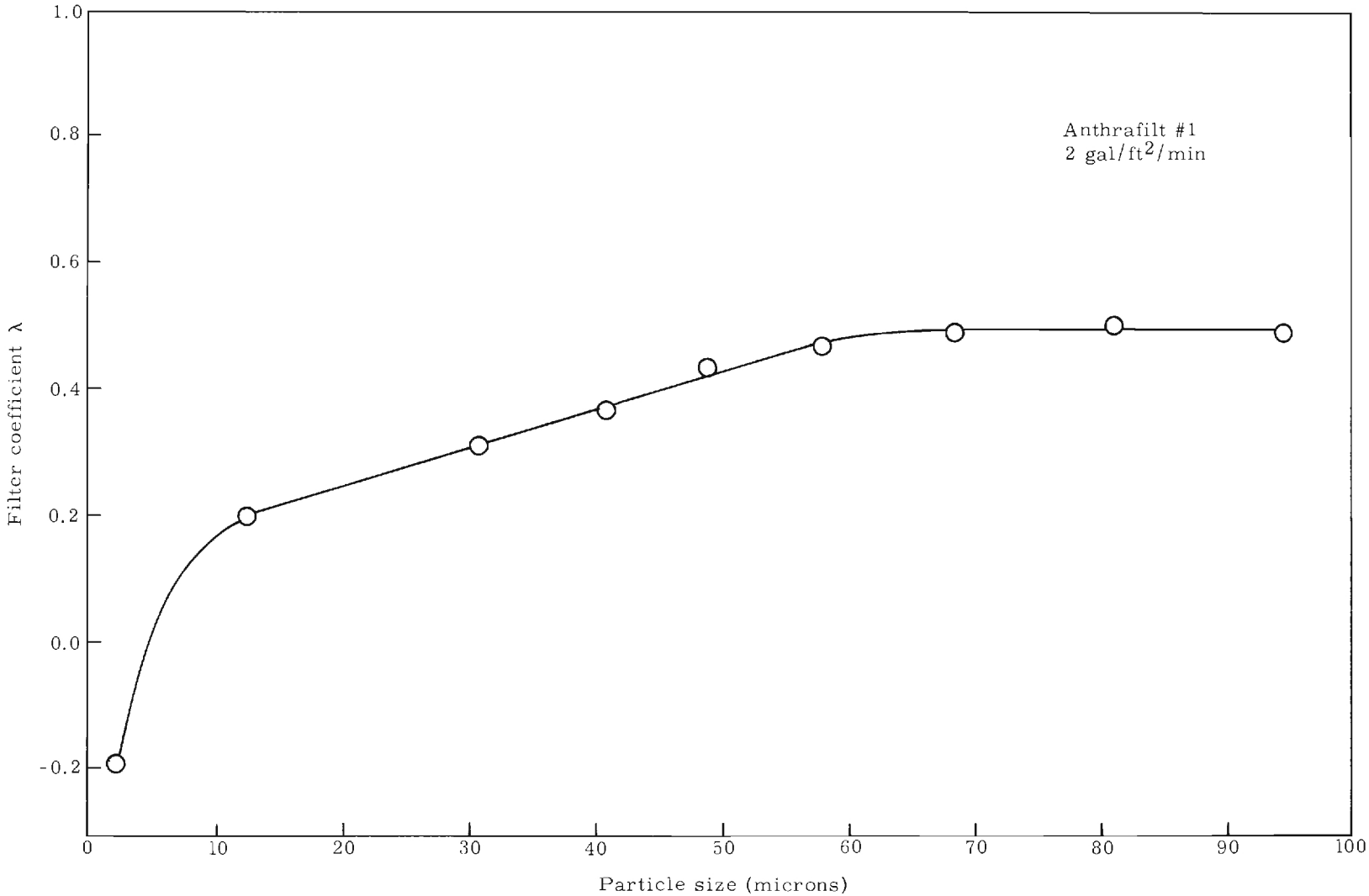

Figure 7. Filter Coefficients for Vermiculite Particles in Anthrafilt No. 1

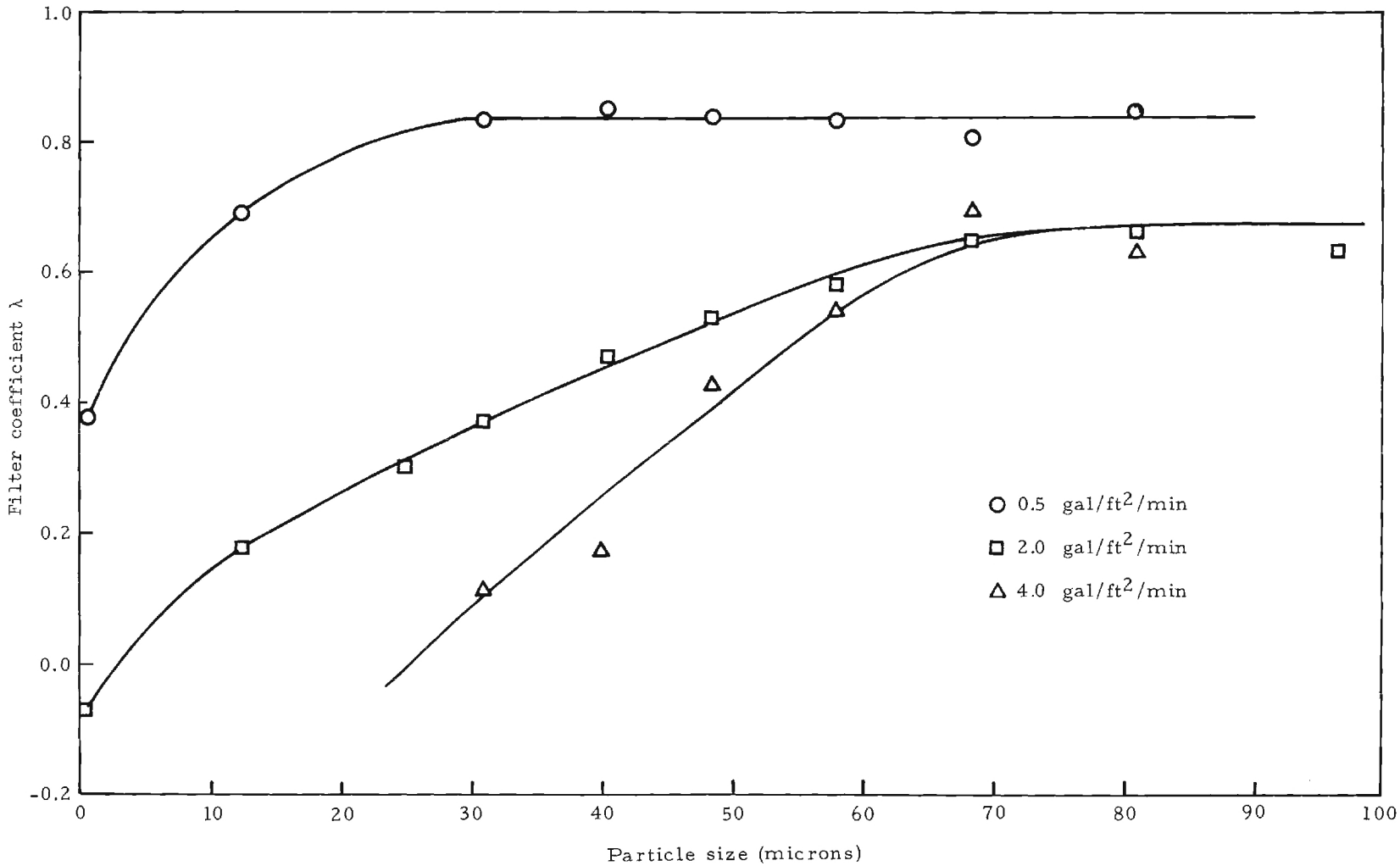

Figure 8. Filter Coefficients for Vermiculite Particles in 30-40 Mesh Sand at Various Flow Rates

Effect of Particle Size

Figures 9, 10, 11, and 12, consisting of linear plots of total counts, C, versus position in the filter bed for representative particle sizes represent the actual pattern of deposition of suspended matter within the filter and illustrate the effects of particle size on activity profiles. In each case, the greatest penetration of the bed was by the particles of smallest size and penetration decreased with progressively larger particles. In Figure 9, the profile produced by all particle sizes larger than 25 μ is approximated by the curve for 53-63 μ particles. Plots of the other profiles are omitted for the sake of clarity. The same situation prevails in Figures 10 and 12 where the 25-37 μ curve represents all larger particle sizes. There were greater differences between the profiles produced by different particle size ranges in the 14-20 mesh sand illustrated in Figure 11. Those omitted from this figure were in the approximate region of the 44-53 μ and 63-74 μ curves.

When comparison between figures is made, it is found that the profile for a given particle size range is not constant but is subject to variation. This difference is due to differences in the filter bed grain size. These findings were expected, as there is no apparent reason that porous media with different characteristics should yield identical profiles even if the particles involved are the same in each case; however, in view of the similarities of the mechanisms, curves of comparable character would be expected.

If particle deposition is exponential with depth as is generally assumed, the profile curves should plot as straight lines on a semi-log grid. Accordingly, semi-log plots were prepared for a number of different particle size ranges in each medium; Figure 13 is typical. In most cases, these curves are essentially linear for depths of one to five inches. The lack of linearity in the first inch of depth, particularly for the smallest particles, is

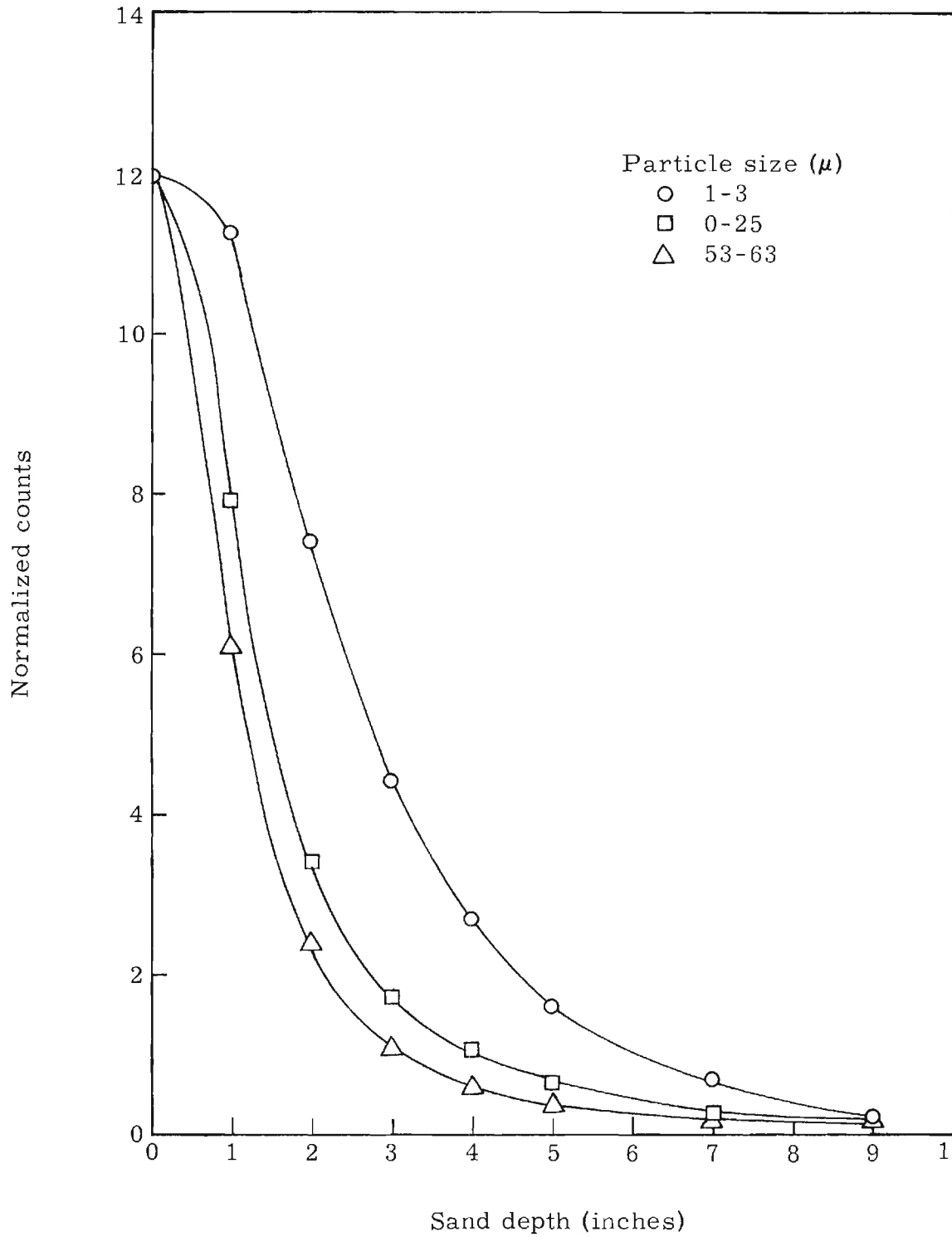

Figure 9. Activity Profiles in 40-60 Mesh Sand at 2 gal/ft^2/min

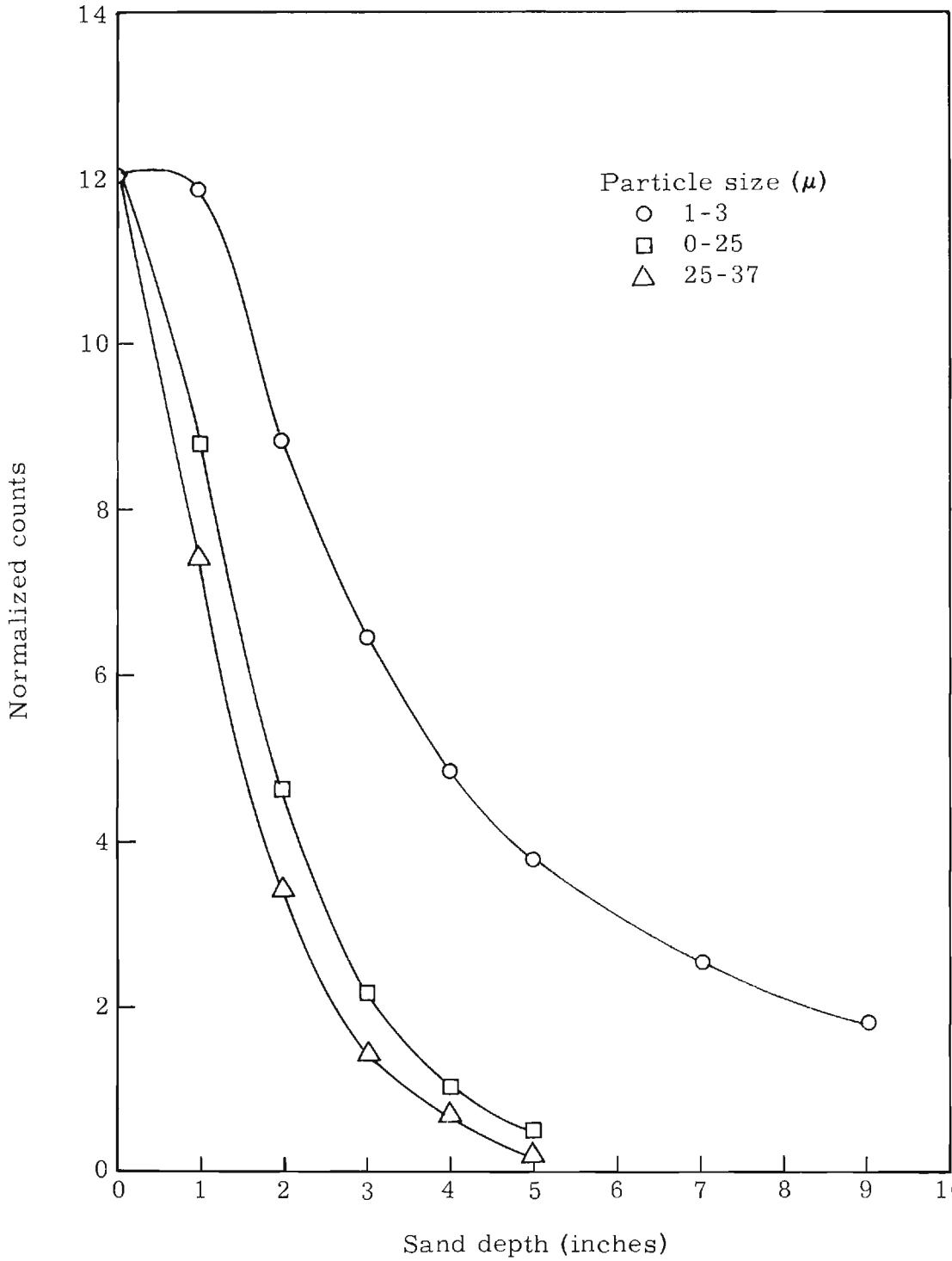

Figure 10. Activity Profiles in 20-30 Mesh Sand at 2 gal/ft^2/min

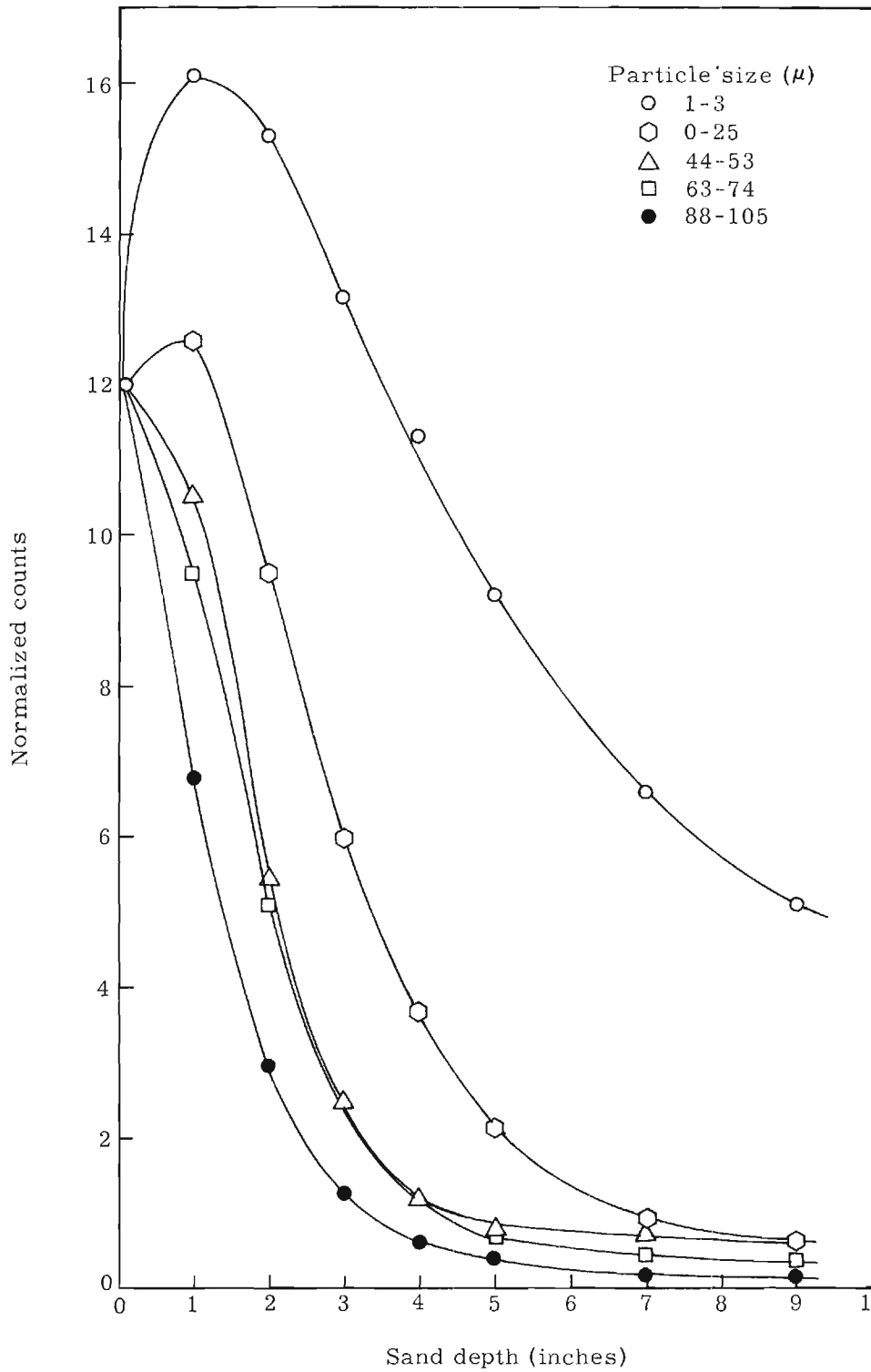

Figure 11. Activity Profiles in 14-20 Mesh Sand at 2 gal/ft^2/min

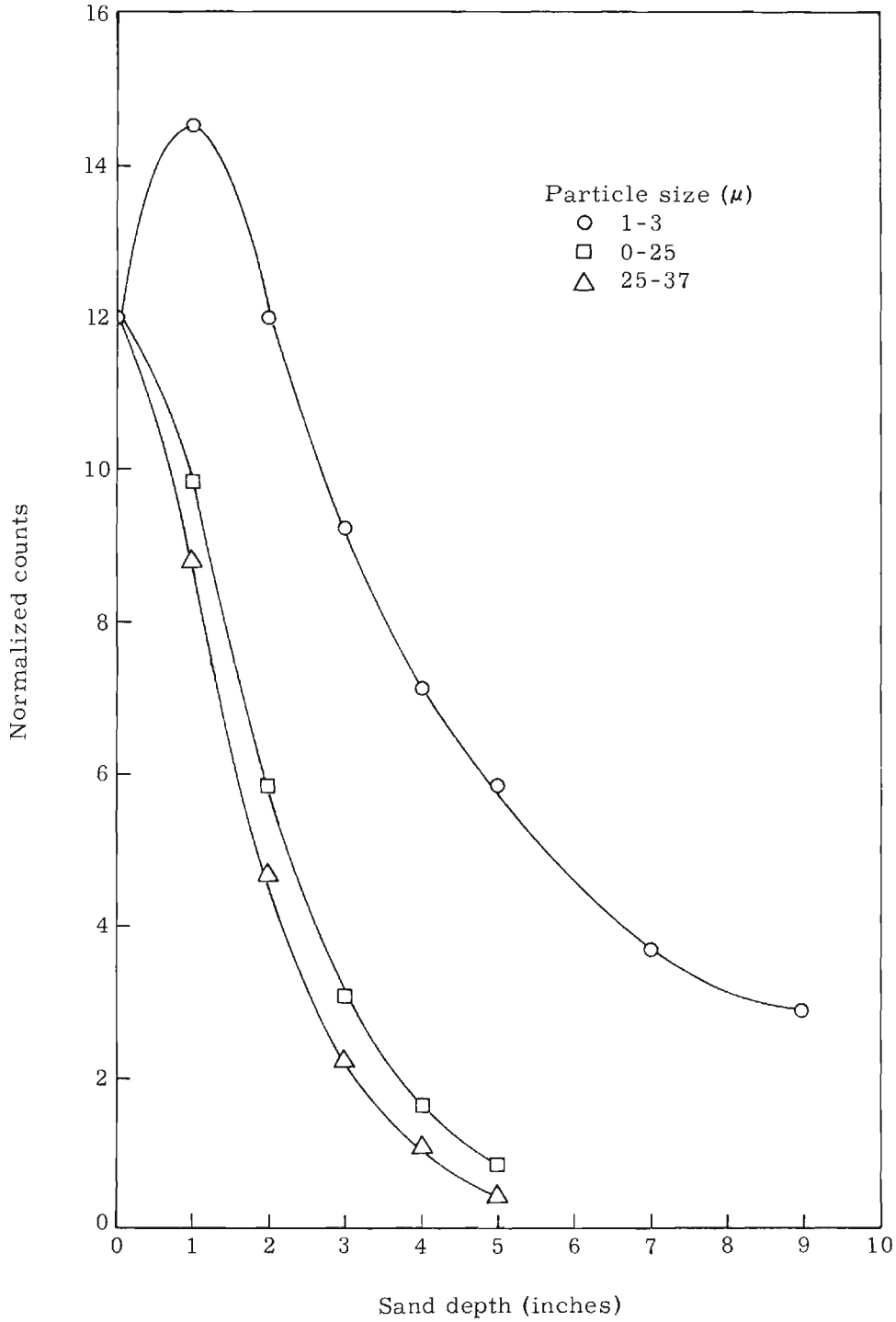

Figure 12. Activity Profiles in Anthrafilt No. 1 at 2 gal/ft^2/min

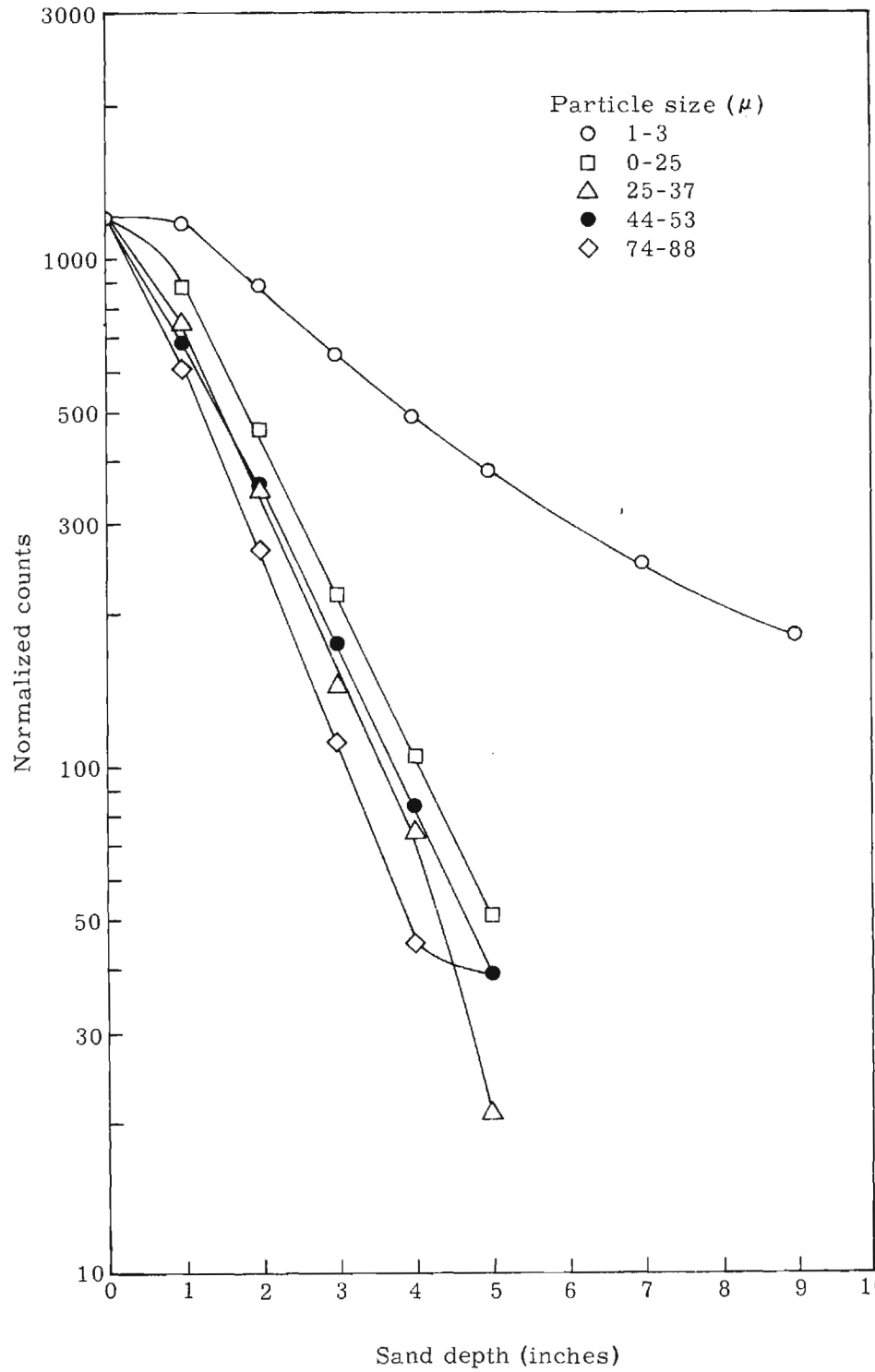

Figure 13. Semi-log Plot of Activity Profiles in 20-30 Mesh Sand at 2 gal/ft^2/min

attributed to geometrical considerations involved where there is much penetration. Below the five inch depth the actual count rate was quite low and was about the same order as the background. Little significance can therefore be attached to the values obtained at the lower levels of the filter. The expectation of an exponential pattern of removal, at least over a specific range, is therefore confirmed.

The time relationship of observed counts was examined in plots such as Figure 14, where the total number of counts at various levels is shown as a function of time. It is seen that a steady level is obtained within minutes of starting the test and there is no subsequent displacement of the particles as flow continues. The random fluctuations around the steady level shown by these values are well within the range of normal statistical variation.

The exact relationship of bed grain size and filter coefficient has been the subject of discussion in the literature. The data obtained in this study were consequently plotted in a manner so that this relationship could be examined. In Figure 15, it may be seen that this relationship depends to a considerable degree on the particle sizes involved. The only straight lines observed are for the 63-74 μ and 74-88 μ particles, and the latter is questionable due to an exceptionally high value (0.78) for λ in the 250 μ (40-60 mesh) sand. Referring to Figure 4, it seems more likely that this value should be about 0.72, which would produce the dotted line included in Figure 15. The filter coefficient as measured in this study therefore appears as a linear function of sand grain diameter only for 63-74 μ particles. A severe limitation is imposed on the interpretation of these plots due to the availability of only three points for each curve, but it is clear that the size of the suspended particles is a factor.

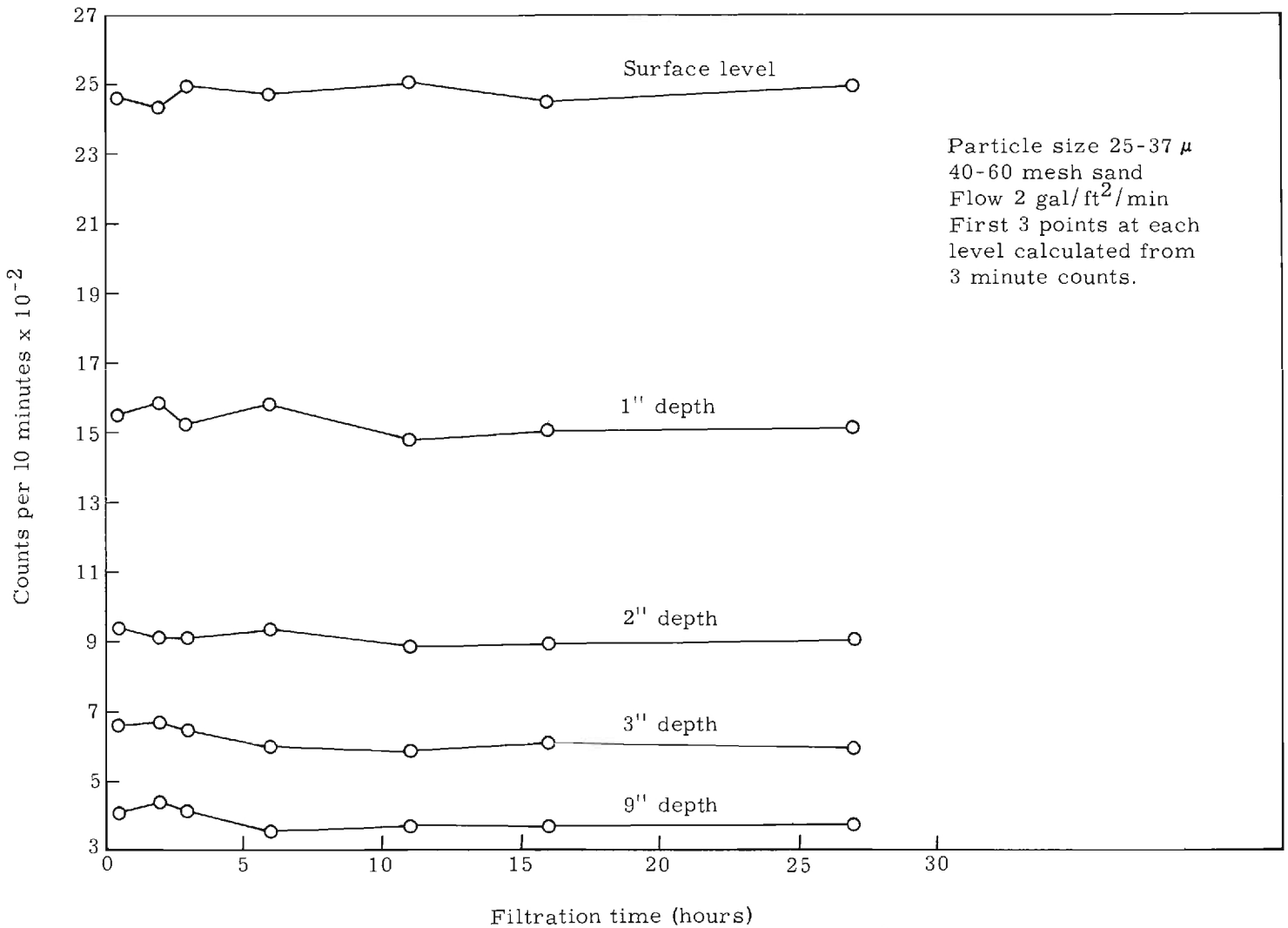

Figure 14. Typical Count Variations at Different Sand Levels

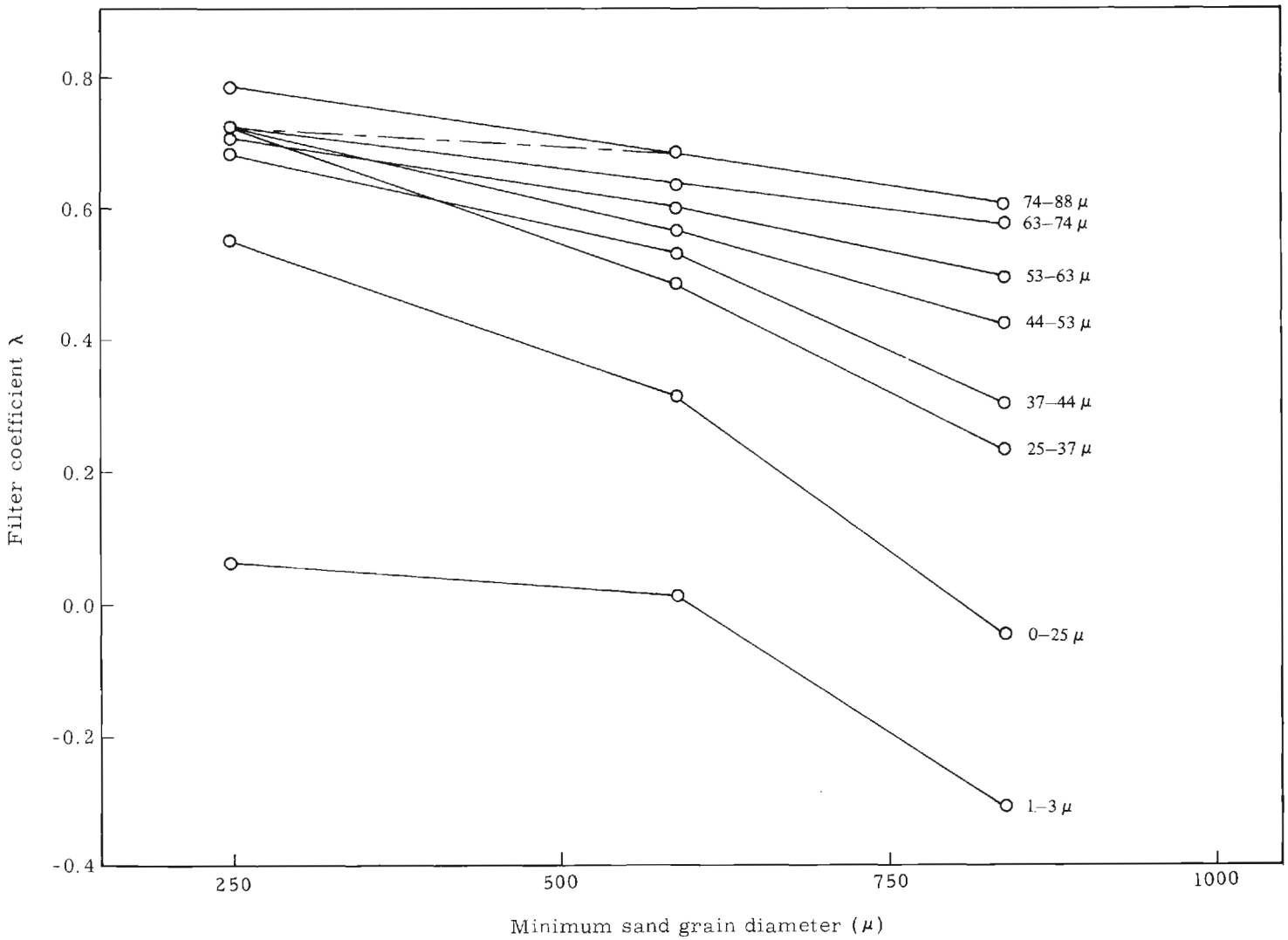

Figure 15. Filter Coefficients at 2 gal/ft^2/min for Minimum Sand Grain Diameters

Effect of Flow Rate

An extended series of experiments were performed to determine the relationship of filter coefficient to flow rate, other factors being held constant. The medium was 30-40 mesh sand and flow rates of 0.5, 2.0, and 4.0 gal/ft^2/min were selected. Deposition of radiotracer particles in a number of different size fractions was observed at each of the flow rates.

Figure 8 presents in graphic form the filter coefficients determined. Sand of this size should theoretically pass spheres of 65 μ diameter, and a constant coefficient value for all particles larger than 65 μ is to be expected. This supposition is confirmed in that at flow rates of 2 and 4 gal/ft^2/min the coefficients are constant in this region. But the coefficients are constant at the 0.5 gal/ft^2/min flow rate down to particles of only 30 μ in diameter.

The magnitude of the coefficients indicates that most of the deposited tracer has come to rest on the sand surface, a situation probably due to gravitational sedimentation of the particles. It is concluded that there is insufficient hydrodynamic force at the low flow rate to cause penetration of the bed by any except the smallest particles. The limit of gravitational action would be at zero flow rate, in which case the filter coefficient would be independent of particle size as all particles would simply settle on or very close to the surface of the porous medium.

The shape of the curve for a flow rate of 2 gal/ft^2/min is very similar to that for the same rate in 20-30 mesh sand which is shown in Figure 5. Three different slopes can be identified signifying the same general considerations.

For a flow rate of 4 gal/ft^2/min the curve exhibits some of the characteristics of the 2 gal/ft^2/min curve, but the two are not identical. Above a certain particle size there appears to be no significant penetration of the bed regardless of flow rate. This is certainly logical if the particles are

indeed larger than the openings. For particles small enough to enter the interstices of the medium, the hydrodynamic force of the flowing water serves to force the suspended particles deeper into the bed. This may be due to the change in the shape of the velocity parabola which would tend to increase the flow rate in the forward direction, allowing less time for lateral dispersion into parts of the flow stream where capture can occur.

A second complete run was made at 4 gal/ft^2/min and the shape of the curve obtained was in agreement with the initial results. There was, however, a slight displacement of the actual values, but this was probably due to a slight difference in the compaction used in the two sets of experiments. No precise mathematical expression relating velocity, particle size, and filter coefficient can be derived from these data, but it is apparent from Figure 8 that for particles small enough to penetrate the filter medium, the filter coefficient varies inversely with flow rate.

Effects of Dissolved Activity

To compare the action of the filter medium on particulates and dissolved materials, the effects on the filter effluent and the filter medium due to passage of dissolved activity through a filter were investigated. A sudden influx of dissolved radioactivity was caused by pouring a solution of cesium-137 chloride into the influent of the experimental filter, which contained 20-30 mesh sand, in order to simulate the sudden arrival of a slug of radioactivity such as might occur following an upstream accident. The resulting activity was monitored by two Geiger counters, one placed inside the filter bed and one immersed in the filter effluent line. Readings were recorded continuously.

Figure 16 shows the results after the background was subtracted and the data were normalized to a constant area under the curves. Curve A illustrates

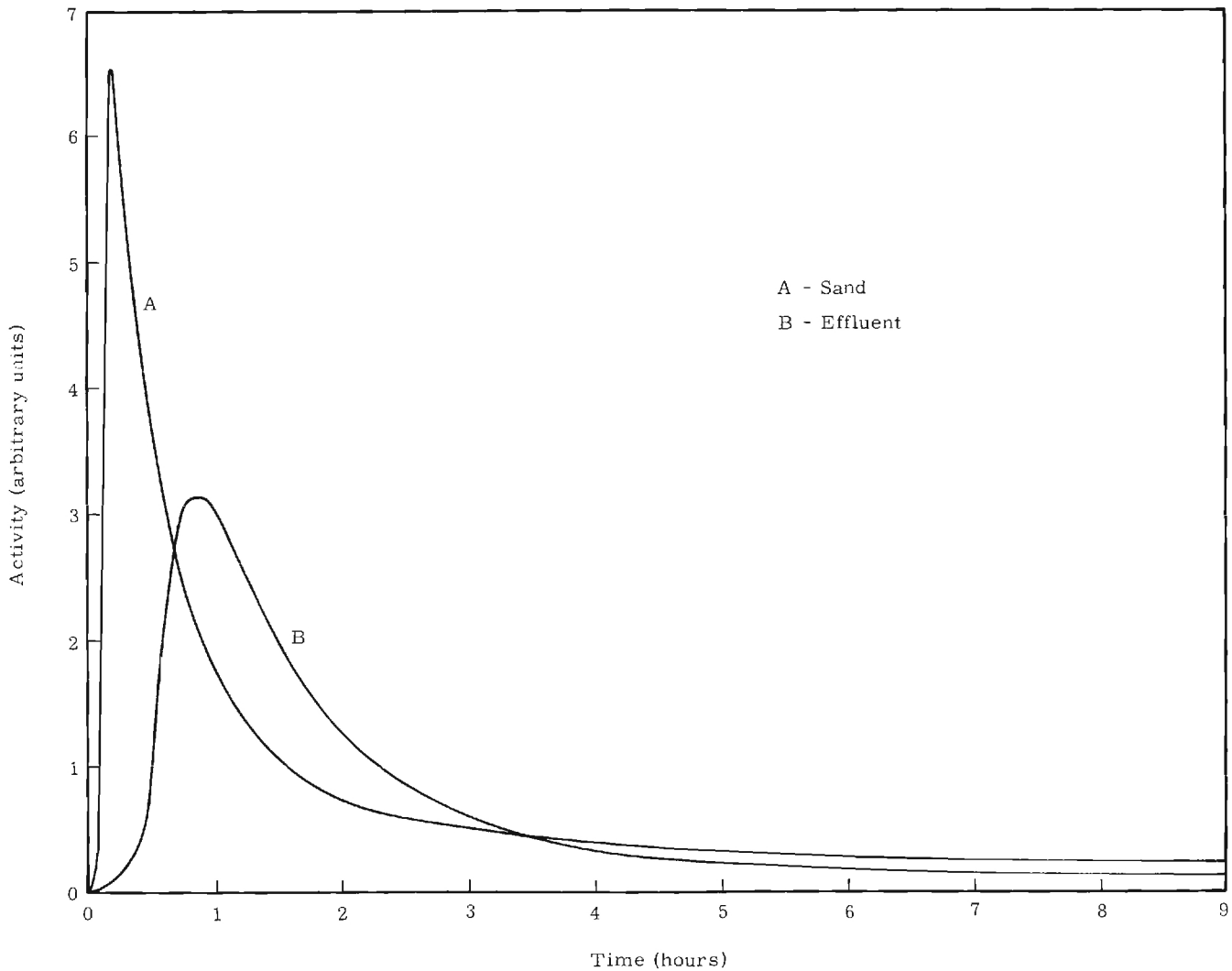

Figure 16. Time-Activity Relationships for Effluent and Filter Bed

the rise and fall of the activity level within the sand bed and curve B gives similar information on the filter effluent. From the initial background level denoted by zero on the activity scale, the activity level in the sand (curve A) is seen to rise very abruptly as the radioisotope begins to enter the sand. A sharp maximum is reached in less than 30 minutes, and thereafter the curve decreases rapidly for a time and then at a more gradual rate. The activity becomes almost constant after six hours.

Activity of the effluent (curve B) follows a somewhat similar pattern, but at a time later than that of the sand. The delay in arrival of activity at the filter exit is due to 1) the time required for liquid to pass through the filter and 2) the capacity of the filter to sorb and retain activity. Sorption by the sand is proportional to concentration of dissolved matter in the liquid, so that a portion of any entering activity will be retained so long as the concentration is increasing and the storage capacity of the sand is not exceeded. If the effluent concentration remains constant, an equilibrium is established and no further changes take place.

The effect of dissolved activity on different bed materials was observed in another test where samples of the filter media were exposed to dissolved activity resulting from the presence of uncalcined labeled particles.

A 1.5 gram sample of 88-105 μ vermiculite was stirred for two hours with a Cs-137 solution, and another sample was treated in the same manner with an I-131 solution. In each case, the particulate matter was then washed repeatedly by stirring with tap water and decanting.

The particles were stirred for 30 minutes with 10 grams of washed Anthrafilt No. 1 in about 500 ml of water. The mixture was then allowed to stand approximately 70 hours. A sample of the supernatant was removed, the Anthrafilt washed free of visible vermiculite particles, and five ml portions of

both the supernatant and the Anthrafilt were counted in a well-type scintillation crystal.

Under the conditions of this experiment, the activities of the wash waters were very similar and the final count rates of the supernatants were essentially identical. Under equilibrium conditions, however, the Anthrafilt had sorbed almost 17 times more Cs-137 activity than I-131 activity indicating a strong affinity for cations. Actual values are shown in Table 5.

Table 5. Isotope Sorption by Anthrafilt
(gross counts per minute)

Sample	Cs-137	I-131
Final wash water	565	157
Supernatant	6,050	5,946
Anthrafilt	267,427	16,412

In another experiment, the affinity of the Anthrafilt for the I-131 was quantitatively determined. A 40 gram sample of washed Anthrafilt No. 1 was put into a beaker containing about 500 ml of water. Iodine-131 was added, the mixture stirred for an hour and allowed to stand overnight. The supernatant was decanted and the activity of a sample of the Anthrafilt was determined with the well-crystal scintillation counter. The Anthrafilt was then washed by vigorous stirring with tap water, allowing it to stand several minutes, and decanting the supernatant. The activity of the Anthrafilt was measured several times, and the results are shown in Table 6.

Table 6. Activity of Anthrafilt Exposed to I-131 (gross counts per minute)

Before Addition of I-131	135
After Addition of I-131	3,508
After 4 Wash Cycles	1,830
After 7 Wash Cycles	1,189
After 10 Wash Cycles	606

Phase II

Field Study

The radiotracer experiments performed in the laboratory provided valuable information on the theoretical aspects of rapid sand filtration, but it was recognized from the beginning that carefully controlled laboratory conditions are not necessarily identical with actual field conditions. A major difference lay in the nature of the suspended particles: light, fluffy, floc particles in the actual filtration process and denser vermiculite particles in the laboratory. It was therefore decided to experiment with water that had been treated in a full-scale operation and was ready for filtration.

Through the splendid cooperation of the Atlanta Water Works, small-scale filters were installed at the Hemphill Water Treatment Plant. These were located so that water could be piped directly to them from the main line feeding water to the plant filters. Before arriving at the filters this water (known to the cognoscenti as "coag water") has passed from the Chattahoochee river into a reservoir with approximately 10 days detention period. Chemical treatment involves liquid alum, plus lime and carbon as needed. After flocculation

and sedimentation, the turbidity of the water is about 1 ppm. A microscopical examination of this water showed that the majority of particles present were smaller than 4 μ in diameter, although there was present an occasional agglomerate in the range of 25-40 μ diameter. Figure 17 is a histogram of the observed particle sizes.

Several filter runs were made to evaluate the effectiveness of closely graded sand, anthracite, the regular filter sand being used by the water works, and a combination of sand plus anthracite. The effect of reverse grading of the water works sand was also determined.

A filtration run was made using a portion of the 20-30 mesh sand previously used in the radiotracer study. Head losses throughout the filter were recorded at the beginning of the run and at later times; the results are plotted in Figure 18. Except for the first inch of bed depth, head loss is initially very close to linear throughout the bed. This indicates a very uniform porosity, which means a very uniform size of sand grain.

During the 30 hours of filtration, changes in head loss occurred only in the top three inches; at lower depths the head loss per inch of depth remained constant. This means that only the top three inches were involved in the removal of particulates after 30 hours. It is believed that progressively lower layers are involved as filtration proceeds, but at 46 hours head loss had increased beyond the capacity of the piezometers, and no readings were possible.

Comparison of Filter Composition

Sand removed from a filter at the Hemphill Plant was used[4] in the comparison of normal versus reverse-graded sand. A portion of this sand was thoroughly mixed by stirring and pouring from one container to another. Alternate scoopfulls of the homogenized sand were then used to fill each of the small filters. As a result of this technique, the particle size distributions

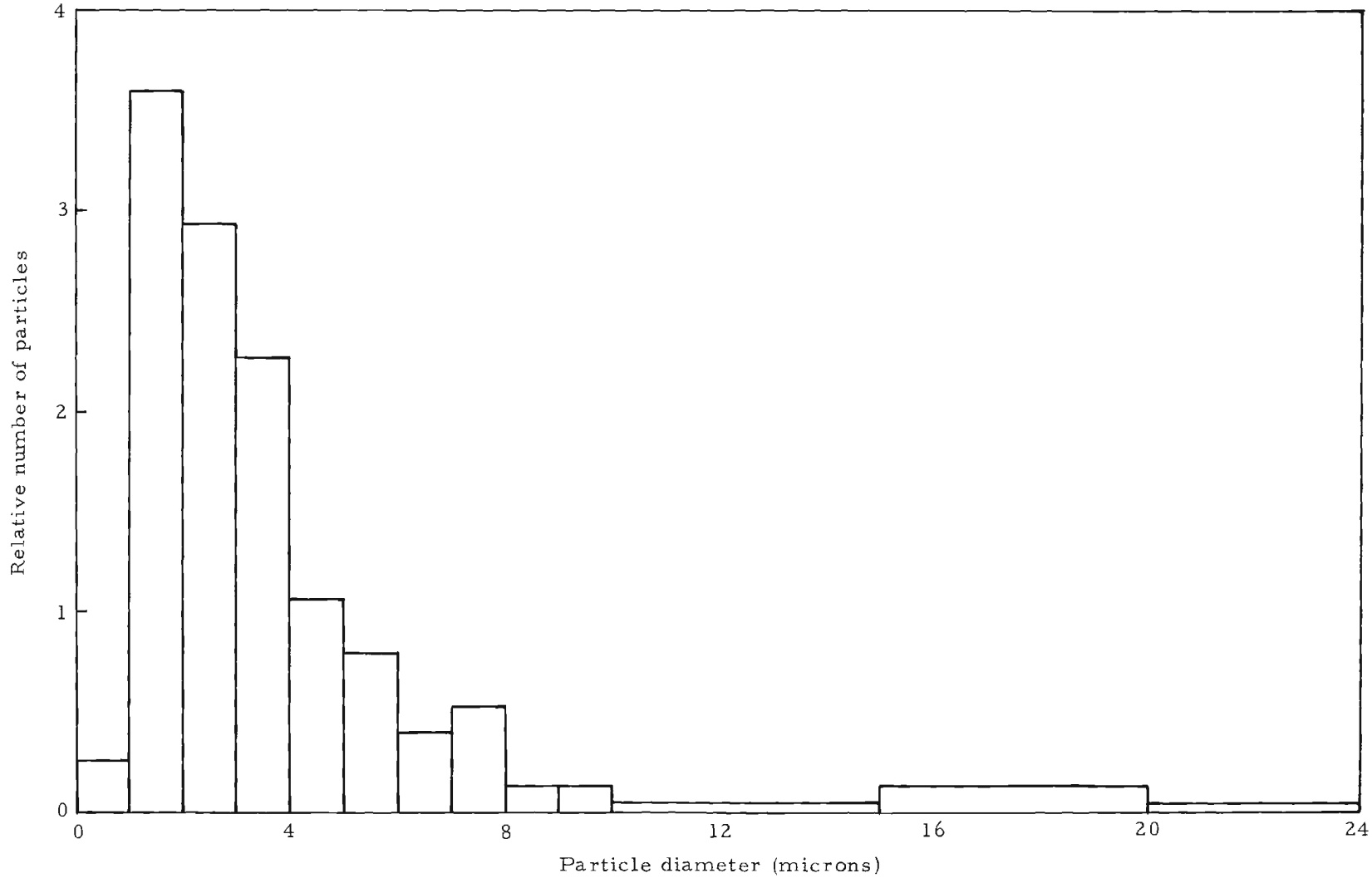

Figure 17. Particle Size Distribution of Atlanta Water Works Filter Influent

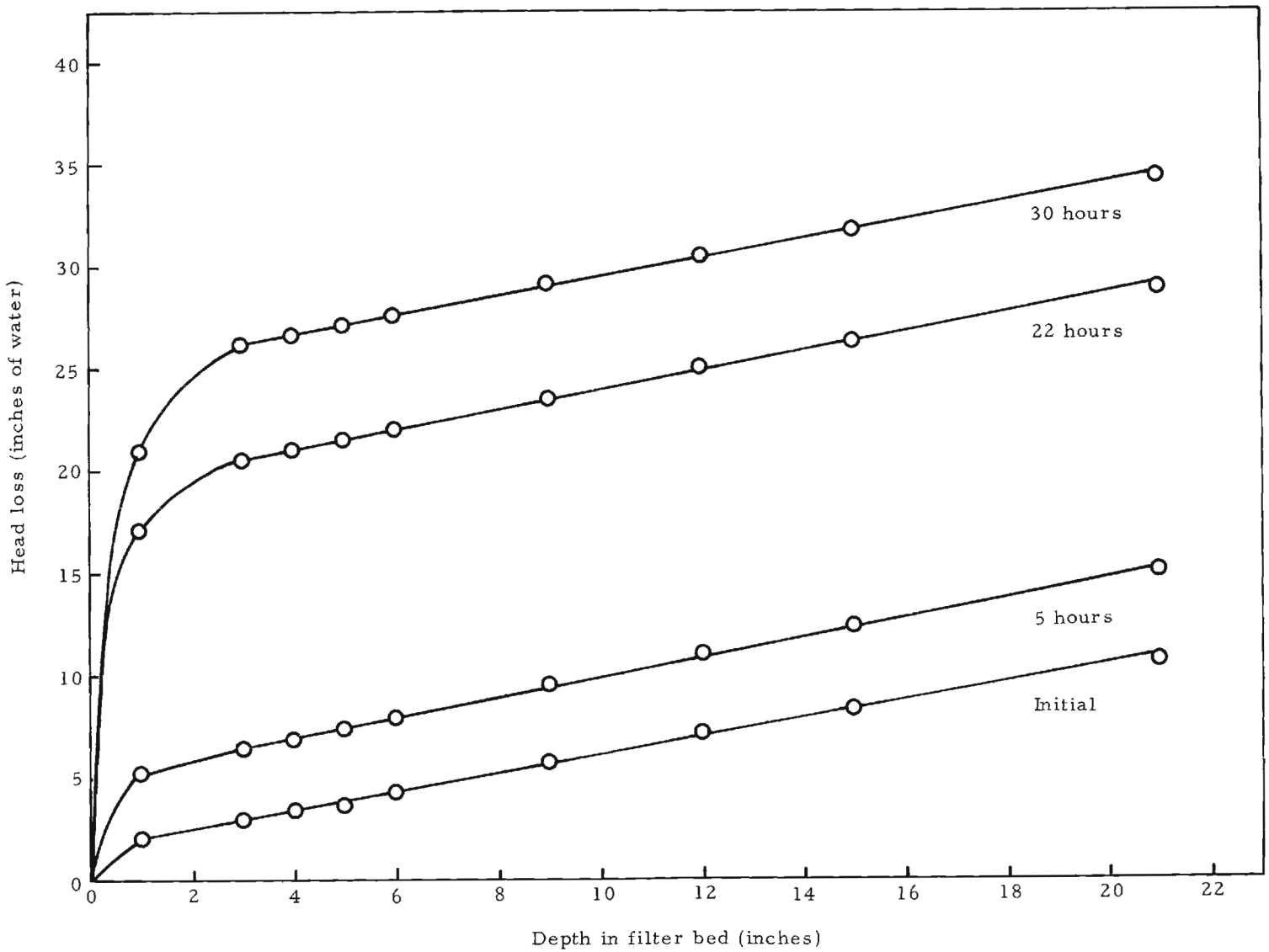

Figure 18. Head Loss in Uniform Sand at Various Times

in the pilot filters were considered identical.

The normally-graded sand was backwashed in the ordinary manner; i.e., water entered the filter at the bottom and exited at the top. Upon completion of backwashing the water was turned off and the sand was compacted by tapping gently on the filter body until the sand surface subsided to a standard level which coincided with the plane of separation at a flanged joint. After this initial compaction, no change in sand surface elevation was ever observed during filtration.

Reverse grading was accomplished in the second filter by first backwashing and compacting the sand in the same manner as in the first filter. Following this, the water level in the filter was lowered until it coincided with the sand surface. The upper portion of the filter was then removed by unbolting the flanged joint, and a 75 mesh screen was placed on top of the sand. The edges of this screen extended into the flange and it was secured by an auxiliary gasket. The upper portion of the filter was then replaced and bolted into position. Water was then admitted from the bottom until the filter was completely filled. Valves at the top and bottom were then closed and the lines to them detached. At this stage the filter medium was held between two screens, and the entire filter could be inverted without disturbing the medium. A set of brackets was provided so that the sand columns in both filters were at the same elevation. Feed and drain lines were attached, and the filter was ready for operation.

Filtration was started at a rate of 2 gal/ft^2/min. As soon as the piezometers reached equilibrium (a matter of a couple of minutes), the elevation of water in each of them was recorded. Successive readings were made at intervals, and the results plotted. Figures 19 and 20 are for the run which was begun on 11-10-69. Here it is seen that the initial total head loss is greater

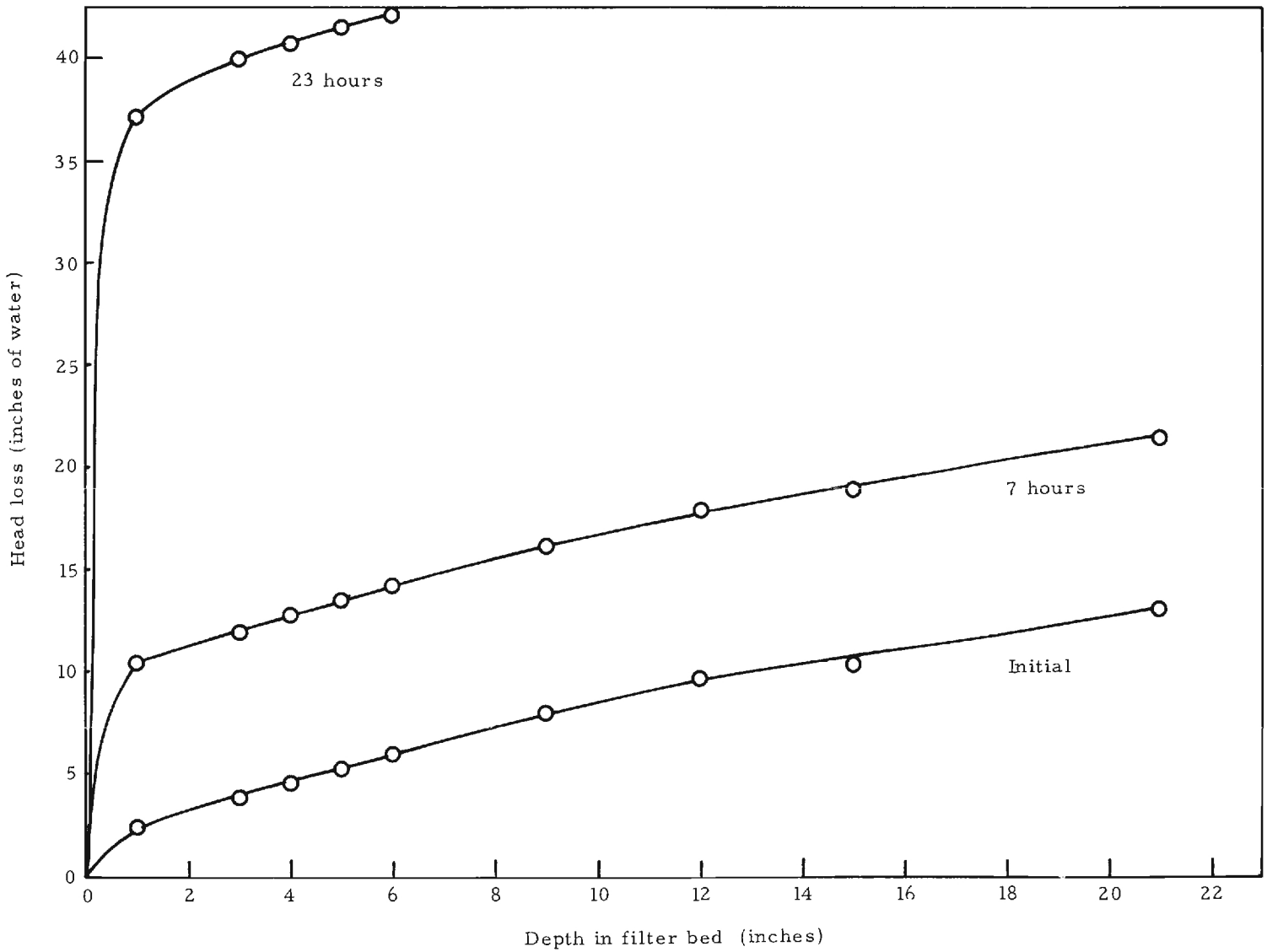

Figure 19. Head Loss in Normally Graded Sand at Various Times

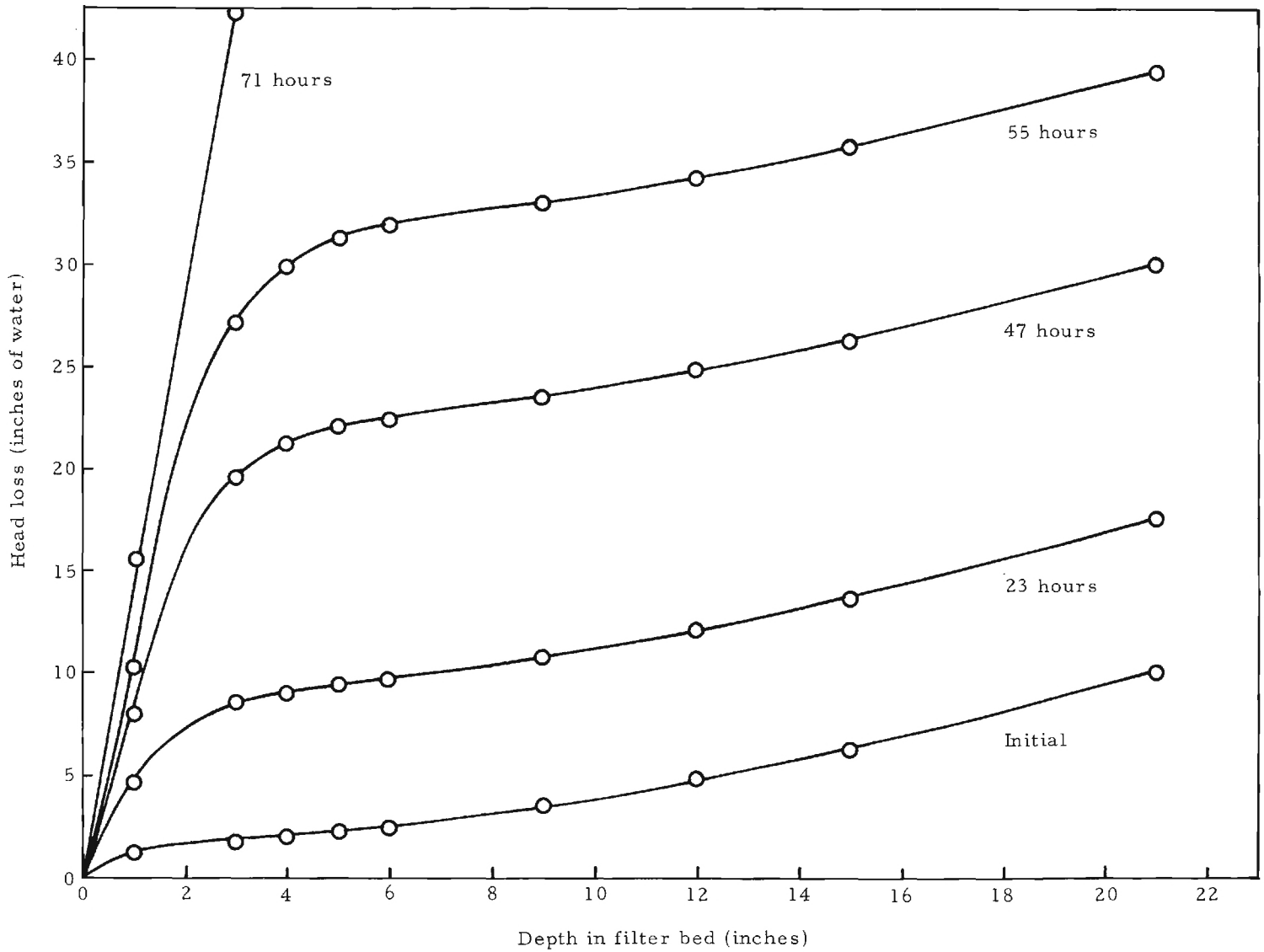

Figure 20. Head Loss in Reverse Graded Sand at Various Times

for normal-graded sand (12 inches) than for the reverse-graded (9 inches). As filtration proceeds, the difference between the two increases. After five hours, for instance, the "normal" loss has risen to 17 inches, while the "reverse" loss has increased only to $10\frac{1}{2}$ inches.

From the standpoint of length of filter runs, it can be seen that the 7 hour head loss of the normal filter is not reached until $30\frac{1}{2}$ hours' operation by the reverse-graded filter. It is not possible to read accurately any losses above 40 inches, and the normal-graded filter exceeded this limit at $22\frac{3}{4}$ hours. This limit had not been reached by the reverse-graded filter when filtration was halted at 54 hours. It is to be noted, however, that the rate of head loss was not constant but increased as filtration proceeded.

It is to be noted also that in the normal-graded filter the loss of head is concentrated in the first inch of sand, whereas in the reverse-graded situation the loss is spread through a greater depth. The actual depth depends on the length of the filter run but is perhaps as much as 6 inches after a run of 54 hours.

From this it is seen that (with reverse-graded sand) a greater proportion of the filter is actively accumulating solids; head loss remains lower because there is no single layer of highly clogged pores to throttle the liquid flow.

The results of this experiment are in accord with those of Oeben, Haines, and Ives[7] who worked with ferric hydroxide floc. They produced their reverse-graded condition by syphoning or spooning backwashed sand from one filter to another. It is believed that the inversion technique produces more uniformity in gradation of the size of the bed particles, but differences between the methods of achieving reverse grading are apparently of no consequence.

The comparison of 20-30 mesh sand with the Water Works sand graded in its normal fashion is instructive. Figure 18 shows a total head loss at 22 hours

of almost 29 inches in the uniform 20-30 mesh sand. Figure 19 for normal sand at 23 hours reveals a head loss far too large to measure but estimated at about 48 inches. The normally graded sand with the smallest particles on top tends to constrict the filter at the top and to concentrate more of the deposited material and, consequently, more of the head loss at the top of the filter bed. Total head loss is lessened in the uniform bed where the deposited load is spread over a greater depth, and there is less constriction in any given layer.

From the practical standpoint of water filtration, it is obvious that reverse grading of sand would be desirable if it could be accomplished easily. However, there is no obvious method for changing either the gravitational or hydraulic forces which produce particle size classification. The methods used by investigators for small-scale situations are not suitable for commercial applications.

Nevertheless, the information is valuable in that it emphasizes the advantage of having a coarse medium at the top of the bed and finer material at the bottom. This can easily be accomplished by the use of two materials of different density. Sand and Anthrafilt are a common combination, and head losses for such a "half and half" filter bed are shown in Figure 21. When the bed is clean (initial condition) it may be seen that head loss per unit depth is slightly greater for the sand (depth greater than 12 inches) than for the Anthrafilt (depth less than 10 inches). There is no sharp inflection in the curve as the difference is not markedly different and there is a transition zone between the 10 and 12 inch depths where there is intermingling of the two media.

The sand plus Anthrafilt bed is clearly a more efficient arrangement than reverse graded sand alone and is much superior to normally graded sand. Head losses at the six inch bed depth at 23 hours are 42 inches in normally-graded

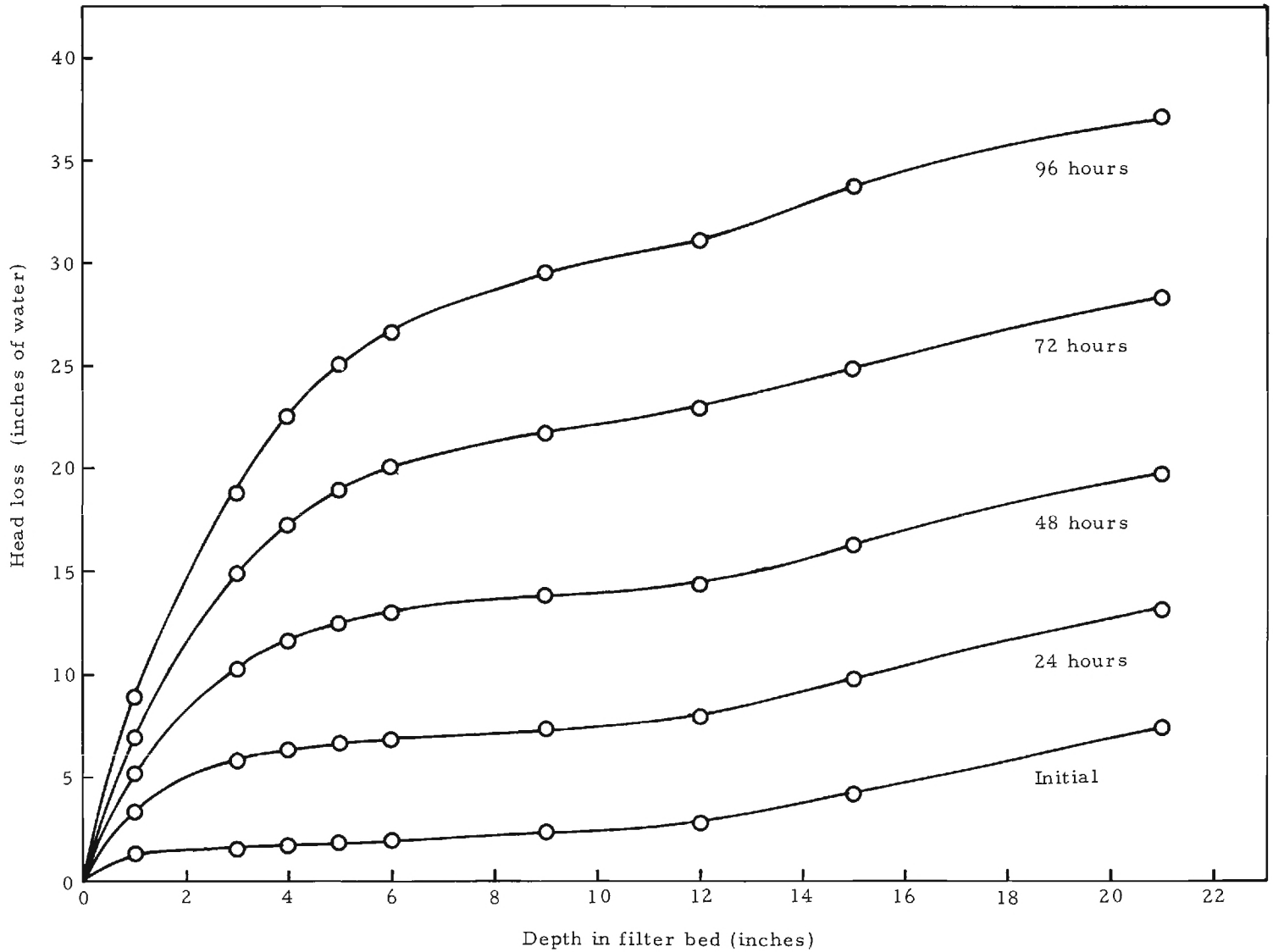

Figure 21. Head Loss in Sand Plus Anthracite at Various Times

sand, 9½ inches in reverse-graded sand, but less than 7 inches in the mixed medium.

To evaluate the situation more fully, a bed consisting of Anthrafilt alone was prepared and tested; Figure 22 summarizes the result. While these data show Anthrafilt to be superior to either normally- or reverse-graded sand alone, the mixed media bed was the best investigated. This is because the loss of head is more linear with depth, indicating that particle deposition is taking place throughout a greater fraction of the bed depth. It is believed that this gives an advantage from the standpoint of the hydraulics involved. If there is a layer where pores are clogged to a high degree, flow through such a layer must be at a higher rate than through subsequent layers where there is more void space. In the limiting case, turbulence could result, but even before the onset of turbulence there could be a deviation in the flow regime away from the strictly laminar condition.

It is to be noted that the total head loss across the entire depth of the bed is somewhat different for Anthrafilt and Anthrafilt-sand. Due to the lower porosity of the sand layer, the initial head loss is higher for the combination but increases at a lower rate; there is no significant difference between the two beds after 96 hours of filtration.

All of the data presented above are based on flow rates of 2 gal/ft^2/min. The influent consisted in all cases of the coagulated water that was entering the filters of the 1923 plant of the Hemphill Water Treatment Plant. This flow is monitored continually by personnel of the plant laboratory, and at no time during the experimental runs did the turbidity exceed 1 ppm. The turbidity of the effluent from the experimental filters was typically in the range of 0.01 to 0.05 ppm, and only a few values as high as 0.1 were ever observed. All these turbidities are highly acceptable with respect to the requirements

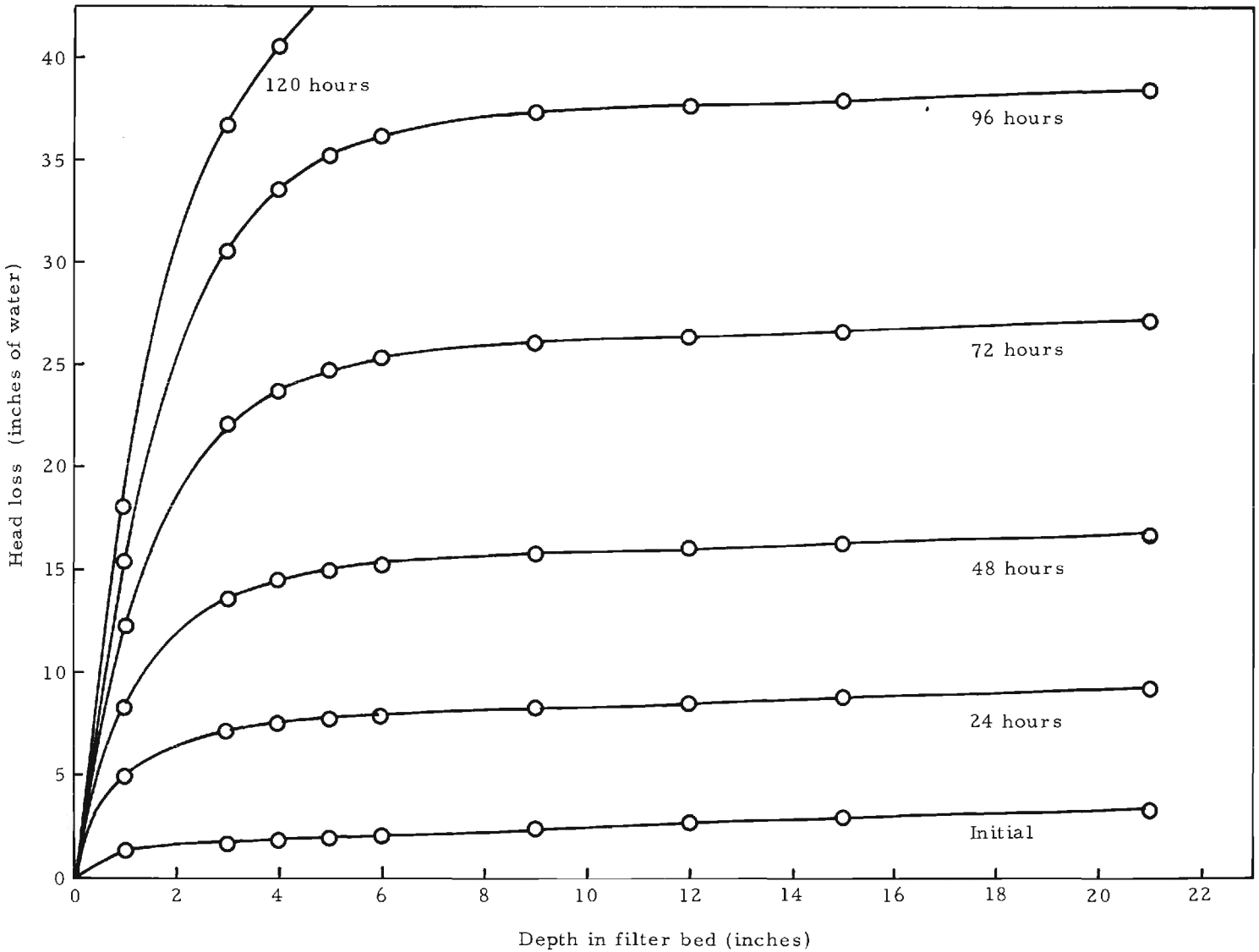

Figure 22. Head Loss in Anthracite at Various Times

of the Drinking Water Standards of 1962, which call for a turbidity not to exceed 10 ppm.

While rate of head loss is an important factor, there are other matters that should be considered in the choice of a filter medium. Traditionally sand filters have been known for their reliability in producing acceptable effluents even when the quality of the influent is poor. This is indeed important, for even in the best regulated water treatment plants equipment failure, sudden fluctuation in raw water quality, or human error can occur with the result that poor quality water reaches the filter. In such a circumstance it is desirable to have a medium capable of withstanding a shock load of high turbidity, and sand is superior to Anthrafilt in this respect.

Based on the studies of sand and Anthrafilt reported here, it is concluded that the most desirable situation is a combination of sand and Anthrafilt. Second is Anthrafilt alone, followed by reverse-graded sand, uniform sand, and then normally-graded sand.

CONCLUSIONS

The theoretical aspects of filtration through a porous medium were emphasized in the initial phase of this study. Through use of the radiotracer technique it was possible to determine the concentration of suspended particles which were deposited at various elevations within the filter. It was clearly shown that deposition occurs in an exponentially decreasing manner. This observation is in agreement with the usual assumption, first noted by Iwasaki,[8] that filtration may be regarded as a first order reaction.

From a measurement of the concentration of deposited tracer material on the surface and at a given depth in the filter bed, the filter coefficient was calculated. This coefficient has a definite physical significance as a measure of filter operation; it is directly proportional to the percentage of suspended matter removed by each layer of the filter. Filter coefficients were determined for suspended particles of different sizes when they were filtered by uniform sand and anthracite beds. Plots of filter coefficient against size of suspended particle were most useful in interpreting the mechanisms involved in the filtration process. It was shown[6] that the shape of the curves such as that of Figure 5 is due to the successive predominance of three different mechanisms. The particular mechanism by which a given particle is trapped in a porous medium is determined primarily by the size of the particle.

Physical hindrance traps on the surface those particles which are too large to pass through the interstices of the porous material. Particles very small in relation to the size of the interstices are governed mainly by physicochemical forces, namely the van der Waals force and the double layer forces. Particles with sizes between these two extremes are trapped through the process of interstitial sieving, which was initially detailed by Hall.[9]

There is a gradual transition between applicable mechanisms; electrical and mechanical forces both may be influencing a given particle, but their relative effectiveness depends on the particle size. The transition is also accentuated experimentally because neither the suspended particles nor the bed media were absolutely uniform in size or shape.

The experimental evidence shows clearly that the mechanical mechanisms are more efficient and should be utilized whenever possible. This implies use of a finer-grained filter medium; however, the head loss would be greater and filter runs shorter. Aside from these very practical considerations, there are logical reasons that suggest that media with lower filter coefficients are actually more effective when all factors are considered.

The ultimate efficiency would involve a filter coefficient of 1, all suspended matter being trapped in the first layer. In this case the top layer would present a zone where interstitial spaces were lessened due to deposited matter and flow would be hindered. Actually it would be preferable to have a somewhat less efficient medium so that appreciable deposition can take place in the lower layers of the medium. Clogging of the medium is then delayed, and filter runs are thereby lengthened.

These conclusions are supported by the experiments of the second phase of this study. Any combination or configuration that spreads the accumulating solids over a greater depth is advantageous from the standpoint of length of filter run. This spreading of the deposit is enhanced by larger grained media and uniformly sized media.

The results obtained here show that reverse-graded sand is superior to normally-graded sand. Grading occurs during backwash, and it is the combination of gravitational and hydraulic forces that produces a bed with the smallest grains at the top and the largest grains at the bottom. It would be advantage-

ous to reverse this order, but no engineering solution to this problem is presently available.

Based on the experimental runs utilizing commercially prepared pre-filter water, a combination of ground anthracite plus sand was found to be the best filter medium tested. Use of the coarser anthracite means less head loss per unit time and therefore potentially longer filter runs. Anthracite alone would be acceptable under ordinary operating conditions, because it lowers turbidity as effectively as sand, but it is considered to be less reliable when there is a sudden worsening of the quality of the filter influent. Such changes in filter influent may be rare, but because of the fallibility of man and machine they do occur.

Cost is an omni-present factor in design, and medium selection may well be influenced by it. Geographical location may have a considerable influence on relative costs due to freight charges involved, but in the final analysis, the designer himself must make a decision concerning the cost-benefit ratio. However, in the absence of compelling influences, it is felt that the optimum filter medium of those tested is the combination of anthracite and sand.

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