A STUDY OF METHODS USED IN

MEASUREMENT AND ANALYSIS OF SEDIMENT LOADS IN STREAMS

REPORT NO. 11

THE DEVELOPMENT AND CALIBRATION OF THE VISUAL-ACCUMULATION TUBE

1957

A Study of Methods Used in

MEASUREMENT AND ANALYSIS OF SEDIMENT LOADS IN STREAMS

A Cooperative Project

Sponsored by the

Subcommittee on Sedimentation
Inter-Agency Committee on Water Resources
(Formerly Federal Inter-Agency River Basin Committee)

Corps of Engineers ** Geological Survey
Soil Conservation Service ** Bureau of Reclamation
Agricultural Research Service ** Coast and Geodetic Survey
Tennessee Valley Authority ** Federal Power Commission
Forest Service

REPORT NO. 11

THE DEVELOPMENT AND CALIBRATION OF THE VISUAL-ACCUMULATION TUBE

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The cooperative study of methods used in

MEASUREMENT AND ANALYSIS OF SEDIMENT LOADS IN STREAMS

covers phases indicated by the following report titles.

Report No. 1

FIELD PRACTICE AND EQUIPMENT USED IN SAMPLING SUSPENDED SEDIMENT

Report No. 2

EQUIPMENT USED FOR SAMPLING BED LOAD AND BED MATERIAL

Report No. 3

ANALYTICAL STUDY OF METHODS OF SAMPLING SUSPENDED SEDIMENT

Report No. 4

METHODS OF ANALYZING SEDIMENT SAMPLES

Report No. 5

LABORATORY INVESTIGATIONS OF SUSPENDED-SEDIMENT SAMPLERS

Report No. 6

THE DESIGN OF IMPROVED TYPES OF SUSPENDED-SEDIMENT SAMPLERS

Report No. 7

A STUDY OF NEW METHODS FOR SIZE ANALYSIS OF SUSPENDED-SEDIMENT SAMPLES

Report No. 8

MEASUREMENT OF THE SEDIMENT DISCHARGE OF STREAMS

Report No. 9

DENSITY OF SEDIMENTS DEPOSITED IN RESERVOIRS

Report No. 10

ACCURACY OF SEDIMENT SIZE ANALYSES MADE BY THE BOTTOM-WITHDRAWAL-TUBE METHOD

Report No. 11

THE DEVELOPMENT AND CALIBRATION OF THE VISUAL-ACCUMULATION TUBE

Report No. 12

SOME FUNDAMENTALS OF PARTICLE-SIZE ANALYSIS
(In preparation for publication)

Report A -- PRELIMINARY FIELD TESTS OF THE U. S. SEDIMENT-SAMPLING EQUIPMENT IN THE COLORADO RIVER BASIN APRIL 1944

Report B -- FIELD CONFERENCES ON SUSPENDED-SEDIMENT SAMPLING SEPTEMBER 1944

Report C -- COMPARATIVE FIELD TESTS ON SUSPENDED-SEDIMENT SAMPLERS PROGRESS REPORT DECEMBER 1944

Report D -- * COMPARATIVE FIELD TESTS ON SUSPENDED-SEDIMENT SAMPLERS PROGRESS REPORT -- AS OF JANUARY 1946

Report E -- STUDY OF METHODS USED IN MEASUREMENT AND ANALYSIS OF SEDIMENT LOADS IN STREAMS JULY 1946
(Paper presented at ASCE convention, Spokane, Washington)

Report F -- FIELD TESTS ON SUSPENDED-SEDIMENT SAMPLERS, COLORADO RIVER AT BRIGHT ANGEL CREEK NEAR GRAND CANYON, ARIZONA AUGUST 1951

Report G -- ** PRELIMINARY REPORT ON U. S. DH-48 (HAND) SUSPENDED-SEDIMENT SAMPLER
(Out of print--Superseded by material in Report No. 6)

Report H -- ** INVESTIGATION OF INTAKE CHARACTERISTICS OF DEPTH-INTEGRATING SUSPENDED-SEDIMENT SAMPLERS AT THE DAVID TAYLOR MODEL BASIN NOVEMBER 1954

Report I -- OPERATION AND MAINTENANCE OF U. S. P-46 SUSPENDED-SEDIMENT SAMPLER

Report J -- OPERATING INSTRUCTIONS, SUSPENDED-SEDIMENT HAND SAMPLER, U. S. DH-48

Report K -- OPERATOR'S MANUAL (PRELIMINARY), THE VISUAL-ACCUMULATION-TUBE METHOD FOR SEDIMENTATION ANALYSIS OF SANDS

Report L -- VISUAL-ACCUMULATION TUBE FOR SIZE ANALYSIS OF SANDS SEPTEMBER 1954
(Paper presented at ASCE convention, Austin, Texas)

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* To be published at a future date
** Very limited distribution

SYNOPSIS

This report presents the visual-accumulation-tube method and apparatus for determining the size frequency distribution of sand samples on the basis of fall velocity or fall diameter. The principles are not new, but former procedures have been improved. The results of analyses were checked thoroughly to establish corrections, limits of applicability, and definiteness of procedure that would elevate the method from the approximate class and eliminate objections sometimes made to this general type of analysis.

The method was originally developed with glass-bead samples. (For characteristics of these samples see Report No. 10, "Accuracy of Sediment Size Analyses Made by the Bottom-Withdrawal-Tube Method," which is one of the reports in this series.) Also, extensive tests of the visual-accumulation tube have been made with sand samples to calibrate the method for use with natural sediments. The results of these tests are given in detail. The calibration of the visual-accumulation-tube method required new techniques for preparing sand samples for which the sedimentation-size distribution was predetermined from the fall velocity of individual particles.

The visual-accumulation-tube method appears to fill a definite need in size-analysis programs, especially those related to the transport of sands in streams. It is a fast, economical, and accurate means of determining the size distribution in terms of the fundamental hydraulic properties of the particles.

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I. INTRODUCTION

1. Scope of the general study--The investigation discussed in this report is one segment of the general project, "A Study of Methods Used in Measurement and Analysis of Sediment Loads in Streams," which has been sponsored by cooperating Federal agencies since 1939. The objective of the project is to gather basic engineering data and information on the characteristics and behavior of sedimentary materials transported by natural streams in order to gain a better knowledge of the fluvial-sediment problem and its solution as related to the development of rivers for industrial, commercial, and domestic purposes. The various aspects of the problem that have been investigated are indicated by the following titles and brief abstracts of previously published reports:

Report No. 1--"Field Practice and Equipment Used in Sampling Suspended Sediment" is a detailed review of the equipment and methods used in suspended-sediment sampling from the earliest known investigations to the present, with discussions of the advantages and disadvantages of the various methods and instruments used. The requirements of a sampler that would satisfy all field conditions are set forth.

Report No. 2--"Equipment Used for Sampling Bed Load and Bed Material" reviews the equipment and methods used in bed-load and bed-material sampling in a manner similar to that in which Report No. 1 covers suspended sediment.

Report No. 3--"Analytical Study of Methods of Sampling Suspended Sediment" covers an investigation of the accuracy of various methods of sampling suspended sediment in a vertical section of a stream. Analytical study is based on the application of turbulence theories to sediment transportation.

Report No. 4--"Methods of Analyzing Sediment Samples" describes many methods developed for determining the size of small particles and for establishing the particle-size gradation and the total concentration of sediment in samples. Detailed instructions are given for many of the common methods that have been developed and used by agencies doing extensive work in sedimentation.

Report No. 5--"Laboratory Investigations of Suspended-Sediment Samplers" reports the effects of intake conditions on the representativeness of sediment samples and on the filling characteristics of slow-filling samplers.

Report No. 6--"The Design of Improved Types of Suspended-Sediment Samplers" describes the development of various integrating samplers suitable for taking vertically depth-integrated samples in flowing streams and others suitable for taking time-integrated samples at a fixed point. Details of the adopted types are given.

Report No. 7--"A Study of New Methods for Size Analysis of Suspended-Sediment Samples" reports on research to develop methods of size analysis suitable for most suspended-sediment investigations and describes a new apparatus and technique, the bottom-withdrawal-tube method.

Report No. 8--"Measurement of the Sediment Discharge of Streams" describes methods and equipment for use in making sediment measurements under the diverse conditions that are encountered in streams.

Report No. 9--"Density of Sediments Deposited in Reservoirs" presents data on the apparent density of sediment deposited in various existing reservoirs. The results are summarized, and certain conclusions useful in engineering studies are given.

Report No. 10--"Accuracy of Sediment Size Analyses Made by the Bottom-Withdrawal-Tube Method" recounts detailed and extensive tests made to evaluate the accuracy of the bottom-withdrawal-tube method. Glass spheres of sand sizes were used as the sediments.

2. Authority and personnel--The general project is currently sponsored by the Subcommittee on Sedimentation of the Inter-Agency Committee on Water Resources. The present investigation was conducted by active participation of the Geological Survey, Bureau of Reclamation, and Corps of Engineers. The laboratory work was done by Byrnon C. Colby, George M. Watts, Clyde O. Johnson, John J. Casey, and Lawrence J. Garfield. The report was prepared by Byrnon C. Colby, Clyde O. Johnson, and George M. Watts with the cooperation of Russell P. Christensen and under the general supervision of Martin E. Nelson and Paul C. Benedict, who also reviewed the report.

3. Acknowledgments--Many helpful suggestions and constructive criticisms have been received from E. W. Lane and W. M. Borland, Bureau of Reclamation; R. F. Kreiss and C. S. Howard, Geological Survey; D. C. Bondurant, Corps of Engineers; and Dr. L. G. Straub, Director of the St. Anthony Falls Hydraulic Laboratory.

4. Purpose of the investigation--The objective of the present investigation was to develop an improved method for determining the size distribution of sand samples, particularly of suspended-sediment samples composed mainly or partly of sand sizes. Emphasis was placed on simplicity, economy of operation, and the accurate determination of the fall velocities of the particles composing the samples. The need for such a method of size analyses of sands has been evident for many years. The importance of the work is attested by the extensiveness of the current field programs of sediment measurement. With recent added attention to sediment-transport problems in streams, this need has become more acute, and the emphasis has shifted toward the determination of fall velocity or sedimentation size instead of physical size or volume of the individual grains. The fall velocity of an individual sediment particle in water appears to be the most significant and fundamental measurement of particle size [1, 2, 3]*.

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* Numbers in brackets indicate references listed on pages 95 and 96.

The acute need for a laboratory method of analyzing sediment samples, particularly in the sand range, rapidly and with reasonably good accuracy appeared to be amenable to solution by means of some type of sedimentation tube. This approach led to the eventual development of the visual-accumulation-tube apparatus and method. Samples of natural sands could be prepared accurately to predetermined fall-velocity distributions only by a long and tedious process. Fortunately, however, the characteristics of glass-bead samples had been established in a previous investigation of the accuracy of the bottom-withdrawal-tube method, the study described in series Report No. 10 [4]. Consequently, glass-bead samples of known fall-velocity distribution by weight could be compounded readily, and such samples were used for the initial development and checking of the visual-accumulation tube.

5. Definitions--Several terms pertinent to analysis of fluvial sediments are defined in this section. Some have special or limited meanings in this report; others have more usual significance, but the generally accepted definitions are not precise enough for the present purpose.

DISPERSED SYSTEM is one in which particles begin to settle from an initial uniform dispersion and in which particles of different sedimentation sizes settle together. Size distribution may be determined by measuring the concentration of sediment at given intervals of depth and settling time, as in the pipette method, or the distribution may be obtained from the quantity of sediment remaining in suspension after various settling times, as in the bottom-withdrawal-tube method.

STRATIFIED SYSTEM is one in which the particles start falling from a common source and become stratified according to settling velocities, as in the visual-accumulation-tube method. At any given instant, the particles coming to rest at the bottom of the tube are of one sedimentation size only and are finer than the particles that have previously settled out and are coarser than those remaining in suspension. Consequently, the determination of size distribution for stratified systems is much simpler than for dispersed systems.

DISPERSE, DISPERSED, or DISPERSION applied to a sedimentation system indicates a distribution of particles that was obtained by mechanical means. Chemical-dispersing agents were not used with the glass beads. However, preliminary treatment of sand samples to remove silt and clay sometimes involved chemicals that may have made subsequent mechanical dispersion of the sand fraction more effective.

SETTLING VELOCITY is any rate of settling of particle or sample.

STANDARD FALL VELOCITY is the average rate of fall that a particle would finally attain if falling alone in quiescent distilled water of infinite extent and at a temperature of 24°C. FALL VELOCITY, for practical purposes, is applied to a settling velocity that closely approximates a standard fall velocity or to a settling velocity that would closely approximate a standard fall velocity if corrected for water temperature. A measured fall velocity at a

temperature within a few degrees of 24°C may be converted to a fall velocity at 24°C by use of the relation for spheres [5].

SIEVE SIZE or SIEVE DIAMETER of a particle is the length of the side of a square sieve opening through which the given particle will just pass.

SAND SIZES are particle sizes from 0.0625 to 2.0 mm (62.5 to 2000 microns) sieve diameter.

SEDIMENTATION SIZE denotes any size or diameter that is determined from the settling or fall velocity of sediment particles or samples.

FALL DIAMETER of a particle is by analogy the diameter of a sphere that has a specific gravity of 2.65 and has the same fall velocity as the particle. Fall diameters may be determined from fall velocities by use of the relation for quartz spheres [5].

SEDIMENTATION DIAMETER of a particle is the diameter of a sphere that has the same specific gravity and the same standard fall velocity as the particle. This differs from the usual definition of sedimentation diameter, which allows the diameter to be based on any settling velocity regardless of fluid or temperature [6].

SIZE DISTRIBUTION, or simply DISTRIBUTION, when applied in relation to any of the size concepts, denotes the size gradation or size spectrum of material in percentages or proportions by weight.

VELOCITY-SIZE RELATION: The visual-accumulation-tube method is a means of determining the sedimentation-size distribution of sand samples based on settling velocities of the particles falling in mass in the tube. The method is calibrated to give results in fall velocities of the individual particles. The analytical results are discussed in terms of velocities and could readily have been reported in those terms; however, the results are reported in fall diameters because the size concept is deeply embedded in sedimentation thinking and for the added convenience in comparing analytical results with sieve-size distributions.

6. Review of sedimentation-size analysis methods--A brief review of several methods of sedimentation-size analysis follows:

a. Bottom-withdrawal tube--In the bottom-withdrawal-tube method of size analysis, sedimentation starts from an initially dispersed suspension of particles in water [2, 4]. Several withdrawals of water and deposited sediment are made from the bottom of the sedimentation tube at timed intervals. The sediment is dried and weighed, and the size distribution is determined by the Odén curve procedure. The method is accurate for samples limited to silt and clay sizes. A single analysis of a sample containing sands is likely to be erratic, and the method is tedious and expensive.

b. Photographic sedimentation--The "photographic sedimentation" method was developed by Carey and Stairmand [7]. This involved measuring, from a photographic plate, the length of the streak that represented the distance a particle settled during a given time of plate exposure. Distance on the plate was correlated with distance in the prototype, and the velocity of fall was computed from the distance of fall in known time. The fall velocities determined were presumably accurate; however, the process required fairly elaborate special equipment and was time consuming and expensive.

c. Fall of representative individual particles--In a comparison of sieve and sedimentation diameters, Serr [8] used a method for obtaining the fall velocities of the individual particles of a sand. He dropped several hundred individual particles to determine the distribution for a sand sample. Serr's method would result in the best type of size analysis if the mathematical treatment was more rigorous and if particles of the smallest sand sizes were dropped; however, the cost would be high.

d. Pressure differential--A pressure-differential method was developed at the University of Iowa [1, 9]. Two piezometers measured a hydrostatic pressure differential that was proportional to the submerged weight of sediment in suspension; the differential pressure traverse, which was recorded by the aid of a transducer, could be calibrated for particle size. Results probably approximate the desired fall velocity, but the accuracy has not been proved. The method has not been adapted to the full range of sand sizes; it is moderately expensive, requires specialized equipment, and involves lengthy computations.

e. Electronic and ultrasonic measurements--The basic principles of two electronic and one ultrasonic method for measuring the concentration of sediment in a fluid will be mentioned briefly.

A method based on the resistance of a sedimentation column to the passage of high-frequency electric current was developed by Morgan and Pirson [10]. If particles were of a mineral for which the combination of sediment and fluid had a resistance to an imposed current much different from the resistance of the fluid alone, the method, when calibrated for that mineral, yielded clearly defined concentrations for particles of uniform size.

A second method, developed by Boyer and Lonsdale [11], was based on the reduction in the internal resistance of an electrolytic cell that results from any movement of the electrolyte at the cathode. Sediment particles falling near the cathode produce movements of the electrolyte and change the internal resistance of the cell. A properly designed external circuit can amplify and record the voltage change caused by varying concentrations of sediment moving past the cathode.

A method reported by Killen [12] depends on the scattering effect that sediment particles exert on supersonic radiation. Supersonic waves were created by electronic means, and the intensity of the waves that passed undeflected

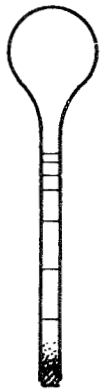
through the water column was recorded. When sediment was mixed with the water, the intensity of the waves that passed through the column without being deflected outside the range of the receiving unit decreased. For particles of one size distribution the decrease in intensity at the receiving unit was a function of the concentration in the column.

The accuracy of most electronic and ultrasonic procedures has not been satisfactorily established for routine analysis of sands. In general, the necessary equipment is expensive, complicated, and difficult for unskilled personnel to operate. This class of measuring methods offers many possibilities for future development.

f. Sieve and microscopic methods--Sieve and microscopic methods have been used extensively for analysis of all sand sizes [5]. By themselves, these methods do not yield fall velocities; but, for a given type of sand, the relation of sieve or microscopic size to fall diameter may be established by dropping individual particles or by analysis in the visual-accumulation tube. The sieve- or microscopic-size distribution may then be used to compute fall-diameter or fall-velocity distribution. If many analyses are made on one type of sand, the cost of each analysis is moderate.

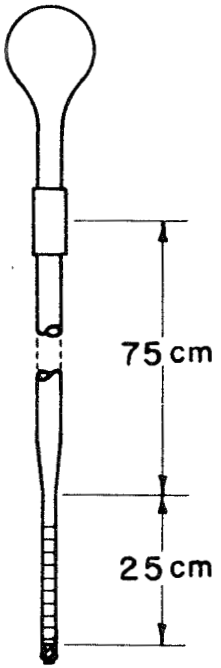
g. General stratified-sedimentation methods--Stratified-sedimentation methods, in which sediment settles from the top of a column of water, have been used by many investigators over a period of several years [5]. Such methods yield a settling velocity that may be much different from the standard fall velocity. However, because the results of such analyses are generally highly reproducible, it appears that the apparatus could be calibrated to obtain results directly in terms of standard fall velocity. The methods are well adapted to the range of sand sizes; and they are rapid, simple, and inexpensive.

The simplest general type of stratified-sedimentation analysis appeared to be a visual-tube method similar to the methods used by Bennigsen [5], Kennedy [13], Clausen [5], Werner [5], Emery [5], Travis [14], and others [5]. Three typical kinds of apparatus are shown in Fig. 1. Bennigsen used a silt flask in which the water-sediment mixture was agitated. Then the flask was inverted, and the depth of the material that settled in the stem in certain time intervals was observed. Clausen improved the equipment by making the stem removable from the mixing or dispersion bulb and by using a smaller bulb and a longer sedimentation column with a contracted section for measuring the accumulated sediment. In 1925, Werner devised a sedimentation apparatus that consisted of a 1.5-cm tube with a smaller, graduated tube inserted at the bottom for volumetric measurements of the accumulation; a magnifying glass was provided to improve the accuracy of readings. The Emery settling tube and method of operation were developed in 1938: The sample was dispersed in a short tube and then was poured into the top of the settling tube; the settling tube was tapped lightly during the sedimentation period to insure even and gradual compaction and to level off the top of the sand column so that accurate readings could be made. In all these methods the size distribution was obtained in terms of the volumetric accumulation of deposited sediment with respect to time.



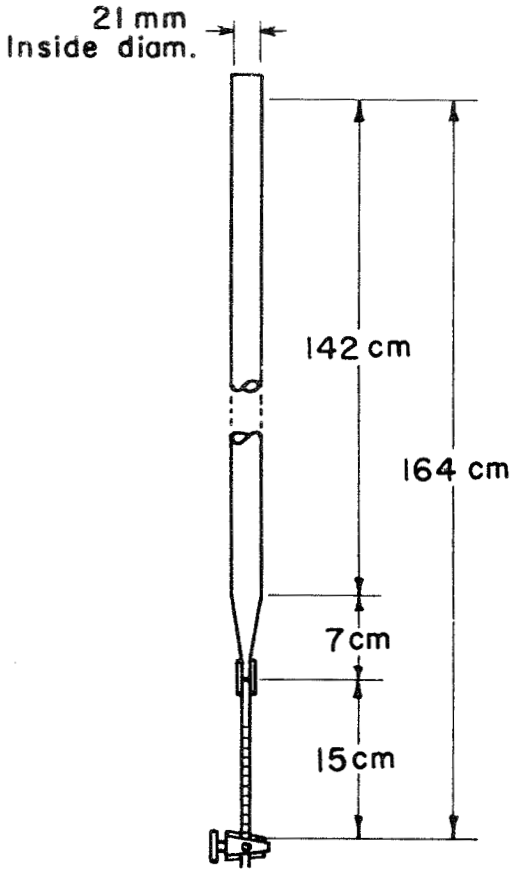
BENNIGSEN'S SILT FLASK

(1860)



CLAUSEN'S MODIFICATION OF BENNIGSEN'S SILT FLASK

(1899)



EMERY'S SETTLING TUBE

(1938)

FIG. 1 – EARLY TYPES OF APPARATUS FOR VISUAL DETERMINATION OF SEDIMENT SIZES

II. GENERAL VISUAL-ACCUMULATION-TUBE METHOD

7. Basic requirements of a satisfactory method--The essential criteria for a satisfactory method of analysis for sand samples are speed of operation, directness of measurements, applicability to analysis of sand sizes, elimination of excessive routine computations, and, most important of all, the accurate determination of fall velocities. The following specific requirements for a satisfactory stratified-sedimentation method are obvious: (1) The settling column must be long enough to allow the separation of the largest particles that normally appear in samples of suspended sediments, about 700 microns, and provision for separation of larger particles would be desirable. In the light of methods of size analysis presented in Report No. 4 [5], the minimum dimensions of the settling tube would be a length of 100 cm and an internal diameter of 2.5 cm. (2) The sample must be introduced at the top of the settling medium to produce a stratified-sedimentation system and to avoid the more complicated analysis of a dispersed-sedimentation system. (3) The quantity of material that has settled out of suspension must be determined in a simple manner. The bottom part of the settling column must be contracted to a small diameter to permit accurate reading of the quantity of accumulated sediment. The measured height of sediment is proportional to volume, whereas the analysis is desired in terms of weight. Although difficulties were anticipated in relation to the contracting and contracted sections of the tube as well as in the conversion of volume measurements to weight, the speed and simplicity of the visual stratified-sedimentation method seemed to warrant further study.

The preceding considerations defined the general requirements for the visual-accumulation-tube (or VA-tube) method of sedimentation analysis. Three questions were basic: (1) Would the method yield accurate fall-velocity analyses? (2) If the uncorrected analyses were not sufficiently accurate, could a calibration be applied to provide requisite accuracy? (3) Just how valuable would the method be in routine laboratory programs if satisfactory accuracy could be attained?

Available sedimentation literature did not fully answer any of these questions but indicated that the results of analyses of this type would be consistent and reproducible. A report of research on the Emery [15] settling tube indicated that such analyses were very consistent except for the coarser sands. To improve analyses in the larger sand sizes, three modifications of the apparatus used in the Emery tube research project were proposed: (1) The method of introducing the sample would be made mechanical to provide greater consistency than could be attained with the manual introduction method. (2) A tapper would be used to jar the tube slightly throughout the analysis, to aid in maintaining a level upper surface on the accumulation, and to reduce bulking of the sands. (3) A manually operated recording device would be used to trace the accumulation of sediment on a time scale controlled by an electric motor. The recorder would eliminate hasty reading and recording of the accumulation at definite time intervals and also would provide a permanent and continuous record of accumulation.

Unfortunately, no information was available on the significance and accuracy of the results that had been obtained with this general method. Some investigators had sieved one or more samples of sand and used these to calibrate the settling-tube method in terms of the time of fall for sieve sizes of sands. A sieve calibration did not satisfy the criteria adopted for this investigation, which required the determination of the fall velocity or fall diameter of the material in suspended-sediment samples. In one sense, the size distribution from a sedimentation analysis is always a function of the settling velocity of the material. However, identical samples would not necessarily fall with the same velocity in a tube as in an identical fluid of unlimited extent, nor would a group of particles necessarily settle in the tube with the same velocity that the individual particles would have if allowed to settle alone.

If the results of an analysis are to be independent of concentration, dispersion, and other variables peculiar to the state of the material at a given time, the fall-velocity distribution obtained for a sample must correspond to the distribution that represents a composite of all the standard fall velocities of the individual particles. Although settling-tube methods that develop stratified-sedimentation systems have been widely used, there was a complete lack of data from which to correlate the size distribution by analysis with the size distribution from the standard fall velocities of the individual particles. Consequently, analytical apparatus had to be made, and complete calibration tests had to be run as a part of this investigation. The first series of tests were made with glass-bead samples because the spherical particles provided a way of correlating physical size with fall velocity. The method was applied afterward to sand samples that were carefully prepared by techniques developed especially for this investigation.

8. Visual-accumulation-tube apparatus--A drawing of the apparatus initially developed for testing the general VA-tube method is shown in Fig. 2. The main section of the glass sedimentation tube was 25 mm in internal diameter and 80 cm in length. The transition section was 20 cm in length and reduced from the size of the main tube to the size of the accumulation section. The accumulation section was 20 cm long and had a uniform inside diameter. Originally, the accumulation sections of the sedimentation tubes were made in different diameters from 2 to 5 mm as a basis for determination of the diameters needed for the range of sample quantities and sizes of sediment to be analyzed. Later, larger sedimentation tubes were tested.

A rubber tube connected a glass funnel to the top of the sedimentation tube. A pinch clamp sealed the walls of the rubber tubing together to isolate the funnel section from the sedimentation tube. Releasing the clamp allowed the tubing to return to a cylindrical shape almost instantly. The upper part of the rubber tube and the stem of the glass funnel formed a chamber in which the particles could be mixed and dispersed in water before release into the sedimentation tube.

A leaf spring near the bottom of the transition section was actuated by an electric motor having a cam attachment that imparted a tapping action to the

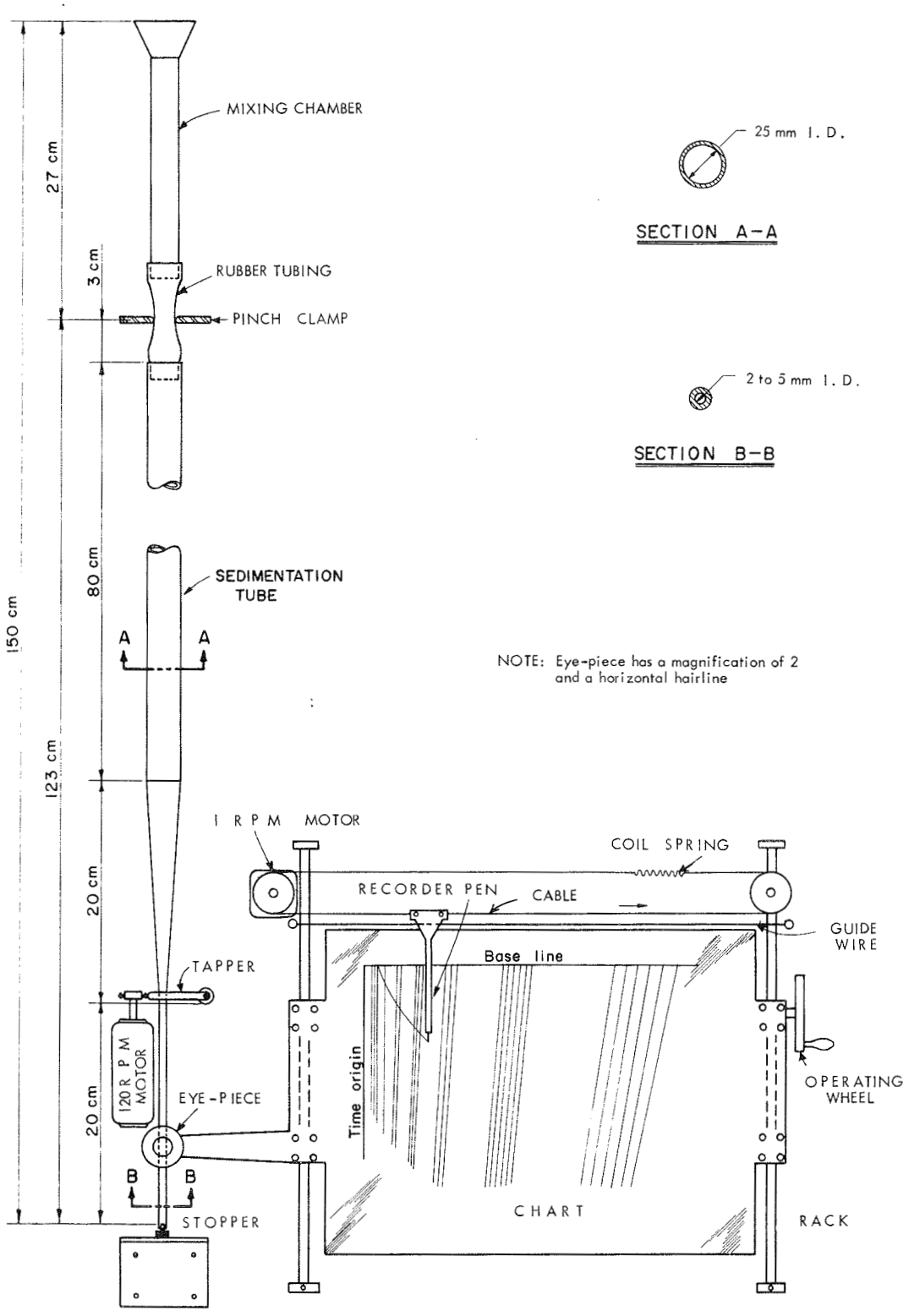


FIG. 2 — VISUAL-ACCUMULATION-TUBE AND RECORDER AS INITIALLY DEVELOPED

spring at the rate of 240 cycles per minute. The spring acted directly on the tube and created a vibration that helped to keep the walls of the transition section free of clinging particles and improved the packing of the sediment in the bottom of the tube.

The recorder consisted of an eyepiece, a plate, a recording pen, and a chart. The eyepiece, which had a magnification of two diameters and a horizontal hairline, facilitated accurate tracking of the level of accumulation. It was attached to a 12-by-9-by-1/16-in. magnetic stainless-steel plate that could be moved vertically on a double rack and pinion by a manually operated wheel. The recording pen, mounted independently of the rack and pinion movement, was driven by a 1-rpm electric motor and cable arrangement. The pen traveled horizontally at the rate of 1.10 mm per sec (later changed to 0.70 mm per sec or 1.653 in. per min). Guided by a tightly stretched piano wire, the pen traveled along a true horizontal line. The recorder chart was held upside down on the plate by small magnets. In recording the accumulation of sediment, the eyepiece and the plate moved upward as a unit while the pen moved horizontally. Thus, the accumulation was recorded directly, but upside down, on the chart.

9. Design of uncalibrated charts--The uncalibrated charts of Figs. 3 and 4, one for glass-bead samples and one for sands, were based on the uncorrected settling velocities of particles falling in mass in the sedimentation tube. The glass-bead chart was based on the relation of size, determined with a microscope, to settling velocity; the relation was established experimentally and presented in Fig. 4 and Table 3 of Report No. 10 [4]. For the sand chart the relation of size to settling velocity was obtained from Fig. 5 of Report No. 4 [5] or from Table 1 of Report No. 7 [2], which show the sizes of quartz spheres that correspond to certain rates of settling.

It was necessary to know the fall distances for particles of various sizes in order to compute the location of the size-temperature lines on the uncalibrated charts. If the sample was not dispersed in the mixing chamber, all particles started falling from the bottom of the mixing chamber, which had an effective elevation about that of the center of the pinch clamp. (Although the bottom of the mixing chamber was slightly higher than the center of the clamp, the capacity of the rubber tube was greater for the cylindrical cross section so that opening the pinch clamp lowered the water column slightly.) The fall distance from the pinch clamp to the stopper in the bottom of the sedimentation tube was 123 cm. When the accumulation reached a height of 10 cm, the fall distance for a particle was 10 cm less, or 113 cm. The slant of the division-size lines of Figs. 3 and 4 is the result of the decrease in fall distance as the accumulation of sediment grows.

Most of the samples were dispersed; therefore, the fall distances, at least for the fine particles of these samples, exceeded those for the undispersed samples. A study of the effectiveness of dispersion indicated that at the time the pinch clamp was opened, the particles larger than 245 microns were resting at the bottom of the mixing chamber, and particles of smaller sizes

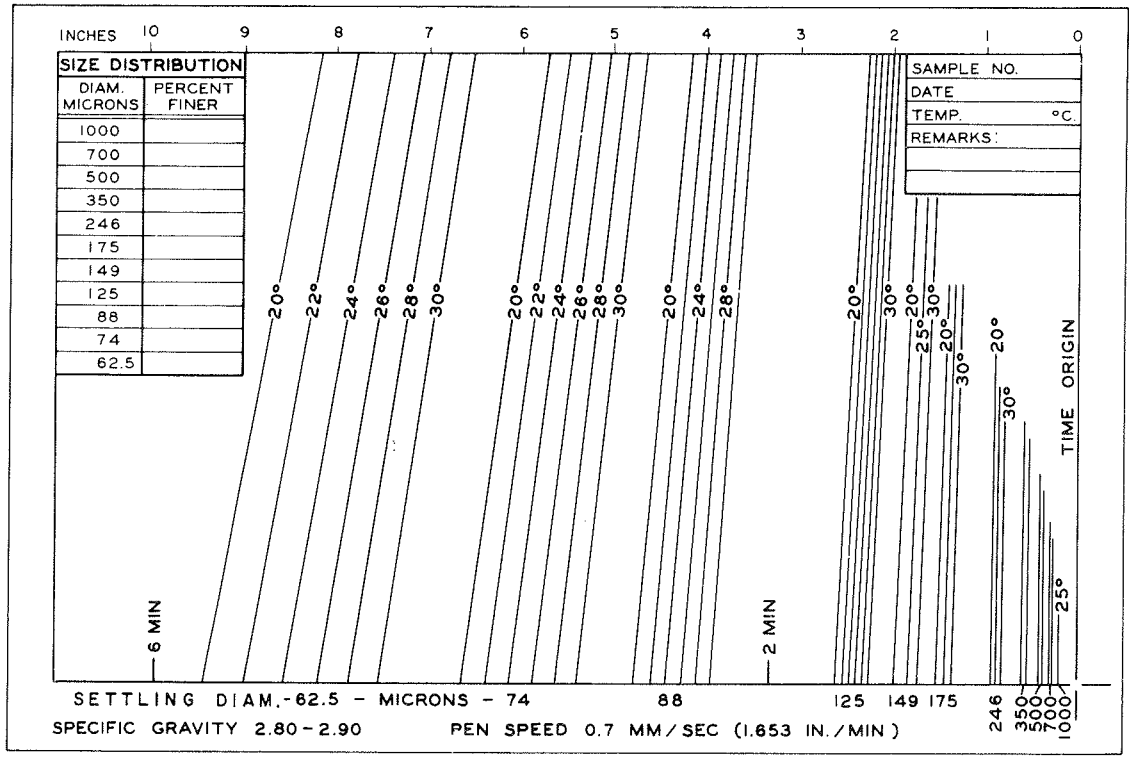


FIG. 3 - UNCALIBRATED CHART FOR ANALYSIS OF GLASS-BEAD SAMPLES

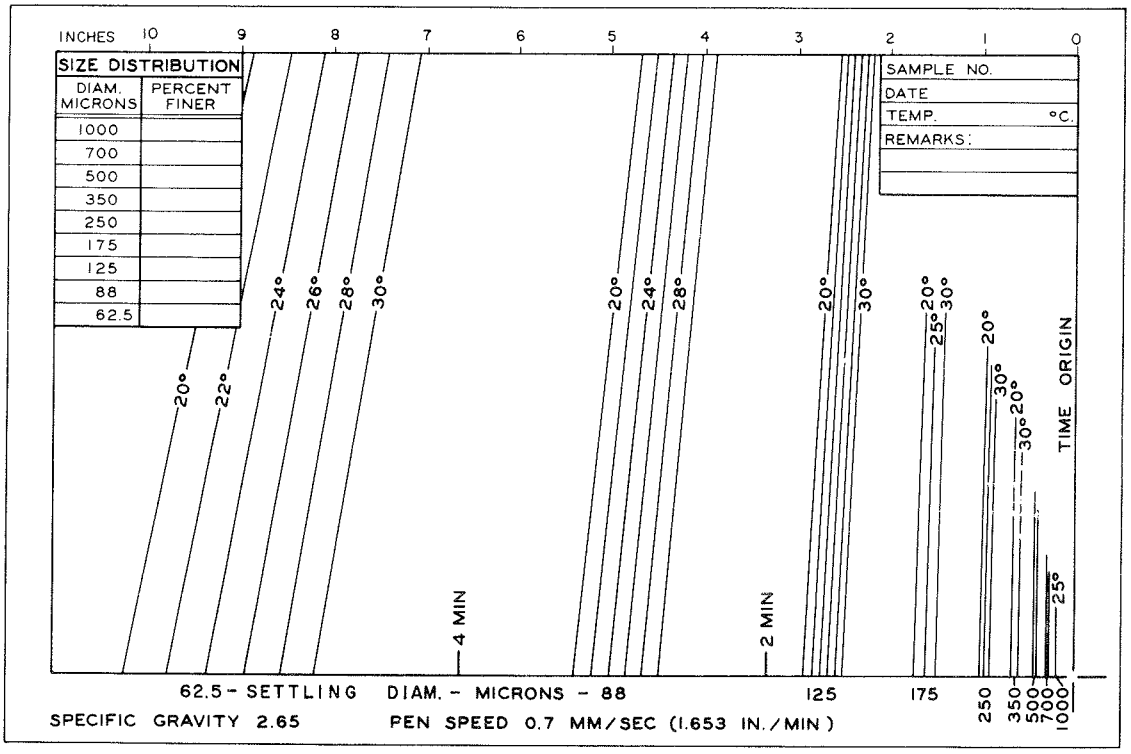


FIG. 4 - UNCALIBRATED CHART FOR ANALYSIS OF SAND SAMPLES

were partly dispersed. The degree of distribution was progressively more complete toward the smallest sizes; however, even at the 62.5-micron size the distribution was not entirely uniform throughout the 20-cm length of the mixing chamber. Points of origin were assumed to vary from the pinch clamp for the 246-micron size to 7 cm above the pinch clamp for the 62.5-micron size.

Computations of distances from the time origin for some of the sizes and temperatures on the uncalibrated charts are shown in Table 1. Many other computations of this type were made for preparing the charts of Figs. 3 and 4. The division sizes are those frequently used in size analysis, but other divisions may be used to meet specific needs. Settling velocities vary with the kinematic viscosity of the fluid and, therefore, with water temperature. Consequently, the effect of water temperature was taken into account in preparing Table 1 and Figs. 3 and 4.

Horizontal distances on the charts are primarily measures of time. If related to corresponding fall distances, they also indicate settling velocities. The sizes shown as settling diameters on the time scales of Figs. 3 and 4 are the diameters of glass beads and of quartz spheres, respectively, that have

TABLE 1

COMPUTATION OF ABSCISSAS FOR UNCALIBRATED RECORDER CHARTS

		Glass beads				Sands			
Sphere size,	microns	500	246	125	62.5	500	250	125	62.5
Fall distance, (A)	cm	123	123	126[a]	130[a]	123	123	126	130
Temperature 20°C									
Time to fall 100 cm, (B) from Repts. 7 and 10	min	0.197	0.460	1.25	4.37	0.218	0.508	1.41	4.77
Total time of fall, (C) = A x B/100	min	0.242	0.566	1.58	5.68	0.268	0.625	1.78	6.20
Base line distance, (D) = C x 1.653*	in.	0.400	0.936	2.61	9.39	0.443	1.033	2.94	10.25
Distance 10 cm above base line, (E) = D (A - 10)/A	in.	0.367	0.860	2.40	8.67	0.407	0.949	2.71	9.46
Temperature 30°C									
Time to fall 100 cm, (B) from Repts. 7 and 10	min	0.180	0.407	1.07	3.50	0.200	0.450	1.20	3.80
Total time of fall, (C) = A x B/100	min	0.221	0.501	1.35	4.55	0.246	0.554	1.51	4.94
Base line distance, (D) = C x 1.653*	in.	0.365	0.828	2.23	7.52	0.407	0.916	2.50	8.17
Distance 10 cm above base line, (E) = D (A - 10)/A	in.	0.335	0.761	2.05	6.94	0.374	0.842	2.30	7.54

a For samples not dispersed before analysis, these figures would be 123.
* Chart speed, 1.653 in. per min.

standard fall velocities equal to the settling velocities at those locations on the charts. If the particles in mass in the VA tube all settled at their respective standard fall velocities, the uncalibrated charts would give size analyses in sedimentation diameters for glass beads and in fall diameters for sands.

10. Procedure for size analysis--The procedure used in development and calibration of the VA-tube method was applied to samples consisting of various selected size distributions and quantities of glass beads or sands. Sand samples were thoroughly wetted and washed before analysis.

The step-by-step procedure for the analysis follows:

1. A stopper was placed in the small end of the sedimentation tube, the tube was fixed in a vertical position and filled with distilled water to approximately 2 cm above the elevation of the pinch clamp, and then the pinch clamp was closed.

2. The eyepiece was adjusted by turning the operating wheel so that the horizontal hairline coincided with the upper surface of the stopper in the bottom of the sedimentation tube.

3. The date, temperature of the distilled water, and the notes necessary to identify the sample were entered on the recorder chart. The chart was adjusted on the recorder plate so that the pen would start at the point of origin on the base line and so that the base line was parallel to the direction of travel of the pen.

4. The electric motor that actuated the spring tapper was started.

5. The test sample was transferred to the chamber above the closed pinch clamp. A disk type of agitator on a rod was used to disperse the particles in the mixing chamber except for those samples that were analyzed without prior dispersion.

6. The pinch clamp was opened immediately, and the electric motor that propelled the recorder pen was started. These two operations were made as nearly simultaneously as possible. A newer mechanism simultaneously releases the clamping device and operates a switch to start the timing clock.

7. The operator, watching through the eyepiece, turned the operating wheel as required to keep the horizontal hairline level with the surface of the accumulating sediment.

8. The tapper and recorder were turned off when practically all particles had settled into the accumulation section.

9. The sample was removed from the bottom of the tube, and the tube was cleaned by flushing.

11. Derivation of particle size from an accumulation curve--The procedure outlined in Section 10 produces a recorded curve having time of fall as the abscissa and height of accumulated sediment as the ordinate. A sedimentation-size distribution cannot be determined from the sediment-accumulation curve without assuming or establishing a relation between time of fall and particle size. The uncalibrated charts were constructed on the basis of the fall velocity

and size relations in the references cited in Section 9, and the fall velocity was related to time and chart distance by means of the computations illustrated in Table 1. The calibrated charts were based on the average relation of time of fall and particle size established by VA-tube analyses of scores of samples with known velocity distribution.

Size distributions were determined from many accumulation curves, from both uncalibrated and calibrated charts. If an accumulation curve was not recorded originally on the desired chart, the curve was superimposed on the chart that had the desired relation of time and size. The size distribution was determined as follows: The intersections of the accumulation curve and the division-size lines for the temperature of analysis were marked by ticks as shown in Fig. 5. The percentages finer than the division sizes were found from the chart by use of any convenient scale that would divide the total accumulation into 100 parts. The zero percent of the scale was placed on the total-accumulation line, and the 100 percent on the zero-accumulation line. The scale was moved horizontally to the tick marks. The percentage finer than the division size was read directly on the scale. These percentages are actually percentages by volume; but, as will be explained later, they do not differ materially from percentages by weight.

III. DEVELOPMENT OF THE VISUAL-ACCUMULATION-TUBE METHOD WITH GLASS SPHERES

12. Pilot samples and their analyses--The fundamental problem in the development of the VA-tube method was to establish its accuracy. The method could be considered accurate only if the size distribution indicated by the analysis agreed with that obtained from a summation of the standard fall velocities of all the individual particles compounded on the basis of weight. The uncalibrated method was not sufficiently accurate, so calibration was required to develop satisfactory accuracy. The development of the VA-tube method and the determination of its accuracy required the analysis of many samples for which the size distributions in terms of standard fall velocities were known.

The preliminary investigation of the VA-tube method was based on analyses of glass-bead samples. Glass beads whose standard fall velocities and other characteristics were known [4] were compounded into pilot samples of various weights and size distributions. The size distributions and the fall velocities at three temperatures are shown in Table 2.

The glass-bead samples were analyzed by the procedure described in Section 10. The analyses are shown in Figs. 6 to 10 in terms of deviations of the size distributions based on the uncalibrated chart from the known size distributions. The known size distribution for the group of samples is shown at the bottom of each figure. The size distribution from analysis differs from the known size distribution by the plotted deviations. For example, if the size distribution obtained from the analysis was 38.2 percent finer than 350 microns

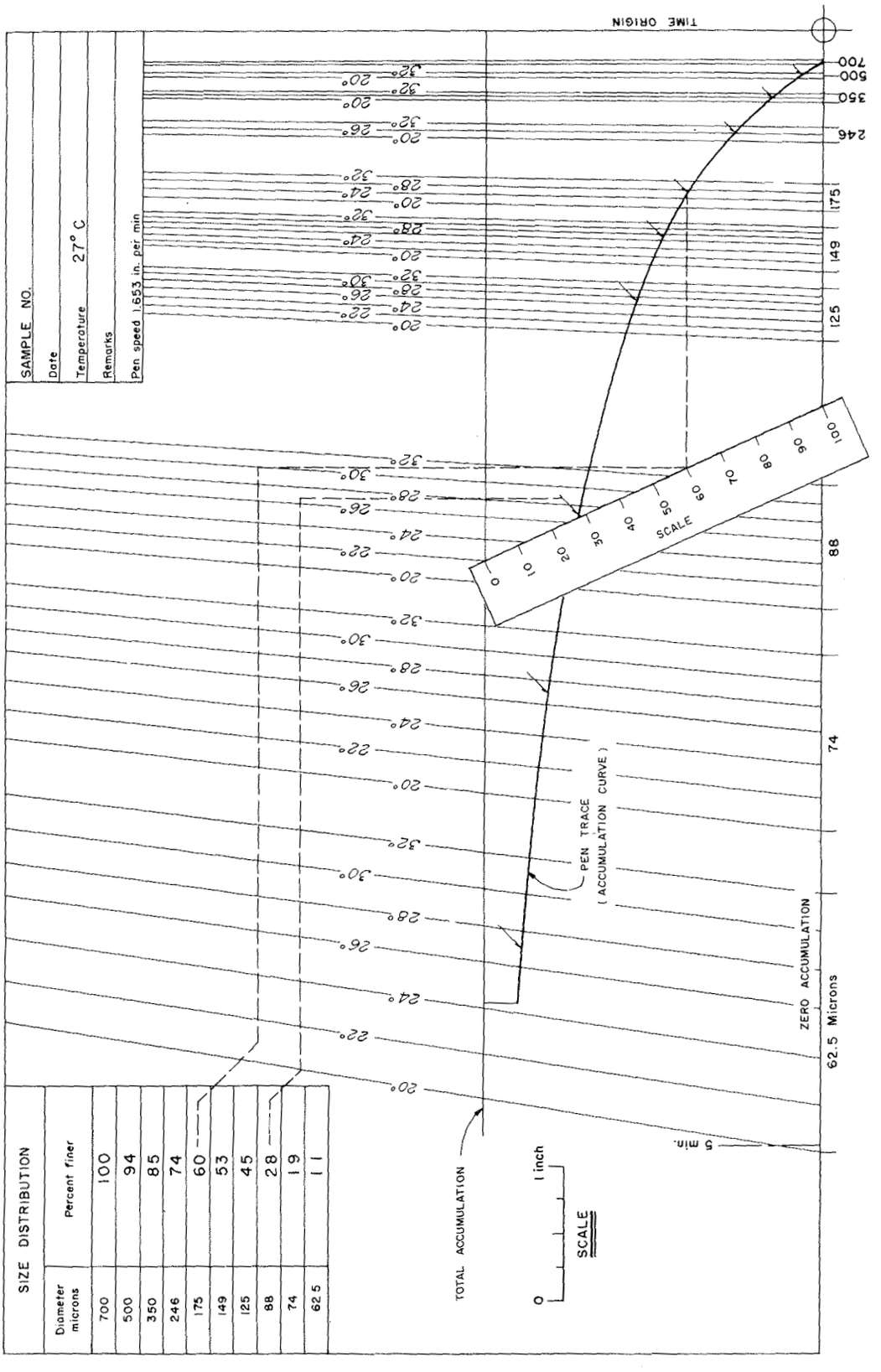


FIG. 5 – USE OF SCALE FOR OBTAINING PERCENTAGES FINER THAN DIVISION SIZES

TABLE 2

GRADATION AND FALL VELOCITY OF GLASS-BEAD SAMPLES

Size[a]	Distribution--percent finer			Fall velocity--cm/sec[b]		
Microns	Fine	Intermediate	Coarse	20°C	25°C	30°C
700	100	100	100	12.08	12.63	13.12
500	96.1	90.4	88.2	8.46	8.87	9.26
350	90.0	79.3	72.0	5.63	5.95	6.24
246	82.1	64.7	54.4	3.62	3.86	4.10
175	69.9	47.0	37.9	2.26	2.42	2.59
149	63.3	39.7	32.2	1.75	1.89	2.03
125	54.6	31.4	26.1	1.33	1.45	1.56
88	33.2	14.9	15.9	0.728	0.809	0.896
74	24.4	10.6	12.2	0.531	0.593	0.656
62.5	17.0	7.5	8.7	0.381	0.427	0.476

a Determined by microscopic methods.
b Determined by dropping particles individually (from Table 3 of Report No. 10[4]). Specific gravity of the glass beads varied with size.

and the known size distribution was 72 percent finer than 350 microns, the deviation was -3.8 percent.

13. Effect of method of introducing the sample--Investigators who have experimented with stratified-sedimentation methods of analysis have used various techniques in introducing the sediment samples at the top of the sedimentation column, but they have not been in agreement as to which technique of introduction is best. Sufficient data are not available for an evaluation of the various techniques of introduction. In the VA-tube method the sample can be dispersed in the mixing chamber or it can be at rest at the bottom of the mixing chamber at the moment the pinch clamp is opened. The same sample could be run repeatedly under both conditions of dispersion, and the effect could readily be compared. The results of such analyses are shown in Figs. 6 to 9. The results for the two conditions did not differ greatly; however, because the analyses for the dispersed samples were somewhat more consistent, sample dispersion in the mixing chamber was adopted as the standard procedure for the VA-tube method.

The data of Figs. 6 to 9 indicate that the technique of introducing the sample into the VA tube does not critically affect the accuracy of analysis.

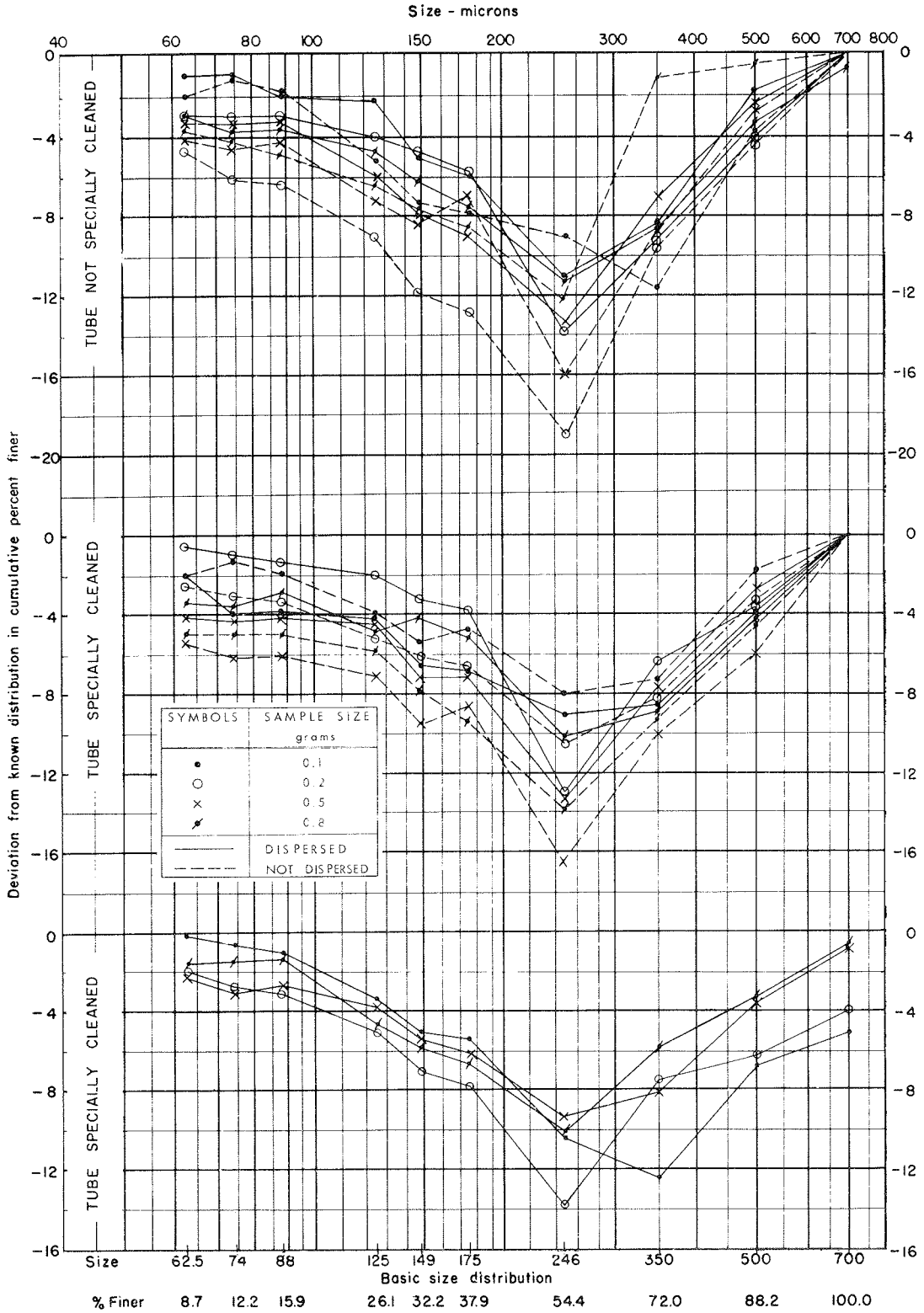


FIG. 6 - EFFECT OF CLEANING AND DISPERSING METHODS FOR COARSE SAMPLES OF GLASS BEADS IN 2-MM TUBE

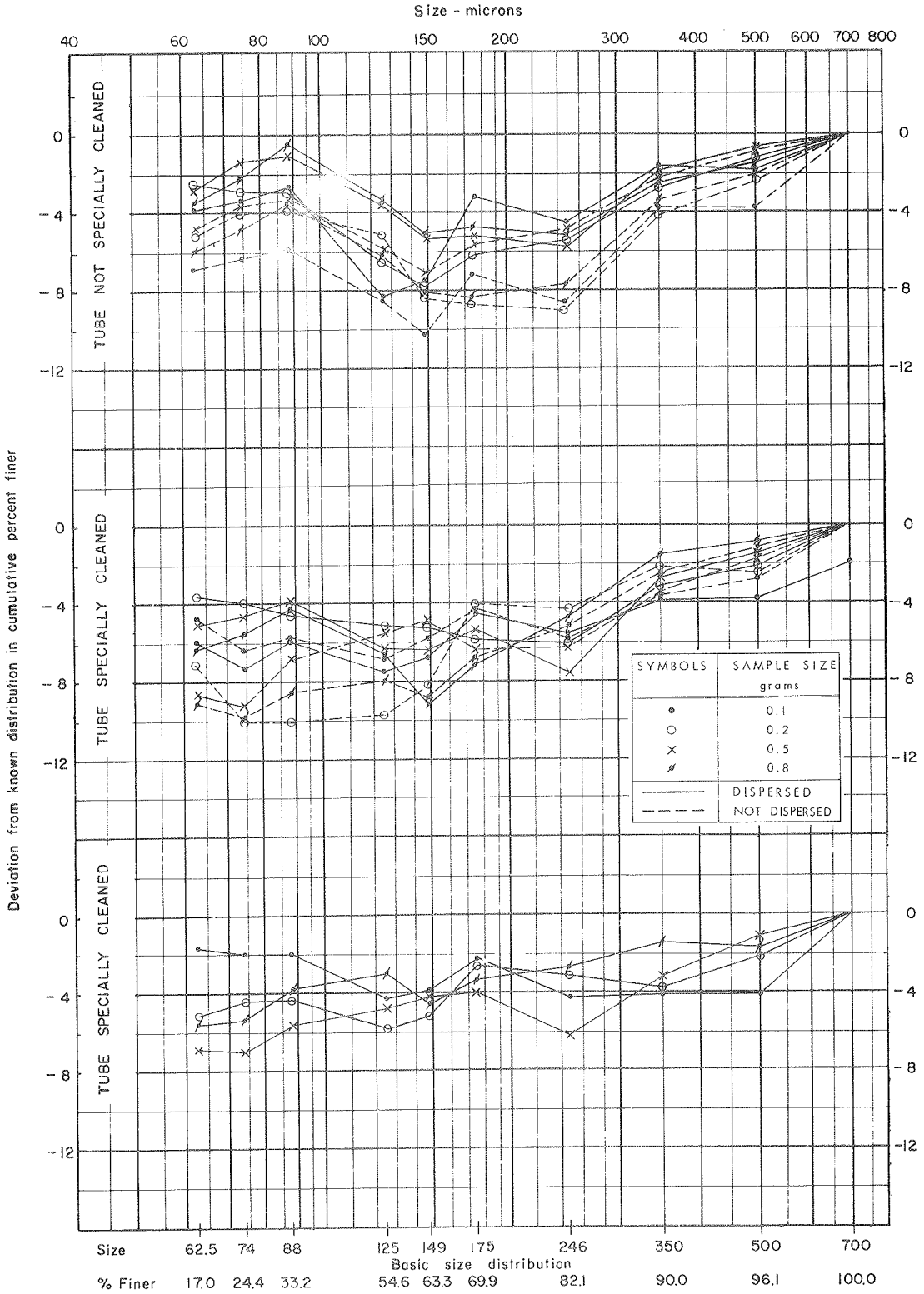


FIG. 7 - EFFECT OF CLEANING AND DISPERSING METHODS FOR FINE SAMPLES OF GLASS BEADS IN 2-MM TUBE

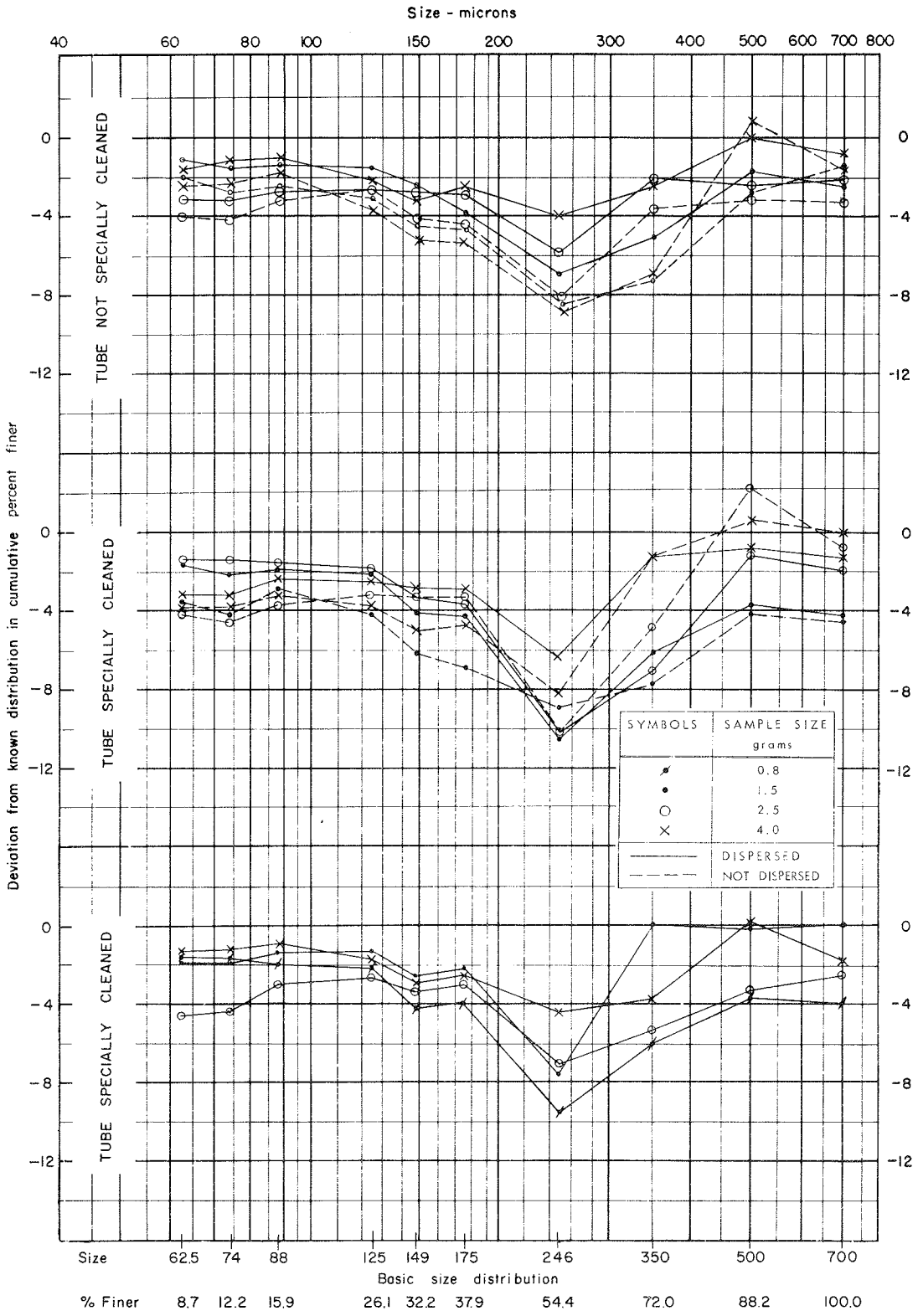


FIG.8 – EFFECT OF CLEANING AND DISPERSING METHODS FOR COARSE SAMPLES OF GLASS BEADS IN 5-MM TUBE

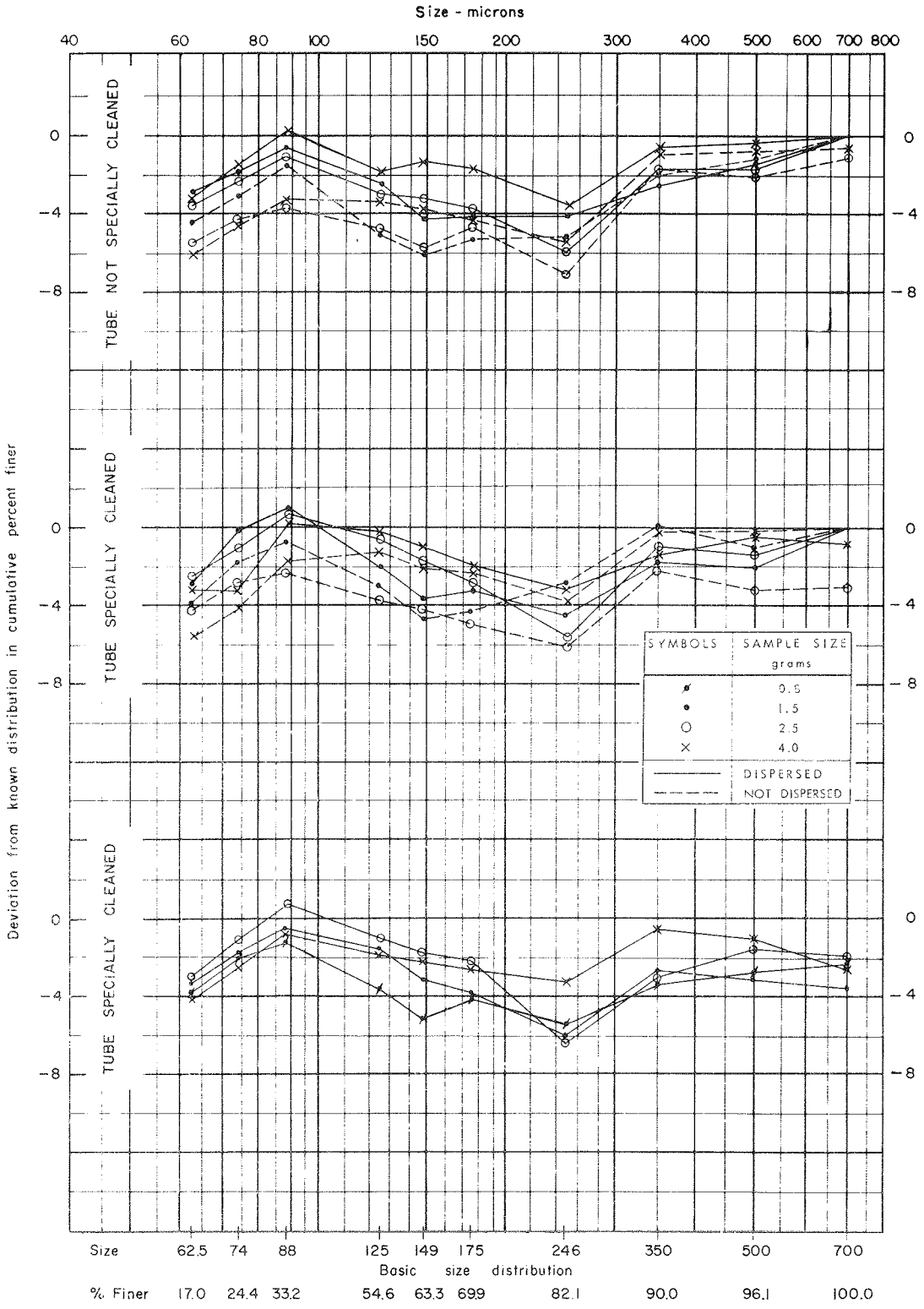


FIG. 9 - EFFECT OF CLEANING AND DISPERSING METHODS FOR FINE SAMPLES OF GLASS BEADS IN 5-MM TUBE

14. Effect of tube-cleaning methods--When glass-bead samples were analyzed either in the bottom-withdrawal tube or in the VA tube, some beads generally adhered to the sides and shoulders of the tubes. Although the adherence of the beads did not appear to affect significantly the accuracy of the analyses, it was a disturbing factor and, as such, warranted investigation.

Rinsing the sedimentation tube with distilled water or cleaning with mild cleansing agents did not inhibit the attraction between the glass beads and tube. However, the following special treatment just before analysis practically eliminated the adherence of the beads. A cleaning solution was prepared by adding 1 liter of concentrated sulphuric acid to 35 ml of saturated sodium dichromate (technical) solution. A small quantity of this cleaning solution was used to rinse the tube until the inside surface was thoroughly wet. The cleaner was drained from the tube, which was then flushed successively with tap water and with distilled water. (The cleaner may be reused. This cleaner is for glassware only; contact with the skin or clothing should be avoided. A detergent, "Alconox," was subsequently found to be an adequate cleaner, at least for analysis of sand samples.)

Tests were made to determine the effect of special cleaning of the VA tubes. The results are shown in Figs. 6 to 9. The curves in the upper group of each figure are from analyses of glass-bead samples in tubes not specially cleaned; those in the middle group are from analyses of the same samples in tubes that were specially cleaned; and the curves in the lower group are from analyses of a check set of similar but not identical samples. Each sample of a given size distribution and weight was analyzed four different ways.

The effect of the cleaning procedure is most apparent for the fine-grained samples and for the analyses in the 2-mm accumulation tubes. (See Fig. 7.) Even for these conditions the average difference between analyses in normally rinsed tubes and specially cleaned tubes is only about 2 percent of the total sample for the finer division sizes and less for the larger sizes. Because the analyses with the specially cleaned tubes were more consistent and adherence was reduced, special cleaning was made a part of the standard procedure for analyses of glass-bead samples. Later tests indicated that sand grains have less tendency to stick to the tube; consequently, the special-cleaning procedure makes the glass-bead behavior duplicate more closely that of sand samples.

15. Corrections applied to glass-bead analyses--The size distributions indicated by the uncalibrated analyses were not sufficiently close to the known size distributions to give satisfactory accuracy. The percentages finer by analysis were generally too small; obviously, the settling velocities of the particles falling in mass in the tube were greater than the standard fall velocities.

The size distributions shown in Figs. 6 to 10 for dispersed samples analyzed in specially cleaned tubes were used to establish correction factors that could be applied to make the results of the analyses check the known size

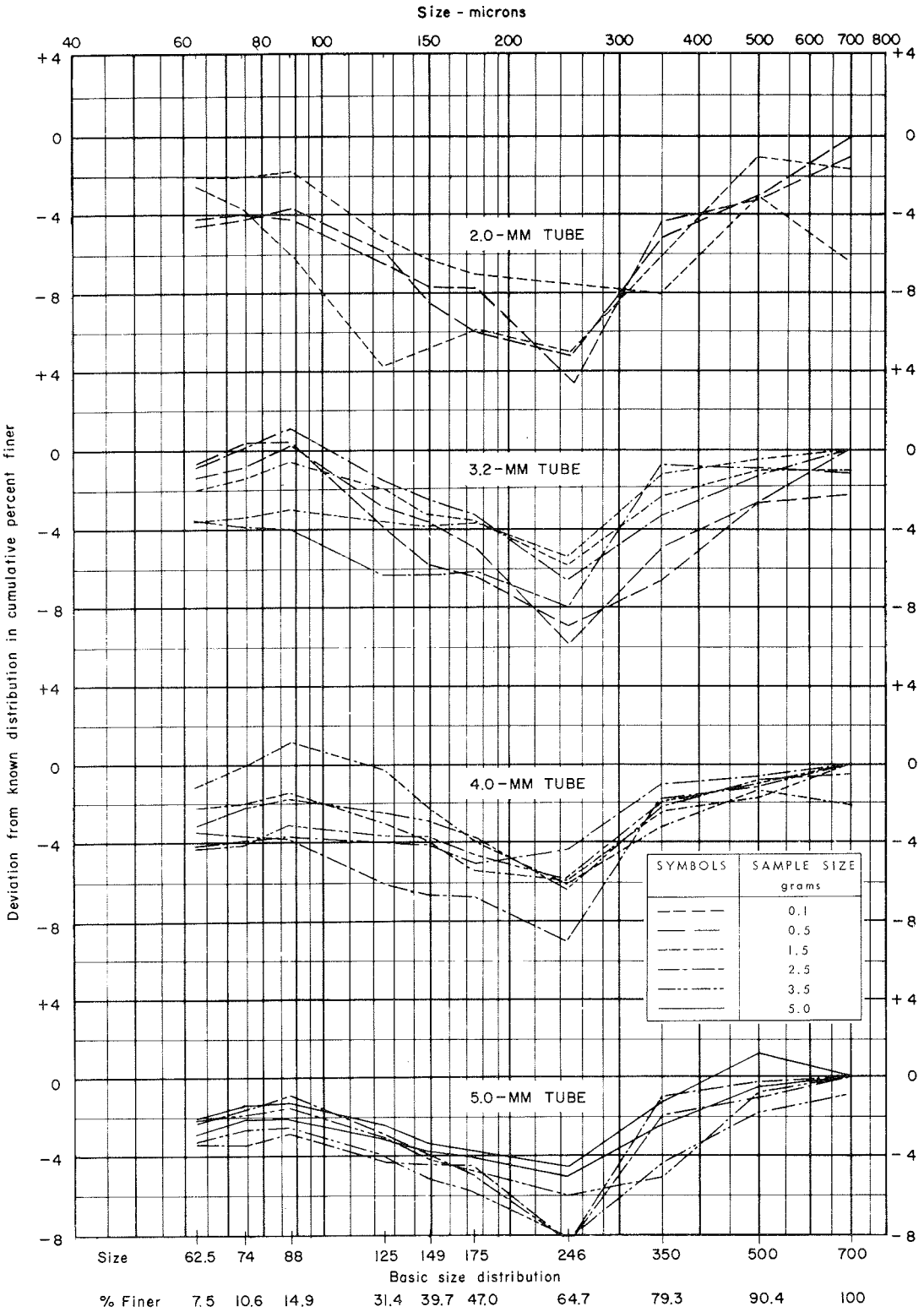


FIG. 10 – ANALYSES OF INTERMEDIATE SAMPLES OF GLASS BEADS IN VARIOUS SIZES OF VISUAL-ACCUMULATION TUBES

distributions more closely. Each size distribution of Fig. 10 is not from a single analysis as in Figs. 6 to 9 but represents the average of at least two analyses of the same sample, and all the analyses were for dispersed samples in specially cleaned tubes. Of many types of adjustments tried, a percentage reduction in the time of fall was chosen because it was simple and reasonably accurate. The corrections applicable to the time of fall were as follows: For the 2-mm tube, -19 percent; for the 3.2-mm tube, -13 percent; for the 4-mm tube, -12 percent; and for the 5-mm tube, -11 percent. The corrections were applied to the data of Figs. 6 to 10, and the corrected deviations were generally within 5 percent. (See Figs. 11 and 12.)

All the curves in Figs. 11 and 12 have certain characteristics that depend upon the respective particle-size distributions in the samples, but a general pattern is more or less typical of all the analyses. A correction that varied from size division to size division could have been used to make the analyses agree better with the known size distributions. However, because the known size distributions could be inaccurate by as much as 3 percent at points in any of the size distributions [4], more complicated corrections did not seem justified.

New charts adjusted for the reduced time of fall can be prepared. The new charts would be the same as the chart of Fig. 3 except that the abscissa scale would be reduced by the correction percentages adopted for each size of tube; for example, 11 percent for the 5-mm tube. No change in analytical procedure would be required in using the new charts.

16. Effect of tube size and sediment concentration--Figs. 11 and 12 indicate very little difference in the accuracy of results obtained with tubes of various sizes. Deviations generally are slightly less for samples analyzed in the larger tubes. The deviations for 0.1-gm samples indicate the effect of smallness of sample on the accuracy of the analyses; the results were slightly erratic, probably because the total height of accumulation was small.

Analyses of samples with a coarse size distribution indicated that appreciable quantities of particles larger than 500 microns tended to reduce the accuracy of analysis in the 2-mm tube. The greatest inaccuracy was obtained with the 0.8-gm sample, which was the heaviest that was run in the 2-mm tube. Analyses in the 5-mm tube were not affected so much by the sizes of the largest particles as by the combination of relatively large size and high concentration at the 350-micron size.

The size of tube did not seem to be a critical factor in accuracy of analysis except when large particles were analyzed in too small a tube. However, because of concentration effects, the quantity of sample should be kept within reasonable limits for each size of tube. A height of accumulation of 3 or 4 in. is normally desirable, and a maximum height of 6 in. and a minimum of 1 in. should be used as limits. The tracking of sediment in the accumulation section is difficult if the accumulation is very rapid at any point in the analysis. Therefore, it is desirable that the quantity of sample be smaller when the size range is very limited.

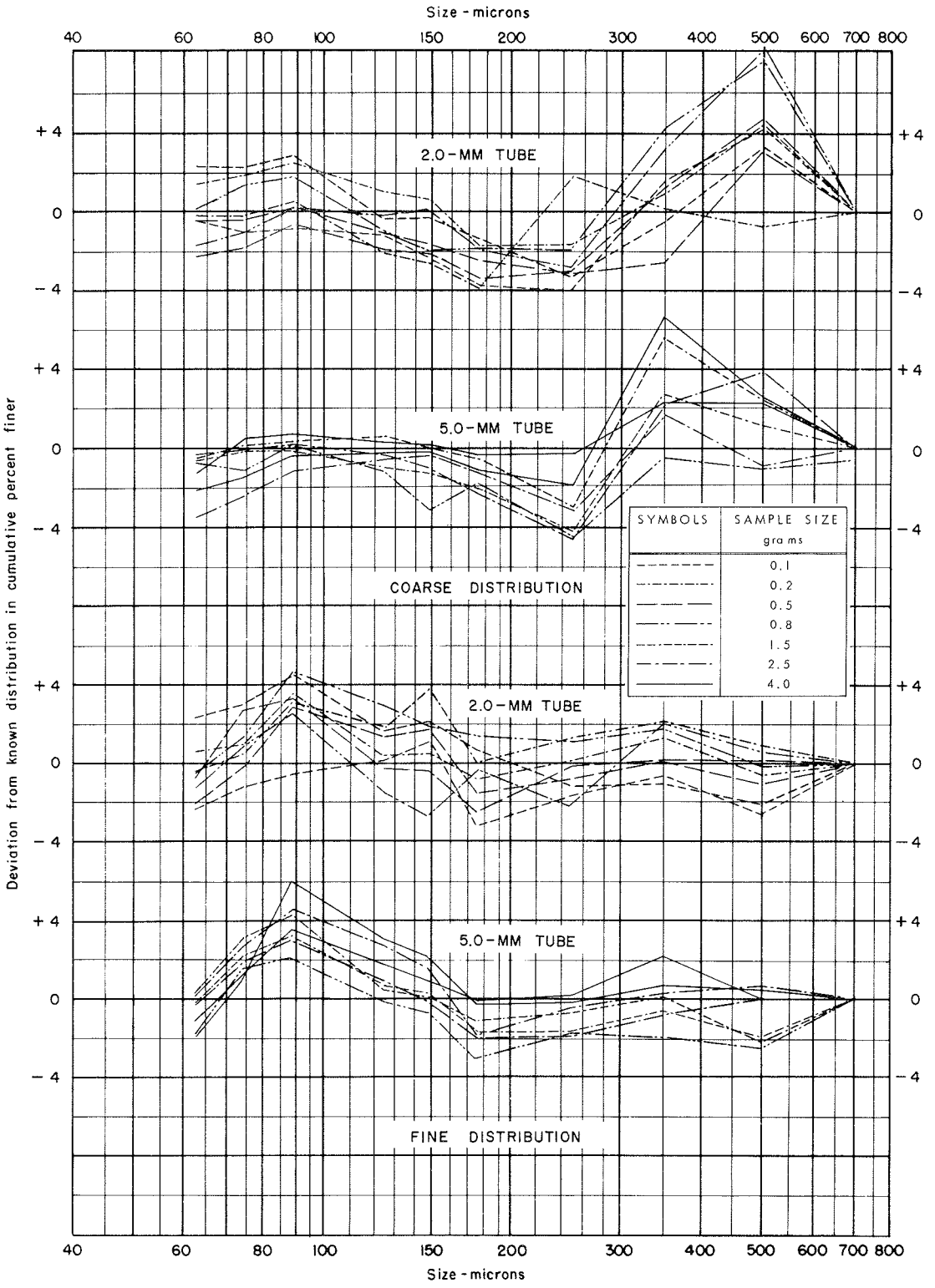


FIG. 11 – ACCURACY OF SIZE ANALYSES FOR GLASS BEADS BY VISUAL-ACCUMULATION TUBE WITH ADJUSTED TIME OF FALL

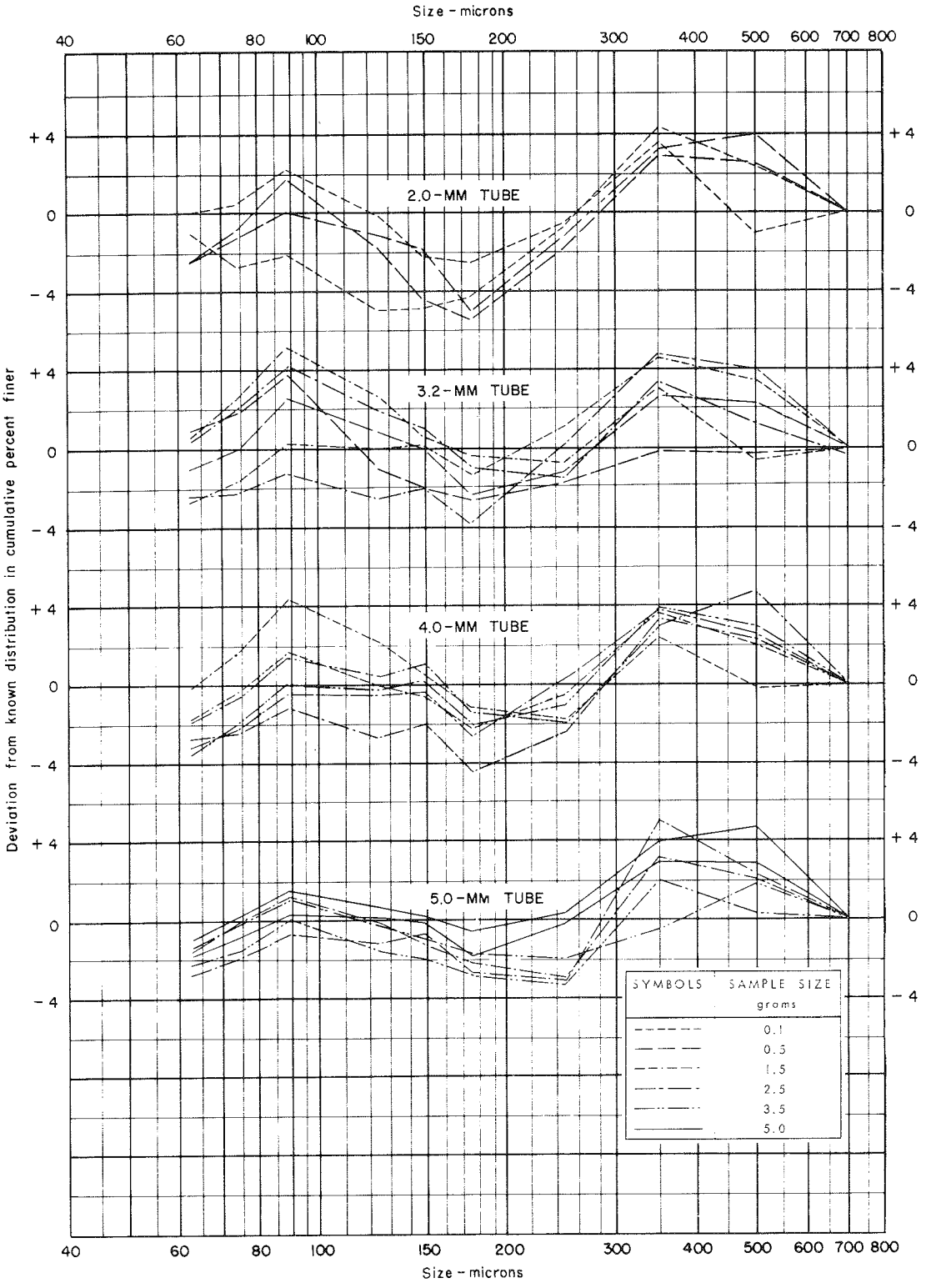


FIG. 12 – ACCURACY OF SIZE ANALYSES FOR INTERMEDIATE SIZE DISTRIBUTION OF GLASS BEADS BY VISUAL-ACCUMULATION TUBE WITH ADJUSTED TIME OF FALL

Differences in the analyses of various weights of samples that were run in one size of tube are inconclusive, but possibly the lighter samples fell slightly faster. If samples with high concentrations of particles that were large in relation to the size of the tube are excluded, there is no evidence that concentration is a critical factor in the accuracy of analysis.

No attempt was made to define precisely the limitations of particle size and concentration for analyzing glass-bead samples because the limitations for glass-bead samples differ from those for sand samples.

17. Accuracy for glass-bead samples--For analyses of glass-bead samples, the VA-tube method was generally accurate within 5 percent at all points of a size distribution as shown in Figs. 11 and 12. Very few of the points deviated from the known size distribution more than 4 percent; in fact, most of the points were within 3 percent. The deviations are due, in part, to the fact that the known size distributions contain errors which may be as large as 3 percent

18. Comparative accuracy of the VA-tube and bottom-withdrawal-tube methods--Six pairs of samples with an intermediate size distribution were analyzed first in the VA tube and later in the bottom-withdrawal tube to compare the accuracy of the two methods. One sample of each pair was analyzed in one size of VA tube and the other in another size of VA tube. The deviations from the known size distribution are plotted on Fig. 13. The results from the VA-tube analyses are more accurate and more consistent.

19. Volume-weight relations for glass beads--The VA-tube analyses are based on percentages by volume, which do not differ substantially from percentages by weight. The heights occupied in the 2-mm tube and in the 3.2-, 4-, and 5-mm tubes by given weights of the various sizes of glass beads are shown in Fig. 14. The only volume-weight relation affecting the VA-tube analysis is the difference in height of accumulation for the different particle sizes, the tube size and sample weight remaining the same.

A method for computing the differences between percentages finer based on volume and those based on weight is shown in Table 3. This comparison depends somewhat on the size distribution of the sample. Even in the 2-mm tube, in which variations are greatest, the change in volume-weight relations seldom makes more than 1 percent difference in percentage-finer figures, except for unusual size distributions.

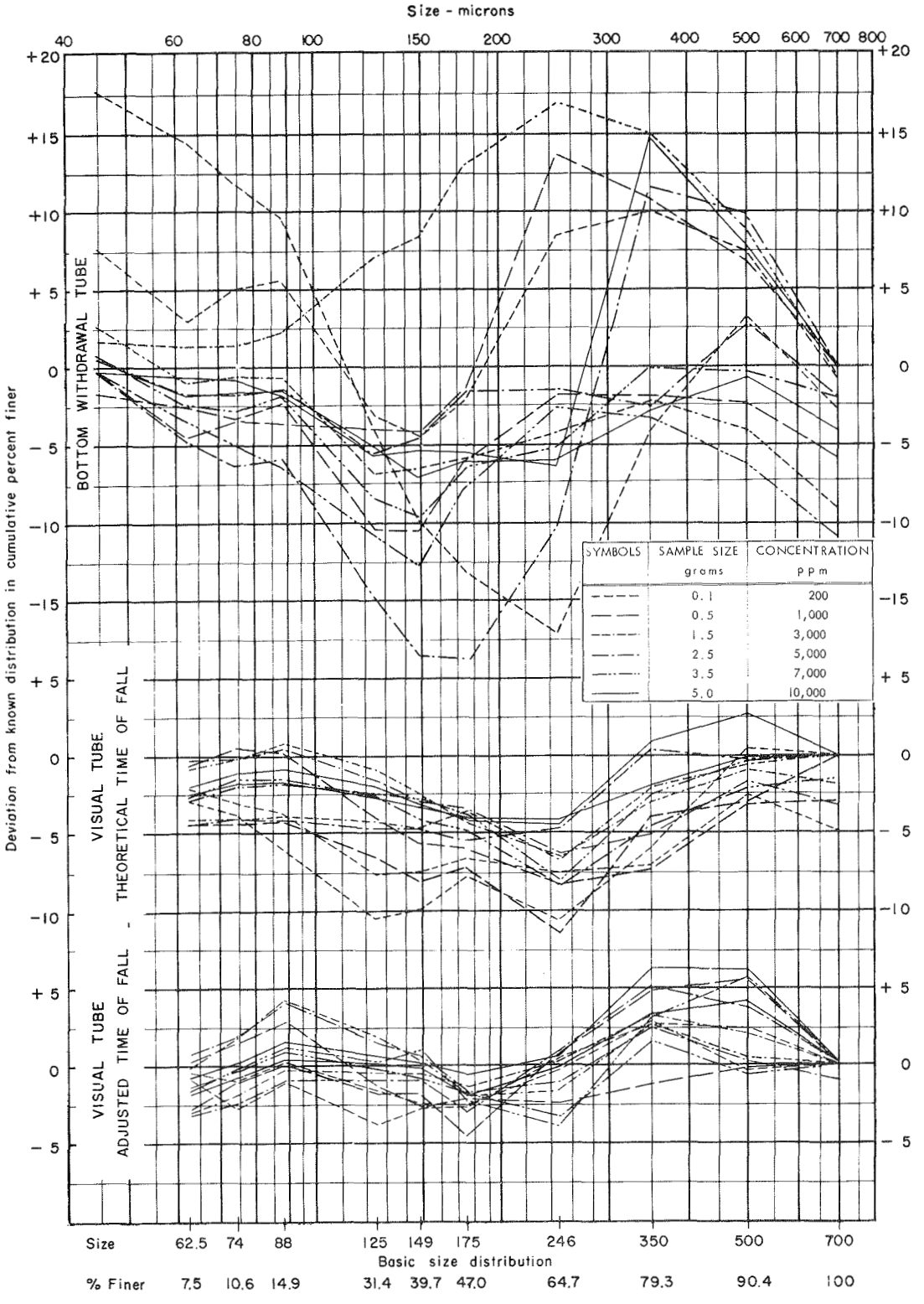


FIG. 13 – SIZE ANALYSES OF GLASS-BEAD SAMPLES BY THE BOTTOM-WITHDRAWAL AND VISUAL-ACCUMULATION TUBES

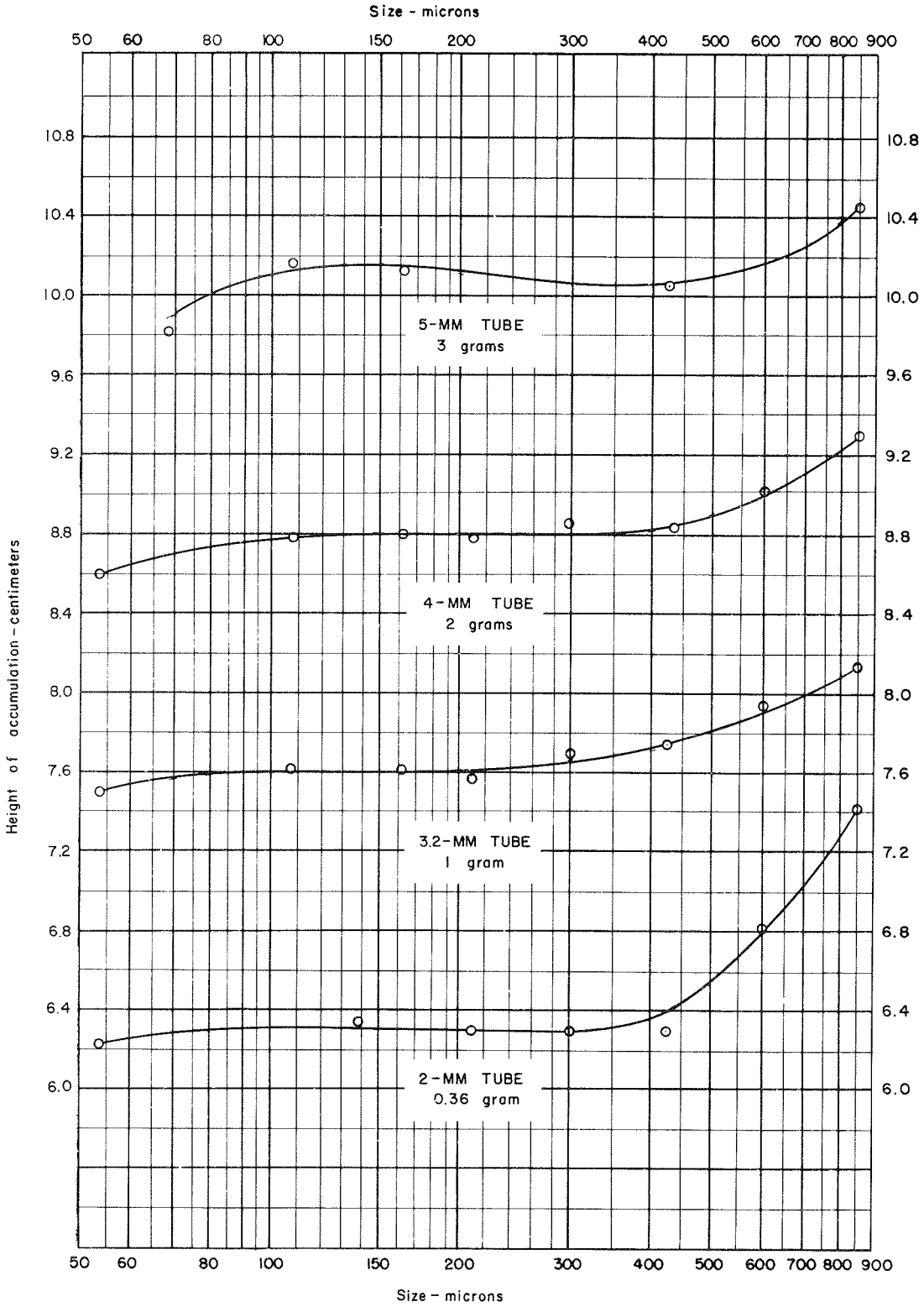


FIG. 14 — VOLUME-WEIGHT RELATIONS FOR GLASS BEADS

(Variation of height of accumulation with sieve size)

TABLE 3

DIFFERENCES IN PERCENTAGES FINER BY WEIGHT AND BY VOLUME FOR A GLASS-BEAD SAMPLE IN A 2-MM TUBE

Sieve size microns (1)	Percent finer by weight (2)	Fractional percent by weight (3)	Accumulation cm per 0.36 gm from Fig. 14 (4)	Relative volume (3) x (4) (5)	Fractional percent by volume (6)[a]	Percent finer by volume (7)[b]	Difference vol - wt percentages (8)[c]
700	100.0					100.0	0.0
		9.8	6.78	66.4	10.45		
500	90.2					89.5	-0.7
		10.9	6.40	69.8	10.99		
350	79.3					78.6	-0.7
		14.9	6.30	93.9	14.78		
246	64.4					63.8	-0.6
		17.3	6.30	109.0	17.17		
175	47.1					46.6	-0.5
		9.0	6.30	56.7	8.92		
149	38.1					37.7	-0.4
		8.2	6.30	51.7	8.14		
125	29.9					29.6	-0.3
		13.8	6.31	87.1	13.71		
88	16.1					15.8	-0.3
		4.9	6.30	30.9	4.86		
74	11.2					11.0	-0.2
		3.2	6.28	20.1	3.16		
62.5	8.0					7.8	-0.2
		4.9	6.23	30.5	4.80		
44.2	3.1					3.0	-0.1
		3.1	6.20	19.2	3.02		

a 100 x column (5) divided by total of column (5).
b Cumulative of column (6).
c Column (2) minus column (7).

IV. CALIBRATION OF THE VISUAL-ACCUMULATION-TUBE METHOD FOR ANALYSIS OF SANDS

20. Sieves and sieve calibration--The accuracy of the sieves used in this investigation has no direct influence on the accuracy of the VA-tube method; however, sieve-size distribution is used for comparison throughout the study. Sieve corrections were based on microscopic analyses of glass-bead samples having size ranges from 20 to 700 microns. The data for sieve correction may be found in Report No. 10 [4]. The sieve analysis was reported in percentages of total material contained between nominal sieve sizes but may be readily changed to cumulative percentages finer than sieve sizes. If the microscopic analysis of the 20- to 700-micron size distribution of Table 4 of Report No. 10 is plotted, the sizes at which the original sieve distribution percentages near the bottom of Fig. 2 of Report No. 10 are equaled may be quickly noted to determine the size at which the sieve actually divided the sample. For example, the sieve analysis showed 29.9 percent (3.1 + 4.9 + 3.2 + 4.9 + 13.8 percent) of the sample finer than the 125-micron sieve, but the microscopic analysis showed a size of 121 microns at the 29.9-percent-finer point. So the sieve with a 125-micron nominal size separated glass

beads at a microscopic size of 121 microns. Similarly, the 250-micron sieve (shown in the glass-bead analyses as 246 microns--the manufacturer's calibration size) actually divided at 245 microns, the 149 divided at 146 microns, the 88 divided at 90 microns, the 74 divided at 78 microns, the 62.5 divided at 64.5 microns, and the 44 divided at 49 microns. The corrections for the other sieves were negligible; that is, they would affect any normal size distribution less than 1 percent.

The corrected sieve-size distributions for sands were determined by plotting cumulative percentages against corrected--not nominal--sieve sizes; from the plotted curves, a distribution for standard sizes was obtained. Throughout the remainder of this report any sieve-size distribution in the text, tables, or figures will be the corrected distribution based on the standard sizes, except that the corrected sizes are used instead of standard sizes in Table 5.

21. Need for calibration of the VA-tube method--Because the evaluation of the accuracy of sedimentation methods of size analysis of sand samples is difficult or time consuming, investigators have tended to study these methods only in relation to reproducibility of results [5] or by calibrating or checking against sieve analyses [16].

Figs. 15 and 16 show the differences between the corrected sieve analyses of two size distributions of Powder River sand (the sands used in this investigation are described in Section 27) and the uncalibrated VA-tube analyses for samples made up with these sieve distributions. The differences are plotted as deviations of the VA-tube analyses from the sieve analyses and are the algebraic differences between the cumulative-percentage-finer figures for the two types of analyses.

Each distribution in the upper three parts of Fig. 15 is the average of four analyses and of Fig. 16 is the average of two analyses. Half the analyses of Fig. 16 were made in tubes specially cleaned with a sulfuric acid-sodium dichromate solution as explained in Section 14. The special cleaning showed no advantages over cleaning with Alconox, which was not considered to be a special cleanser but was used for the other half of the analyses of Fig. 16 and for all other analyses of sands. The uncalibrated VA-tube analyses were obtained by using the uncorrected chart for sands, which is shown in Fig. 4. Figs. 15 and 16 show that the relation between sieve and uncalibrated VA-tube analyses varies not only for fine and coarse distributions composed of the same basic sand but also with particle sizes. The uncalibrated VA-tube analyses do not approximate the sieve-size distribution.

The VA-tube method could be calibrated to provide fairly consistent analyses in terms of sieve sizes, but particle shape and specific gravity might affect the results significantly. The calibration would be applicable only to one set of sieves under a single system of operation. Even if a sieve calibration established a more uniform standard of comparison, it would not meet the need of this study, which required the development of a method of size analysis based on the fall velocities of the sediment particles.

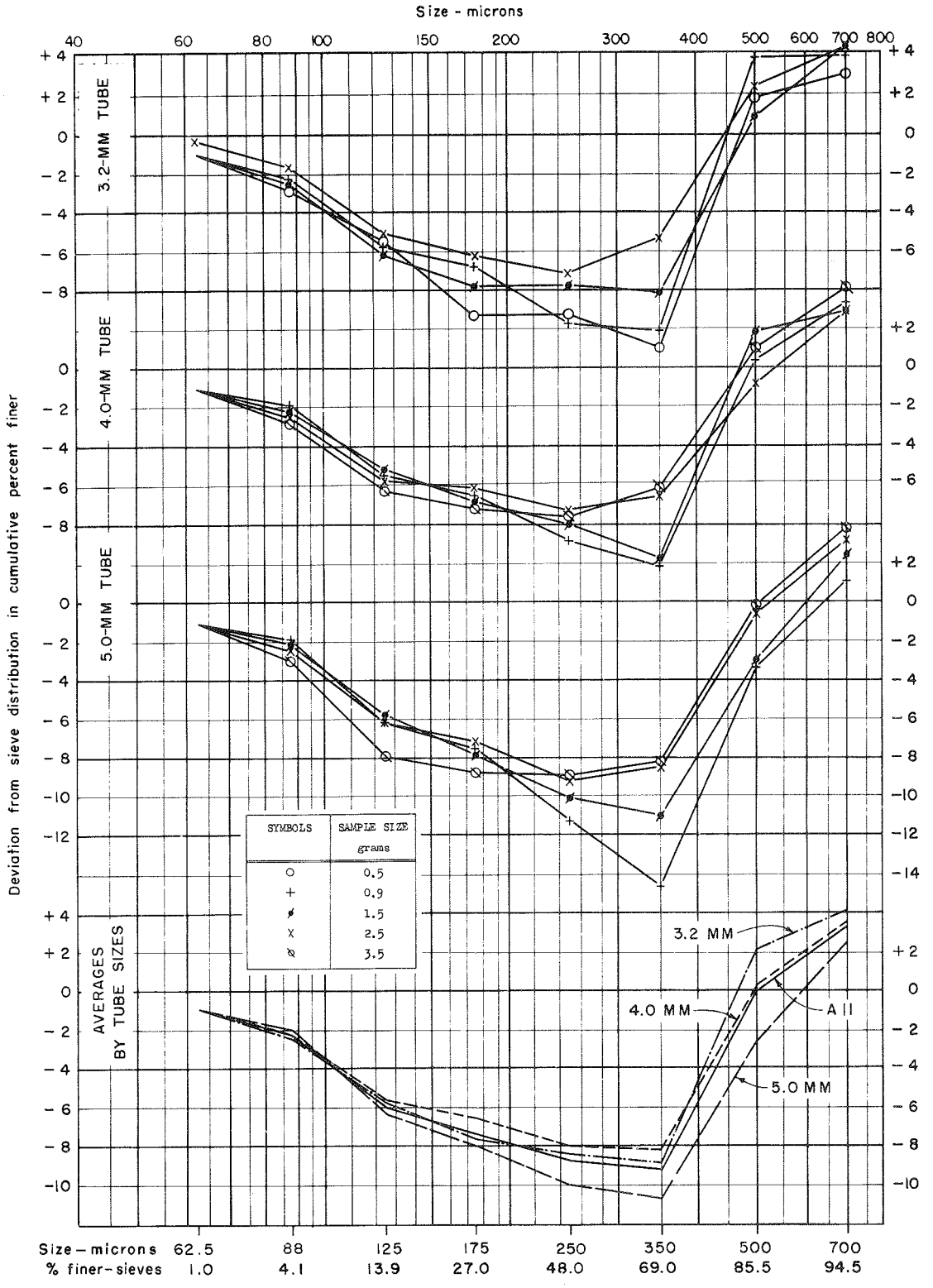


FIG. 15 – SIEVE SIZE vs UNCALIBRATED VISUAL-ACCUMULATION-TUBE ANALYSIS OF COARSE DISTRIBUTION OF POWDER RIVER SAND

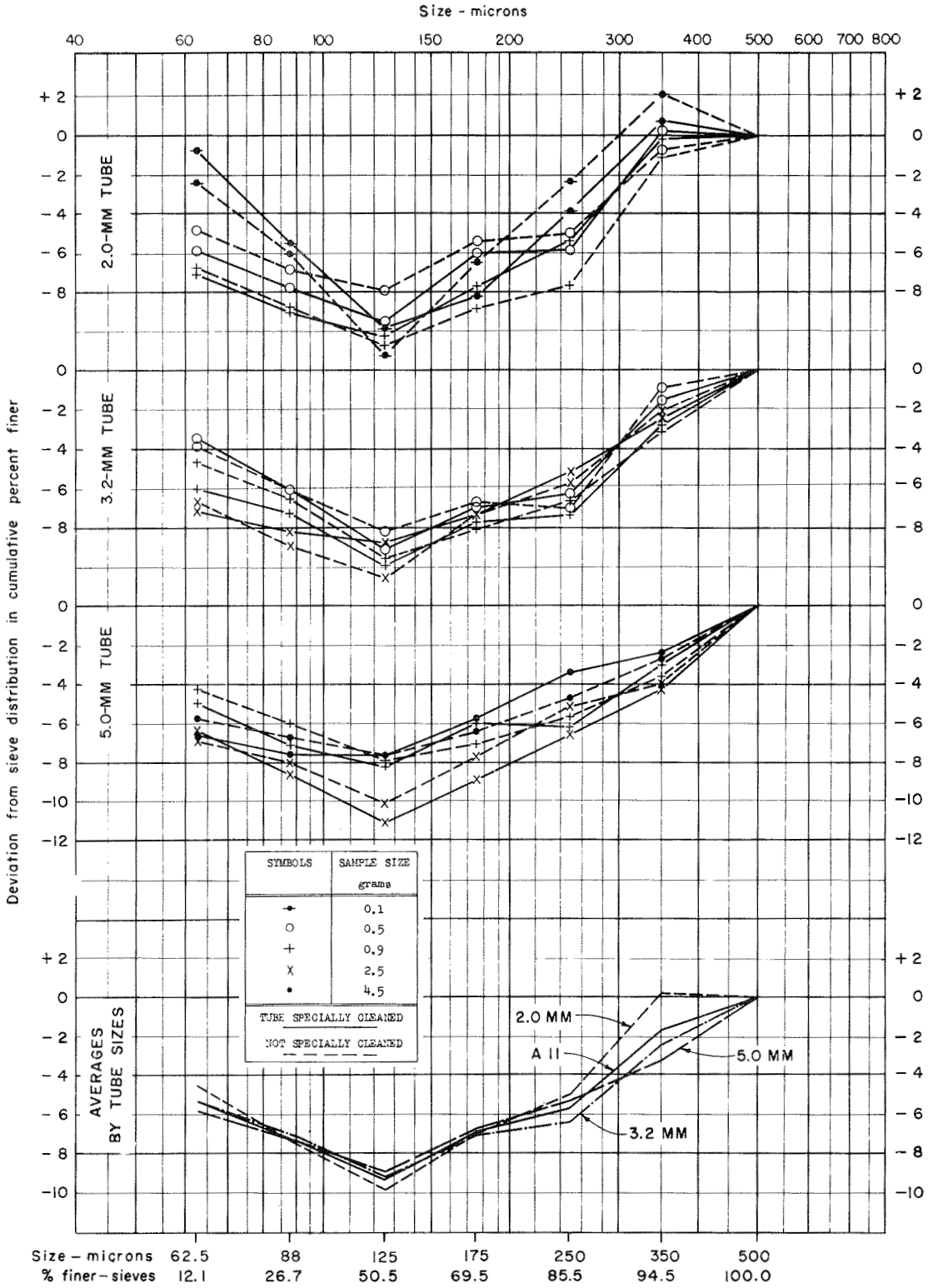


FIG. 16 - SIEVE SIZE vs UNCALIBRATED VISUAL-ACCUMULATION-TUBE ANALYSIS OF FINE DISTRIBUTION OF POWDER RIVER SAND

To make the VA-tube analyses of universal use, it was necessary to calibrate the method in terms of some definite, easily understood, and readily reproducible unit of sedimentation size. The concepts of standard fall velocity and fall diameter as defined in this report provide a simple foundation for the expression of the size distribution of samples analyzed by sedimentation methods. This system of units expresses the fundamental hydraulic properties of the sediment sample on the basis of the fall of the individual particles; a type of analysis which, whether its use becomes general or not, is at least susceptible of ready and precise definition.

The initial development of the VA-tube procedure, with glass-bead samples, indicated that the method was practical and gave highly reproducible results, but it also showed that the analyses did not directly determine the standard fall-velocity distribution which would be obtained by a summation of the fall velocities of the individual particles. That fundamental type of distribution could only be obtained by application of a calibration correction to the VA-tube results. The glass-bead analyses indicated that the method would require calibration for use on sand samples; however, there was no assurance that the calibration corrections for sands would be the same as, or similar to, the calibration coefficients found for glass beads.

A calibration for sands was attempted by such indirect means as the comparison of analyses of a given sample in several different tubes or the comparison of analyses of samples having like distribution but different total weights. Determinations of calibration corrections by these means were not conclusive enough for assured accuracy. For sands, the only way to calibrate the VA-tube method in terms of the standard fall velocity appeared to be by use of sand samples for which the standard fall-velocity distribution had been predetermined by another method.

22. Method for determining fall-diameter distribution--For this investigation a new method for determining the fall-diameter distribution of a sand was developed. A bulk sample of each of five different sands (see Section 27) was sieved, 10 gm at a time, until the desired supply of material of each sieve fraction had been obtained. The sieve-size distribution based on the total weight of each fraction was recorded. Then each sieve fraction for which fall-diameter distribution was to be determined was carefully split and resplit until about 100 representative particles remained; the remaining particles were dropped individually in distilled water. The fall velocity of each was determined, and the mean fall velocity was accurate within about 5 percent. Fall velocity was converted into fall diameter by Table 10 in the appendix.

The fall diameters of the particles were cubed to approximate their relative volumes and weights. A fall diameter was chosen at about the median division of a summation of the cubed diameters arranged in order of size. A summation was made of all cubed figures smaller than the cube of the chosen fall diameter, and this sum was expressed as a fraction of the total of all the cubes; for example, 0.517 smaller than (and 0.483 larger than) the cube of 400 microns in the sieve fraction 350 to 500 microns. (See Table 4.) Similar

TABLE 4

FALL-DIAMETER DISTRIBUTION BASED ON FALL VELOCITIES OF 100 INDIVIDUAL PARTICLES

Fall distance 100 cm. Temperature of distilled water 25.2° C.

Sieve size--350 to 500 microns

Time of fall seconds	Velocity cm/sec	Fall diameter microns	Cube of fall diameter	Time of fall seconds	Velocity cm/sec	Fall diameter microns	Cube of fall diameter
21.1	4.74	318	322×10^5	16.7	5.99	388	584×10^5
15.2	6.58	421	746	18.5	5.41	355	447
17.4	5.75	374	523	14.0	7.14	452	923
14.0	7.14	452	923	13.5	7.41	467	1018
17.7	5.65	369	502	20.3	4.93	329	356
19.1	5.24	346	414	14.0	7.14	452	923
18.4	5.43	356	451	18.3	5.46	358	459
18.1	5.52	361	470	16.9	5.92	384	566
15.6	6.41	411	694	16.7	5.99	388	584
15.6	6.41	411	694	16.0	6.25	402	650
16.0	6.25	402	650	16.8	5.95	385	571
17.4	5.75	374	523	13.5	7.41	467	1018
16.8	5.95	385	571	20.4	4.90	327	350
18.9	5.29	349	425	15.7	6.37	409	684
15.0	6.67	426	773	17.3	5.78	376	532
18.3	5.46	358	459	18.5	5.41	355	447
15.9	6.29	404	659	14.7	6.80	433	812
15.4	6.49	416	720	16.6	6.02	389	589
19.6	5.10	338	386	19.8	5.05	335	376
19.1	5.24	346	414	18.2	5.49	360	467
16.0	6.25	402	650	17.5	5.71	372	515
17.0	5.88	381	553	16.2	6.17	398	630
15.0	6.67	426	773	15.5	6.45	413	704
20.6	4.85	324	340	15.4	6.49	416	720
13.0	7.69	483	1127	20.0	5.00	333	369
14.9	6.71	428	784	23.1	4.33	296	259
13.3	7.52	473	1058	16.6	6.02	389	589
17.2	5.81	377	536	19.1	5.24	346	414
18.0	5.56	364	482	16.8	5.95	385	571
16.5	6.06	391	598	14.8	6.76	431	801
16.3	6.13	395	616	14.8	6.76	431	801
16.7	5.99	388	584	18.5	5.41	355	447
19.7	5.08	337	383	15.4	6.49	416	720
15.4	6.49	415	715	17.0	5.88	381	553
16.6	6.02	389	589	16.4	6.10	394	612
21.0	4.76	319	325	16.3	6.13	395	616
15.8	6.33	407	674	16.9	5.92	384	566
19.2	5.21	344	407	17.9	5.59	365	486
15.9	6.29	404	659	18.7	5.35	352	436
16.3	6.13	395	616	17.9	5.59	365	486
17.9	5.59	365	486	16.6	6.02	389	589
16.6	6.02	389	589	19.5	5.13	340	393
19.6	5.10	338	386	16.0	6.25	402	650
13.4	7.46	470	1038	17.1	5.85	380	549
13.6	7.35	464	999	13.6	7.35	464	999
16.0	6.25	402	650	17.3	5.78	376	532
14.7	6.80	433	812	18.7	5.35	352	436
13.0	7.69	483	1127	21.8	4.59	310	298
15.8	6.33	407	674	20.7	4.83	323	337
17.4	5.75	374	523	17.2	5.81	377	536
				Totals	598.25	38725	60042
				Averages	5.98	387	600

Total of cubes smaller than the cube of 400 is 31020. 31020/60042=.517. Then 51.7% of the sieve class has fall diameters finer than 400 microns.

Fall diameter in microns obtained from fall velocity by use of Table 10.

data were obtained for each sieve fraction for which fall-diameter distribution was determined. If 37.0 percent of the sample was contained in the sieve fractions finer than 350 microns, and 25.0 percent in the 350- to 500-micron fraction, then 49.9 percent (37.0 plus the product of 0.517 x 25.0) of the total sample had fall diameters smaller than 400 microns. These data illustrate the derivation of the fall-diameter distribution. Table 5 shows the data for a Cheyenne River sand.

Four assumptions or qualifications that pertain to the method of determining fall-diameter distribution justify comment.

1. The cube of the fall diameter was assumed to be proportional to the weight of the particle. The relationship is not direct, but the cube more nearly represents the volume and weight than would the first power of the fall diameter. Even the use of the first power of the fall diameter would not significantly alter the results if the range of sizes in each sieve fraction was small.

2. The computations in the cited example are generally adequate. However, occasionally a significant percentage of material in the sieve fractions coarser than 500 microns has fall diameters less than 400 microns, or a significant percentage of material in the sieve fractions finer than 350 microns has fall diameters greater than 400 microns. Then, by extra computations, the weight equivalent of offending material was moved from the sieve fraction where it was originally to the proper side of the 400-micron size.

Table 6 shows data from 100 particles of a 1000- to 1400-micron sieve fraction. The fall-diameter distribution of this coarse sieve fraction overlaps the median fall diameters of adjacent fractions. When there is overlap, the determination of size distribution requires the type of computations shown in Table 7.

3. A 100-particle split as the basis for determining the fall-diameter distribution for a sieve fraction was satisfactorily accurate as shown by the consistency of results throughout the size ranges of the samples. (See Section 28.) Usually about eight such splits were used to define a curve of fall-diameter distribution for a complete sample. Because the shape of this curve was necessarily very similar to that for the sieve-diameter distribution, an inconsistent split was immediately obvious. If inconsistencies were minor, adjacent results were averaged; but if any major discrepancy was found, the split was rechecked. In the cited example, if the 0.517 smaller than the cube of 400 microns should actually have been 0.600 (an extreme variation), the percentage finer would have been changed from 49.9 to 52.0 percent, which is within acceptable limits of accuracy. Errors in individual splits are independent of those for other splits, are not subject to cumulative errors, and generally apply to minor fractions of a total sample.

4. Within the temperature range of 20° to 35°C, the effect of temperature on the settling velocity for a particle of sediment in water is considered to be essentially the same as that for a sphere of specific gravity 2.65. Table 11 (in the appendix), which was derived from the data of Fig. 5 of Report No. 4 [5], may then be used to find the fall velocity at 24°C if the settling velocity is known at another temperature. Also, Table 10 may be used to find the sedimentation size or fall diameter of a particle from the fall velocity at 24°C or directly from the settling velocity at another temperature.

Possibly there will be some sand grains for which the effect of temperature on fall velocity will be radically different from that for spheres of specific gravity 2.65. A study of resistance curves for settling particles has indicated that generally for a group of

TABLE 5

COMPUTATION OF FALL-DIAMETER DISTRIBUTION FOR A CHEYENNE RIVER SAND

Sieve			Fall diameter					
Sizes microns	Cumulative % finer	Percent in fraction	Median size microns	in sieve fraction: finer than median	in sieve fraction: finer (% of total)	Cumulative % finer: than median size	Cumulative % finer: than division size	Division size microns
1	2	3	4	5	6	7	8	9
from sieve fractions			a	b	Col.3xCol.5	Col.2+Col.6	c	selected
1000	100.0						100.0	1000
			670			92.5		
		14.0		.466	6.5			
700	86.0						94.4	700
			515			73.5		
		24.0		.479	11.5			
500	62.0						70.2	500
			400			49.9		
		25.0		.517	12.9			
350	37.0						40.0	350
			295			27.0		
		20.0		.501	10.0			
245	17.0						18.4	250
			212			11.8		
		9.8		.465	4.6			
175	7.2						7.2	175
			160			6.1		
		2.0		.441	0.9			
146	5.2							
			135			4.4		
		1.3		.408	0.5			
121	3.9						3.8	125
		0.9						
104	3.0							
			100			2.6		
		0.7		.484	0.3			
90	2.3						1.9	88
		0.6						
78	1.7							
			80			1.5		
		0.4		.516	0.2			
64.5	1.3						0.8	62.5
		1.3						
		100.0						

a Approximate median size in microns

b Fraction finer than median size from data similar to that of Table 4

c Data of columns 4 & 7 were plotted and percentages finer than division sizes were taken from curve (Fig. 34)

TABLE 6

FALL-DIAMETER DISTRIBUTION BASED ON FALL VELOCITIES OF 100 INDIVIDUAL PARTICLES

Fall distance 100 cm. Temperature of distilled water 27.2° C.

1000-1400 microns sieve size

Time of fall seconds	Velocity cm/sec	Fall diameter microns	Cube of fall diameter
6.3	15.9	974	924×10^6
6.4	15.6	954	868
7.5	13.3	808	528
8.4	11.9	720	373
7.1	14.1	859	634
6.3	15.9	974	924
6.8	14.7	897	722
6.5	15.4	942	836
7.1	14.1	859	634
7.1	14.1	859	634
7.3	13.7	834	580
7.6	13.2	802	516
5.5	18.2	1124	1421
5.7	17.5	1077	1249
4.8	20.8	1303	2212
7.9	12.7	770	457
7.1	14.1	859	634
7.7	13.0	789	491
6.2	16.1	986	959
7.5	13.3	808	528
7.1	14.1	859	634
7.3	13.7	834	580
7.9	12.7	770	457
7.2	13.9	847	608
8.8	11.4	690	329
7.4	13.5	821	553
8.1	12.3	745	413
12.0	8.3	510	133
7.2	13.9	847	608
6.0	16.7	1026	1080
7.6	13.2	802	516
6.1	16.4	1006	1018
6.1	16.4	1006	1018
15.4	6.5	409	68
6.8	14.7	897	722
5.2	19.2	1192	1694
6.6	15.2	929	802
6.9	14.5	884	691
8.2	12.2	739	404
6.7	14.9	910	754
7.0	14.3	872	663
6.0	16.7	1026	1080
8.2	12.2	739	404
6.2	16.1	986	959
6.7	14.9	910	754
6.4	15.6	954	868
8.0	12.5	758	436
6.6	15.2	929	802
7.9	12.7	770	457
8.1	12.3	747	417
7.3	13.7	834	580×10^6
7.6	13.2	802	516
6.5	15.4	942	836
6.5	15.4	942	836
6.4	15.6	954	868
6.4	15.6	954	868
6.3	15.9	974	924
8.0	12.5	758	436
9.7	10.3	625	244
7.4	13.5	821	553
10.7	9.3	567	182
8.0	12.5	758	436
6.8	14.7	897	722
7.9	12.7	770	457
6.1	16.4	1006	1018
8.6	11.6	702	346
6.3	15.9	974	924
8.0	12.5	758	436
6.5	15.4	942	836
8.3	12.0	726	383
7.4	13.5	821	553
7.7	13.0	789	491
8.4	11.9	720	373
7.1	14.1	859	634
7.6	13.2	802	516
6.6	15.2	929	802
11.7	8.5	522	142
8.5	11.8	714	364
7.7	13.0	789	491
6.5	15.4	942	836
6.1	16.4	1006	1018
8.6	11.6	702	346
6.3	15.9	974	924
7.2	13.9	847	608
7.4	13.5	821	553
7.2	13.9	847	608
7.0	14.3	872	663
7.0	14.3	872	663
5.3	18.9	1171	1606
8.1	12.3	745	413
7.2	13.9	847	608
7.0	14.3	872	663
6.3	15.9	974	924
4.7	21.3	1338	2395
9.2	10.9	660	287
6.8	14.7	897	722
7.2	13.9	847	608
8.4	11.9	720	373
7.4	13.5	821	553
7.5	13.3	808	528
Totals	1406.1	85846	68712
Averages	14.1	858	687

Cubed figures between division sizes:			
Over 1400 microns		0	0.000
1400-1120	do	9328×10^6	.135
1120- 880	do	30088	.438
880- 720	do	26296	.383
720- 540	do	2657	.039
540- 390	do	343	.005
under 390	do	0	.000
Totals		68712	1.000

Fall diameter in microns obtained from fall velocity by use of Table 10.

TABLE 7

COMPUTATION OF FALL-DIAMETER DISTRIBUTION FOR A VERY COARSE SAND

Sieve			Fall diameter range in microns											
Sizes microns	Cumulative % finer	Percent in fraction	2000 - 1400		1400 - 1120		1120 - 880		880 - 720		720 - 540		540 - 390	
from sieve fractions			a	b	a	b	a	b	a	b	a	b	a	b
2000	100.0													
		50.0	0.125	6.25	0.493	24.65	0.339	16.95	0.032	1.60	0.011	0.55		
1400	50.0													
		40.0			0.135	5.40	0.438	17.52	0.383	15.32	0.039	1.56	0.005	0.20
1000	10.0													
		10.0					0.068	0.68	0.441	4.41	0.482	4.82	0.009	0.09
700	0.0													
Partials (sum of column)				6.25		30.05		35.15		21.33		6.93		0.29
Reference sizes			2000		1400		1120		880		720		540	
Cumulative percentages finer (cumulative of partials)			100.00		93.75		63.70		28.55		7.22		0.29	
Division sizes			2000		1400		1000		700		500			
Cumulative percentages finer (from plotting of cumulative percentages finer than median sizes. See Fig. 35.)			100.00		93.8		46.0		6.2		0.0			

a That part of the sieve fraction within the given fall-diameter range (from Table 6 for 1000 to 1400-micron sieve fraction)
b (a) multiplied by "percent in sieve fraction"

particles the relation for spheres is adequate. Unpublished tests by the Corps of Engineers on Missouri River sand indicate that the relation for spheres may be used satisfactorily for sand grains settling at water temperatures of 3° to 31°C [17]. Additional studies of the effect of temperature on the fall velocity of sands are being made for the report "Some Fundamentals of Particle-Size Analysis."

23. Test samples of known fall-diameter distribution--The supply of each of the sieve fractions of a sand was used to compound samples whose fall-diameter distributions were determined from the known distributions of the fractions. First, the required weight of the coarsest fraction was placed in a freshly tared dish, and the gross weight was recorded; this procedure was continued until all size fractions were included. Those samples that were synthesized in proportion to the weights of the original sieve fractions had a fall-diameter distribution the same as that of the original supply. Samples that were synthesized in other proportions had different fall-diameter distributions. The fall-diameter distributions within the individual sieve fractions were not altered; therefore, the fall-diameter distribution for the entire synthetic sample did not generally form a smooth curve. Sieve fractions from two sands or more sometimes were combined to obtain a desired size range or type of sample.

How well the computed distributions represent the distributions in the test samples is important but hard to determine. When the data for each of about eight sieve fractions were used to compute a cumulative fall-diameter distribution, the percentages at division sizes were probably within 2 percent. That is, if the percentage finer was computed as 45 at 350 microns, the true percentage finer was within the range 43 to 47. Inevitably, minor errors also occurred in weighing out the samples and in obtaining representative material from each sieve fraction for use in compounding test samples.

24. Analysis of samples of known fall-diameter distribution--Each of the known samples was analyzed according to the procedure of Section 10. The sedimentation tubes were cleaned with Alconox before use each day. The samples were dispersed in the mixing chamber before analysis.

Duplicate samples were made up and analyzed for the first sand that was investigated (Powder River); otherwise, only single samples of each weight were used in these tests. Each sample was analyzed at least twice in each of the tube sizes suitable to the sample. The repetitious use of the samples provided consistency checks independent of the fall-diameter distribution and also independent of any differences between samples.

Generally flocculation was not a significant problem in the analysis of the sands investigated, but there were occasional analyses in which particles fell as groups or conglomerates. If samples were allowed to stand for a long time in water, the particles would sometimes fall as groups of two or more rather than settle as single particles. Stirring up the sample, allowing the

particles to settle, and decanting the supernatant liquid usually conditioned the sample sufficiently for analysis, especially if that process were repeated. A few drops of a chemical dispersing agent could be added if desired; but, except for the oxidation of organic matter, chemicals were not used in these tests.

Samples that contained objectionable quantities of organic matter or that had been left in a moist condition for so long that organic matter had formed a binder, which washing did not remove, were treated with a 6-percent solution of hydrogen peroxide. One to ten ml of the peroxide was added; the amount depended on the estimate of organic matter in the sample. The sample was boiled gently on a hot plate and stirred occasionally until the oxidation of organic matter was complete. The sample was washed three times by adding distilled water, stirring, allowing to settle, and decanting the supernatant liquid; then the sample was cooled to room temperature before analysis.

The VA-tube method is adapted to the analysis of sand sizes only. The method of compounding the known samples eliminated the problem of separating the sands from finer particles, except for the "Taylors Falls" sand which was a surface wash sand that contained a large portion of organic material and very fine silts and clays. The usual dry-sieving operation was used in preparing the original sieve fractions of the Taylors Falls sand, but it did not eliminate the very fine particles that were attached to the sand particles. Those particles with fall diameters less than 44 microns were removed from the sands by allowing the sample to settle through a water column. To obtain the final sieve analysis, the dry weight of the fines removed was added to that part of the sample shown by sieve analysis to be finer than 49 microns.

A special series of samples of the Taylors Falls sand was compounded so that more than 50 percent of the sample was finer than 62 microns; much of this fine material was of clay size. The series was used for studying the removal of fine material from the sample prior to VA-tube analysis of the sand. Each sample was introduced at the top of a sedimentation tube and allowed to settle for the time of fall of a 55-micron quartz sphere. Then, the settled particles were removed and analyzed in the VA tube. The results of the analyses were satisfactory; but, because the separation procedure had not eliminated the fine particles, the time required for complete settling of the sample in the VA tube was excessive. A second similar separation by settling in the sedimentation tube eliminated most of the finer material so that the remainder could be analyzed rapidly and accurately.

The differences between the fall-diameter distribution from the uncalibrated VA-tube analyses and the known fall-diameter distribution for Powder River sand samples are shown in Figs. 17 and 18. The same VA-tube analyses were previously compared with sieve-diameter distribution in Figs. 15 and 16. The uncalibrated VA-tube results did not check the fall-diameter distribution; therefore, a calibration adjustment was necessary.

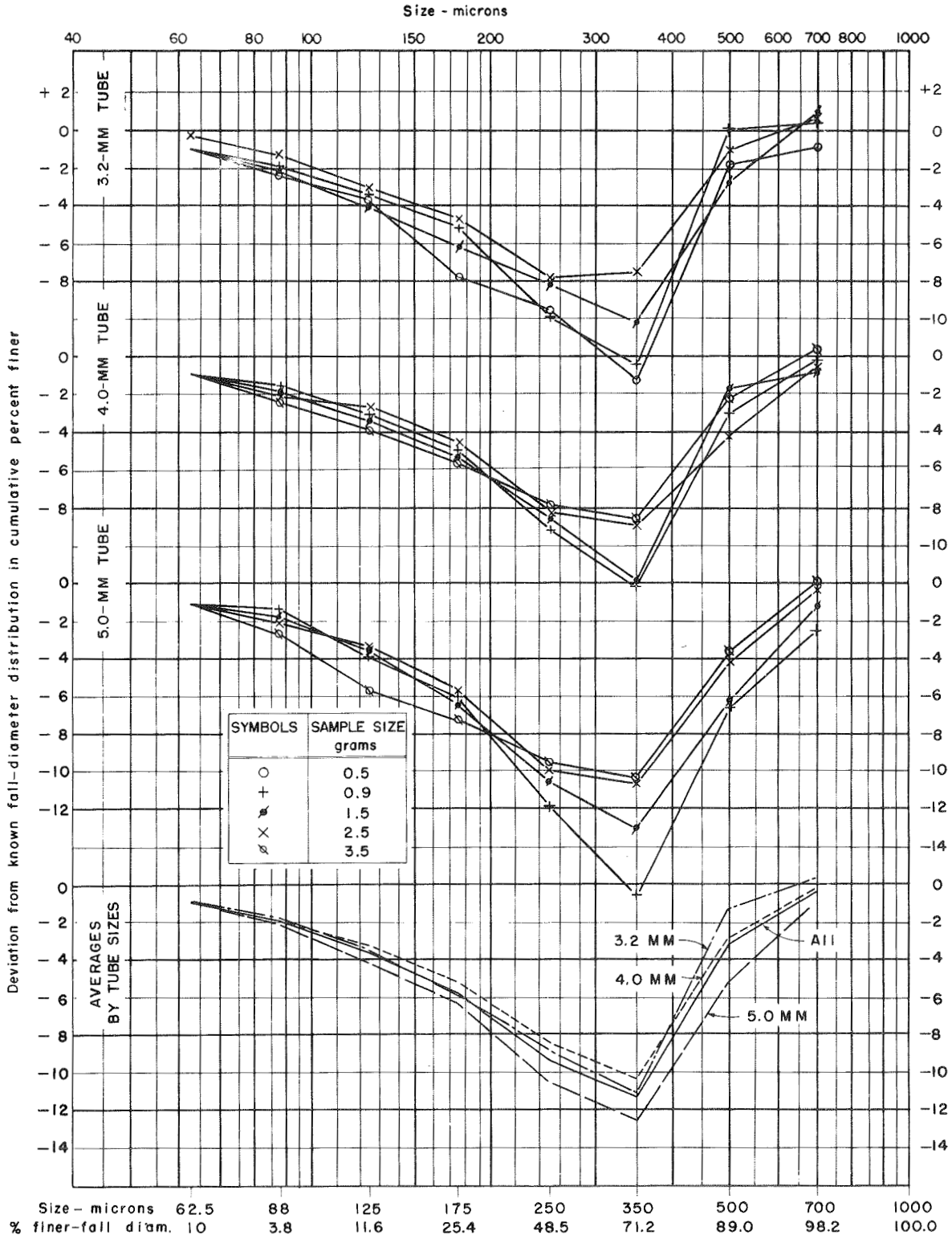


FIG. 17—FALL DIAMETER vs UNCALIBRATED VISUAL-ACCUMULATION-TUBE ANALYSIS OF COARSE DISTRIBUTION OF POWDER RIVER SAND

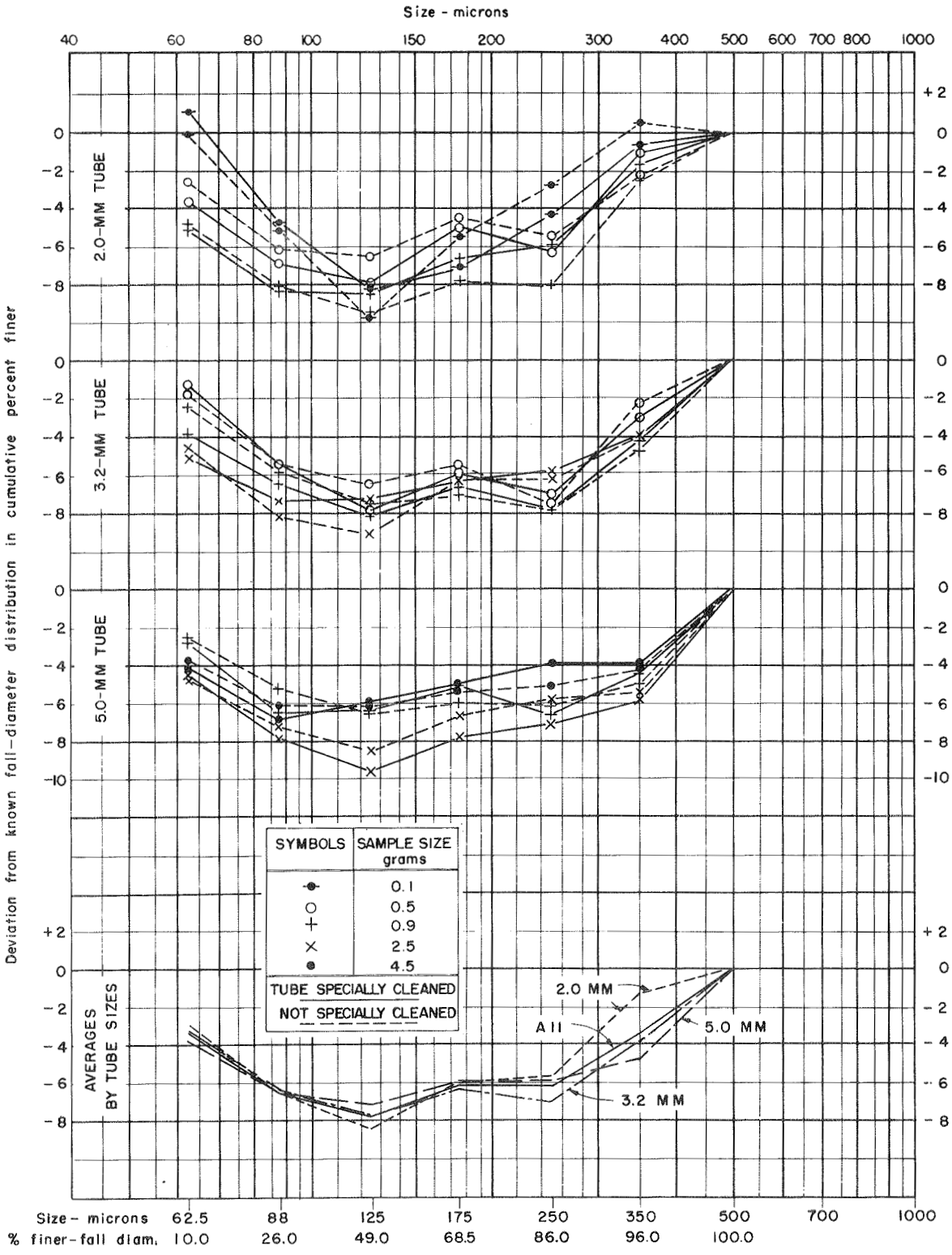


FIG. 18—FALL DIAMETER vs UNCALIBRATED VISUAL-ACCUMULATION-TUBE ANALYSIS OF FINE DISTRIBUTION OF POWDER RIVER SAND

Because of currents generated by the movement of particles or of water-sediment mixtures, the settling velocity of the particles falling in mass in the VA tube is generally greater than the standard fall velocity of the particles. Percentagewise, the greatest differences within the range of sand sizes are for the finer sediments. Very coarse sand particles fall in mass in the VA tube at velocities close to their standard fall velocities. The settling velocity for a given sediment seems to be fastest at a rather low concentration, lower than generally used for VA-tube analyses. As concentrations increase throughout the range of VA-tube analyses, the settling velocities tend to become progressively slower.

The effects of concentration on the settling velocity of sediments in water probably depend on particle size and density, on tube dimensions, and to a lesser extent on particle shape and water temperature. Present theory and knowledge are inadequate to evaluate the relationships, especially for a stratified sedimentation system in which the sample is introduced at the top of a sedimentation column.

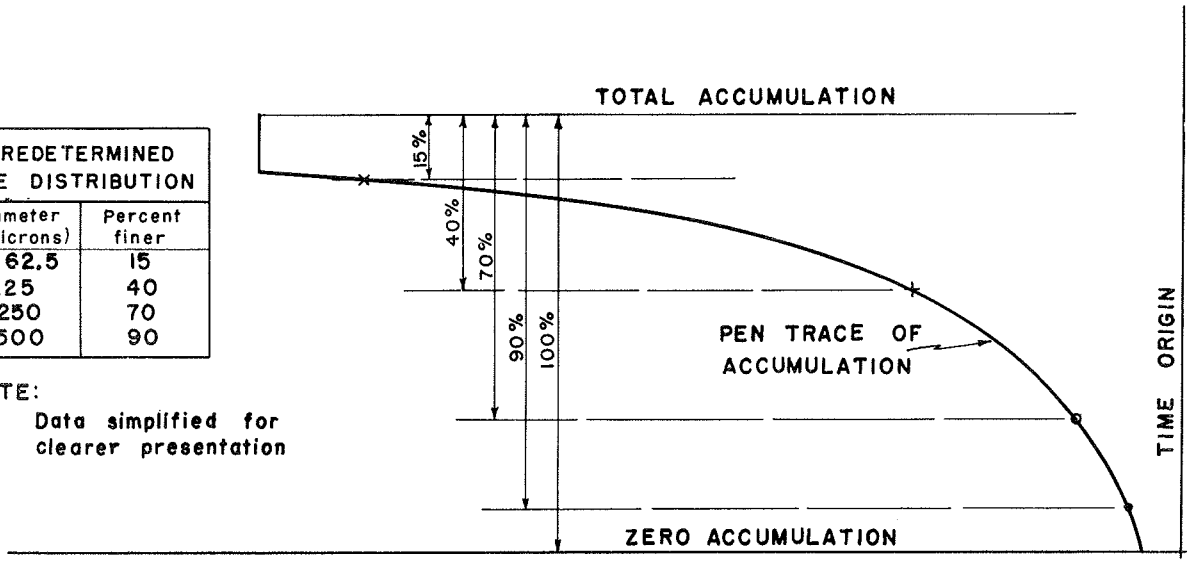
25. Calibration of charts--The calibration of the VA-tube method corrects for the effect of fluid currents generated in the tube and also corrects for volume-weight relations. Nearly 300 analyses of samples with predetermined fall-diameter distributions were available for the calibration of the VA-tube method. The calibration is an average based on the variety of sands, size distributions, and known concentrations analyzed. Two charts were required for the calibration, one for the 120-cm tubes and one for the 180-cm tubes.

Each analysis produced a curve (Fig. 19A) of sediment accumulation with time. For each analysis, points representing the percentages of the known fall-diameter distribution for selected division sizes were marked on the curve. If 40 percent of a calibration sample was finer than 125 microns, the intersection of the curve with the 40-percent-finer line fixed the distance from the time origin for the 125-micron size. Consequently, for the temperature of analysis, each analysis established a point for each division size for use in calibrating the VA tube. Points from several analyses were transferred to a chart, Fig. 19B. A line to represent a particular division size and water temperature was drawn through each set of points. The distance of a division-size line from the time origin of the chart was a measure of the time for that division size of particle to fall in the VA tube.

Analyses at different temperatures provided information for temperature adjustments. The analyses did not define completely the effect of temperature on the time of fall but indicated that the effect of changes in temperature was approximately proportional to the effect on the fall velocities of quartz spheres. Because the relation for quartz spheres could not introduce much error for the relatively narrow range of temperatures in the calibration, the effect of temperature changes on the fall velocities of sediment particles was assumed to be the same as that for quartz spheres.

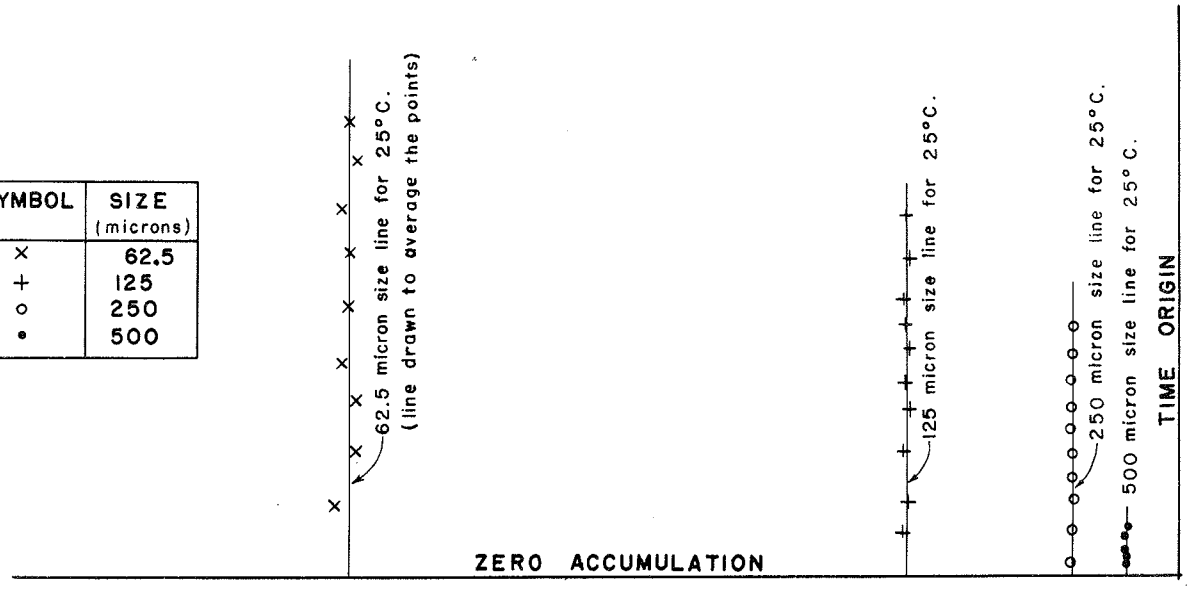
PREDETERMINED SIZE DISTRIBUTION	
Diameter (microns)	Percent finer
62.5	15
125	40
250	70
500	90

NOTE:
Data simplified for clearer presentation



A-- CALIBRATION POINTS FROM A SINGLE ANALYSIS

SYMBOL	SIZE (microns)
×	62.5
+	125
○	250
•	500



B-- CALIBRATION POINTS FROM SEVERAL ANALYSES AT 25°C

FIG. 19 — FUNDAMENTALS OF CALIBRATION METHOD

The calibration charts show nearly vertical size-temperature lines, although the uncalibrated charts of Figs. 3 and 4 showed a reduction in time of fall as the accumulation of sediment increased and the fall distance became less. Consequently, for a division size the correction to time of fall differs with height of accumulation. The difference was caused by the retarding effect of the greater concentrations of material in the samples with the larger accumulations of sediment.

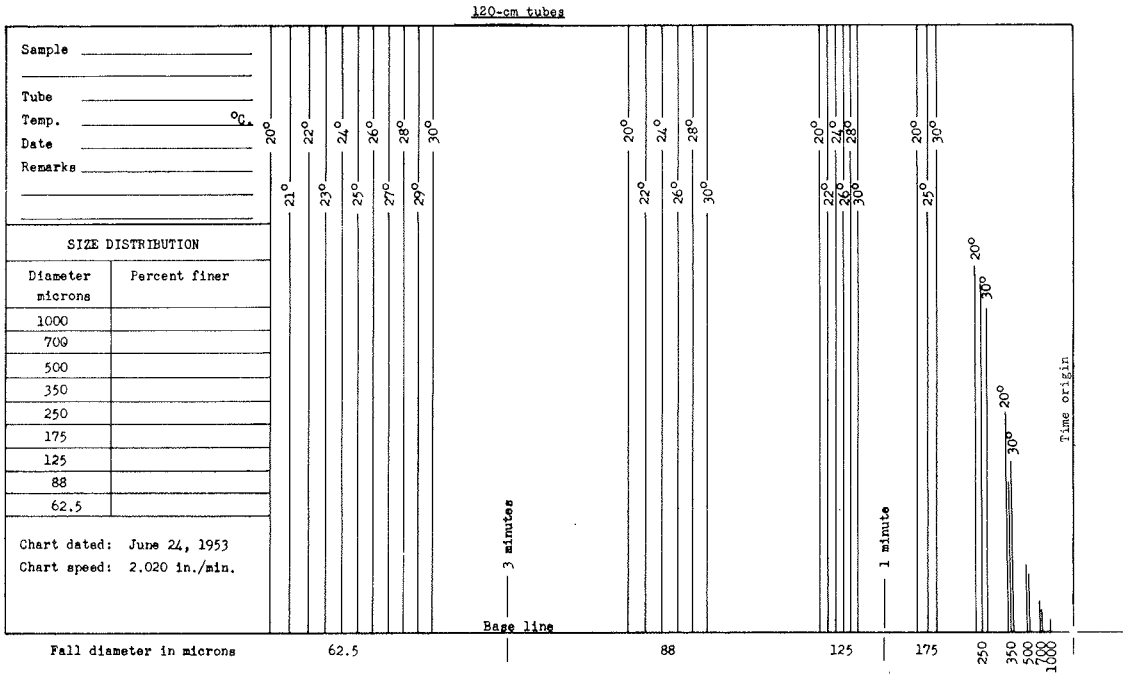
The final calibrated charts for the VA-tube analysis of sands are shown in Fig. 20. The chart of Fig. 20A is for a tube length of 120 cm and collecting tubes of 2.1- to 7.0-mm inside diameter. The chart of Fig. 20B is for a tube length of 180 cm and a collecting tube of 9- or 10-mm inside diameter. The fall distances from the pinch clamp to the stopper in the bottom of the tube (see Fig. 2)--the minimum fall distances for sands-- were 125 (123 cm in original design) and 185 cm, respectively, at the start of sedimentation. These calibrations were based on those samples that were analyzed within acceptable limits of particle size and concentration. The final charts were smoothed for continuity of adjustment and equalizing of errors.

Some of the analyses showed reduced accuracy because of the large quantities of material analyzed or because of high concentrations of certain sizes of particles. Such analyses were not used directly in the chart calibration. However, they helped establish the upper limits of sample quantity and particle size that could be analyzed satisfactorily in the respective sizes of VA tubes. These upper limits are necessary because the fall of the sample was retarded by excesses in either particle size or quantity or by any combination of the two that was excessive.

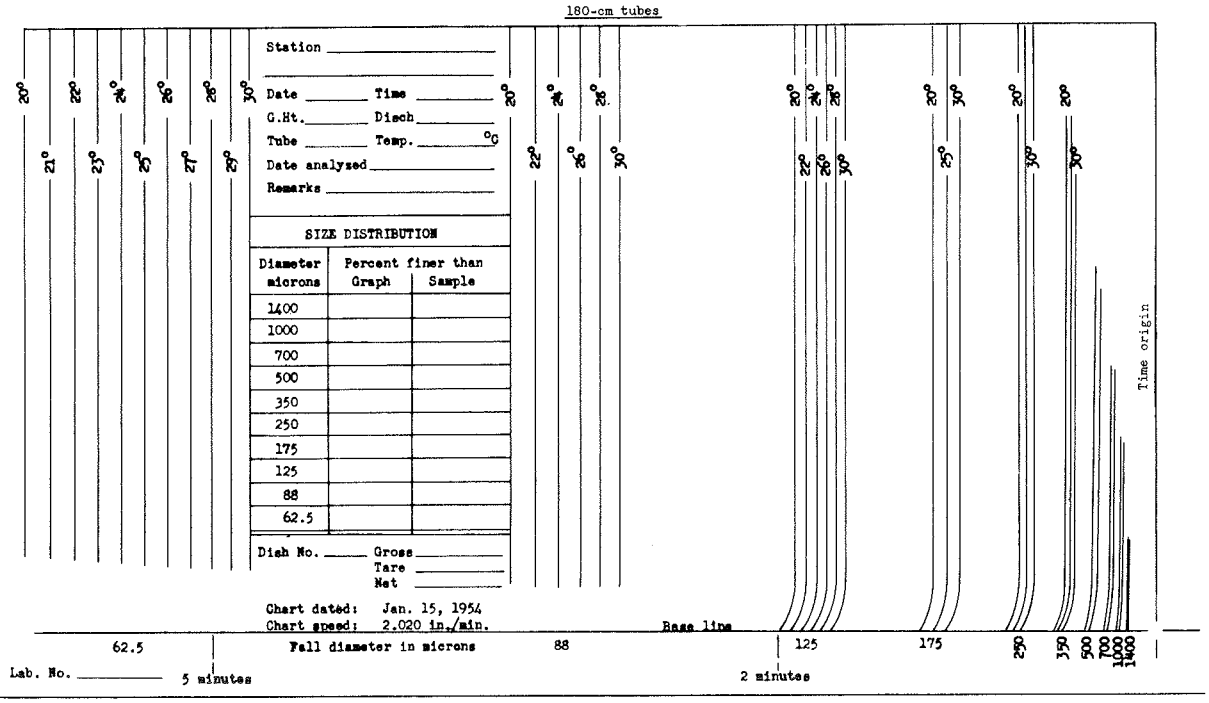
The smallest particle size analyzed was 62 microns. The presence of some coarse silt in the sample did not destroy the accuracy of analysis but made the analysis take longer. The smallest quantity of material in test samples was 0.1 gm, and this weight was run only in the 2.0-mm tube. The minimum quantities of sample for other sizes of tube were based on the least height of accumulation that permitted reasonably accurate analyses. The top of the accumulation was more difficult to follow accurately in the larger tubes, and a greater minimum height of accumulation was desirable.

A study of the analyses of test samples indicated approximate limits on the particle sizes and quantities of sample that could be analyzed accurately in the various sizes of sedimentation tubes. (See Table 8.)

Sedimentation-tube sizes in Table 8 differ from some that were used in the analyses. The tube sizes shown are the ones finally accepted as standard. The maximum particle sizes are those that should not be exceeded by a significant percentage of the sample. The percentage of excess could be greater if the sample were small in relation to the capacity of the tube or if the analysis of the coarser part were not highly important. Generally the best results were obtained if the total height of accumulation in the bottom of the tube was between 1 and 4 in., but a reduction in this maximum height was desirable for a sample of very limited size range or of predominantly coarse material.



A. FOR 120-CM TUBES



B. FOR 180-CM TUBES

FIG. 20 — CALIBRATED CHARTS FOR ANALYSES OF SANDS

TABLE 8

GUIDE TO SELECTION OF CORRECT VA-TUBE SIZE

Sample		Maximum particle size		Sedimentation tube	
Dry weight gm	Volume of sand ml	Fall diameter microns	Sieve diameter microns	Length cm	Diameter mm
0.05-0.8	0.03-0.5	250	250	120	2.1
0.4-2.0	0.2-1.2	350	400	120	3.4
0.8-4.0	0.5-2.4	500	600	120	5.0
1.6-6.0	1.0-4.0	700	1000	120	7.0
5.0-15.0	3.0-9.0	---	2000	180	10.0

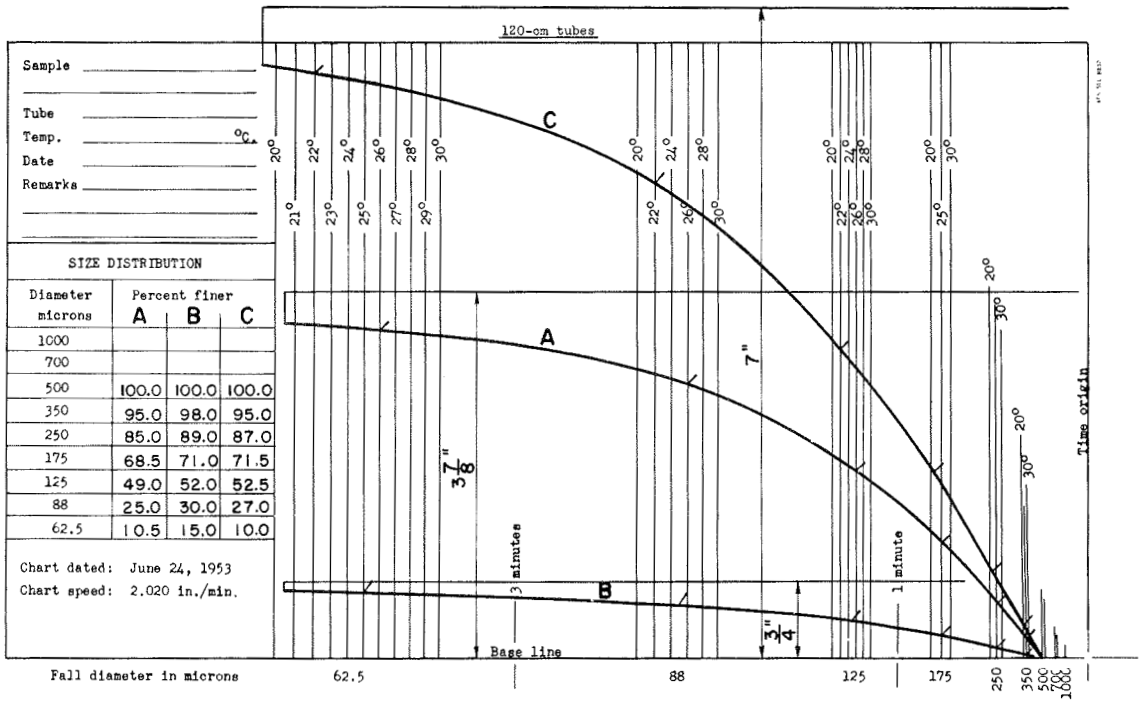
V. ACCURACY OF ANALYSES OF SAND SAMPLES

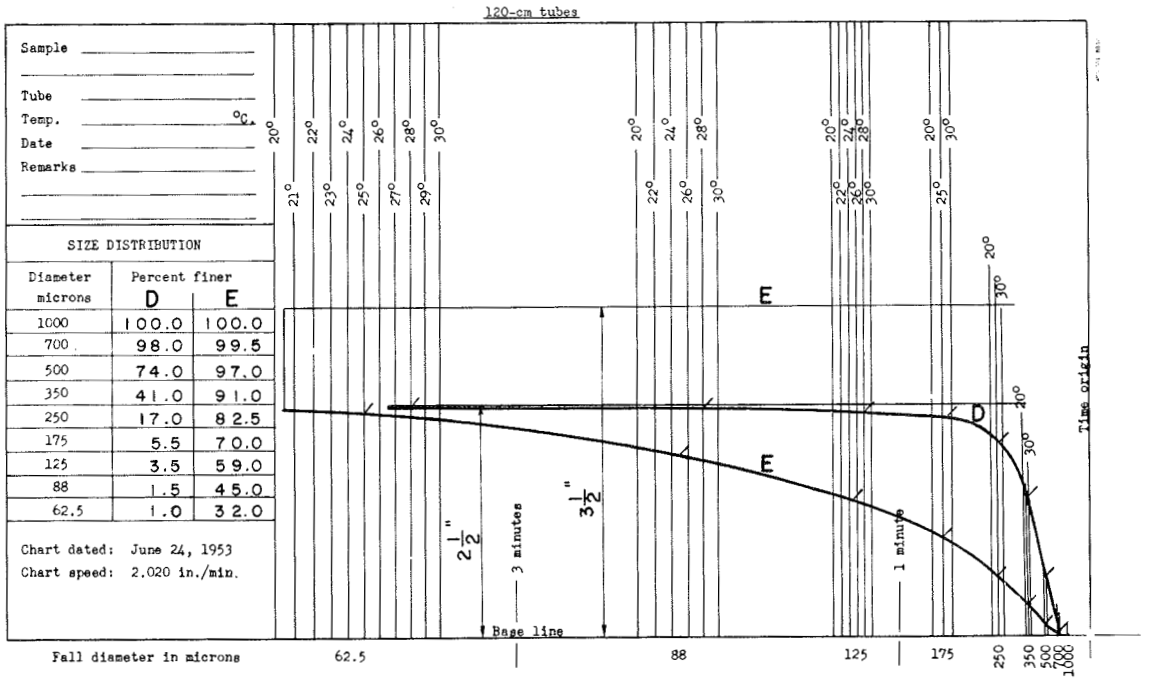
26. Records of VA-tube analyses--The recorder pen traces a continuous curve of accumulation of sediment with time. The ordinate is the height of sediment settled on the bottom of the tube. The abscissa is time of settling; 1 min is equal to 2.020 in. chart distance on standard recorders. Accumulation curves for different types of sediment samples are shown on Fig. 21.

Accumulation curve A of Fig. 21 shows a total accumulation of sufficient height for accurate reading of percentages but not excessively high with regard to concentration, The curve represents a uniform distribution and has intercepts cutting the size lines at angles that make percentages easy to read. Ten percent of the total sample is finer than 62 microns. The analysis took longer than it would have if the fines had not been present.

Accumulation curve B has the same characteristics as A except that the total height of accumulation is only about 3/4 in. Inherent errors in the recording of the accumulation and in reading percentages are likely to become significant at such a low total height. However, this height record is satisfactory for the 2.0- or 2.1-mm tube.

Accumulation curve C is similar to curves A and B except that the total height of accumulation is a maximum. The results from curve C are satisfactory only because the distribution in the sample is uniform and because the concentration of material is not high at any of the division sizes. Even for a uniform distribution, the total height of accumulation of curve A would be more desirable.





ANALYSIS A – Powder River sand, fine distribution, Sample No. 7, 5.0 mm tube, 26° C
B – Powder River sand, fine distribution, Sample No. 1, 2.0 mm tube, 25° C
C – Powder River sand, fine distribution, Sample No. 9, 5.0 mm tube, 22° C
D – Cheyenne River sand, Sample No. 4, 7.0 mm tube, 28° C
E – Republican River sand, fine distribution, Sample No. 2, 2.0 mm tube, 25° C

FIG. 21 – CURVES OF VISUAL-ACCUMULATION-TUBE ANALYSES

Curve D shows a desirable maximum accumulation for a sample that has a distribution concentrated in a limited medium and coarse sand size range. If the total height of accumulation had been greater, the 500-micron lines would not, without extension, intersect the curve. The division-size lines are already drawn to the safe maximum height. If the total height of accumulation at the 500-micron line had been greater, the rate of accumulation would have been excessive. A rapid rate of accumulation is difficult to track, and it indicates that particle settling may be adversely affected by an excessive concentration in the accumulation section. Because the sample was concentrated in the coarser sizes, great care was required in setting the pen to the zero-time line of the chart.

Curve E shows that 32.0 percent of the sample was silt. The presence of the silt did not destroy the accuracy of analysis. Because the silt settles at a slow rate, the analysis required 30 min for reasonable accuracy and 60 min were actually taken for these test samples.

Table 8 is the primary guide to the relation of tube size and sample. The type of sediment-accumulation curve indicates what is important to consider in determining the best tube size for a given sample. These are general criteria for guidance; departures from the best conditions normally make only nominal differences in analyses.

27. Basic sands analyzed--Test samples were compounded from five basic sands that had different size distributions.

The "Powder River sand" was taken from the stream bed of the Powder River at Sussex, Wyoming, Mar. 1, 1951.

The "Republican River sand" was taken from the stream bed of the Republican River at Stratton, Nebraska, Apr. 3, 1951.

The "Cheyenne River sand" was taken from the stream bed of the Cheyenne River near Hot Springs, South Dakota, Mar. 9, 1951.

The "Taylors Falls sand" was surface wash material composed of medium and fine sands and a high percentage of silt and clay. The material was not as well sorted and washed as sands found in main stream channels. The sand was obtained near Taylors Falls, Minnesota, on Aug. 11, 1952.

The "special sand" was chosen for its coarse size distribution. The sand was from a bulk supply that was reportedly from the banks or bed of the Missouri River near Garrison, North Dakota.

Figs. 22 to 26 show the specific gravities determined for various sieve fractions of each sand and also show the volume-weight relations for several sieve fractions of each sand. Volume weights are shown as heights of accumulation of given weights of the sieve fractions of the sands. The volume-weight changes from tube size to tube size or from sand to sand are not

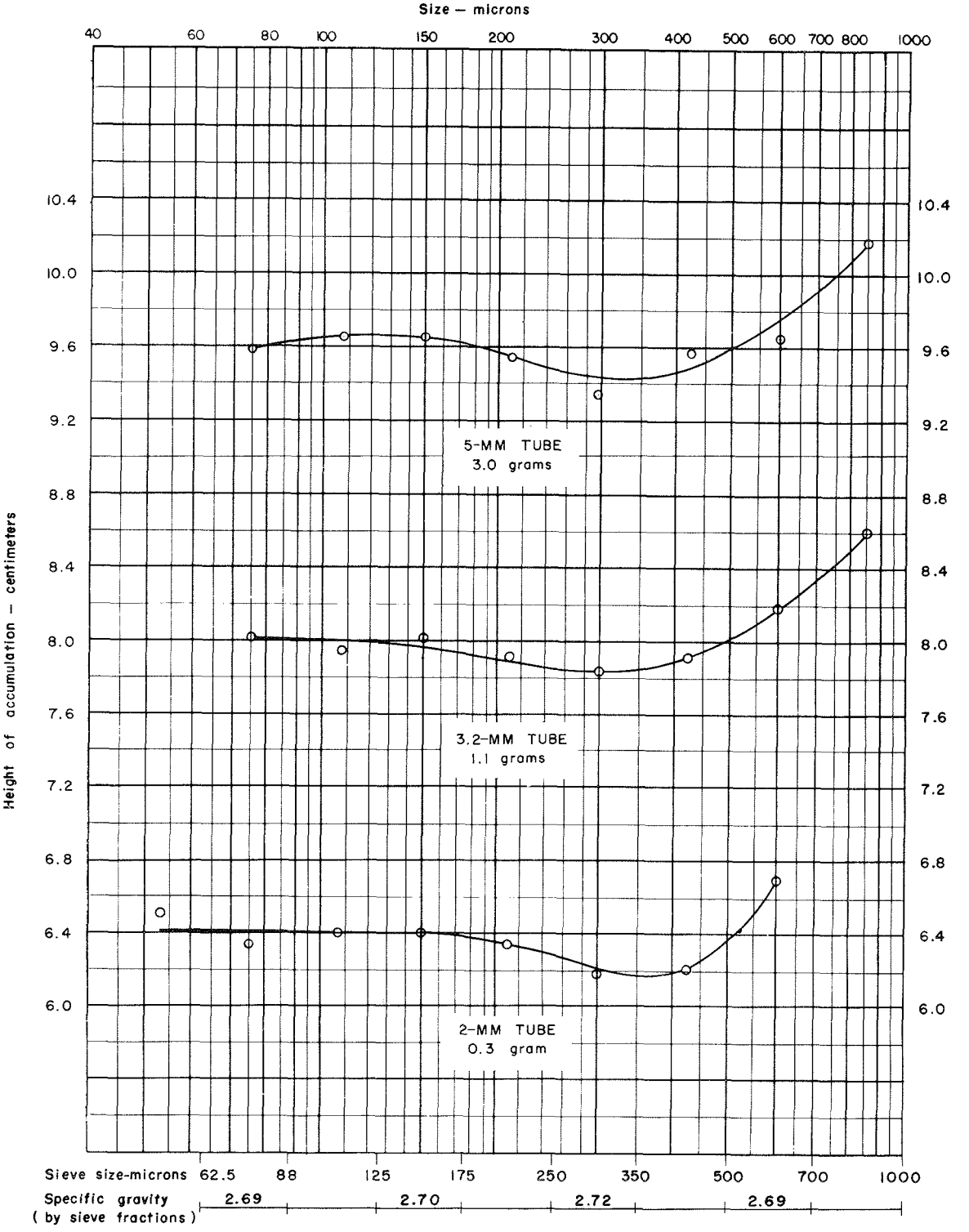


FIG. 22 — VOLUME — WEIGHT RELATIONS FOR POWDER RIVER SAND

(Variation of height of accumulation with sieve size)

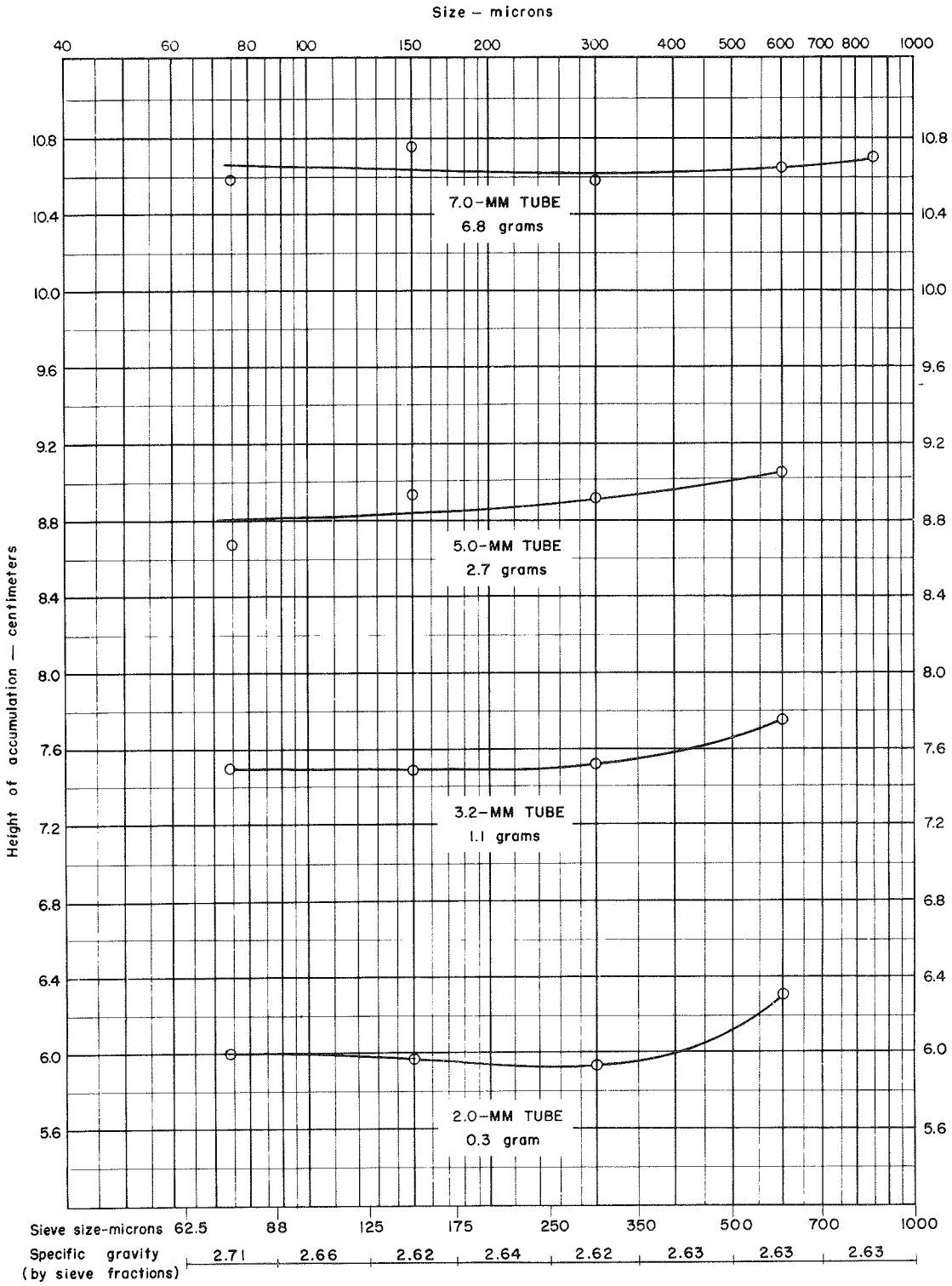


FIG. 23 — VOLUME — WEIGHT RELATIONS FOR REPUBLICAN RIVER SAND

(Variation of height of accumulation with sieve size)

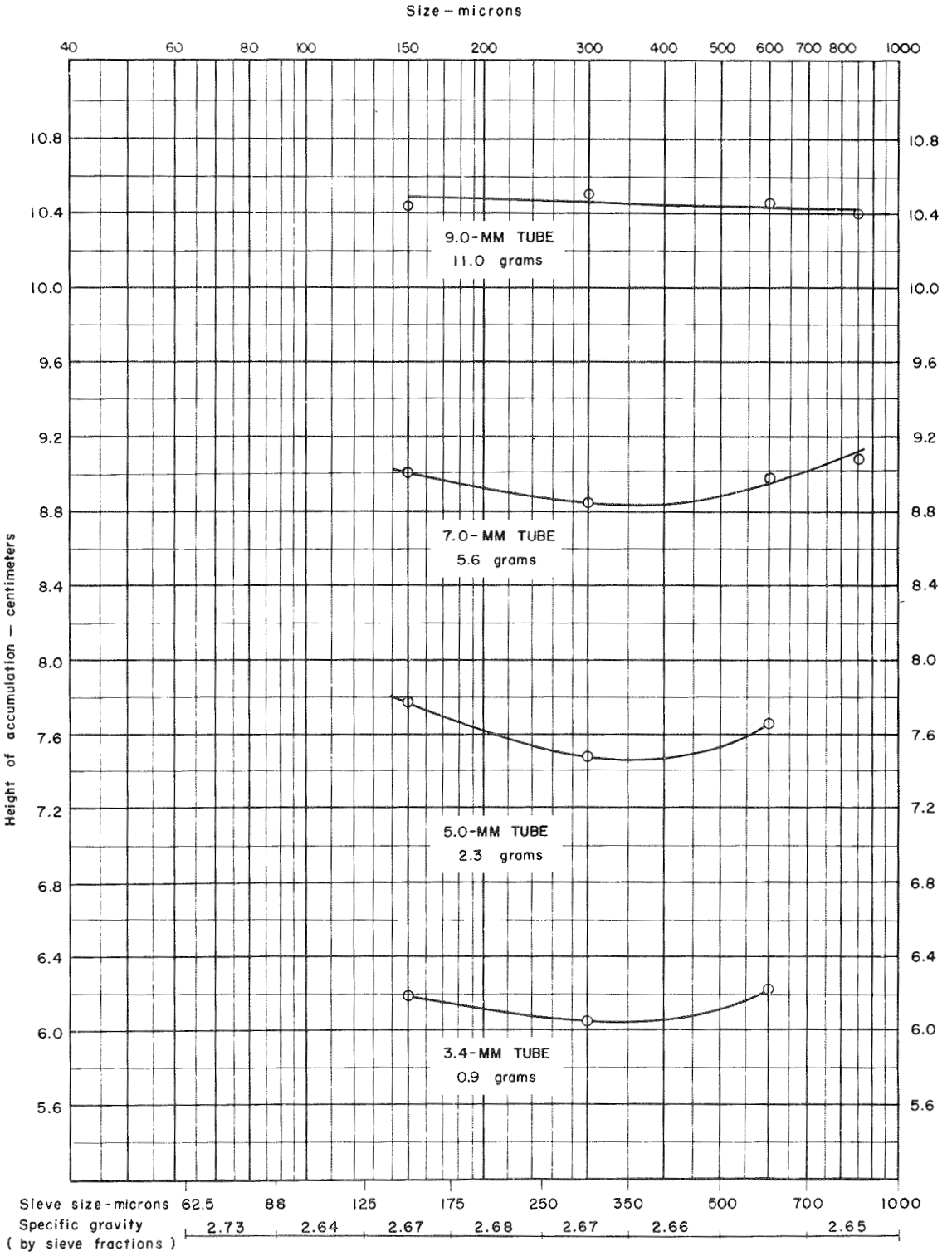


FIG. 24 — VOLUME-WEIGHT RELATIONS FOR CHEYENNE RIVER SAND

(Variation of height of accumulation with sieve size)

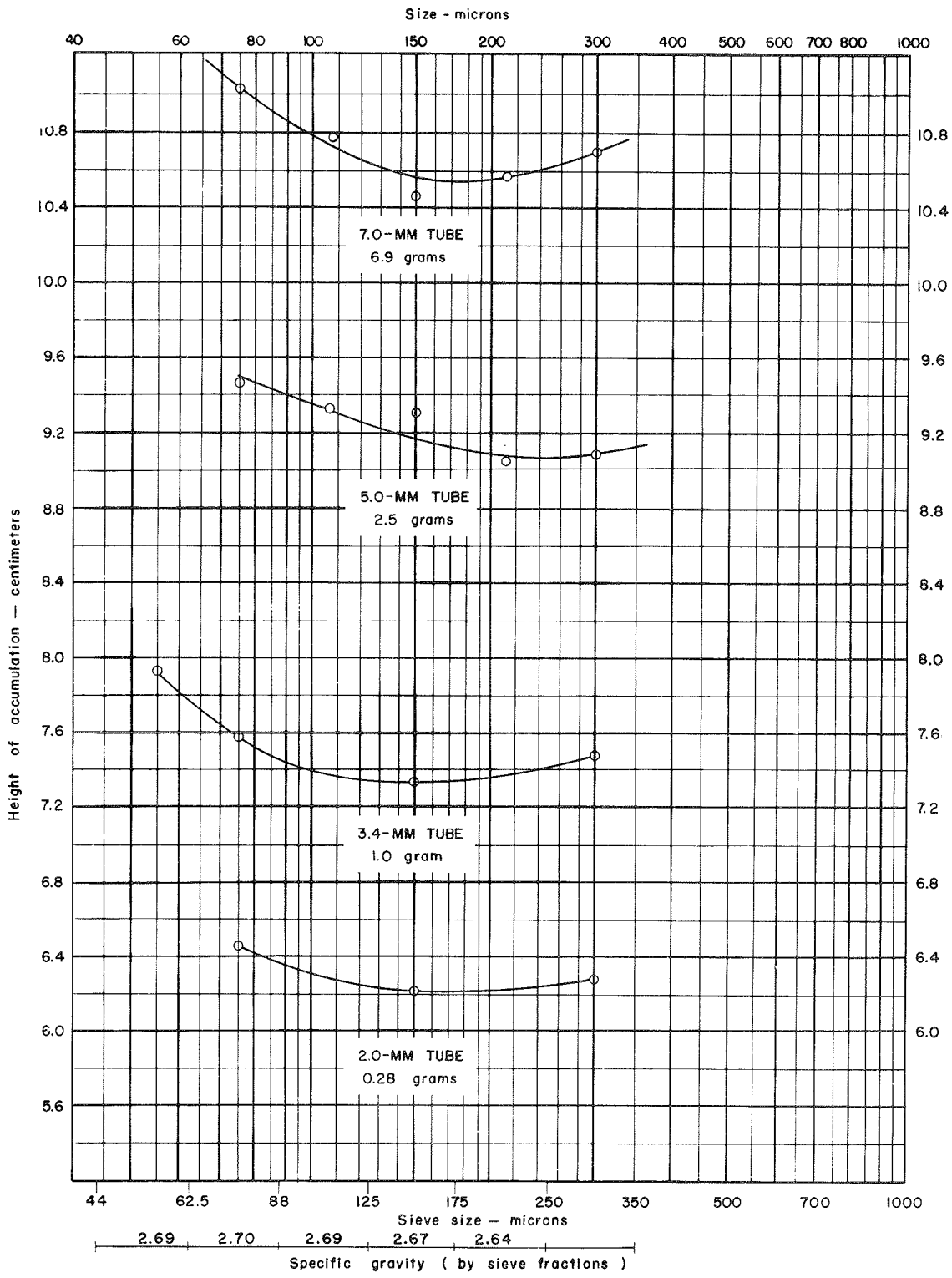


FIG. 25 — VOLUME-WEIGHT RELATIONS FOR TAYLORS FALLS SAND

(Variation of height of accumulation with sieve size)

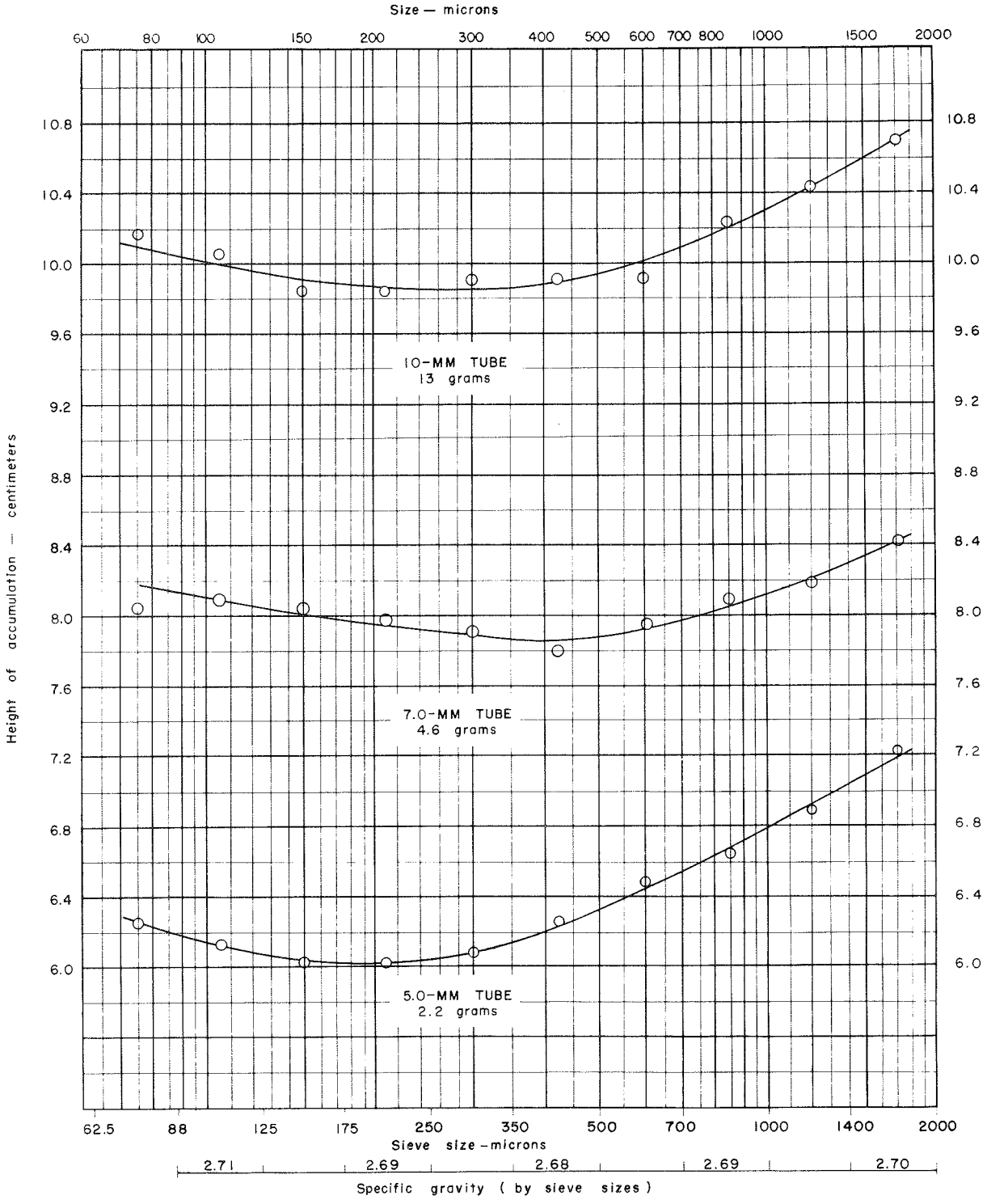


FIG. 26 — VOLUME — WEIGHT RELATIONS FOR SPECIAL SAND

(Variation of height of accumulation with sieve size)

significant to the analyses. Only the changes in height of accumulation from sieve fraction to sieve fraction of a given sand are significant.

The differences in percentages by volumes and by weights may be computed for a given size distribution from the variation of height of accumulation with size. Table 3 showed the computations for a glass-bead sample and demonstrated the relative magnitude of the volume-weight effects. However, volume-weight effects as well as many others are covered by the calibration of the VA-tube method.

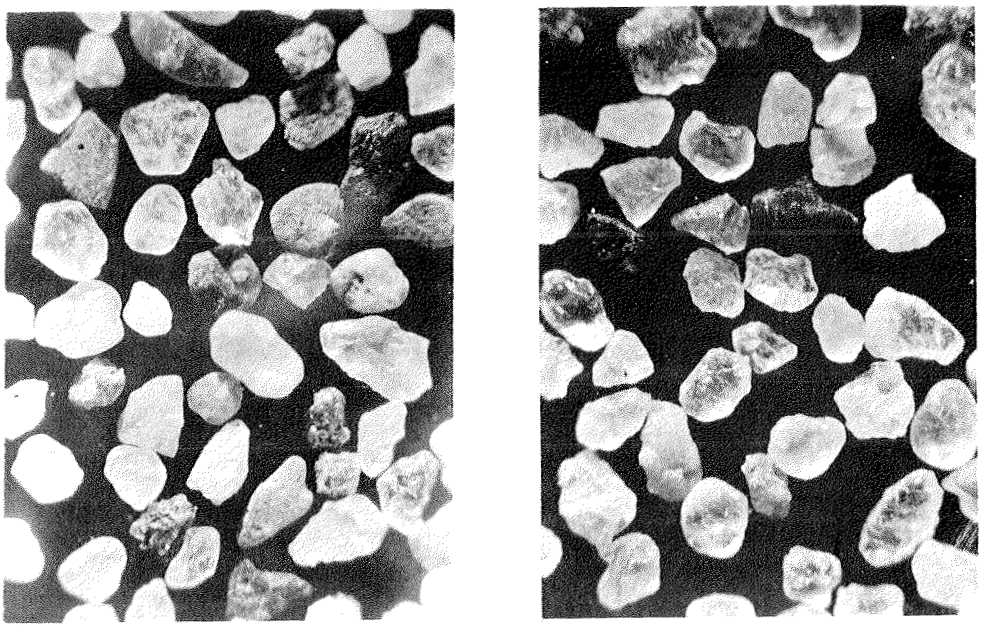
Figs. 27 to 31 show microphotographs of representative particles from four sieve fractions of each sand and indicate the general shape and roughness characteristics of the particles. (The samples were photographed by the Missouri River Division Laboratory, Corps of Engineers, Omaha, Nebraska.) Shape factors were not determined for this study because the primary interest was in fall velocity, which could be directly determined far more easily and accurately than the shape factor could be determined.

28. Size distributions of test samples--The known fall-diameter distributions for the test samples of naturally worn sands are shown in Figs. 32 to 36 and Table 12. The natural size distributions for each sand were always used and artificial distributions were sometimes used. Distributions are designated as fine, medium, or coarse, but the terms have only a comparative meaning within an individual illustration and do not imply standard size classifications of sands.

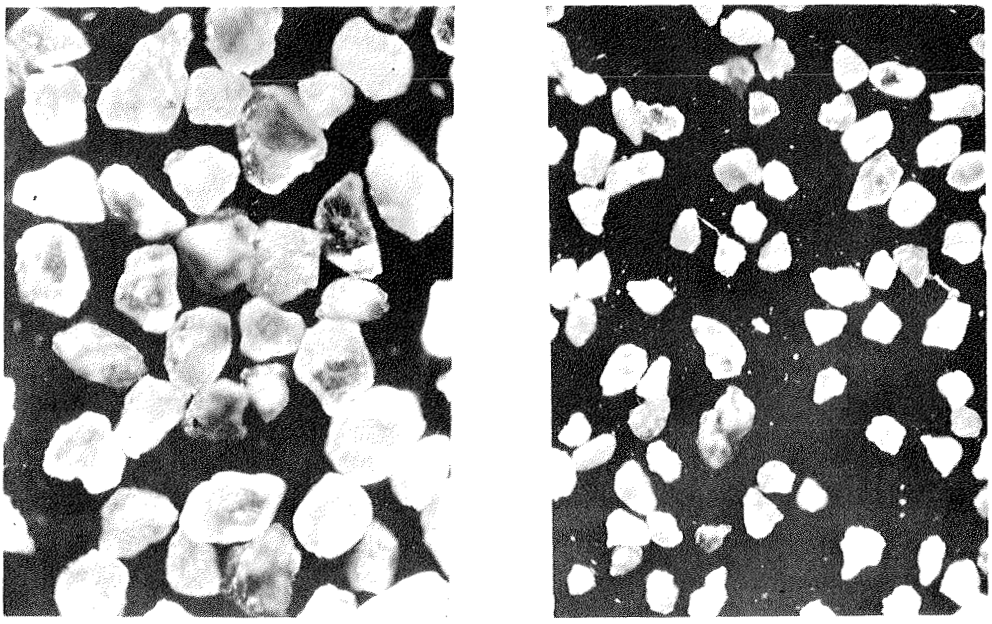
The natural sieve-size distribution of each sand is identified. The curves are normally smooth for natural size-frequency distributions. Some curves for artificial size distributions were irregular because the size distribution within each sieve fraction was the same as the natural distribution, whereas the sieve fractions were not proportioned as in the natural sand. The sharpest irregularities in the curves occurred at the actual size at which a sieve divided. For example, in Fig. 32 the fine distribution breaks at 121 microns, which was the dividing size for the nominal 125-micron sieve.

The known fall-diameter distribution shown for each sieve distribution was based on the plotted points, each of which was computed from fall-velocity data on at least 100 particles. (See Tables 4 to 7.) The fall-diameter distributions were based on fundamental computations of basic data that were entirely independent of the VA-tube analysis.

In general, for sand particles with specific gravities of about 2.65, the fall diameter of naturally worn sediments is greater than the sieve diameter for the smaller sand sizes, equals the sieve diameter at some intermediate sizes, and is less than the sieve diameter at the coarser sand sizes. Because the openings of most sieves are square, an irregular particle with a nominal diameter perhaps 10 percent greater than the sieve diameter will pass through a sieve. For small sand particles (which fall at low Reynolds numbers) the effect of the 10-percent larger size in accelerating the fall velocity is much

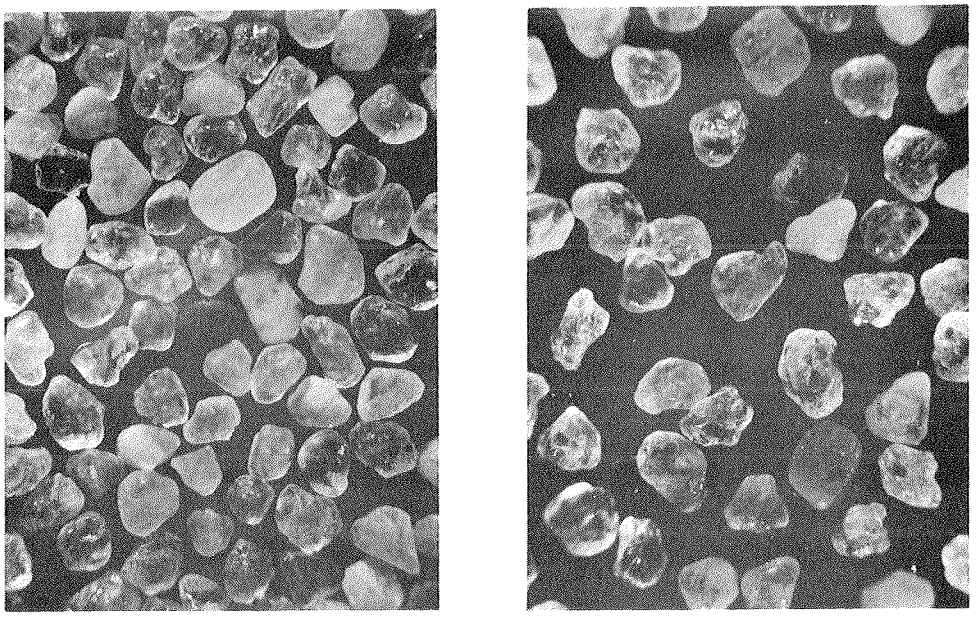


500 - 700 -- NOMINAL SIEVE SIZES, MICRONS -- 250 - 350
11 X MAGNIFICATION 24 X

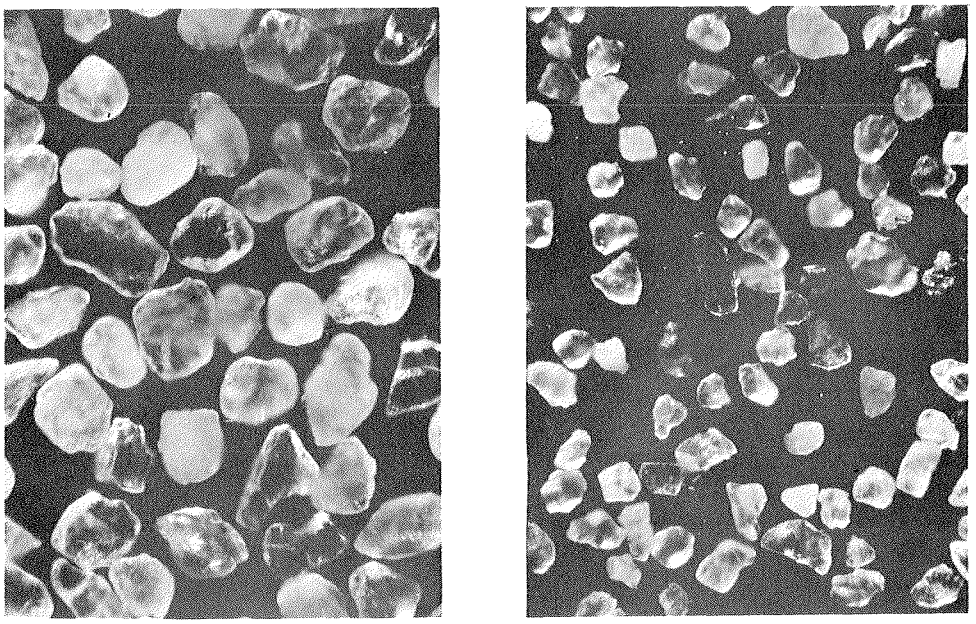


125 - 175 -- NOMINAL SIEVE SIZES, MICRONS -- 62 - 88
45 X MAGNIFICATION 45 X

FIG. 27-REPRESENTATIVE PARTICLES FROM FOUR SIEVE FRACTIONS OF POWDER RIVER SAND

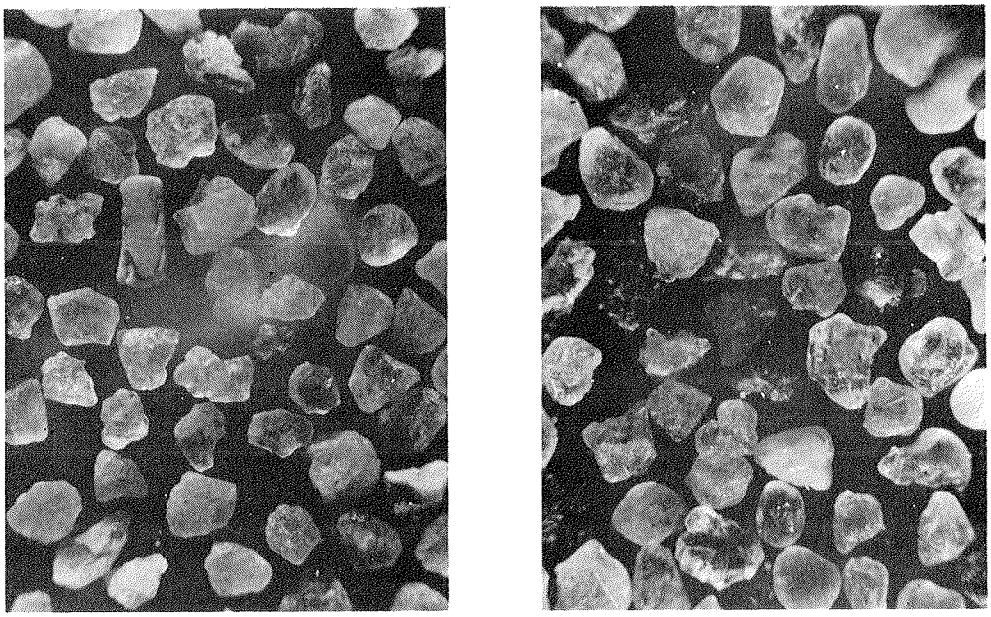


500 - 700 -- NOMINAL SIEVE SIZES, MICRONS -- 250 - 350
11 X MAGNIFICATION 24 X

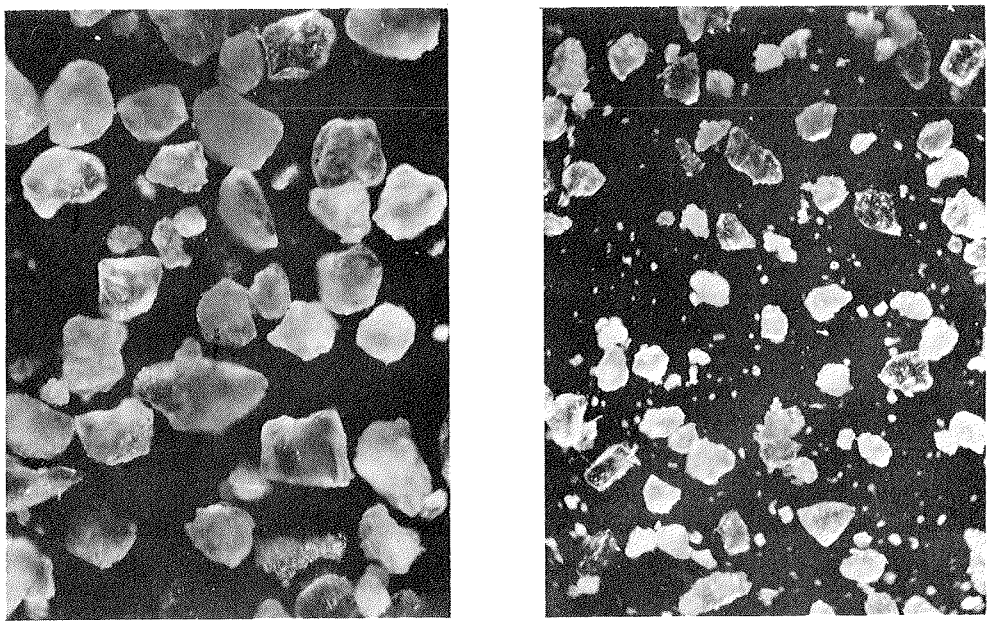


125 - 175 -- NOMINAL SIEVE SIZES, MICRONS -- 62 - 88
45 X MAGNIFICATION 45 X

FIG. 28—REPRESENTATIVE PARTICLES FROM FOUR SIEVE FRACTIONS OF REPUBLICAN RIVER SAND

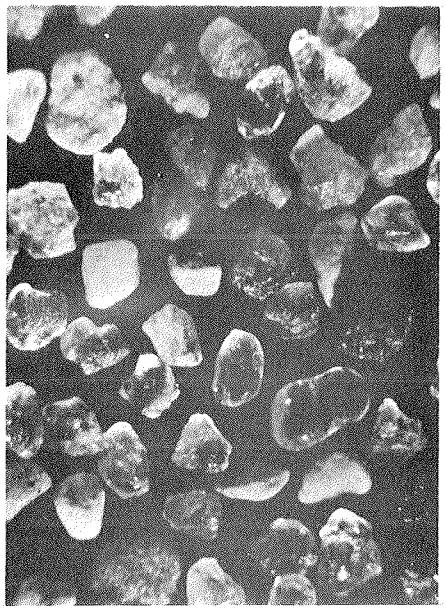


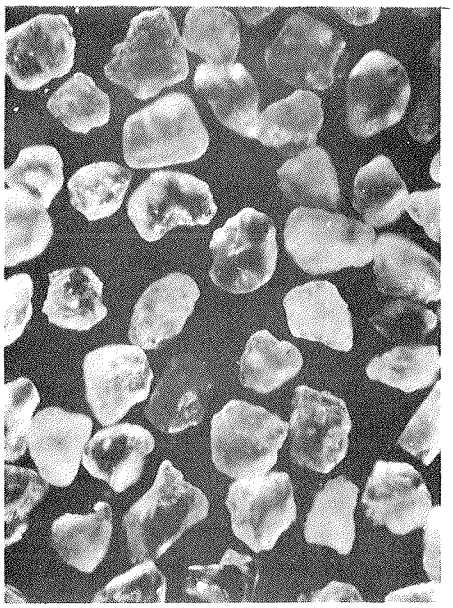
500 - 700 -- NOMINAL SIEVE SIZES, MICRONS -- 250 - 350
11 X MAGNIFICATION 24 X



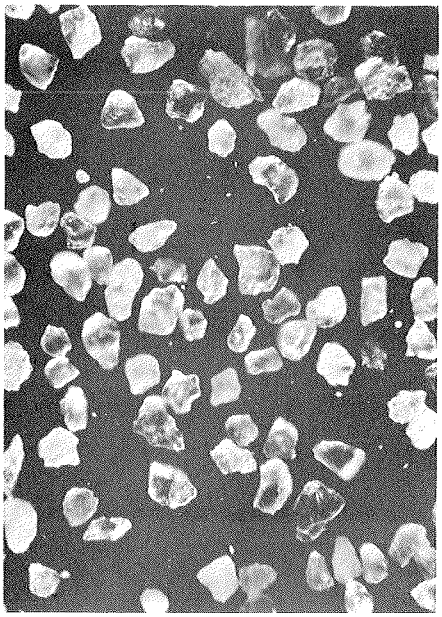
125 - 175 -- NOMINAL SIEVE SIZES, MICRONS -- 62 - 88
45 X MAGNIFICATION 45 X

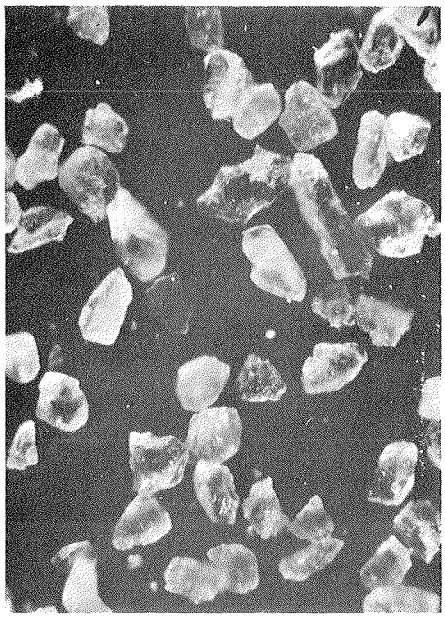
FIG. 29—REPRESENTATIVE PARTICLES FROM FOUR SIEVE FRACTIONS OF CHEYENNE RIVER SAND





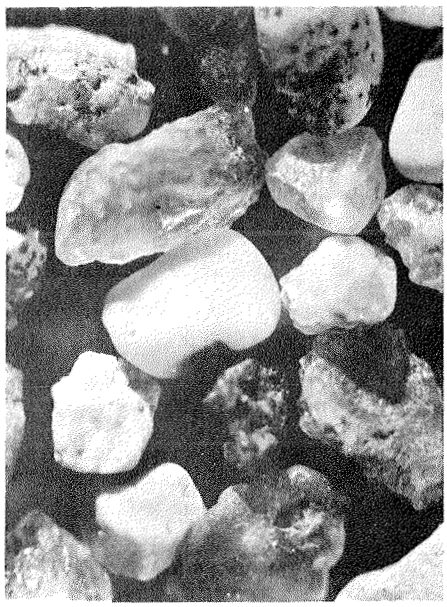
250 - 350 -- NOMINAL SIEVE SIZES, MICRONS -- 125 - 175
24 X MAGNIFICATION 45 X

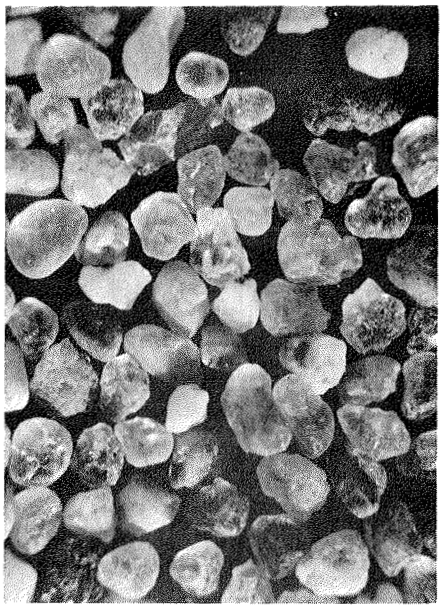




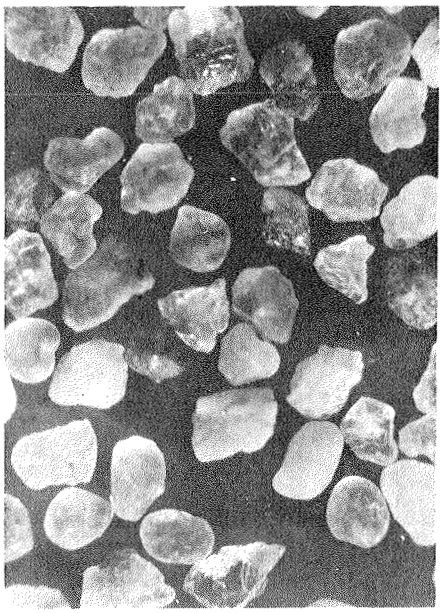
62 - 88 -- NOMINAL SIEVE SIZES, MICRONS -- 44 - 62
45 X MAGNIFICATION 100 X

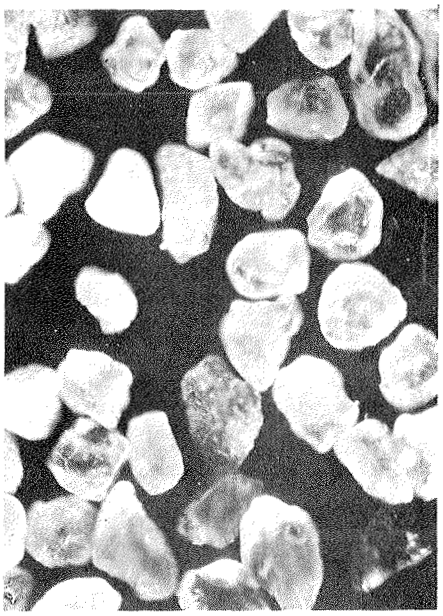
FIG. 30—REPRESENTATIVE PARTICLES FROM FOUR SIEVE FRACTIONS OF TAYLORS FALLS SAND





1000 - 1400 -- NOMINAL SIEVE SIZES, MICRONS -- 500 - 700
11 X MAGNIFICATION 11 X





250 - 350 -- NOMINAL SIEVE SIZES, MICRONS -- 125 - 175
24 X MAGNIFICATION 45 X

FIG. 31—REPRESENTATIVE PARTICLES FROM FOUR SIEVE FRACTIONS OF SPECIAL SAND

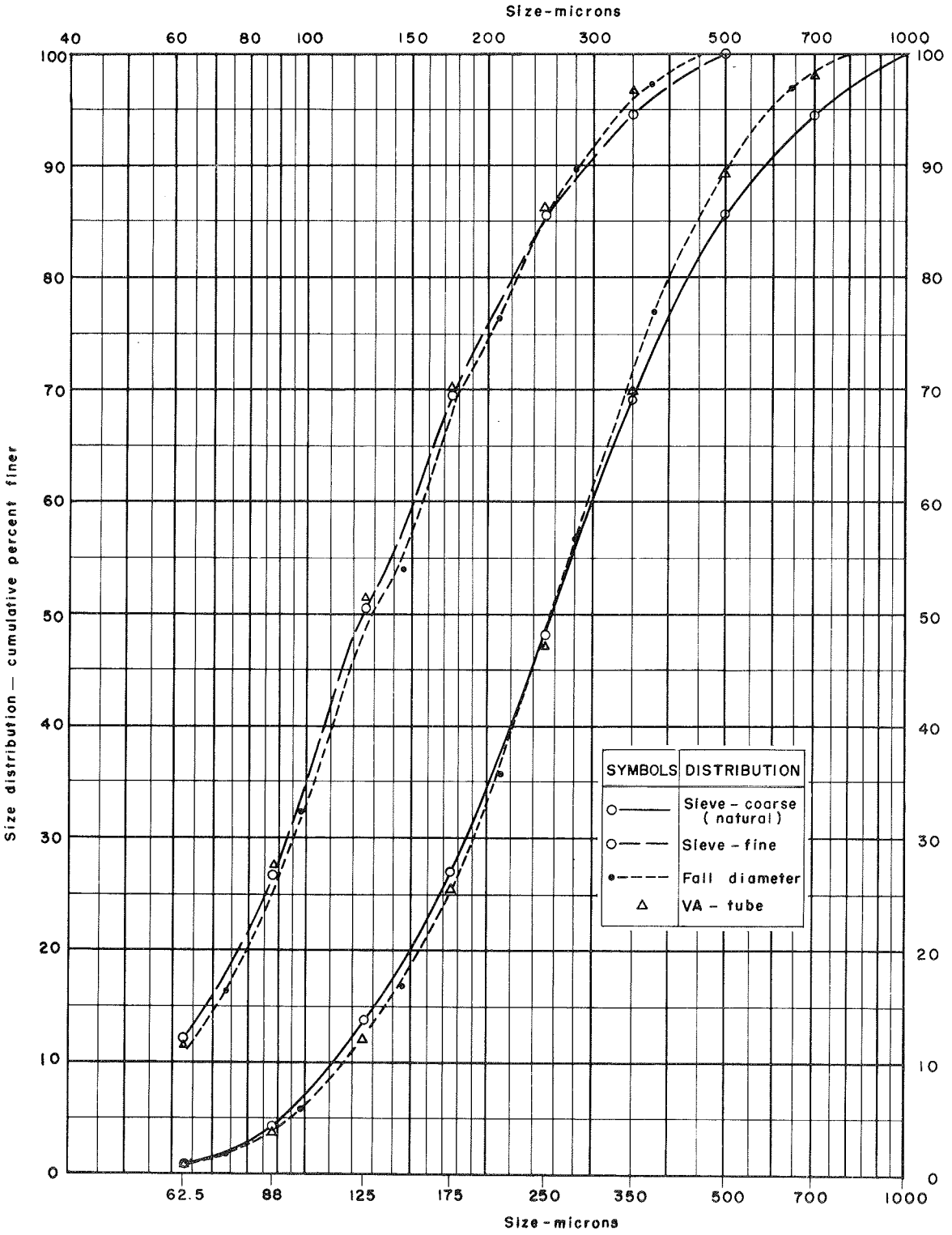


FIG. 32 — SIZE DISTRIBUTIONS OF POWDER RIVER SAND

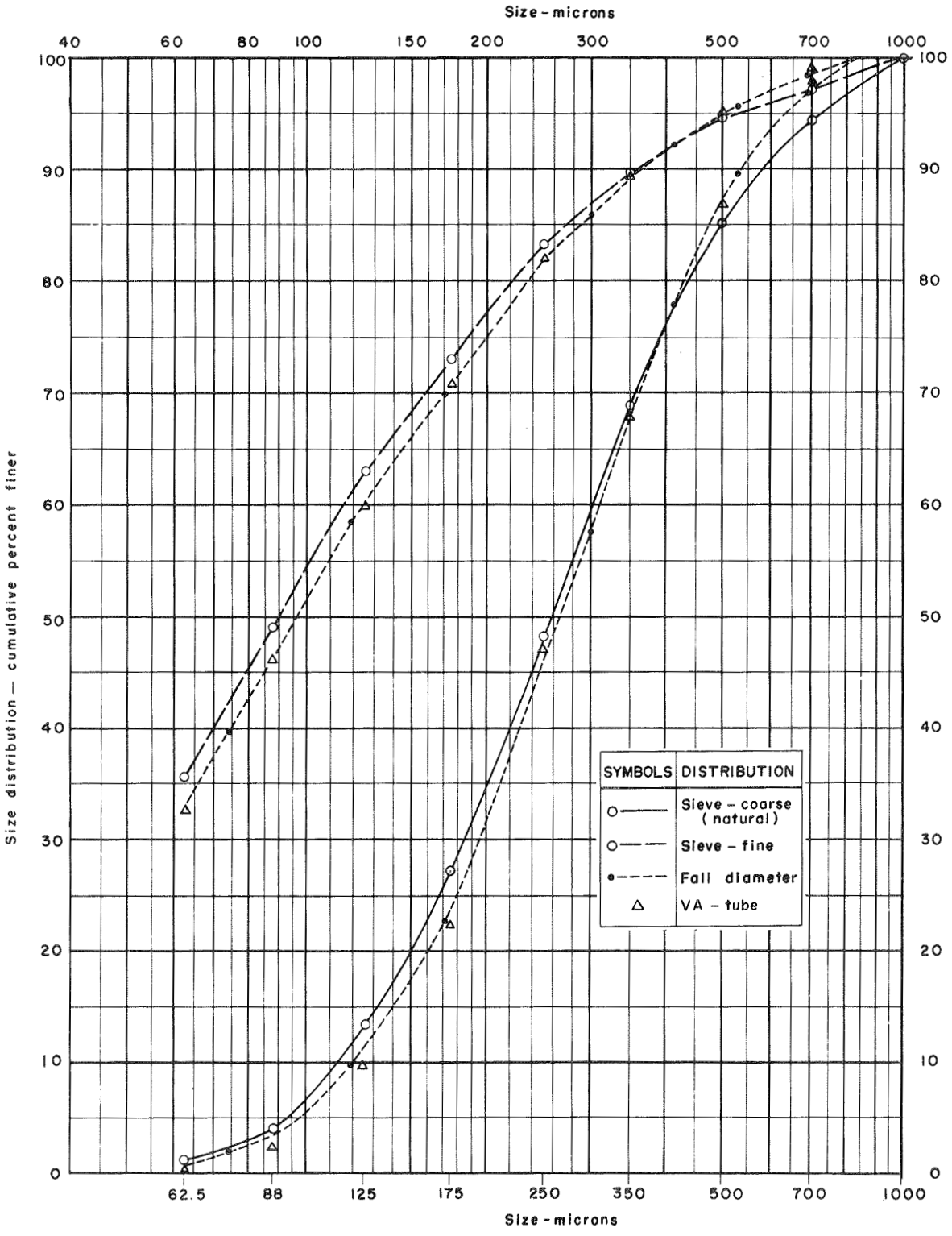


FIG. 33 — SIZE DISTRIBUTIONS OF REPUBLICAN RIVER SAND

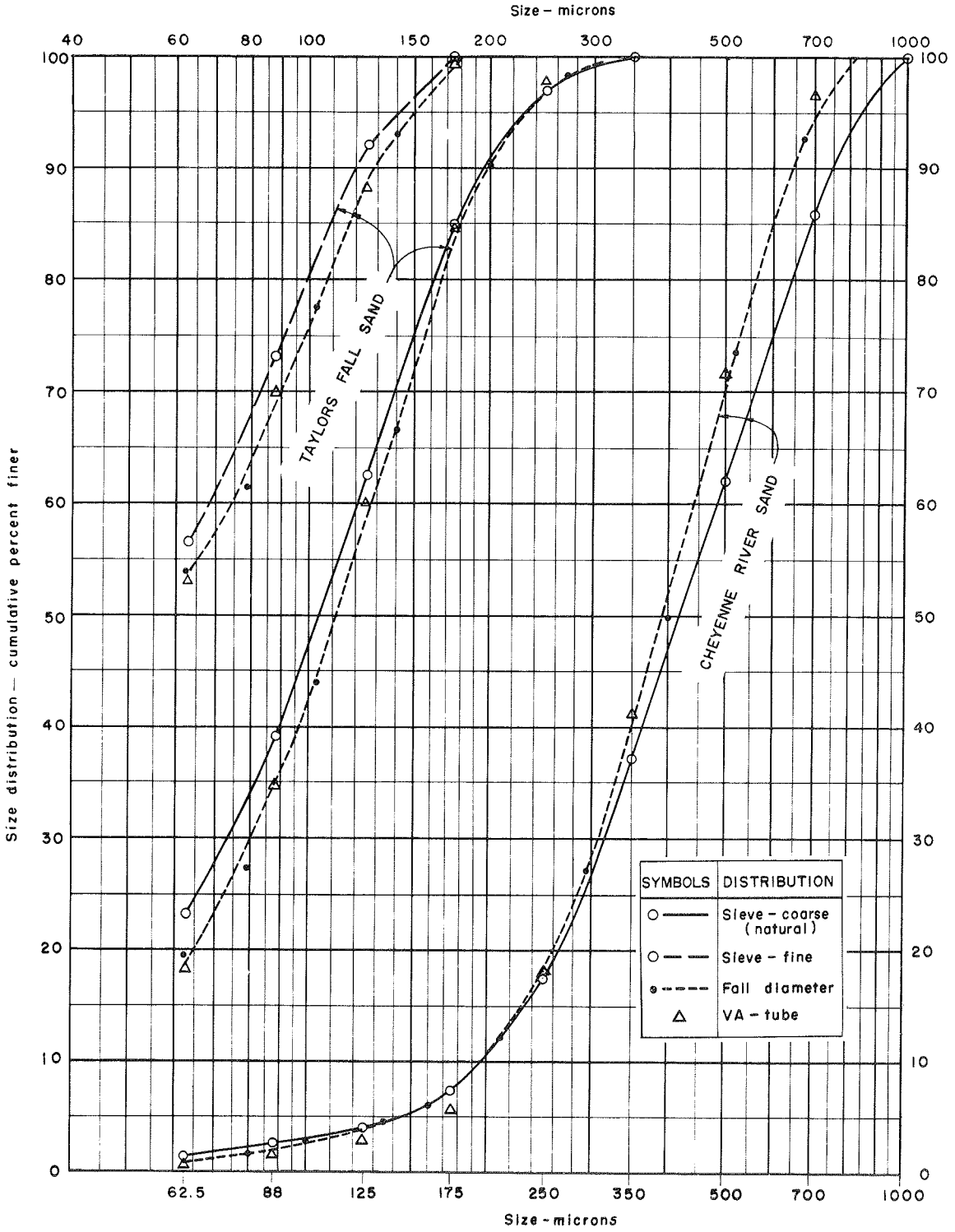


FIG. 34 — SIZE DISTRIBUTIONS OF CHEYENNE RIVER AND TAYLORS FALLS SANDS

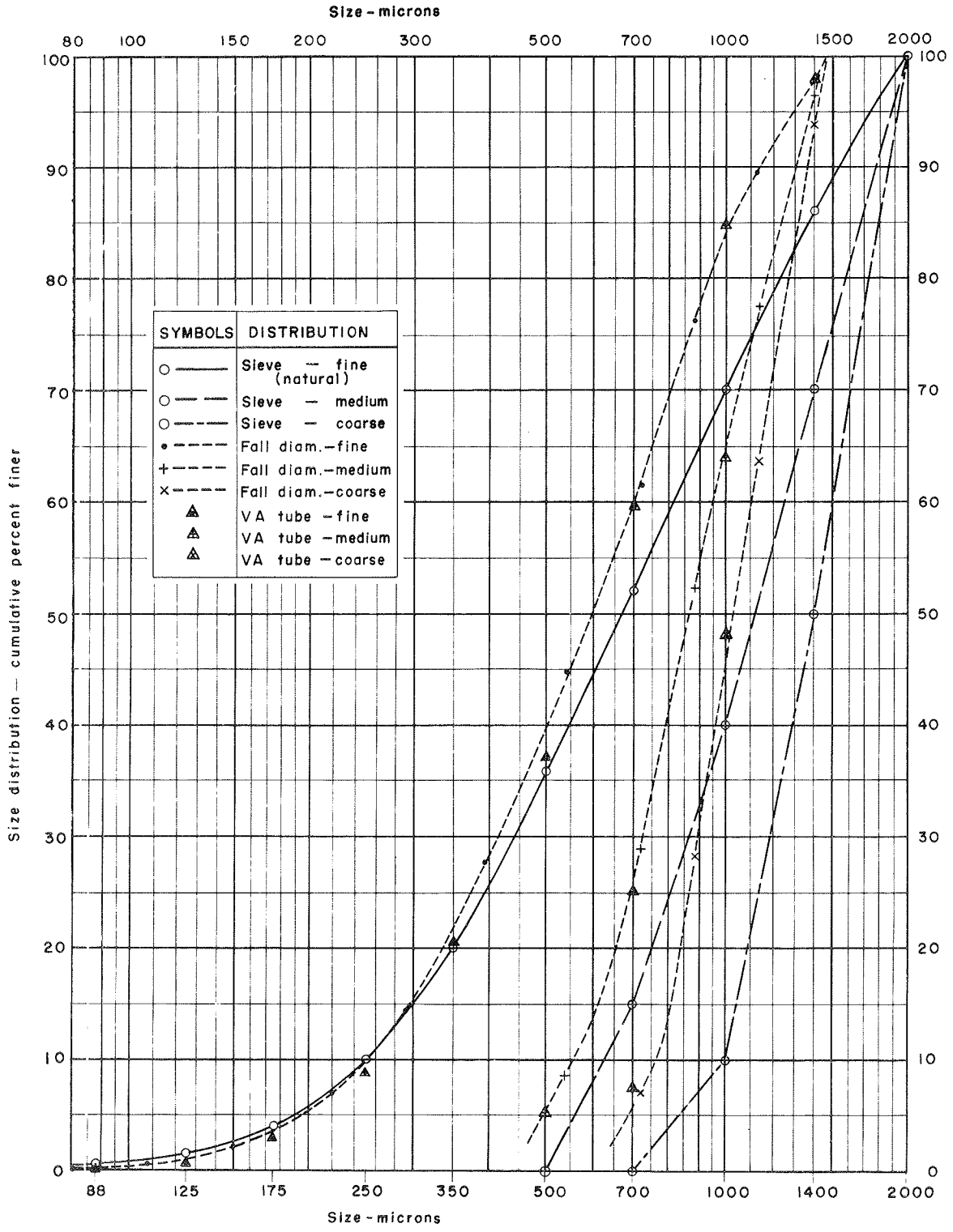


FIG. 35 — SIZE DISTRIBUTIONS OF SPECIAL SAND

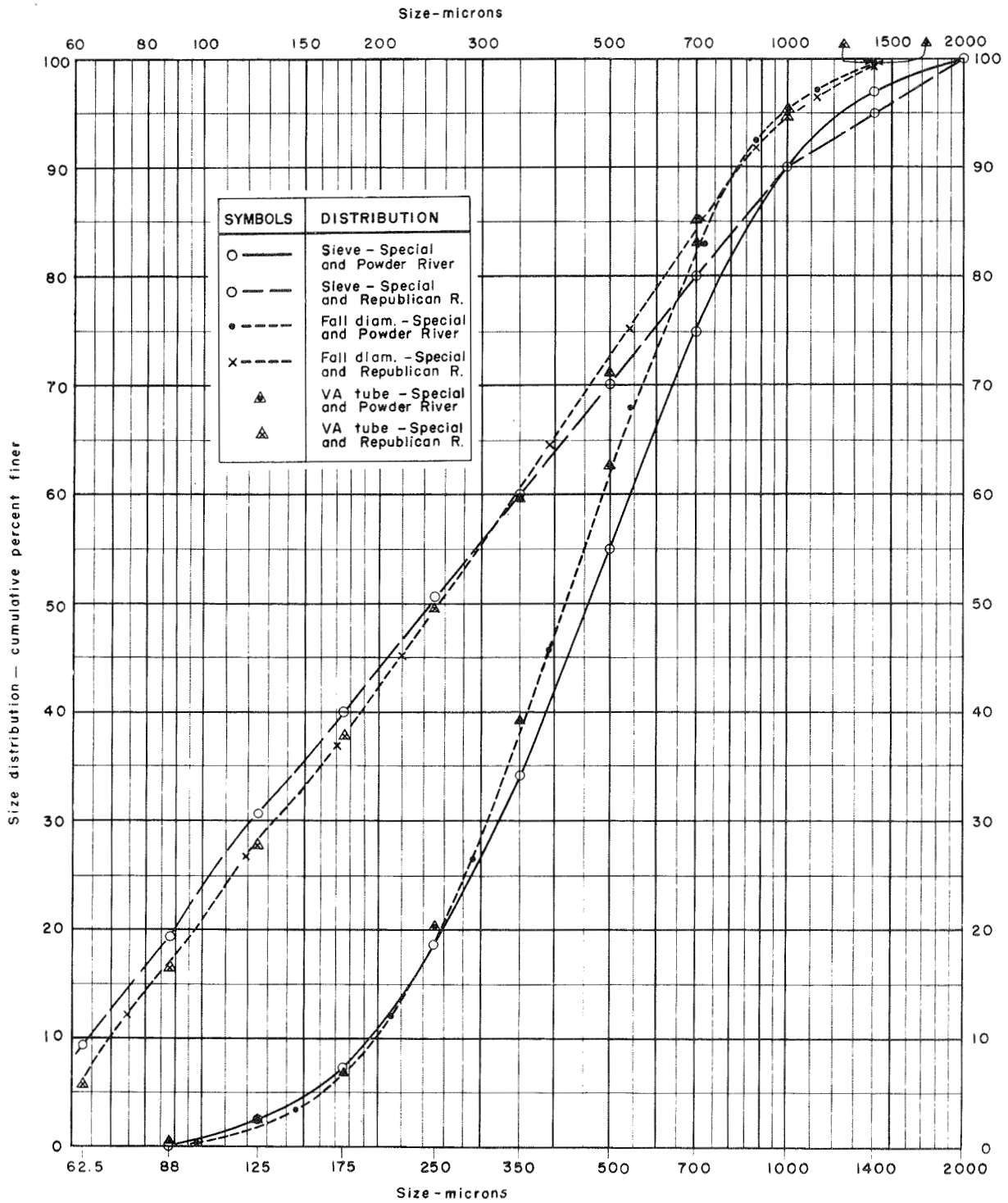


FIG. 36 — SIZE DISTRIBUTIONS OF COMBINATIONS OF SANDS

more significant than the retarding effect of shape and roughness; consequently, the fall diameter is greater than the sieve diameter. At larger sand sizes shape and roughness have a relatively greater retarding effect on the fall velocity, and the slowing effect becomes paramount.

The average fall-diameter distributions from VA-tube analyses are plotted for each of the division sizes listed along the bottom of the figure. The points are identified by triangles, but the points were not connected to form a separate curve. The average analysis data were based on all analyses within the acceptable ranges of quantity of sample and particle size. (See Table 12.) Samples omitted from the averages and from future discussion of accuracy are indicated in the table by an asterisk.

29. Accuracy of analysis of individual sand samples--The accuracy for about a quarter of the available analyses with the VA tube is shown in Figs. 37-41. Analyses were selected to cover as wide a range of sands, size distributions, and sizes of VA tube as possible. The first three analyses of a sample were plotted whenever there were that many. Data for Figs. 37 to 40 were from analyses in VA tubes 120 cm long.

The upper two groups of curves on each figure show the accuracy of analysis based on the deviations of the cumulative percentage-finer data for the analysis from the known fall-diameter distribution for the individual particle drops. That is, if the fall-diameter distribution showed 89 percent finer than 500 microns and the analysis showed 92.5 percent finer, this plotting would show +3.5 percent at 500 microns. Such deviations may be readily obtained from Table 12 and are plotted to indicate the errors at division sizes of percentage finer or coarser curves.

To some extent the magnitude of deviations in cumulative percentage-finer curves increased as the relative quantities of material at a given division size increased. Part of the cause may be inherent in the difficulty of reading percentages finer accurately from steep accumulation curves such as curve D of Fig. 21, but part is undoubtedly the result of small errors in the analytical determination of fall velocity. If the curve is steep, a small error in fall velocity results in a relatively large error in percentage finer.

The accuracy of analyses in the upper two groups of curves of Figs. 37 to 39 is consistently within 5 percent of the total sample. Fig. 40 shows rather high deviations at the 88-micron size especially for the 3.4-mm tube, but three-fourths of the sample analyzed in the VA tube was in the size range 62.5 to 125 microns. Fig. 41 also shows some deviations around 5 percent, but these are for distributions with high concentrations of material at the division sizes at which the relatively large deviations occur.

The lower two groups of curves on each of Figs. 37 to 41 show the accuracy of the VA-tube analyses in terms of errors in fall velocities at each division size. The derivation of the data may be illustrated with curve A of Fig. 21: At a fall diameter of 88 microns the percentage finer should have been

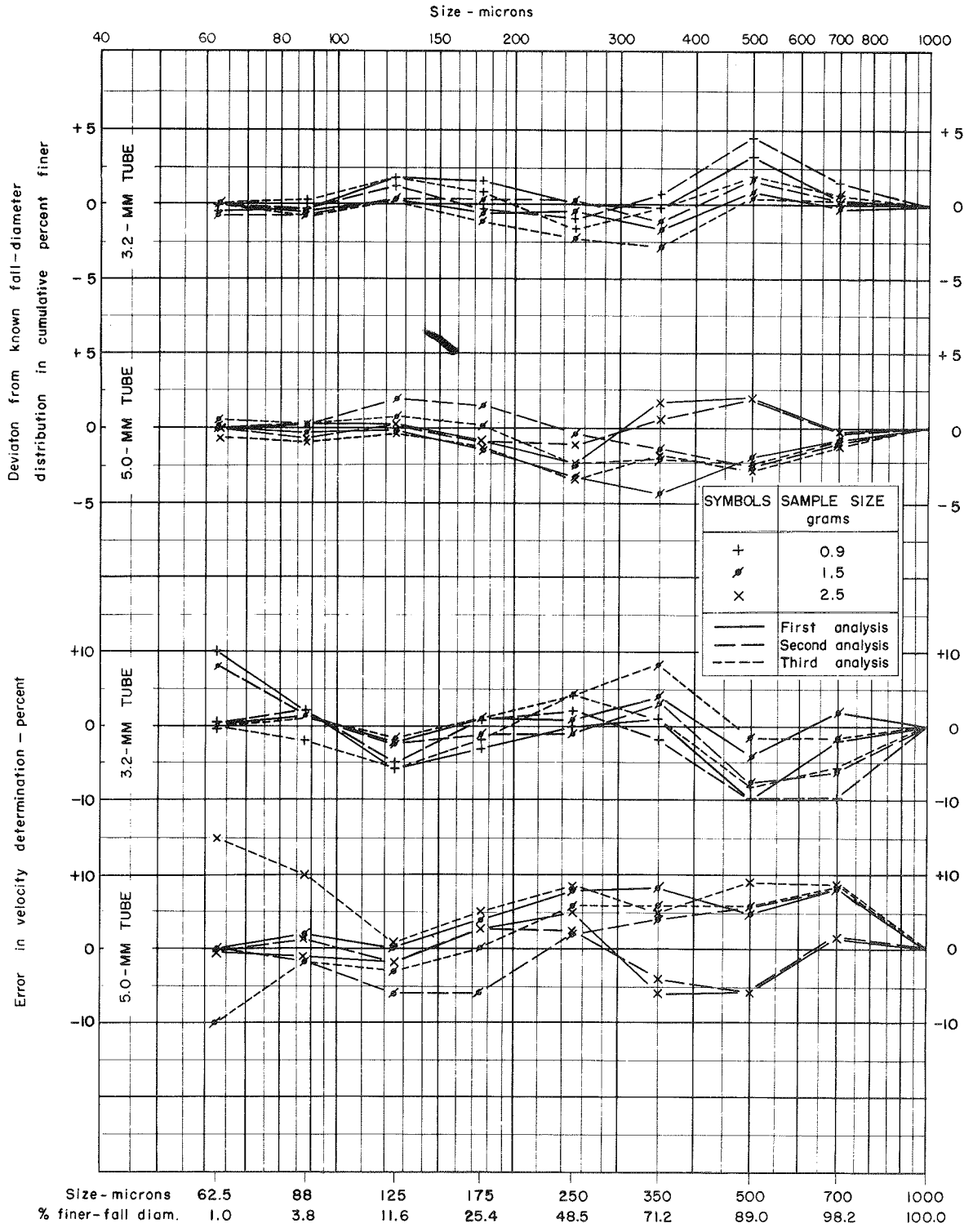


FIG. 37 — ACCURACY OF INDIVIDUAL SIZE ANALYSIS
POWDER RIVER SAND — COARSE DISTRIBUTION

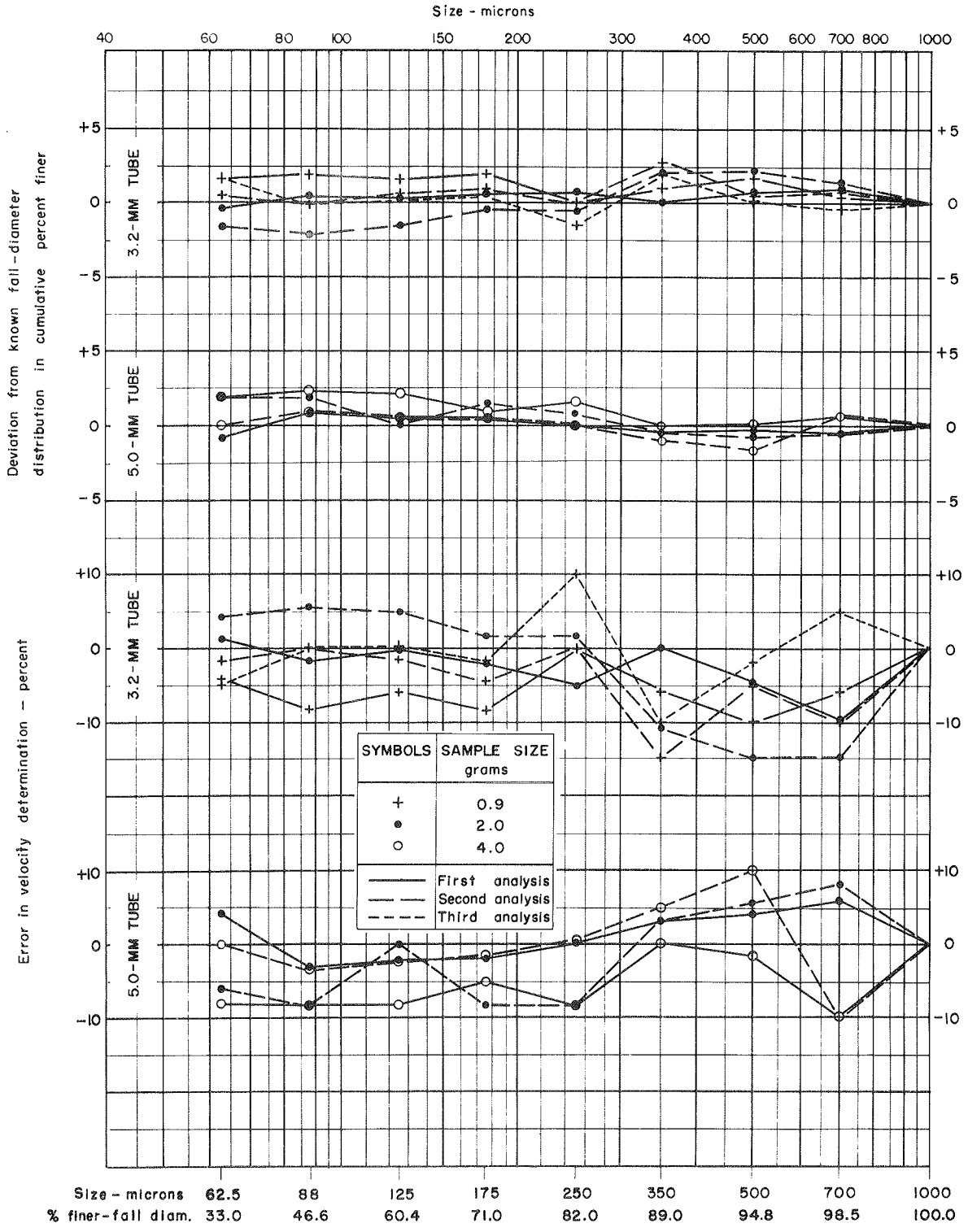


FIG. 38 - ACCURACY OF INDIVIDUAL SIZE ANALYSIS
REPUBLICAN RIVER SAND - FINE DISTRIBUTION

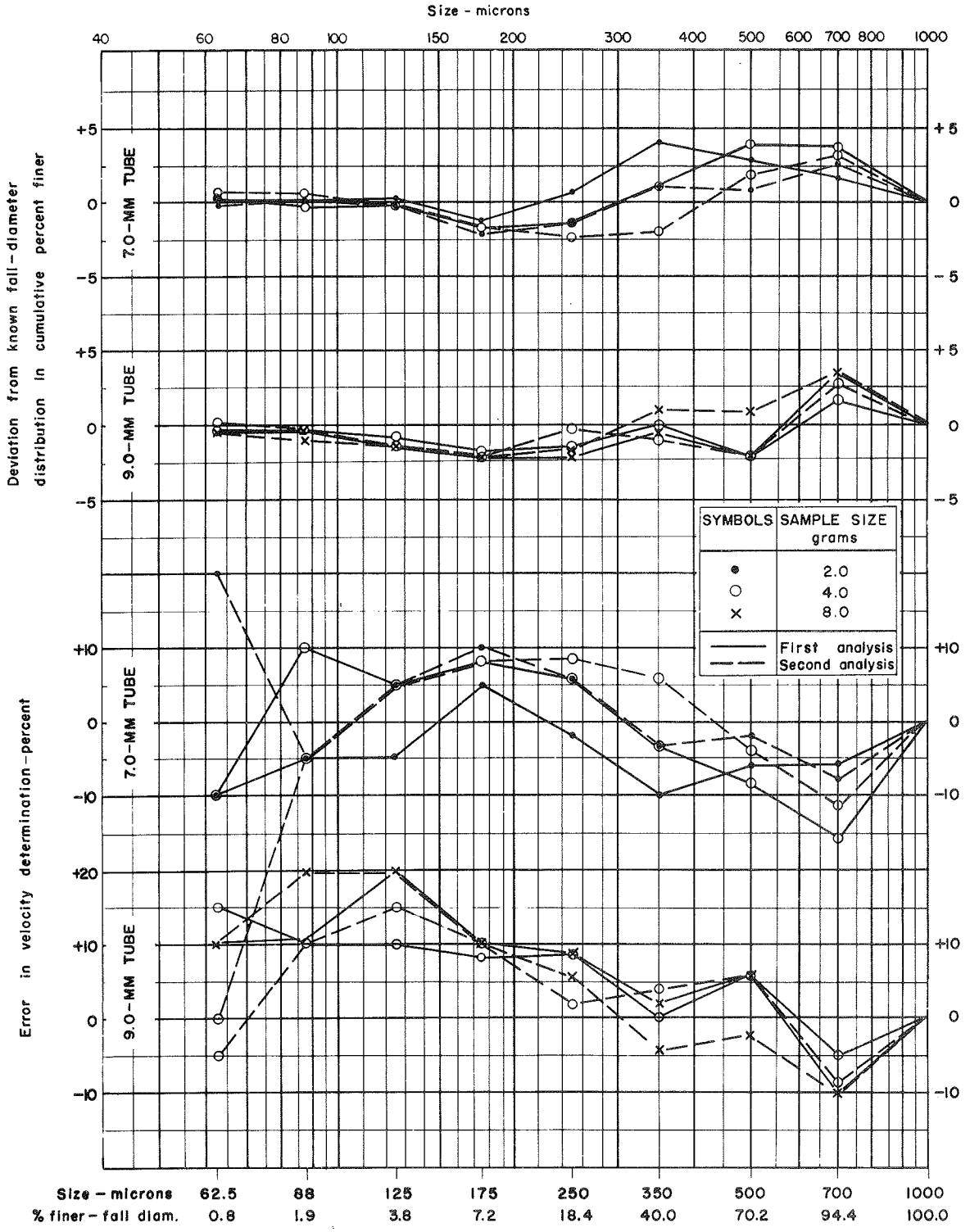


FIG. 39 — ACCURACY OF INDIVIDUAL SIZE ANALYSIS
CHEYENNE RIVER SAND

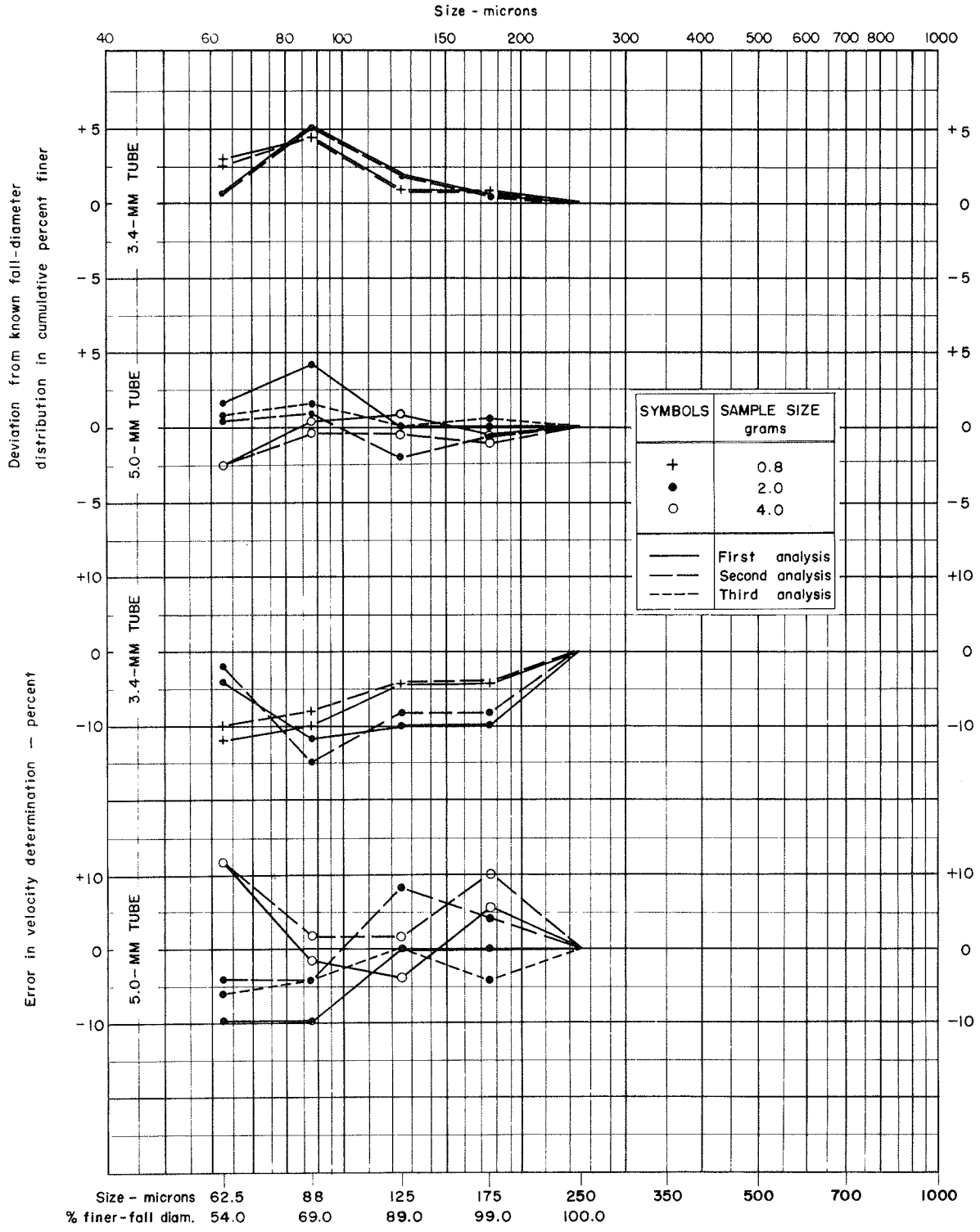


FIG. 40 — ACCURACY OF INDIVIDUAL SIZE ANALYSIS
TAYLORS FALLS SAND — FINE DISTRIBUTION

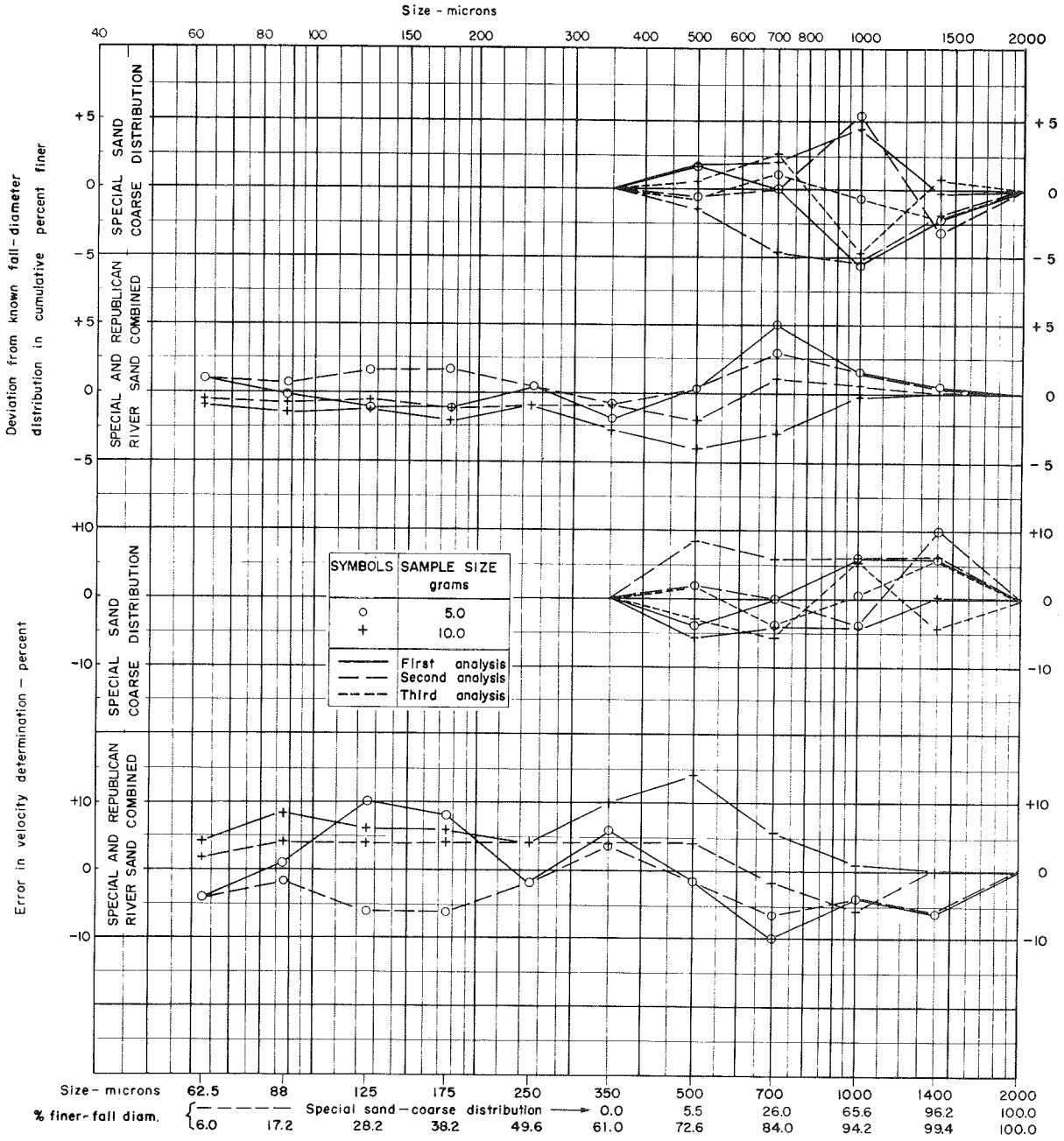


FIG. 41 – ACCURACY OF INDIVIDUAL SIZE ANALYSIS

TUBES 180 CM LONG

26 percent. At 25.9°C, which was the temperature of analysis, the 88-micron division-size line was 4.22 in. from the time origin. The 26-percent-finer point on curve A occurs at a distance of 4.08 in. from the time origin. Because the distances also represent time of fall, the ratio of the velocity from the analysis to the true velocity is 4.22/4.08 or 1.034. That is, the analysis showed a fall velocity that was 3.4 percent too high.

The errors in velocity shown in the figures were taken directly from the analytical curves drawn by the VA-tube recorder. Approximately the same results could be obtained by plotting an analysis from Table 12 as a smooth curve on one of the calibrated charts and proceeding as indicated above.

In general, the fall velocities were determined within 10 percent as compared to fall-diameter deviations of 5 percent in percentage-finer curves. The largest errors are those at 62.5 microns in Fig. 39. These errors result from the difficulty of tracking, recording, and interpreting analyses closer than 1 percent of the total sample. These large velocity errors apply only to very small portions of the total sample. In Figs. 37 and 38 errors around 10 percent are associated with sizes of 700, 500, and to some extent 350 microns in the 3.2-mm tube. These fall diameters are larger than recommended for analysis in that size of tube. A somewhat similar condition is found at 700 microns in Fig. 39. Although the 700-micron size was not of itself too large for analysis in the 7- and 9-mm tubes, the combination of the size and high concentration was undesirable for the 9-mm tube and was excessive for the 7-mm tube.

A study of the velocity errors indicated that if the desirable limits of particle size and concentration are respected, velocities determined with the VA tube will seldom be more than 10 percent in error at any point in the analysis where an appreciable quantity of the total sample is involved.

30. General accuracy of all analyses--Table 9 presents a summary of the accuracy of the VA-tube analyses of sand samples. The errors are the algebraic differences between the known fall-diameter distribution and the distribution by analysis. These errors may be obtained directly from Table 12 in the appendix. The errors did not exceed 2 percent for over three-fourths of all analyses, 3 percent for nine-tenths of all analyses, and 5 percent for practically 99 percent of the analyses.

Analyses in the various sizes of tube were about equally accurate except for the greater deviations in tubes having a 2.0-mm accumulation section. The greater deviations probably reflected difficulties in compounding duplicate samples and in analyzing the small quantities of the samples for this small tube.

The accuracy differed somewhat for the various size distributions. The very coarse sands contained only a small range of sizes and, consequently, had high concentrations of material at some of the division sizes; the deviations were greater for these sands. Any small difference in chart time, fall

TABLE 9

ACCURACY OF ANALYSES

Qualification	Observations within given limits, %					Total observations
	Within 1%	Within 2%	Within 3%	Within 5%	Within 10%	
Sedimentation tube						
Diameter of accumulation section, mm:						
2.1 (2.0)	36.9	64.2	81.0	95.5	100.0	179
3.4 (3.2)	56.8	80.5	92.4	99.7	100.0	384
5	54.2	75.7	90.7	99.3	100.0	432
7	62.0	84.3	95.2	100.0	100.0	166
10[a]	50.9	77.0	88.7	98.1	100.0	318
4 and 9[b]	59.4	82.1	95.1	100.0	100.0	224
All observations-------	53.8	77.5	90.7	98.9	100.0	1703
Sand mixture						
Predominant size:						
Very coarse sand--------	44.4	61.1	77.7	94.4	100.0	18
Do------------------	33.3	52.8	63.9	86.1	100.0	36
Coarse sand----------	50.0	81.2	92.2	100.0	100.0	64
Do------------------	48.2	83.9	92.9	100.0	100.0	56
Do------------------	51.7	81.7	93.3	100.0	100.0	60
Do------------------	52.3	75.0	93.8	100.0	100.0	128
Medium sand----------	59.4	81.2	95.0	100.0	100.0	160
Do------------------	55.2	79.6	92.5	99.6	100.0	496
Fine sand------------	62.0	87.5	96.0	99.5	100.0	200
Do------------------	44.3	63.0	82.1	98.0	100.0	246
Very fine sand---------	53.3	82.2	91.1	98.5	100.0	135
Do------------------	62.5	76.9	89.4	98.1	100.0	104
All observations-------	53.8	77.5	90.7	98.9	100.0	1703
Fall diameter						
Division size, microns:						
1400	72.2	80.6	88.9	97.2	100.0	36
1000	25.0	58.3	75.0	86.1	100.0	36
700	56.6	79.2	89.3	100.0	100.0	159
500	46.4	75.2	94.1	100.0	100.0	153
350	45.4	70.3	87.6	99.5	100.0	185
250	53.8	78.8	93.9	100.0	100.0	212
175	50.4	80.7	92.9	98.7	100.0	238
125	49.2	75.6	88.2	99.2	100.0	238
88	56.5	74.4	87.9	98.2	100.0	223
62	71.3	87.0	95.1	99.1	100.0	223
All observations-------	53.8	77.5	90.7	98.9	100.0	1703

a 180-cm sedimentation tube; other sizes refer to 120-cm tubes.
b Experimental tube not used for routine analyses.

velocity, or calibration produced much greater deviations in percentage of the total sample if the concentration of particles was high at a division size.

Variations in accuracy at the different fall diameters were probably not significant except that the high concentrations of material at the 1000-micron size resulted in greater deviations. Only a few samples had high concentrations at other division sizes. Analyses at the 62-micron size tended to be accurate because in many samples the concentration at this size was rather low.

Occasionally there may be samples that depart from the probability of accuracy of Table 9. The effect of specific gravities much different from 2.65 has not been evaluated, except that samples containing some relatively lightweight material showed no identifiable reduction in accuracy. Several samples composed of one or two sieve fractions have been analyzed, but no general evaluation of accuracy has been made for these samples. Analysis of a single sieve fraction is undesirable because of high and rapidly changing concentrations.

VI. VISUAL-ACCUMULATION-TUBE METHOD FOR ROUTINE ANALYSES OF SANDS

31. General--The experimental apparatus and procedure for testing the VA-tube method were described in Sections 8-11. Because the method showed definite promise, the apparatus was redesigned for commercial manufacture and routine laboratory use, and the procedures and operating techniques were altered correspondingly. Added experience should indicate modifications and refinements that would improve the method. However, the VA-tube apparatus and procedure described here have been used by several laboratories for a total of thousands of analyses.

32. Apparatus--The apparatus for the VA-tube method of analysis consists of the following main parts as shown in Fig. 42:

1. A glass funnel, about 25 cm long. A reference mark on the stem of the funnel indicates the proper height for the water column prior to analysis.

2. A rubber tube, which connects the funnel and the main sedimentation tube and which together with a special clamping mechanism serves as a valve. (Details of the mechanism for clamping the rubber tube together are shown in Fig. 43.)

3. A glass sedimentation tube. Tubes are of two lengths. A 180-cm tube has a 140-cm section of 50-mm inside diameter, a 20-cm contracting section, and a 20-cm accumulation section of 10-mm inside diameter. This long tube is used for the analysis of bed, beach, or other sands of coarse sizes when a sufficient quantity of the material is available. A 120-cm tube has an 80-cm section of 25-mm inside diameter; a 20-cm contracting section; and a 20-cm accumulation section with an inside diameter of 2.1, 3.4, 5.0, or 7.0 mm. The short tube is suitable for the analysis of samples that contain

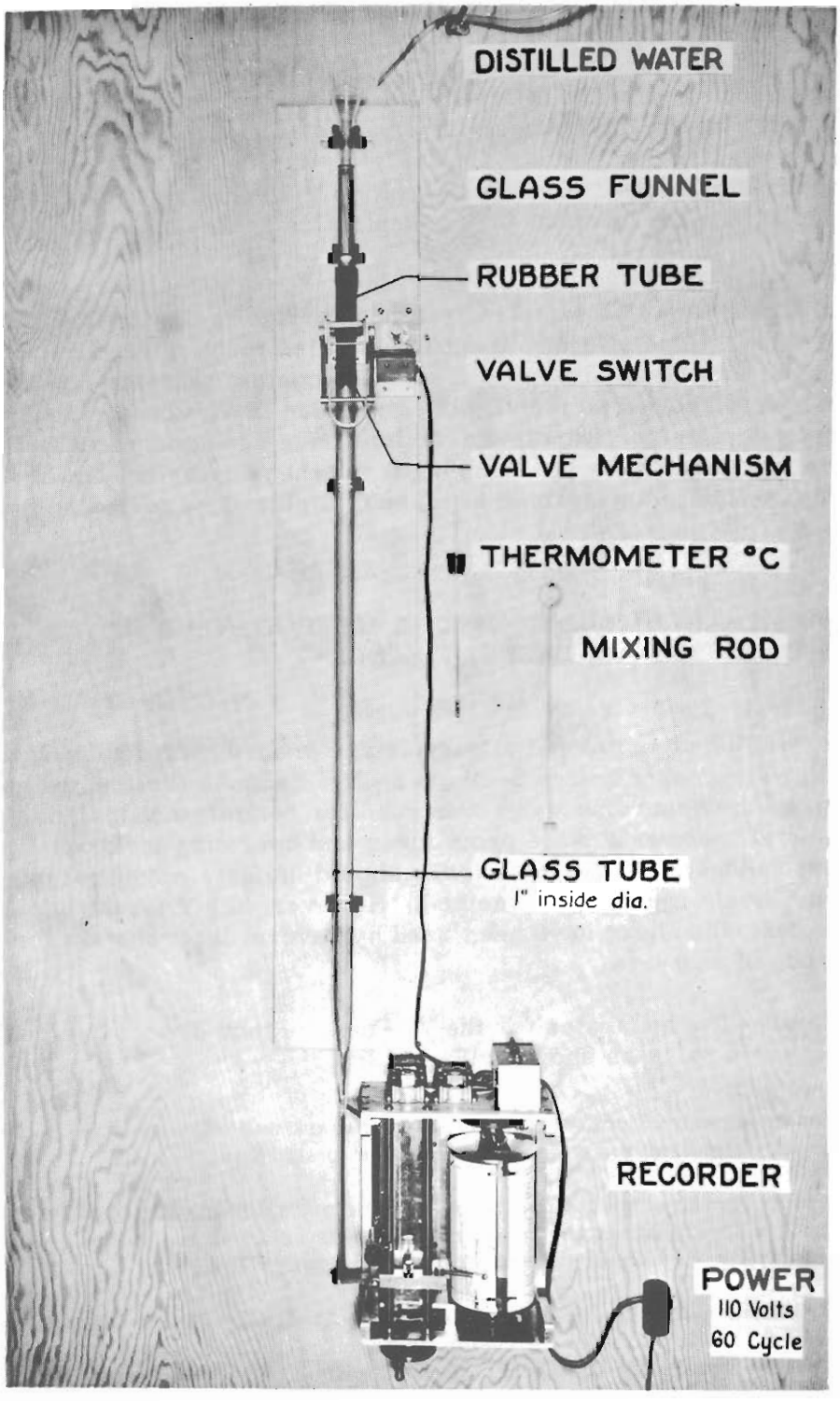
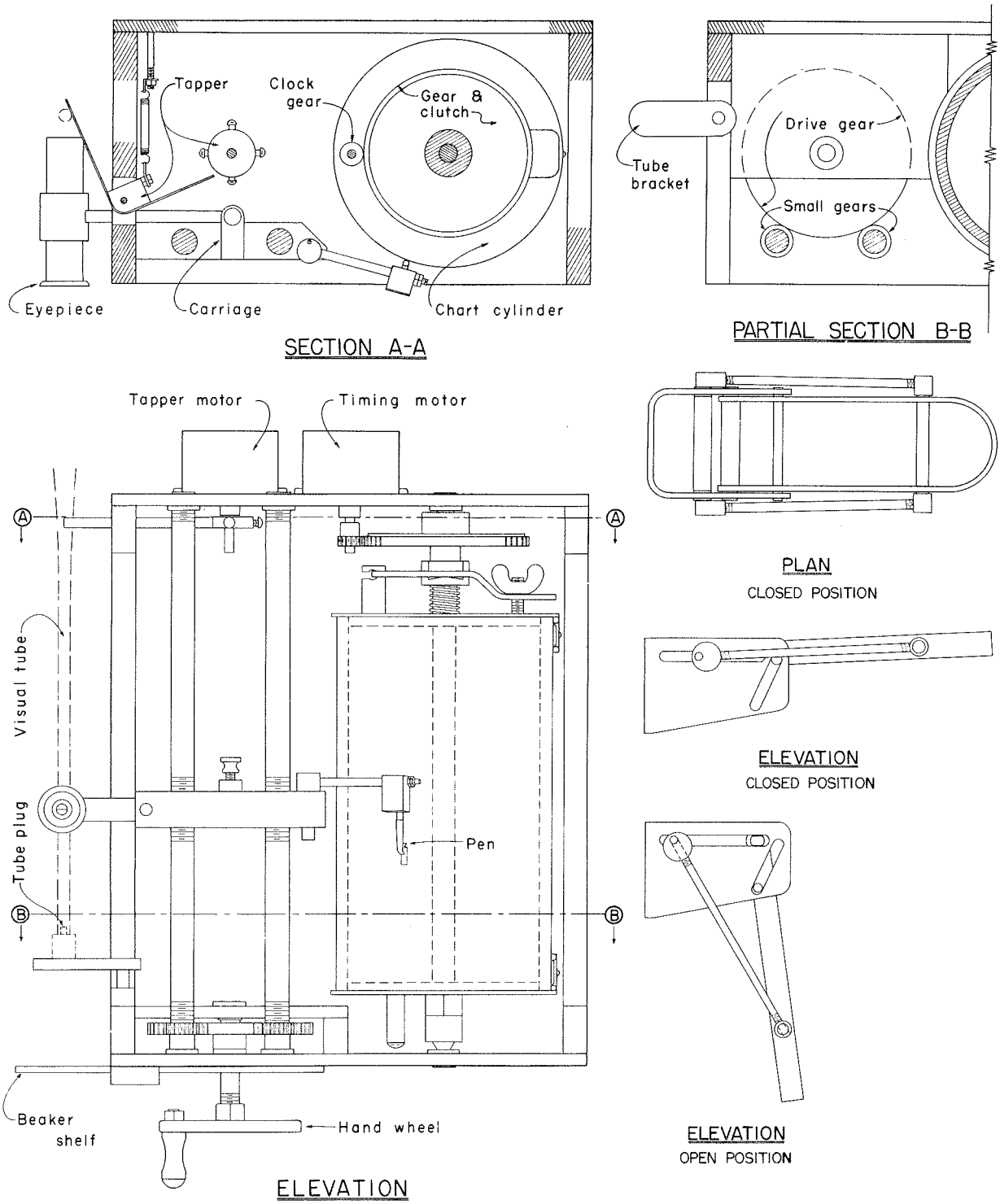


FIG. 42 - VISUAL-ACCUMULATION-TUBE APPARATUS



VISUAL TUBE RECORDER VALVE MECHANISM

FIG. 43 – VISUAL-ACCUMULATION-TUBE MECHANISMS

only small quantities of sand mostly less than 1 mm in sieve diameter. An elastic plug is inserted in the bottom of the accumulation section.

4. An electrically operated tapping mechanism, which strikes against the glass tube and helps keep the accumulation of sediment uniformly packed and level on top.

5. A special VA-tube recorder, which consists of: (1) A carriage, which can be moved vertically by a hand-operated mechanism and on which are mounted a recording pen and an optical instrument consisting of a two-power telescope eyepiece with a horizontal cross hair. (2) A cylinder, which carries a chart and rotates at a constant rate during the analysis.

6. The recorder chart, which is a printed form incorporating the fall-diameter calibration. The recorder pen draws a continuous curve of sediment accumulation on the chart.

Plans and specifications are available for all items of the VA-tube equipment. The cost of the complete VA-tube apparatus is about $500, or approximately that of a set of sieves and sieve shaker.

33. Samples suitable for analysis--Samples whose particles are mainly in the range of sand sizes are suitable for analysis in the VA tube. The weight of the samples may be as small as 0.05 gm for fine sands and as large as 15 gm for samples with a normal size distribution. If many coarse particles, larger than a sieve diameter of 1 or 2 mm, are present in a sample, they are removed by sieving. If any clay or much silt (sizes under 62 microns) is contained in a sample, it is removed before analysis. Some coarse silt does not affect the accuracy of results, but appreciable quantities of silt require additional time for making the analysis. The clay and silt fractions should be separated from the sand by sieving or by sedimentation processes, but the division need not be at a precise size.

The calibration of the VA-tube method has been made with sand particles; that is, the grains were of irregular shape and the specific gravity for each sample was about 2.65 even though many particles of higher and lower specific gravities were sometimes included. For special particle shapes, or samples with specific gravities much different from 2.65, accurate analyses might require a special calibration.

34. Preparation of samples for analysis--Because most samples to be analyzed by the VA-tube method originally contain clays and silts, the separation of sand sizes from the finer material prior to analysis is a basic problem. The more thoroughly the clays and silts are removed from the sample, the simpler and faster the VA-tube analysis will be. Present methods of removing the clays and silts are not entirely satisfactory, and further investigation of the problem should be made with a view toward reducing the total time of analysis.

Two wet-sieving processes may be used to separate the sands from the finer sizes. If separation is made with a 62.5-micron sieve, some particles

with fall diameters larger than 62.5 microns will pass the sieve; but, partly because of incomplete sieving, many particles with fall diameters much smaller than that size will be retained on the sieve. An accurate sedimentation analysis requires that the silt (fall diameters smaller than 62.5 microns) retained by the sieve should be identified and also the sand (fall diameters coarser than 62.5 microns) must be identified in the fraction passed by the sieve. If separation is made with a 50-micron sieve, very little sand will be passed and an accurate sedimentation analysis can be made by combining a sedimentation analysis of the clay and silt in the passed fraction with the VA-tube analysis of the retained fraction. However, the smaller the opening of the sieve, the more time consuming and difficult is the sieving process.

By another process, initial separation of sands from silts and clays may be made with a sedimentation tube. The sample may be introduced at the top of a tube and allowed to settle for the time interval that will permit, for the given water temperature and distance of fall, all the particles with sedimentation diameters greater than 62.5 microns to settle to the bottom of the column. The part of the sample settled may be analyzed in the VA tube, and the part not settled may be analyzed by any method suitable for silts and clays. This type of separation allows accurate analyses, but the time for analysis in the VA tube may be undesirably long because some fine material may be present.

Sand particles should be thoroughly soaked in water before analysis so that every particle is completely wetted; they should be contained in not more than 40 ml of water at a temperature no lower than that of the water in the VA tube. Samples for analysis should be relatively free of organic matter and in such condition that the grains will fall as individual particles and not as aggregates.

If the organic matter in a sample is of sufficient volume to decrease the accuracy of analysis, it will be visible in the sample and very obvious as the sample settles in the VA tube. Also, during a VA-tube analysis, the presence of aggregates is noticeable through the eyepiece, and a competent operator will realize the analysis is erroneous.

Whether particles will fall individually may be determined in a beaker prior to analysis by stirring the immersed sample in a rapid circular motion for a few moments and then allowing the particles to settle and accumulate at the center of the bottom of the container. If there is only a slight tendency to form aggregates, a few repetitions of a washing process--adding distilled water to the sample, stirring, allowing to settle, and decanting the supernatant liquid--will generally improve the settling characteristics.

Organic matter, which may be objectionable because of its volume or because it forms a binding agent for floccules, may be oxidized by the following procedure: A 6-percent solution of hydrogen peroxide is added to the sample that is contained in about 40 ml of water. About 5 ml of the solution is added for each gram of dry sample. The mixture is stirred thoroughly and covered. If the oxidation is slow, or after it has slowed, the mixture is heated to around 200°F and allowed to remain at that temperature with occasional stirring,

and possibly the addition of more hydrogen peroxide, until the oxidation appears complete. Then two or three repetitions of the washing process of the preceding paragraph adequately prepares the sample for analysis except that additional cooling may be desirable.

The water in the VA tube should be changed frequently if contamination from repeated analyses of treated samples is to be avoided. The contamination does not seem to alter the accuracy of the analyses; but if the sample is dried and weighed after analysis, the weight may be changed.

35. Selection of tube size--A necessary preliminary to analysis is the choice of the proper tube size for a given sample. Frequently, two sizes or more would be satisfactory. The quantity of sand and the upper particle-size limit in a sample are used as guides in selecting the tube size. Table 8 indicates the size of tube for limits of sand samples. If the pertinent characteristics of samples are not known from previous experience with the sampled stream, the sample to be analyzed may be compared with a set of synthetic samples. For example, a sample may be analyzed in a 2.1-mm tube if it does not exceed in quantity or particle size a synthetic sample containing 0.8 gm of sand with a maximum particle size of 250 microns.

The maximum particle sizes shown in Table 8 are those that should not be exceeded by a significant percentage of the sample. The percentage of excess may be greater if the sample is small in relation to the capacity of the tube or if the analysis of the coarser portion is not highly important.

Normally, the best results are obtained if the total height of accumulation in the bottom of the tube is between 1 and 4 in. If a sample has a very limited size range or the material is predominantly coarse, better results are obtained with maximum heights less than 4 in. If a satisfactory tube size is not selected the first time, the sample can be rerun in another size of tube. However, the choice of a suitable tube is not difficult because the usable limits of the respective tubes overlap considerably.

36. Method of analysis--The procedure for size analysis that was given in Section 10 has been modified for the improved VA-tube recorder. Analyses may be made in less than 10 min if the particles in the sample have fall diameters greater than 62 microns. More time is required if silt is present in the sample. The recommended chronological procedure for VA-tube analysis is as follows:

1. The chart is chosen for the length of the tube; after notes to identify the sample, operator, and analysis are recorded, the chart is placed on the cylinder. The base line of the chart should be parallel to the bottom of the cylinder so that the pen trace will be parallel to the base line except when sediment is accumulating. (The 180-cm and the 120-cm tubes require different charts because of the unequal distances through which the sample must settle.)

2. The recorder pen is oriented on the zero-accumulation and zero-time lines of the chart. The pen should be started to the right of the zero-time line and brought to the line by the motor-driven rotation of the cylinder.

3. The recorder is adjusted to bring the horizontal hair in the eyepiece level with the top of the tube plug where the accumulation of sediment begins.

4. When the apparatus, including the proper sedimentation section, is assembled, the tube is filled with distilled water to just above the valve. The temperature of the water in the tube is determined and recorded, and the valve is closed. Normally the water need not be changed after each analysis.

5. The electrical tapping mechanism is started; this operation also closes the electrical circuit to a switch at the valve so that rotation of the cylinder will start when the valve is opened.

6. The sand sample is washed into the funnel above the closed valve; the funnel is filled to the reference mark; then the sample is stirred briskly for 10 sec with a special stirring rod.

7. The valve is immediately and fully opened. Because opening the valve automatically starts the cylinder, the chart time and the settling of the particles in the tube begin simultaneously.

8. The operator watches through the eyepiece and, as soon as the first particles reach the bottom of the tube, he starts moving the carriage vertically at a rate that keeps the horizontal hair level with the top of the accumulation of sediment. This procedure continues until the pen has passed the 62-micron size on the chart. Then rotation of the cylinder automatically stops. If material is still falling, the tracking operation is continued, at least intermittently, until the maximum height of accumulation is determined.

9. While the pen stands at the maximum height of accumulation, the cylinder drive clutch is released and the cylinder is rotated by hand to extend the line of maximum accumulation across the chart.

10. After the valve is closed, the sample is drained into a beaker by removing the tube plug. The valve is opened slightly to drain out excess water and to wash out the lower end of the tube more completely. The plug is replaced.

11. The chart is removed from the recorder.

37. Size distribution from the chart--The procedure of Section 36 produces a pen trace on a chart that incorporates the fall-diameter calibration for the VA-tube method. The trace is a continuous curve of sediment accumulation, with time as the abscissa and height of accumulated sediment as the ordinate. Generally, analytical results are desired as percentages of the sample finer (or coarser) than certain definite sizes. One common series of these sizes is shown on the calibrated charts. The percentages finer than those sizes on the chart may be read from the chart by use of a scale that will conveniently divide the total accumulation into 100 equal parts. (The general procedure was shown in Fig. 5.) The intersections of the accumulation curve and the division-size lines (interpolated, if need be, for the temperature of analysis) are marked by ticks. The chart is spread out flat; the zero percent of the scale is placed on the total-accumulation line and the 100 percent on the zero-accumulation line. The scale is moved horizontally to the intersection of the curve with the size-temperature line. If horizontal lines instead of ticks are drawn through the intersections, all percentages may be read from one position of the scale. The percentage finer than the division size may be read directly

on the scale as it is represented by the portion of the total accumulation that lies above the curve. Percentages coarser may be read by reversing the scale.

If 10 percent of material coarser than that analyzed in the VA tube was removed from the sample prior to analysis, then the 90-percent mark may be used on the zero-accumulation line to show readings directly in percentages of the total sample. Similarly, if 40 percent of the original sample was removed as silt and clay before VA-tube analysis, the 40-percent mark may be used on the total-accumulation line to obtain direct readings in percentages of the total sample.

VII. CONCLUSIONS

38. Conclusions--Many investigators have used a basic type of sedimentation analysis in which sediment was introduced at the top of a column of distilled water and the settling velocity distribution was determined from the rate of accumulation of sediment at the bottom. The basic type of analysis was developed into the VA-tube method.

A sediment-introducing device activated by a valve was designed that simplified and systematized the introduction of sediment and promoted reproducibility of analyses.

A recorder was evolved that provided a simple means of obtaining a permanent, continuous, and accurate record of sediment accumulation without the need for specially talented or trained operators. The record could be converted easily to size distribution.

Glass-bead samples were an aid in the initial development of the VA-tube method. However, a calibration was required to obtain satisfactory accuracy, and the calibration for glass-bead samples was not adequate for sands.

The VA tube required special calibration for accurate analysis of natural sand samples. Calibration was in terms of the standard fall-velocity or fall-diameter distribution by weight and was based on 300 analyses of sand samples for which the fall-diameter distribution was known. Previous investigators had not calibrated the basic method or had calibrated against sieve-size distribution. The unique type of calibration for the VA tube was much more laborious but also much more significant for analysis of sediments.

The accuracy of the VA-tube method was established by many analyses.

The VA-tube method is a simple, fast, and economical procedure for size analysis of sediments of sand sizes. The method has been used for thousands of routine analyses in different laboratories.

A 400-ft, 16-mm, colored film is available for demonstrating the method.

The calibration procedure required a new process for preparing sand samples for which the size distribution based on the standard fall velocity of the individual particles was known. The process may be advantageously applied to other sedimentation problems.

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16. Emery, K. O., "Rapid Method of Mechanical Analysis of Sands," Journal of Sedimentary Petrology, Vol. 8, No. 3, 1938. Pages 105-110.

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APPENDIX

39. Explanation of tables--Tables 10 and 11 show the relations of diameter and fall-velocity of quartz spheres in distilled water at various temperatures. For many purposes the tables are a more convenient and accurate tool than the more usual graphical presentation.

Table 12 shows the series of analyses on which the calibration of the VA tube was based. The sieve and known fall-diameter distributions, in percentages finer by weight, are shown for each series of samples. The known fall-diameter distribution was computed from the fall velocities of groups of 100 particles, each of the particles having been dropped individually. The VA-tube analyses, after calibration, are shown for the various samples and tube diameters. Both sieve- and fall-diameter distributions were always 100 percent finer than 2000 microns.

The following symbols are used in Table 12:

* Indicates an analysis that was not used directly in calibration or in the probability of accuracy in Table 9 because the sample was far outside the range of concentration and particle size recommended for the diameter of the tube.

a Denotes a duplicate sample that was substituted because of loss or contamination of the original sample.

TABLE 10

RELATION OF DIAMETER TO FALL VELOCITY
FOR QUARTZ SPHERES
Fall diameter in microns

Velocity	Temperature in degrees Centigrade														Velocity
cm/sec	0°	10°	20°	21°	22°	23°	24°	25°	26°	27°	28°	29°	30°	40°	cm/sec
0.10	45	38	33.4	33.0	32.6	32.2	31.9	31.5	31.2	30.9	30.6	30.3	30.0	27	0.10
0.20	63	54	47.4	46.8	46.2	45.6	45.0	44.5	44.0	43.5	43.1	42.6	42.2	38	0.20
0.30	77	66	58.5	57.6	56.8	56.0	55.2	54.5	53.8	53.2	52.7	52.2	51.8	47	0.30
0.40	90	76	67.8	66.8	65.8	64.9	64.0	63.2	62.4	61.7	61.0	60.4	59.8	55	0.40
0.50	101	86	76.5	75.3	74.1	73.0	72.0	71.1	70.2	69.4	68.6	67.9	67.2	62	0.50
0.70	121	104	92.0	90.4	89.1	87.9	86.8	85.8	84.8	83.8	82.8	81.9	81.0	75	0.70
0.90	140	120	106.7	105.1	103.6	102.2	100.9	99.7	98.5	97.4	96.3	95.3	94.3	87	0.90
1.10	157	135	120.8	119.0	117.4	115.9	114.5	113.2	111.9	110.7	109.5	108.3	107.2	98	1.10
1.30	174	150	134.4	132.4	130.7	129.1	127.6	126.1	124.7	123.3	121.9	120.6	119.3	108	1.30
1.50	190	164	147.5	145.3	143.4	141.7	140.1	138.5	137.0	135.5	134.0	132.6	131.2	118	1.50
1.70	206	178	160.1	157.8	155.8	153.9	152.2	150.6	149.0	147.4	145.9	144.4	142.9	129	1.70
1.90	222	191	172.3	169.7	167.5	165.6	163.9	162.2	160.6	159.0	157.4	155.8	154.3	139	1.90
2.10	237	204	184.1	181.6	179.4	177.4	175.5	173.7	171.9	170.2	168.5	166.9	165.3	149	2.10
2.30	252	217	195.6	193.1	190.9	188.9	187.0	185.1	183.2	181.4	179.6	177.9	176.2	159	2.30
2.50	267	230	206.9	204.4	202.2	200.1	198.1	196.1	194.2	192.3	190.4	188.5	186.7	169	2.50
3.00	304	262	234.9	232.4	230.1	227.8	225.6	223.5	221.4	219.3	217.2	215.1	213.0	193	3.00
3.50	340	294	263.1	260.5	258.0	255.6	253.2	250.8	248.4	246.0	243.6	241.3	239.0	217	3.50
4.00	375	326	291.4	288.7	286.0	283.4	280.8	278.2	275.6	273.0	270.4	267.8	265.2	242	4.00
4.50	409	357	319.8	316.9	314.0	311.2	308.4	305.6	302.8	300.0	297.2	294.4	291.6	267	4.50
5.00	443	389	348.4	345.3	342.2	339.2	336.2	333.2	330.2	327.2	324.2	321.2	318.2	292	5.00
6.00	512	452	406.0	402.5	399.0	395.6	392.2	388.8	385.4	382.0	378.6	375.3	372.0	342	6.00
7.00	581	513	463.6	459.8	456.0	452.3	448.6	444.9	441.2	437.6	434.0	430.4	426.8	394	7.00
8.00	650	577	522.0	518.0	514.0	510.0	506.0	502.0	498.0	494.0	490.0	486.0	482.0	447	8.00
9.00	720	641	581.0	576.7	572.4	568.1	563.8	559.5	555.2	550.9	546.6	542.4	538.2	501	9.00
10.00	791	706	641.0	636.0	631.4	626.6	622.0	617.5	613.0	608.6	604.2	599.8	595.4	556	10.00
11.00	864	773	702	696	691	686	681	676	671	667	662	657	653	612	11.00
12.00	938	841	765	759	753	747	742	737	732	727	722	717	712	668	12.00
13.00	1014	910	829	823	817	811	805	799	793	788	783	778	773	725	13.00
14.00	1090	980	893	887	881	875	869	863	857	851	845	840	835	784	14.00
15.00	1170	1050	958	951	945	939	933	927	921	915	919	903	898	844	15.00
16.00	1250	1120	1026	1018	1011	1004	998	992	986	980	974	968	962	906	16.00
17.00	1330	1192	1094	1086	1078	1070	1063	1056	1050	1044	1038	1032	1026	969	17.00
18.00	1410	1264	1162	1153	1144	1136	1129	1122	1115	1108	1102	1196	1091	1033	18.00
19.00	1490	1336	1230	1221	1213	1205	1197	1190	1183	1176	1169	1163	1157	1098	19.00
20.00	1570	1410	1300	1291	1282	1274	1266	1259	1252	1245	1238	1231	1225	1165	20.00
22.00	1730	1560	1444	1434	1425	1416	1408	1400	1393	1386	1379	1372	1365	1302	22.00
24.00	1900	1710	1592	1581	1571	1561	1552	1544	1537	1530	1523	1516	1509	1444	24.00
26.00	2080	1870	1742	1731	1721	1711	1702	1694	1686	1678	1671	1664	1657	1590	26.00
28.00	2280	2040	1906	1894	1883	1872	1862	1853	1845	1837	1829	1821	1813	1742	28.00
30.00	2480	2230	2079	2067	2055	2043	2032	2022	2013	2014	1996	1988	1980	1904	30.00
35.00	2990	2730	2556	2544	2532	2521	2510	2501	2492	2484	2476	2468	2460	2380	35.00
40.00	3510	3250	3074	3062	3051	3040	3030	3021	3012	3004	2996	2988	2980	2900	40.00
45.00	4080	3830	3654	3742	3731	3720	3610	3601	3592	3584	3576	3568	3560	3490	45.00
50.00	4700	4470	4342	4331	4320	4310	4300	4293	4286	4279	4272	4266	4260	4190	50.00
60.00	6500	6320	6230	6222	6214	6207	6200	6193	6186	6179	6172	6166	6160	6100	60.00

TABLE 11

CHANGE OF FALL VELOCITY WITH WATER TEMPERATURE
FOR QUARTZ SPHERES
Fall velocity changes in cm/sec

Velocity	Temperature in degrees Centigrade														Velocity
cm/sec	0°	10°	20°	21°	22°	23°	24°	25°	26°	27°	28°	29°	30°	40°	cm/sec
0.10	+0.10	+0.042	+.010	+.007	+.004	+.002	0	-.002	-.005	-.007	-.009	-.011	-.014	-.030	0.10
0.20	+0.19	+0.085	+.022	+.016	+.010	+.005	0	-.005	-.009	-.014	-.018	-.022	-.026	-.056	0.20
0.30	+0.27	+0.125	+.032	+.024	+.016	+.008	0	-.007	-.014	-.020	-.026	-.032	-.038	-.080	0.30
0.40	+0.34	+0.16	+.041	+.030	+.020	+.010	0	-.009	-.018	-.026	-.034	-.042	-.050	-.10	0.40
0.50	+0.40	+0.19	+.050	+.037	+.024	+.012	0	-.011	-.022	-.032	-.042	-.051	-.060	-.12	0.50
0.60	+0.46	+0.22	+.058	+.042	+.027	+.013	0	-.012	-.024	-.036	-.048	-.059	-.070	-.14	0.60
0.70	+0.51	+0.24	+.066	+.048	+.031	+.015	0	-.014	-.028	-.041	-.054	-.067	-.079	-.16	0.70
0.80	+0.56	+0.27	+.074	+.052	+.033	+.016	0	-.016	-.031	-.046	-.061	-.075	-.088	-.18	0.80
0.90	+0.60	+0.29	+.081	+.058	+.037	+.018	0	-.017	-.034	-.050	-.066	-.082	-.097	-.21	0.90
1.00	+0.65	+0.32	+.088	+.063	+.040	+.019	0	-.019	-.037	-.055	-.072	-.089	-.105	-.23	1.00
1.10	+0.69	+0.34	+.095	+.067	+.043	+.021	0	-.020	-.039	-.058	-.077	-.095	-.113	-.25	1.10
1.20	+0.73	+0.36	+.102	+.072	+.046	+.022	0	-.021	-.041	-.062	-.082	-.102	-.121	-.27	1.20
1.30	+0.77	+0.38	+.108	+.076	+.049	+.024	0	-.023	-.045	-.067	-.088	-.108	-.128	-.29	1.30
1.40	+0.81	+0.40	+.114	+.081	+.052	+.025	0	-.024	-.047	-.070	-.092	-.114	-.136	-.32	1.40
1.50	+0.85	+0.42	+.120	+.085	+.054	+.026	0	-.025	-.050	-.074	-.098	-.122	-.143	-.34	1.50
1.60	+0.89	+0.44	+.126	+.090	+.058	+.028	0	-.026	-.052	-.077	-.102	-.126	-.150	-.36	1.60
1.70	+0.93	+0.46	+.132	+.095	+.061	+.029	0	-.027	-.054	-.080	-.106	-.132	-.157	-.38	1.70
1.80	+0.98	+0.48	+.138	+.100	+.063	+.030	0	-.028	-.056	-.083	-.110	-.137	-.163	-.40	1.80
1.90	+1.02	+0.50	+.144	+.102	+.065	+.031	0	-.029	-.058	-.086	-.114	-.142	-.169	-.41	1.90
2.00	+1.06	+0.52	+.150	+.106	+.067	+.032	0	-.030	-.060	-.089	-.118	-.146	-.174	-.43	2.00
3.00	+1.42	+0.69	+.18	+.13	+.08	+.04	0	-.04	-.08	-.12	-.15	-.19	-.23	-.57	3.00
4.00	+1.66	+0.83	+.21	+.15	+.10	+.05	0	-.05	-.10	-.14	-.19	-.24	-.28	-.69	4.00
5.00	+1.87	+0.94	+.23	+.17	+.11	+.06	0	-.06	-.12	-.17	-.23	-.28	-.33	-.80	5.00
6.00	+2.06	+1.04	+.25	+.18	+.12	+.06	0	-.06	-.12	-.18	-.24	-.30	-.36	-.89	6.00
7.00	+2.25	+1.12	+.27	+.20	+.13	+.07	0	-.07	-.13	-.19	-.26	-.32	-.38	-.97	7.00
8.00	+2.44	+1.21	+.29	+.21	+.14	+.07	0	-.07	-.14	-.21	-.28	-.34	-.41	-1.04	8.00
9.00	+2.62	+1.29	+.31	+.23	+.15	+.08	0	-.07	-.14	-.22	-.29	-.36	-.43	-1.11	9.00
10.00	+2.80	+1.36	+.33	+.25	+.16	+.08	0	-.08	-.16	-.24	-.32	-.39	-.45	-1.17	10.00
15.00	+3.60	+1.75	+.43	+.32	+.21	+.10	0	-.10	-.19	-.28	-.37	-.46	-.55	-1.40	15.00
20.00	+4.20	+2.00	+.50	+.37	+.24	+.12	0	-.11	-.21	-.31	-.41	-.51	-.60	-1.50	20.00
25.00	+4.30	+2.10	+.55	+.40	+.26	+.13	0	-.11	-.21	-.31	-.41	-.51	-.60	-1.50	25.00
30.00	+4.40	+2.10	+.50	+.37	+.25	+.12	0	-.11	-.21	-.31	-.41	-.51	-.60	-1.50	30.00
35.00	+4.30	+2.00	+.45	+.33	+.22	+.11	0	-.10	-.19	-.28	-.37	-.46	-.55	-1.40	35.00
40.00	+4.10	+1.80	+.40	+.30	+.20	+.11	0	-.09	-.18	-.25	-.33	-.41	-.50	-1.30	40.00
45.00	+3.40	+1.50	+.35	+.27	+.18	+.09	0	-.07	-.14	-.21	-.27	-.33	-.40	-1.05	45.00
50.00	+2.30	+1.00	+.25	+.18	+.12	+.06	0	-.05	-.10	-.15	-.20	-.25	-.30	-0.80	50.00
60.00	+1.10	+0.50	+.12	+.09	+.06	+.03	0	-.03	-.06	-.10	-.13	-.16	-.20	-0.50	60.00

NOTE: To the velocity at a given temperature add the change from this table to obtain the fall velocity for the same quartz sphere in distilled water at 24°C.

TABLE 12

SIZE DISTRIBUTIONS OF TEST SAMPLES

IN CUMULATIVE PERCENTAGES FINER THAN DIVISION SIZES

Division size--microns	62.5	88	125	175	250	350	500	700	1000	1400
Powder River Sand--Coarse Distribution										
Sieve diam. distribution	1.0	4.1	13.9	27.0	48.0	69.0	85.5	94.5	100.0	
Known fall diam. distribution	1.0	3.8	11.6	25.4	48.5	71.2	89.0	98.2	100.0	
Fall Diameter Distributions Obtained in 3.2 mm. Tube										
Sample analyzed										
1 (0.5 gm.)	1.0	4.5	14.0	27.5	49.0	73.0	91.0	97.0	100.0	
do	0.5	4.0	13.5	26.0	46.0	68.0	88.0	96.0	100.0	
do	1.0	3.5	13.0	27.0	48.5	69.0	88.0	97.0	100.0	
2 (0.5 gm.)	1.0	5.0	14.5	27.0	48.0	72.0	91.0	99.0	100.0	
do	1.5	5.0	14.0	27.5	47.0	73.0	90.0	99.0	100.0	
Average	1.0	4.4	13.8	27.0	47.7	71.0	89.6	97.6	100.0	
4 (0.9 gm.)	0.5	3.5	13.5	27.0	48.5	71.0	92.5	98.5	100.0	
do	1.0	3.5	13.0	25.0	47.5	72.0	93.5	100.0	100.0	
do	1.0	4.0	13.5	26.5	47.0	71.0	91.0	99.0	100.0	
do	1.0	4.0	13.0	26.5	46.5	70.0	92.0	98.0	100.0	
Average	0.9	3.8	13.2	26.2	47.4	71.0	92.2	98.9	100.0	
5 (1.5 gm.)	1.0	3.5	12.0	25.0	48.0	69.5	90.0	98.0	100.0	
do	0.5	3.5	12.0	26.0	49.0	70.0	91.0	99.0	100.0	
6 (1.5 gm.)	1.0	3.5	12.0	24.5	46.5	68.0	89.5	98.5	100.0	
do	0.5	3.5	12.0	24.5	47.5	69.0	91.0	98.5	100.0	
Average	0.8	3.5	12.0	25.0	47.8	69.1	90.4	98.5	100.0	
7 (2.5 gm.)	1.5	3.5	12.0	24.0	48.0	71.5	90.0	99.0	100.0	
do	1.2	3.5	12.0	25.0	49.0	75.0	93.0	99.5	100.0	
8 (2.5 gm.)	1.0	3.5	11.0	23.0	45.0	69.5	92.0	99.0	100.0	
do	0.8	3.5	11.5	25.0	47.5	71.0	90.0	99.0	100.0	
do	1.0	2.5	10.5	23.5	47.5	72.0	92.0	99.0	100.0	
Average	1.1	3.3	11.4	24.1	47.4	71.8	91.4	99.1	100.0	
Fall Diameter Distributions Obtained in 4.0 mm. Tube										
3 (0.9 gm.)	1.0	4.0	14.0	27.0	47.0	68.0	87.0	98.0	100.0	
do	1.5	4.0	14.0	28.0	47.0	67.0	89.0	96.5	100.0	
4 (0.9 gm.)	1.5	4.5	13.0	27.0	50.0	72.0	90.0	98.0	100.0	
do	1.0	3.5	13.5	26.5	50.0	71.0	90.0	98.0	100.0	
Average	1.2	4.0	13.6	27.1	48.5	69.5	89.0	97.6	100.0	
5 (1.5 gm.)	1.0	4.0	12.5	25.5	47.5	67.0	86.0	97.0	100.0	
do	1.0	4.0	12.5	26.5	48.5	68.0	90.0	97.0	100.0	
6 (1.5 gm.)	1.0	4.0	12.5	26.0	47.5	70.0	89.0	98.5	100.0	
do	1.0	4.0	12.5	26.5	48.5	69.0	88.0	98.0	100.0	
Average	1.0	4.0	12.5	26.1	48.0	68.5	88.2	97.6	100.0	
7 (2.5 gm.)	1.0	3.5	12.5	26.0	49.0	72.0	87.0	97.0	100.0	
do	1.5	4.0	12.0	25.0	47.0	70.0	89.0	97.0	100.0	
do	1.0	3.5	12.5	26.0	50.5	72.0	91.0	98.0	100.0	
8 (2.5 gm.)	0.5	3.0	12.0	26.0	48.5	69.0	88.0	98.0	100.0	
do	0.5	3.5	12.0	25.5	47.5	69.0	88.0	98.0	100.0	
Average	0.9	3.5	12.2	25.7	48.5	70.4	88.6	97.6	100.0	
9 (3.5 gm.)	0.5	3.0	10.5	25.0	48.0	72.0	92.0	99.0	100.0	
do	0.5	2.8	10.5	22.0	46.5	69.0	88.0	98.0	100.0	
do	0.5	3.0	10.5	23.5	46.0	70.0	89.0	98.0	100.0	
do	0.5	3.0	11.0	23.0	46.5	68.0	88.0	98.0	100.0	
10 (3.5 gm.)	0.5	2.5	10.5	23.0	49.0	72.0	92.0	99.0	100.0	
do	0.5	2.0	10.5	23.5	45.0	70.0	91.0	98.0	100.0	
do	0.5	2.5	9.5	22.0	46.0	69.0	89.0	97.5	100.0	
Average	0.5	2.7	10.4	23.1	46.7	70.0	89.9	98.2	100.0	
Fall Diameter Distributions Obtained in 5.0 mm. Tube										
3 (0.9 gm.)	0.5	4.0	12.0	25.0	45.0	66.0	89.0	96.0	100.0	
do	0.5	4.5	13.0	26.0	46.0	67.0	88.0	96.0	100.0	
4 (0.9 gm.)	1.0	4.0	12.0	27.0	44.0	69.0	89.0	96.0	100.0	
do	1.5	4.0	14.0	27.0	47.0	69.0	86.0	95.0	100.0	
Average	0.9	4.1	12.8	26.2	45.5	67.8	88.0	95.8	100.0	

TABLE 12--Continued

SIZE DISTRIBUTIONS OF TEST SAMPLES

IN CUMULATIVE PERCENTAGES FINER THAN DIVISION SIZES

Division size--microns	62.5	88	125	175	250	350	500	700	1000	1400
Powder River Sand--Coarse Distribution										
Sieve diam. distribution	1.0	4.1	13.9	27.0	48.0	69.0	85.5	94.5	100.0	
Known fall diam. distribution	1.0	3.8	11.6	25.4	48.5	71.2	89.0	98.2	100.0	
Fall Diameter Distributions Obtained in 5.0 mm. Tube--Continued										
Sample analyzed										
5 (1.5 gm.)	1.0	3.5	11.5	24.0	45.0	67.0	87.0	97.0	100.0	
do	1.0	4.0	13.5	27.0	48.0	70.0	86.0	97.0	100.0	
do	1.5	4.0	12.5	25.5	46.0	69.0	86.0	97.0	100.0	
6 (1.5 gm.)	0.5	3.5	12.0	25.0	45.5	68.0	90.0	97.0	100.0	
do	1.0	4.0	12.5	25.0	45.5	70.0	89.0	97.0	100.0	
Average	1.0	3.8	12.4	25.3	46.0	68.8	87.6	97.0	100.0	
7 (2.5 gm.)	1.0	4.0	12.0	24.5	46.0	73.0	91.0	98.0	100.0	
do	1.0	3.5	12.0	24.5	47.5	72.0	91.0	98.0	100.0	
8 (2.5 gm.)	0.5	3.0	11.5	24.0	45.0	69.0	86.0	97.0	100.0	
do	1.5	4.0	13.0	26.5	48.0	70.0	91.0	98.0	100.0	
Average	1.0	3.6	12.1	24.9	46.6	71.0	89.8	97.8	100.0	
9 (3.5 gm.)	0.5	2.0	9.0	23.0	47.0	71.0	90.0	98.0	100.0	
do	0.5	3.0	11.5	24.0	46.0	70.0	91.0	98.0	100.0	
do	1.0	2.5	12.0	24.5	48.0	70.0	87.0	97.5	100.0	
do	0.5	2.0	7.5	21.0	45.0	70.0	92.0	99.0	100.0	
do	0.0	2.0	10.0	24.0	45.5	68.5	90.0	99.0	100.0	
do	0.0	1.5	9.0	23.0	46.0	70.0	90.0	99.0	100.0	
do	0.5	1.8	10.0	24.0	45.5	68.0	86.5	97.5	100.0	
10 (3.5 gm.)	0.5	1.5	8.0	20.0	44.5	67.5	87.5	97.5	100.0	
do	0.5	2.4	11.0	24.0	47.0	69.0	89.0	98.0	100.0	
do	0.0	1.5	8.5	21.5	45.5	68.5	88.0	97.0	100.0	
do	0.2	1.8	9.0	22.0	44.5	67.0	89.0	98.0	100.0	
Average	0.4	2.0	9.5	22.8	45.9	69.0	89.1	98.0	100.0	

Division size--microns	12.1	26.7	50.5	69.5	85.5	94.5	100.0
Powder River Sand--Fine Distribution							
Sieve diam. distribution	12.1	26.7	50.5	69.5	85.5	94.5	100.0
Known fall diam. distribution	10.0	26.0	49.0	68.5	86.0	96.0	100.0
Fall Diameter Distributions Obtained in 2.0 mm. Tube							
Sample analyzed							
1 (0.1 gm.)	15.0	30.0	52.0	71.0	89.0	98.0	100.0
do	14.0	29.0	53.0	71.0	91.0	99.0	100.0
do	17.0	32.0	53.0	71.0	90.0	98.0	100.0
2 (0.1 gm.)	14.0	29.0	53.0	70.0	89.0	98.0	100.0
do	16.0	30.0	51.0	70.0	89.0	98.5	100.0
Average	15.2	30.0	52.4	70.6	89.6	98.3	100.0
3 (0.5 gm.)	9.5	25.0	51.0	70.5	86.0	97.0	100.0
do	11.0	27.5	53.0	72.0	86.5	97.0	100.0
4 (0.5 gm.)	12.0	28.5	52.5	71.0	86.5	97.5	100.0
do	12.5	29.5	53.0	71.5	86.5	98.0	100.0
Average	11.2	27.6	52.4	71.2	86.4	97.4	100.0
5 (0.9 gm.)	8.0	23.5	49.0	68.5	86.5	98.0	100.0
do	9.0	23.0	47.5	67.5	85.0	98.0	100.0
6 (0.9 gm.)	8.5	24.0	49.5	68.5	86.5	98.0	100.0
do	8.5	23.0	48.0	67.0	83.5	97.0	100.0
Average	8.5	23.4	48.5	67.9	85.4	97.8	100.0
Fall Diameter Distributions Obtained in 3.2 mm. Tube							
3 (0.5 gm.)	13.0	29.0	52.0	69.5	85.5	96.0	100.0
do	14.0	30.5	53.0	71.0	84.5	97.0	100.0
4 (0.5 gm.)	15.0	31.0	52.5	70.0	84.5	96.0	100.0
do	15.0	32.0	54.0	70.0	86.0	97.0	100.0
Average	14.2	30.6	52.9	70.1	85.4	96.5	100.0

TABLE 12--Continued

SIZE DISTRIBUTIONS OF TEST SAMPLES

IN CUMULATIVE PERCENTAGES FINER THAN DIVISION SIZES

Division size--microns	62.5	88	125	175	250	350	500	700	1000	1400
Powder River Sand--Fine Distribution										
Sieve diam. distribution	12.1	26.7	50.5	69.5	85.5	94.5	100.0			
Known fall diam. distribution	10.0	26.0	49.0	68.5	86.0	96.0	100.0			
Fall Diameter Distributions Obtained in 3.2 mm. Tube--Continued										
Sample analyzed										
5 (0.9 gm.)	12.5	28.5	53.5	69.0	85.5	96.0	100.0			
do	13.0	28.5	52.0	69.0	84.5	96.0	100.0			
6 (0.9 gm.)	12.0	29.0	51.5	69.5	84.0	95.0	100.0			
do	13.0	29.5	52.0	70.5	86.0	96.0	100.0			
Average	12.6	28.9	52.2	69.5	85.0	95.8	100.0			
7 (2.5 gm.)	8.8	25.5	50.0	68.5	85.0	96.0	100.0			
do	10.0	25.5	50.0	68.5	84.0	96.0	100.0			
8 (2.5 gm.)	9.2	25.5	50.5	70.0	85.5	96.0	100.0			
do	9.0	23.0	47.0	68.0	85.0	97.0	100.0			
Average	9.2	24.9	49.4	68.8	84.9	96.2	100.0			
Fall Diameter Distributions Obtained in 5.0 mm. Tube										
5 (0.9 gm.)	13.0	31.0	55.0	72.0	85.5	96.5	100.0			
do	9.5	29.0	52.5	71.0	84.0	97.0	100.0			
6 (0.9 gm.)	13.0	30.0	53.0	71.0	86.0	98.0	100.0			
do	13.0	30.0	52.5	72.0	87.0	98.0	100.0			
Average	12.1	30.0	53.2	71.5	85.6	97.4	100.0			
7 (2.5 gm.)	10.5	25.0	49.0	68.5	85.0	95.0	100.0			
do	11.0	26.5	50.0	69.0	85.0	95.0	100.0			
8 (2.5 gm.)	10.5	27.0	51.0	70.0	86.5	96.0	100.0			
do	12.0	27.5	51.5	70.0	86.0	96.0	100.0			
Average	11.0	26.5	50.4	69.4	85.6	95.5	100.0			
9 (4.5 gm.)	10.0	27.0	52.5	71.5	87.0	95.0	100.0			
do	10.8	27.0	52.0	70.5	86.0	95.0	100.0			
Average	10.4	27.0	52.2	71.0	86.5	95.0	100.0			
Republican River Sand--Fine Distribution										
Sieve diam. distribution	35.6	48.8	63.1	73.0	83.2	89.2	94.2	97.0	100.0	
Known fall diam. distribution	33.0	46.6	60.4	71.0	82.0	89.0	94.8	98.5	100.0	
Fall Diameter Distributions Obtained in 2.0 mm. Tube										
Sample analyzed										
1 (0.1 gm.)	28.0	43.0	55.0	71.5	84.5	91.0	95.0	99.0	100.0	
do	28.0	42.5	56.0	71.0	83.0	90.0	95.0	99.0	100.0	
Average	28.0	42.8	55.5	71.2	83.8	90.5	95.0	99.0	100.0	
2 (0.5 gm.)	32.0	45.0	59.0	70.0	82.5	91.0	97.0	99.5	100.0	
do	32.0	45.5	59.5	71.0	80.5	90.5	97.0	99.5	100.0	
Average	32.0	45.2	59.2	70.5	81.5	90.8	97.0	99.5	100.0	
3 (0.9 gm.)	30.0	43.5	58.5	70.0	81.0	89.5	95.0	100.0	100.0	
do	31.5	44.5	59.0	71.0	82.0	90.5	96.5	100.0	100.0	
Average	30.8	44.0	58.8	70.5	81.5	90.0	95.8	100.0	100.0	
Fall Diameter Distributions Obtained in 3.2 mm. Tube										
2 (0.5 gm.)	35.0	47.5	60.0	69.0	79.5	91.0	94.0	97.0	100.0	
do	35.0	47.0	61.0	71.0	81.5	91.5	96.0	99.5	100.0	
Average	35.0	47.2	60.5	70.0	80.5	91.2	95.0	98.2	100.0	
3 (0.9 gm.)	34.5	48.5	62.0	73.0	82.0	90.0	96.5	99.0	100.0	
do	33.5	46.5	61.0	72.0	82.0	92.0	95.5	99.5	100.0	
do	34.5	46.5	60.5	71.5	80.5	91.0	95.0	98.0	100.0	
Average	34.2	47.2	61.2	72.2	81.5	91.0	95.7	98.8	100.0	

TABLE 12--Continued

SIZE DISTRIBUTIONS OF TEST SAMPLES

IN CUMULATIVE PERCENTAGES FINER THAN DIVISION SIZES

Division size--microns	62.5	88	125	175	250	350	500	700	1000	1400
Republican River Sand--Fine Distribution										
Sieve diam. distribution	35.6	48.8	63.1	73.0	83.2	89.2	94.2	97.0	100.0	
Known fall diam. distribution	33.0	46.6	60.4	71.0	82.0	89.0	94.8	98.5	100.0	
Fall Diameter Distributions Obtained in 3.2 mm. Tube--Continued										
Sample analyzed										
4 (2.0 gm.)	32.5	47.0	60.5	71.5	83.0	89.0	95.5	99.5	100.0	
do	31.5	44.5	59.0	70.5	81.5	91.0	97.0	100.0	100.0	
Average	32.0	45.8	59.8	71.0	82.2	90.0	96.2	99.8	100.0	
Fall Diameter Distributions Obtained in 5.0 mm. Tube										
3 (0.9 gm.)	32.0	47.0	60.0	72.0	81.0	88.0	94.0	99.5	100.0	
do	33.0	46.5	61.0	72.0	80.5	88.0	93.0	97.0	100.0	
Average	32.5	46.8	60.5	72.0	80.8	88.0	93.5	98.2	100.0	
4 (2.0 gm.)	32.0	47.5	61.0	71.5	82.0	88.5	94.5	98.0	100.0	
do	35.0	48.5	60.5	72.5	83.0	88.5	94.0	98.0	100.0	
Average	33.5	48.0	60.8	72.0	82.5	88.5	94.2	98.0	100.0	
5 (4.0 gm.)	35.0	49.0	62.5	72.0	83.5	89.0	95.0	99.5	100.0	
do	33.0	47.5	61.0	71.5	82.0	88.0	93.0	99.5	100.0	
Average	34.0	48.2	61.8	71.8	82.8	88.5	94.0	99.5	100.0	
Fall Diameter Distributions Obtained in 7.0 mm. Tube										
4 (2.0 gm.)	32.0	45.0	58.0	69.0	81.0	87.0	95.0	99.5	100.0	
do	31.0	44.5	58.0	70.0	81.5	87.0	95.0	99.0	100.0	
Average	31.5	44.8	58.0	69.5	81.2	87.0	95.0	99.2	100.0	
5 (4.0 gm.)	32.5	45.0	57.5	67.0	80.5	87.5	94.0	98.0	100.0	
do	33.5	46.0	59.5	70.0	81.5	89.0	96.0	99.0	100.0	
Average	33.0	45.5	58.5	68.5	81.0	88.2	95.0	98.5	100.0	
6 (8.0 gm.)	34.5	47.5	60.5	71.5	82.0	89.0	93.5	98.0	100.0	
do	36.0	48.0	60.5	71.0	82.0	89.0	94.0	99.5	100.0	
Average	35.2	47.8	60.5	71.2	82.0	89.0	93.8	98.8	100.0	
Republican River Sand--Coarse Distribution										
Sieve diam. distribution	1.1	4.0	13.6	27.0	48.0	68.8	85.3	94.2	100.0	
Known fall diam. distribution	0.6	3.3	11.0	23.8	46.5	68.0	87.0	97.0	100.0	
Fall Diameter Distributions Obtained in 3.4 mm. Tube										
Sample analyzed										
1 (0.5 gm.)	0.5	3.5	10.0	23.0	46.0	64.0	85.0	95.0	100.0	
do	0.0	3.0	10.5	24.0	44.0	67.0	87.0	97.0	100.0	
Average	0.2	3.2	10.2	23.5	45.0	65.5	86.0	96.0	100.0	
2 (1.0 gm.)	0.0	2.5	9.5	23.0	46.0	65.0	87.0	97.0	100.0	
do	0.0	2.0	9.0	21.5	44.0	64.5	87.5	98.0	100.0	
Average	0.0	2.2	9.2	22.2	45.0	64.8	87.2	97.5	100.0	
3 (2.0 gm.)	0.5	2.2	8.0	20.0	43.5	65.5	86.5	97.0	100.0	
do	0.0	2.4	9.0	21.2	45.5	66.0	85.5	97.5	100.0	
Average	0.2	2.3	8.5	20.6	44.5	65.8	86.0	97.2	100.0	
Fall Diameter Distributions Obtained in 5.0 mm. Tube										
2 (1.0 gm.)	0.5	3.0	10.0	24.0	46.5	65.0	84.0	98.0	100.0	
do	0.5	3.5	11.0	25.0	47.0	65.0	85.0	95.0	100.0	
Average	0.5	3.2	10.5	24.5	46.8	65.0	84.5	96.5	100.0	
3 (2.0 gm.)	0.5	2.5	10.5	24.0	49.0	70.0	86.0	97.0	100.0	
do	1.0	3.5	10.5	23.5	49.0	68.0	85.0	96.5	100.0	
Average	0.8	3.0	10.5	23.8	49.0	69.0	85.5	96.8	100.0	

TABLE 12--Continued

SIZE DISTRIBUTIONS OF TEST SAMPLES

IN CUMULATIVE PERCENTAGES FINER THAN DIVISION SIZES

Division size--microns	62.5	88	125	175	250	350	500	700	1000	1400
Republican River Sand--Coarse Distribution										
Sieve diam. distribution	1.1	4.0	13.6	27.0	48.0	68.8	85.3	94.2	100.0	
Known fall diam. distribution	0.6	3.3	11.0	23.8	46.5	68.0	87.0	97.0	100.0	
Fall Diameter Distributions Obtained in 5.0 mm. Tube--Continued										
Sample analyzed										
4 (4.0 gm.)	1.0	2.0	9.5	22.5	50.5	72.0	88.0	99.5	100.0	
do	1.0	2.5	9.5	22.0	47.5	71.5	88.0	99.0	100.0	
Average	1.0	2.2	9.5	22.2	49.0	71.8	88.0	99.2	100.0	
Fall Diameter Distributions Obtained in 7.0 mm. Tube										
3 (2.0 gm.)	0.0	2.5	11.0	24.0	49.0	71.0	86.0	98.5	100.0	
do	0.5	3.0	9.0	22.0	46.0	68.0	85.0	97.0	100.0	
Average	0.2	2.8	10.0	23.0	47.5	69.5	85.5	97.8	100.0	
4 (4.0 gm.)	0.5	2.0	9.5	23.0	46.0	69.0	86.0	98.0	100.0	
do	0.5	2.0	10.0	25.0	50.0	71.0	87.0	99.0	100.0	
Average	0.5	2.0	9.8	24.0	48.0	70.0	86.5	98.5	100.0	
5* (8.0 gm.)	0.0	1.5	8.5	22.0	47.0	68.0	89.0	98.0	100.0	
do	0.5	2.5	9.5	23.5	49.0	69.5	87.5	99.5	100.0	
do	0.5	2.5	8.5	22.5	49.0	70.0	90.0	99.5	100.0	
Average	0.3	2.2	8.8	22.7	48.3	69.2	88.8	99.0	100.0	
Fall Diameter Distributions Obtained in 9.0 mm. Tube										
4 (4.0 gm.)	0.0	3.0	10.0	24.0	48.0	67.0	84.5	98.0	100.0	
do	0.0	3.0	10.0	23.5	49.0	72.0	88.0	98.0	100.0	
4a (4.0 gm.)	0.0	1.5	11.0	25.0	49.0	71.0	89.0	99.0	100.0	
do	0.0	1.0	9.0	23.0	46.5	68.0	88.0	97.0	100.0	
Average	0.0	2.1	10.0	23.9	48.1	69.5	87.4	98.0	100.0	
5* (8.0 gm.)	0.5	3.0	15.0	31.0	56.5	73.5	90.5	99.0	100.0	
do	0.0	2.5	13.5	29.0	53.0	72.0	87.5	99.0	100.0	
do	0.5	2.5	14.0	29.0	54.0	73.5	88.0	99.0	100.0	
do	0.0	2.0	10.0	25.0	51.0	69.0	86.0	97.5	100.0	
do	1.0	3.0	11.0	26.0	52.0	69.5	87.5	98.0	100.0	
Average	0.4	2.6	12.7	28.0	53.3	71.5	87.9	98.5	100.0	
6* (12.0 gm.)	0.5	2.8	13.0	29.0	55.0	75.0	90.5	99.5	100.0	
do	0.5	2.5	12.5	28.0	55.0	71.5	88.0	99.5	100.0	
do	0.5	2.5	11.0	27.0	55.0	73.0	89.0	99.0	100.0	
do	0.5	2.5	11.0	27.5	53.0	72.5	88.0	99.0	100.0	
Average	0.5	2.6	11.9	27.9	54.5	73.0	88.9	99.2	100.0	
Cheyenne River Sand										
Sieve diam. distribution	1.2	2.2	4.0	7.2	17.6	37.0	62.0	86.0	100.0	
Known fall diam. distribution	0.8	1.9	3.8	7.2	18.4	40.0	70.2	94.4	100.0	
Fall Diameter Distributions Obtained in 3.4 mm. Tube										
Sample analyzed										
1* (0.5 gm.)	1.0	2.5	4.0	7.5	19.0	37.0	79.0	99.0	100.0	
do	1.0	2.5	5.0	8.5	21.0	41.0	79.0	99.0	100.0	
Average	1.0	2.5	4.5	8.0	20.0	39.0	79.0	99.0	100.0	
2* (1.0 gm.)	1.0	1.8	4.0	6.5	19.0	36.0	83.0	98.0	100.0	
do	0.5	1.5	3.0	6.0	19.0	42.0	81.0	98.0	100.0	
Average	0.8	1.6	3.5	6.2	19.0	39.0	82.0	98.0	100.0	
3* (2.0 gm.)	1.5	2.5	4.0	6.5	16.0	40.5	79.0	99.0	100.0	
do	2.0	3.0	4.0	6.5	17.0	46.0	83.0	99.0	100.0	
Average	1.8	2.8	4.0	6.5	16.5	43.2	81.0	99.0	100.0	

TABLE 12--Continued

SIZE DISTRIBUTIONS OF TEST SAMPLES

IN CUMULATIVE PERCENTAGES FINER THAN DIVISION SIZES

Division size--microns	62.5	88	125	175	250	350	500	700	1000	1400
Cheyenne River Sand										
Sieve diam. distribution	1.2	2.2	4.0	7.2	17.6	37.0	62.0	86.0	100.0	
Known fall diam. distribution	0.8	1.9	3.8	7.2	18.4	40.0	70.2	94.4	100.0	
Fall Diameter Distributions Obtained in 5.0 mm. Tube										
Sample analyzed										
2 (1.0 gm.)	1.0	2.0	4.0	6.5	19.0	43.0	73.0	97.0	100.0	
do	0.0	1.0	2.0	5.0	20.0	43.0	74.0	97.0	100.0	
Average	0.5	1.5	3.0	5.8	19.5	43.0	73.5	97.0	100.0	
3* (2.0 gm.)	0.0	1.0	2.5	5.5	18.0	43.5	79.0	98.0	100.0	
do	1.0	2.0	2.5	6.0	19.0	46.0	75.0	98.0	100.0	
Average	0.5	1.5	2.5	5.8	18.5	44.8	77.0	98.0	100.0	
4* (4.0 gm.)	1.0	1.5	3.5	5.5	18.0	43.0	80.0	99.0	100.0	
do	1.5	2.0	3.5	5.5	17.0	43.0	80.0	98.5	100.0	
Average	1.2	1.8	3.5	5.5	17.5	43.0	80.0	98.8	100.0	
Fall Diameter Distributions Obtained in 7.0 mm. Tube										
3 (2.0 gm.)	1.0	2.0	4.0	6.0	19.0	44.0	73.0	96.0	100.0	
do	0.5	2.0	3.5	5.0	17.0	41.0	71.0	97.0	100.0	
Average	0.8	2.0	3.8	5.5	18.0	42.5	72.0	96.5	100.0	
4 (4.0 gm.)	1.0	1.5	3.5	5.5	17.0	41.0	74.0	98.0	100.0	
do	1.5	2.5	3.5	5.5	16.0	38.0	72.0	97.5	100.0	
Average	1.2	2.0	3.5	5.5	16.5	39.5	73.0	97.8	100.0	
5* (8.0 gm.)	1.5	2.5	3.5	6.0	18.0	44.0	77.0	98.0	100.0	
do	1.5	2.0	3.5	5.5	16.0	42.0	76.0	98.5	100.0	
Average	1.5	2.2	3.5	5.8	17.0	43.0	76.5	98.2	100.0	
Fall Diameter Distributions Obtained in 9.0 mm. Tube										
4 (4.0 gm.)	0.5	1.5	3.0	5.5	17.0	40.0	68.0	96.0	100.0	
do	1.0	1.5	2.5	5.0	18.0	39.0	68.0	97.0	100.0	
Average	0.8	1.5	2.8	5.2	17.5	39.5	68.0	96.5	100.0	
5 (8.0 gm.)	0.5	1.5	2.5	5.0	16.0	39.5	68.0	98.0	100.0	
do	0.5	1.0	2.5	5.0	17.0	41.0	71.0	98.0	100.0	
Average	0.5	1.2	2.5	5.0	16.5	40.2	69.5	98.0	100.0	
6* (12.0 gm.)	1.0	1.5	2.5	5.0	20.0	46.5	84.5	99.5	100.0	
do	1.0	1.5	2.5	5.0	20.5	43.5	77.0	99.5	100.0	
Average	1.0	1.5	2.5	5.0	20.2	45.0	80.8	99.5	100.0	
Taylors Falls Sand--Coarse Distribution										
Sieve diam. distribution	23.0	39.0	62.5	84.9	97.0	100.0				
Known fall diam. distribution	18.5	35.0	59.0	84.0	97.0	100.0				
Fall Diameter Distributions Obtained in 2.0 mm. Tube										
Sample analyzed										
1 (0.1 gm.)	17.0	34.0	55.0	89.0	99.0	100.0				
do	17.0	32.0	56.0	90.0	99.0	100.0				
do	19.0	33.0	55.0	90.0	98.0	100.0				
Average	17.7	33.0	55.3	89.7	98.7	100.0				
2 (0.5 gm.)	18.0	34.0	60.0	86.0	99.0	100.0				
do	17.5	33.5	58.0	85.0	99.0	100.0				
Average	17.8	33.8	59.0	85.5	99.0	100.0				
Fall Diameter Distributions Obtained in 3.4 mm. Tube										
2 (0.5 gm.)	17.0	32.0	56.0	80.0	99.0	100.0				
do	19.0	34.0	57.0	80.0	99.0	100.0				
Average	18.0	33.0	56.5	80.0	99.0	100.0				

TABLE 12--Continued

SIZE DISTRIBUTIONS OF TEST SAMPLES

IN CUMULATIVE PERCENTAGES FINER THAN DIVISION SIZES

Division size--microns	62.5	88	125	175	250	350	500	700	1000	1400
Taylor Falls Sand--Coarse Distribution										
Sieve diam. distribution	23.0	39.0	62.5	84.9	97.0	100.0				
Known fall diam. distribution	18.5	35.0	59.0	84.0	97.0	100.0				
Fall Diameter Distributions Obtained in 3.4 mm. Tube--Continued										
Sample analyzed										
3 (0.9 gm.)	18.5	35.0	59.0	82.0	98.5	100.0				
do	20.0	36.5	59.5	82.0	99.0	100.0				
Average	19.2	35.8	59.2	82.0	98.8	100.0				
4 (2.0 gm.)	18.0	34.0	61.5	86.0	98.0	100.0				
do	17.0	34.0	63.0	87.0	98.0	100.0				
4a (2.0 gm.)	19.0	36.0	60.0	84.0	97.5	100.0				
do	19.0	36.0	62.5	85.0	98.0	100.0				
Average	18.2	35.0	61.8	85.5	97.9	100.0				
Fall Diameter Distributions Obtained in 5.0 mm. Tube										
3 (0.9 gm.)	16.5	35.0	58.0	82.0	98.0	100.0				
do	19.0	37.0	62.0	82.0	99.0	100.0				
Average	17.8	36.0	60.0	82.0	98.5	100.0				
4 (2.0 gm.)	18.0	34.5	60.5	84.0	97.0	100.0				
do	19.0	36.0	61.0	85.0	96.0	100.0				
4a (2.0 gm.)	20.0	37.0	60.0	83.0	98.0	100.0				
do	20.0	37.5	62.5	84.5	98.0	100.0				
Average	19.2	36.2	61.0	84.1	97.2	100.0				
5 (4.0 gm.)	15.5	31.0	60.0	85.0	97.0	100.0				
do	17.0	36.0	64.0	87.0	98.0	100.0				
Average	16.2	33.5	62.0	86.0	97.5	100.0				
Fall Diameter Distributions Obtained in 7.0 mm. Tube										
4 (2.0 gm.)	17.0	35.0	58.0	86.0	97.0	100.0				
do	16.0	35.0	61.0	85.0	96.0	100.0				
4a (2.0 gm.)	18.0	36.0	59.0	82.0	98.0	100.0				
do	19.5	36.0	59.0	82.0	97.0	100.0				
Average	17.6	35.5	59.2	83.8	97.0	100.0				
5 (4.0 gm.)	17.0	34.0	60.0	83.0	96.5	100.0				
do	18.5	36.0	61.5	84.0	96.5	100.0				
Average	17.8	35.0	60.8	83.5	96.5	100.0				
6* (8.0 gm.)	18.0	38.0	65.0	85.0	95.5	100.0				
do	18.5	37.0	65.0	86.0	97.0	100.0				
Average	18.2	37.5	65.0	85.5	96.2	100.0				
Taylors Falls Sand--Fine Distribution										
Sieve diam. distribution	56.5	73.0	92.0	100.0	100.0					
Known fall diam. distribution	54.0	69.0	89.0	99.0	100.0					
Fall Diameter Distributions Obtained in 2.0 mm. Tube										
Sample analyzed										
1 (0.1 gm.)	53.0	67.0	91.0	100.0	100.0					
do	56.0	68.0	93.0	100.0	100.0					
Average	54.5	67.5	92.0	100.0	100.0					
2 (0.5 gm.)	54.0	72.0	90.0	100.0	100.0					
do	53.0	70.0	90.0	99.5	100.0					
Average	53.5	71.0	90.0	99.8	100.0					
3 (0.8 gm.)	54.8	71.8	90.8	99.8	100.0					
do	55.5	74.5	91.8	100.0	100.0					
do	56.5	75.0	92.5	100.0	100.0					
Average	55.6	73.8	91.7	99.9	100.0					

TABLE 12--Continued

SIZE DISTRIBUTIONS OF TEST SAMPLES

IN CUMULATIVE PERCENTAGES FINER THAN DIVISION SIZES

Division size--microns	62.5	88	125	175	250	350	500	700	1000	1400
Taylors Falls Sand--Fine Distribution										
Sieve diam. distribution	56.5	73.0	92.0	100.0	100.0					
Known fall diam. distribution	54.0	69.0	89.0	99.0	100.0					
Fall Diameter Distributions Obtained in 3.4 mm. Tube										
Sample analyzed										
2 (0.5 gm.)	53.0	69.0	88.0	99.5	100.0					
do	55.0	71.0	90.0	99.0	100.0					
Average	54.0	70.0	89.0	99.2	100.0					
3 (0.8 gm.)	57.0	73.0	90.0	100.0	100.0					
do	56.5	73.0	90.0	100.0	100.0					
Average	56.8	73.0	90.0	100.0	100.0					
4 (2.0 gm.)	54.8	74.0	91.0	99.5	100.0					
do	54.8	74.0	91.0	99.5	100.0					
Average	54.8	74.0	91.0	99.5	100.0					
Fall Diameter Distributions Obtained in 5.0 mm. Tube										
3 (0.8 gm.)	56.0	69.0	90.0	100.0	100.0					
do	55.0	69.0	86.0	100.0	100.0					
Average	55.5	69.0	88.0	100.0	100.0					
4 (2.0 gm.)	55.5	73.0	89.0	99.0	100.0					
do	54.5	70.0	87.0	98.5	100.0					
do	54.8	70.5	89.0	99.5	100.0					
Average	54.9	71.2	88.3	99.0	100.0					
5 (4.0 gm.)	51.5	69.5	90.0	98.5	100.0					
do	51.5	68.5	88.5	98.0	100.0					
Average	51.5	69.0	89.2	98.2	100.0					
Fall Diameter Distributions Obtained in 7.0 mm. Tube										
4 (2.0 gm.)	53.0	69.0	88.0	99.0	100.0					
do	53.5	71.5	88.5	98.5	100.0					
Average	53.2	70.2	88.2	98.8	100.0					
5 (4.0 gm.)	50.5	67.5	86.5	97.5	100.0					
do	51.5	69.5	87.5	98.0	100.0					
Average	51.0	68.5	87.0	97.8	100.0					
6 (8.0 gm.)	54.5	71.5	89.5	98.5	100.0					
do	55.0	72.5	89.5	98.5	100.0					
Average	54.8	72.0	89.5	98.5	100.0					
Special Sand--Fine Distribution										
Sieve diam. distribution	0.0	0.5	1.6	4.0	10.0	20.0	36.0	52.0	70.0	86.0
Known fall diam. distribution	0.0	0.2	1.0	3.7	9.6	21.4	39.0	59.6	84.2	98.2
Fall Diameter Distributions Obtained in 10.00 mm. Tube										
Sample analyzed										
1* (2.0 gm.)	0.0	0.0	0.5	3.0	8.5	20.0	36.5	57.0	87.0	99.0
do	0.0	0.0	0.0	4.0	12.0	23.0	43.5	67.0	93.0	99.0
Average	0.0	0.0	0.2	3.5	10.2	21.5	40.0	62.0	90.0	99.0
2 (5.0 gm.)	0.0	0.0	1.0	3.5	10.0	22.0	36.0	56.0	86.0	98.0
do	0.0	0.0	1.0	3.5	9.0	20.0	37.0	64.0	87.0	98.0
do	0.0	0.0	1.5	2.5	8.0	18.0	35.0	60.0	83.0	98.0
Average	0.0	0.0	1.2	3.2	9.0	20.0	36.0	60.0	85.3	98.0
3 (10.0 gm.)	0.0	0.0	1.0	3.0	8.5	20.5	37.0	61.0	86.0	97.5
do	0.0	0.0	1.2	3.0	8.5	20.5	38.0	60.0	82.0	98.0
Average	0.0	0.0	1.1	3.0	8.5	20.5	37.5	60.5	84.0	97.8
4 (15.0 gm.)	0.0	0.0	0.3	2.2	8.0	19.5	36.5	61.0	87.0	99.0
do	0.0	0.0	0.2	3.0	8.5	21.5	39.0	59.0	86.0	99.0
do	0.0	0.0	0.8	2.5	8.5	19.0	36.0	56.0	83.0	99.0
Average	0.0	0.0	0.4	2.6	8.3	20.0	37.2	58.7	85.3	99.0

TABLE 12--Continued

SIZE DISTRIBUTIONS OF TEST SAMPLES

IN CUMULATIVE PERCENTAGES FINER THAN DIVISION SIZES

Division size--microns	62.5	88	125	175	250	350	500	700	1000	1400
Special Sand--Medium Distribution										
Sieve diam. distribution						0.0	0.0	15.0	40.0	70.0
Known fall diam. distribution						0.0	5.5	26.0	65.6	96.2
Fall Diameter Distributions Obtained in 10.0 mm. Tube										
Sample analyzed										
1 (2.0 gm.)						0.0	4.0	22.0	58.0	88.0
do						0.0	3.5	25.0	63.0	92.0
do						0.0	5.0	22.0	66.0	93.0
Average						0.0	4.2	23.0	62.3	91.0
2 (5.0 gm.)						0.0	7.0	26.0	60.0	94.0
do						0.0	5.0	26.0	71.0	93.0
do						0.0	5.0	27.0	65.0	94.0
Average						0.0	5.7	26.3	65.3	93.7
3 (10.0 gm.)						0.0	7.0	28.0	70.0	96.0
do						0.0	4.0	21.5	60.0	94.5
do						0.0	6.0	28.5	61.0	97.0
Average						0.0	5.7	26.0	63.7	95.8
Special Sand--Coarse Distribution										
Sieve diam. distribution							0.0	0.0	10.0	50.0
Known fall diam. distribution							0.0	6.2	46.0	93.8
Fall Diameter Distributions Obtained in 10.0 mm. Tube										
Sample analyzed										
1* (1.0 gm.)							0.0	0.0	30.0	93.0
do							0.0	5.0	39.0	95.0
do							0.0	5.0	40.0	95.0
Average							0.0	3.3	36.3	94.3
2 (2.0 gm.)							0.0	6.0	47.0	92.0
do							0.0	10.0	44.0	94.0
Average							0.0	8.0	45.5	93.0
3 (5.0 gm.)							0.0	9.0	50.0	95.0
do							0.0	7.0	43.0	93.0
Average							0.0	8.0	46.5	94.0
4 (8.0 gm.)							0.0	7.0	54.0	96.0
do							0.0	6.0	50.0	93.0
Average							0.0	6.5	52.0	94.5
Combination of Special and Powder River Sand										
Sieve diam. distribution	0.0	0.0	2.4	7.0	18.6	34.0	55.0	75.0	90.0	97.0
Known fall diam. distribution	0.0	0.0	1.3	6.4	19.0	38.0	61.6	81.6	95.5	99.6
Fall Diameter Distributions Obtained in 10.0 mm. Tube										
Sample analyzed										
1 (5.0 gm.)	0.0	0.0	2.0	6.5	19.0	37.0	62.0	82.0	94.0	99.0
do	0.0	0.0	3.0	7.0	19.0	41.0	65.0	86.0	97.0	99.5
do	0.0	0.0	3.0	7.0	20.0	40.0	66.0	83.0	95.0	100.0
Average	0.0	0.0	2.7	6.8	19.3	39.3	64.3	83.7	95.3	99.5
2 (10.0 gm.)	0.0	1.0	3.0	7.5	21.0	41.0	63.0	84.0	95.0	99.5
do	0.0	1.0	2.5	7.0	21.5	39.0	61.0	85.0	97.0	99.5
Average	0.0	1.0	2.8	7.2	21.2	40.0	62.0	84.5	96.0	99.5
3 (15.0 gm.)	0.0	0.5	2.5	7.0	19.5	37.0	60.5	81.0	94.0	100.0
do	0.0	1.5	3.0	7.5	20.5	41.0	63.0	80.0	96.0	99.5
Average	0.0	1.0	2.8	7.2	20.0	39.0	61.8	80.5	95.0	99.8

TABLE 12--Continued

SIZE DISTRIBUTIONS OF TEST SAMPLES

IN CUMULATIVE PERCENTAGES FINER THAN DIVISION SIZES

Division size--microns	62.5	88	125	175	250	350	500	700	1000	1400
Combination of Special and Republican River Sand										
Sieve diam. distribution	9.2	19.2	30.8	40.0	50.6	60.0	70.0	80.0	90.0	95.0
Known fall diam. distribution	6.0	17.2	28.2	38.2	49.6	61.0	72.6	84.0	94.2	99.4
Fall Diameter Distributions Obtained in 10.0 mm. Tube										
Sample analyzed										
1* (2.0 gm.)	5.0	15.0	28.0	37.0	47.0	59.0	70.0	83.0	94.0	100.0
do	7.5	19.0	27.0	40.0	46.0	60.0	71.0	90.0	95.0	99.0
Average	6.2	17.0	27.5	38.5	46.5	59.5	70.5	86.5	94.5	99.5
2 (5.0 gm.)	7.0	17.0	27.0	37.0	50.0	59.0	73.0	89.0	96.0	100.0
do	7.0	18.0	30.0	40.0	50.0	60.0	73.0	87.0	96.0	100.0
Average	7.0	17.5	28.5	38.5	50.0	59.5	73.0	88.0	96.0	100.0
3 (10.0 gm.)	5.0	15.5	27.0	36.0	48.5	58.0	68.5	81.0	94.0	99.5
do	5.5	16.5	27.5	37.0	48.5	60.0	70.5	85.0	95.0	99.5
Average	5.2	16.0	27.2	36.5	48.5	59.0	69.5	83.0	94.5	99.5
4 (15.0 gm.)	4.5	16.0	28.0	38.5	49.5	61.0	71.0	80.5	92.0	99.5
do	4.0	15.0	27.0	36.5	49.5	61.0	72.0	88.0	95.0	100.0
Average	4.2	15.5	27.5	37.5	49.5	61.0	71.5	84.2	93.5	99.8
Cheyenne River Sand										
Sieve diam. distribution	1.2	2.2	4.0	7.2	17.6	37.0	62.0	86.0	100.0	100.0
Known fall diam. distribution	0.8	1.9	3.8	7.2	18.4	40.0	70.2	94.4	100.0	100.0
Fall Diameter Distributions Obtained in 10.0 mm. Tube										
Sample analyzed										
1* (2.0 gm.)	1.0	3.0	4.0	11.0	24.0	50.0	80.0	97.0	100.0	100.0
do	1.0	2.0	4.0	12.0	25.0	50.0	84.0	97.0	100.0	100.0
Average	1.0	2.5	4.0	11.5	24.5	50.0	82.0	97.0	100.0	100.0
2 (5.0 gm.)	1.0	2.0	4.0	7.5	21.0	40.0	73.0	96.0	100.0	100.0
do	1.0	2.0	4.0	6.5	20.0	41.0	71.5	95.0	99.5	100.0
Average	1.0	2.0	4.0	7.0	20.5	40.5	72.2	95.5	99.8	100.0
3 (10.0 gm.)	0.5	1.5	3.5	6.5	20.0	44.0	73.0	97.0	100.0	100.0
do	0.0	1.0	2.5	6.0	19.0	40.0	71.5	97.0	100.0	100.0
Average	0.2	1.2	3.0	6.2	19.5	42.0	72.2	97.0	100.0	100.0
4 (15.0 gm.)	1.0	2.0	4.5	7.5	20.0	42.0	73.0	94.0	100.0	100.0
do	1.5	2.5	4.5	7.0	18.0	42.0	72.0	93.0	100.0	100.0
Average	1.2	2.2	4.5	7.2	19.0	42.0	72.5	93.5	100.0	100.0
Powder River Sand--Fine Distribution										
Sieve diam. distribution	12.1	26.7	50.5	69.5	85.5	94.5	100.0	100.0		
Known fall diam. distribution	10.0	26.0	49.0	68.5	86.0	96.0	100.0	100.0		
Fall Diameter Distributions Obtained in 10.0 mm. Tube										
Sample analyzed										
1* (2.0 gm.)	6.0	25.0	52.0	63.0	86.0	98.0	100.0	100.0		
do	8.0	26.0	47.0	57.0	78.0	98.0	100.0	100.0		
do	8.0	25.0	45.0	60.0	85.0	98.0	100.0	100.0		
Average	7.3	25.7	48.0	60.0	83.0	98.0	100.0	100.0		
2 (5.0 gm.)	9.0	29.0	48.0	66.0	83.0	95.0	98.0	100.0		
do	9.0	31.0	50.0	67.0	85.0	96.0	100.0	100.0		
Average	9.0	30.0	49.0	66.5	84.0	95.5	99.0	100.0		
3 (10.0 gm.)	10.0	30.0	48.5	65.5	86.5	96.5	100.0	100.0		
do	9.5	29.0	48.0	64.5	85.5	95.5	100.0	100.0		
Average	9.8	29.5	48.2	65.0	86.0	96.0	100.0	100.0		
4 (15.0 gm.)	9.5	29.5	50.0	67.0	87.0	96.0	100.0	100.0		
do	10.5	30.5	50.0	67.0	86.0	96.0	100.0	100.0		
Average	10.0	30.0	50.0	67.0	86.5	96.0	100.0	100.0		