A STUDY OF METHODS USED IN

MEASUREMENT AND ANALYSIS OF SEDIMENT LOADS IN STREAMS

REPORT NO. 7

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

JUNE 1943

A Study of Methods Used in

MEASUREMENT AND ANALYSIS OF SEDIMENT LOADS IN STREAMS

Planned and conducted jointly by

Office of Indian Affairs, Bureau of Reclamation

Tennessee Valley Authority, Corps of Engineers

Geological Survey, Department of Agriculture

and Iowa Institute of Hydraulic Research

Report No. 7

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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

SYNOPSIS

In Report No. 4 of this series, "Methods of Analyzing Sediment Samples," a study of available literature on methods of determining the sizes of sediment particles was described. It was concluded that none of the present methods for analyzing suspended sediment samples can be applied satisfactorily to all sizes and concentrations which are encountered in flowing streams. The present study was undertaken in an attempt to supply this deficiency. The bottom withdrawal tube developed in the course of this study appears to meet the need. This device is a glass tube, 50 to 100 cm. in length, equipped with a volumetric scale and a quick-acting outlet at the lower end. First the sample is uniformly dispersed in the tube. Then the tube is placed in an upright position and samples of known volume are drawn from the bottom at known time intervals. When the sediment weight in each fraction has been determined the particle size distribution can be computed with the aid of a so-called Odén curve.

The report includes a review of the range of conditions for which the present methods of size analysis are suitable. The various devices investigated and the method of computing the size analysis of sediments on the basis of a uniform dispersion of particles are described. The modification of this method for application to data obtained with the bottom withdrawal tube is explained. A description of the tests made to determine the accuracy and range of applicability of the apparatus is also included.

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

I. INTRODUCTION

1. Purpose of report--The original purpose of this study was to develop a device suitable for analyzing suspended sediment samples with a wider range of particle sizes and concentrations than is possible with any of the methods known heretofore. As the study was curtailed due to war conditions, the present purpose of the report is to describe the progress that has been made, the devices developed, the methods of using them, and the tests conducted to determine their accuracy and sufficiency, in anticipation that the study can be resumed and carried to completion at a more favorable time without loss of valuable ideas or information.

2. Purpose and scope of the general study--The various phases covered in the general project, "A Study of Methods Used in Measurement and Analysis of Sediment Loads in Streams," of which the present study is a part, are indicated by the following titles and brief abstracts of preceding reports which have been published.

> 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 investigation to the present, with discussions of the advantages and disadvantages of the various methods and instruments. The requirements of a sampler which would meet all field conditions satisfactorily are set forth.

> Report No. 2--"Equipment Used for Sampling Bed-Load and Bed Material," deals with bed-load and bed material in a manner similar to that in which Report No. 1 covers suspended load.

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 based on the latest developments in the application of turbulence theories to sediment transportation.

Report No. 4--"Methods of Analyzing Sediment Samples," describes and discusses many methods developed for determining the size of small particles in sediment analyses. Detailed instructions are given for many of the common methods in use for determining the particle size and the total concentration of sediment in samples as developed by agencies doing extensive work in these fields.

Report No. 5--"Laboratory Investigations of Suspended Sediment Samplers," describes experiments to investigate the effect of various intake conditions on the accuracy of sediment samples and the filling characteristics of slow filling samplers under various conditions.

Three additional reports, now in preparation, will be issued shortly on the following subjects:

Report No. 6--"The Design of Improved Types of Suspended Sediment Samplers," describes the development of two types of integrating samplers, one suitable for taking vertically depth-integrated samples in flowing streams and another for taking time-integrated samples at given depths.

Report No. 8--"Measurement of the Sediment Discharge of Streams," describes the most efficient methods and equipment to be used in making sediment measurements under the various conditions encountered in natural 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 of value in engineering studies are given.

3. Authority and personnel--The comprehensive program of which this report is a part was conducted by the informal cooperation of the Geological Survey, Office of Indian Affairs, Bureau of Reclamation, Department of Agriculture Flood Control Coordinating Committee, War Department Corps of Engineers, Tennessee Valley Authority, and the Iowa Institute of Hydraulic

Research. The investigation was conducted at the Hydraulic Laboratory of the Iowa Institute of Hydraulic Research, State University of Iowa, Iowa City, Iowa, under the supervision of Professor E. W. Lane. The following representatives of the cooperating agencies participated in various phases of the general project: Vernon J. Palmer, Flood Control Coordinating Committee; Cleveland R. Horne, Jr., and Morgan D. Dubrow, Corps of Engineers; Victor A. Koelzer, and Paul C. Benedict, Geological Survey; Clarence A. Boyll, Tennessee Valley Authority; Philip M. Noble, Donald E. Rhinehart, and John W. Stanley, Bureau of Reclamation; and Frank W. Parker, Office of Indian Affairs.

The research work connected with the present study was conducted by John W. Stanley, Bureau of Reclamation, and Frank W. Parker, Office of Indian Affairs, who collaborated also in the preparation of this report.

The personnel of the U. S. Engineer Sub-Office, Iowa City, and of the Hydraulic Laboratory of the University of Iowa, assisted in the administrative details, the testing program, and in the preparation of the report. This report was edited by Mr. Martin E. Nelson, Engineer in charge of the U. S. Engineer Sub-Office, Iowa City, Iowa.

4. Acknowledgments--Many suggestions and constructive criticisms have been received from the cooperating agencies which have added materially to the value of the report in its final form. Particular acknowledgment is given to employees of the Geological Survey, Bureau of Reclamation, Soil Conservation Service, and Corps of Engineers for their detailed review of the preliminary report. Much credit is also due Dr. W. C. Krumbein of the University of Chicago for his aid in analyzing the behavior of soil particles in suspension.

II. NATURE OF THE PROBLEM

5. The importance of particle size in sediment studies--In recent years it has become generally recognized that the particle size of sediment is an important factor in predicting the behavior of the material when carried by water. Therefore, in studying any engineering problem involving the behavior of fluvial sediment it is necessary to know not only the concentration of the sediment contained in the water, but also the sizes of the particles of which it is composed. In determining the rate at which a reservoir will silt up, it is necessary to know not only the weight of the sediment that will be deposited, but also the particle size, since the density of the sediment in place is in part a function of the particle size. For many years data on the concentration of sediment in streams have been collected which are invaluable in sedimentation studies, but these data alone are not adequate for making accurate predictions of deposition and for many purposes can not be used without the corresponding data on particle size. It is anticipated, therefore, that considerable research and experimental work will be carried on in the future to determine the size of sediment particles carried by streams under various conditions. The laws governing the transportation of sediment will also be studied more fully, and in that connection a great deal of size analysis work will be required. Therefore, it is desirable to develop a method of analysis which will be rapid and accurate, and which will be suitable for analyzing samples of low concentration.

6. The relation between size and settling rate--It has long been known that the fundamental property governing the action of a suspended

sediment particle is not its size, but rather the rate at which the particle will settle in quiet water, which rate is closely related to the size.

Statistical analysis of turbulence indicates that the vertical components of upward currents in a turbulent stream balance those of downward currents, but, inasmuch as the sediment concentration in a section of the stream increases from the surface to the bottom, the upward currents, coming from a region of higher concentration, carry sediment particles upward at faster rates than do the downward currents in the opposite direction. However, the particles of sediment in suspension are attracted downward also by the force of gravity and they continue settling toward the stream bed as long as the upward velocity components of the turbulence do not exceed their respective settling velocities. A recent study (1) has shown that the movement of material in rolling or sliding along the bed also is related more closely to its settling rate than to its size. Therefore, from the viewpoint of the hydraulic engineer, settling rate appears to be the most important property of sediments carried in suspension by flowing water.

In other phases of engineering, sedimentary materials have been dealt with on the basis of particle size, and studies of geologists in the field of sediments have been largely on a similar basis. Moreover, it is much easier to form a reasonably accurate mental picture of a particle of a given size than of a certain settling rate, and there is no practicable way of measuring the settling rate of very large particles. Although, in the future the settling rate will no doubt be more widely used as the basis of sedimentary particle classification, for the present, particle size will undoubtedly be used in most cases as the classification basis, partly because of a reluctance to accept new methods and partly because

it is more convenient. The settling rate can be determined from the known particle size by means of a fairly definite relation between particle size and settling rate.

The relationship between particle size and settling rate is discussed at some length in Report No. 4 of this series, but considerable study will be required before this relationship has been determined with sufficient accuracy to be applicable under all conditions. For fine materials, below about 1/16 mm. in diameter, the determination of particle size is tedious and for convenience the size ordinarily is not determined at all, but rather the settling rate is observed from which the corresponding size is computed because in this range the settling rate can be measured more readily than the size.

For practical purposes in hydraulic engineering studies, however, it does not matter which method of classification is used, because if the relation between the size and settling rate is known either classification can readily be converted to the other.

Due to the variety of shapes particles may take, there are innumerable relations between size and settling rate, and since sediments are composed of particles of different shapes, a single relation will not express all of them. However, this relationship for spheres is well known, which relationship is customarily used in translating one dimension to the other. The particle size computed from the settling rate by this method is known as the sedimentation diameter and may be defined as the diameter of a sphere having the same specific gravity and settling rate as the particle under consideration. Where the sediment is analyzed by measuring the settling rates of the particles, and the particle sizes determined by means

of this relation, the sedimentation diameters can be reconverted to exact settling rates, but when the size is determined by any other process, it becomes more difficult to determine the relation between the size and settling rate and, consequently, between the size as measured and the sedimentation diameter. As these relationships become established, however, this difficulty will also be overcome.

In the remainder of this report the particle size will be considered in terms of the corresponding settling rate in water. The translation from sedimentation diameter to settling rate, or vice versa, can be made by means of diagrams such as that shown in Fig. 1, it being assumed that all the particles have the same specific gravity as quartz, i. e., 2.65.

7. Review of previous methods of size analysis--Report No. 4 of this series, entitled "Methods of Analyzing Sediment Samples," is a study of all available data on size analysis methods made in an attempt to find the one which is best suited to suspended sediment samples. This review showed that, although no single method was found satisfactory over the wide range of samples of suspended sediment found in streams, the following methods have been found suitable in certain conditions and have been extensively used in sediment studies: sieves, decantation, pipette, hydrometer, siltometer, and microscope.

Sieve analysis, either wet or dry, is limited to particles of approximately 1/16 mm. diameter or larger. Analysis with finer screens is generally not practicable due to the difficulty of constructing accurate screens with smaller mesh. It often happens that the amount of material coarser than 1/16 mm. in a suspended sediment sample is so minute as to

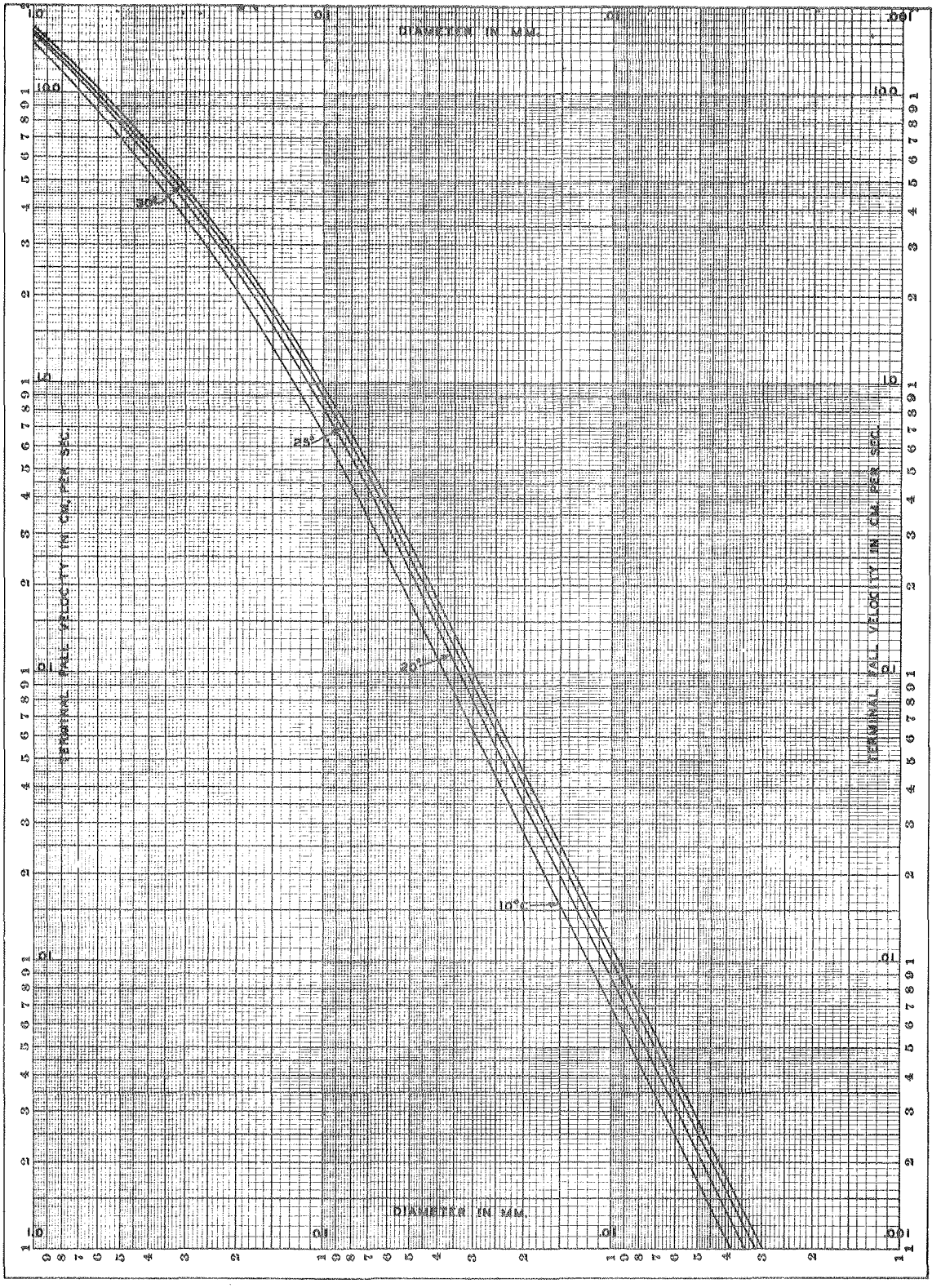


FIG. I - TERMINAL FALL VELOCITY OF QUARTZ SPHERES IN WATER

preclude the possibility of obtaining an accurate sieve analysis. For sediment studies sieve analyses are less satisfactory than the methods involving the measurement of settling rates, as the relation between sieve size and settling rate is not accurately known.

Although the decantation method is suitable for fine particles and low concentrations, as was pointed out in Report No. 4, the method is laborious and time consuming. The speed with which the coarser particles fall in water makes it difficult to analyze material above about 1/16 mm.

For material below 1/16 mm. the pipette method seems to be considered the most accurate by those who have studied comparative methods. When the supply of material is adequate the pipette analysis is usually run using a concentration of 20,000 p.p.m. by weight but pipette analyses can be used on lighter concentrations. A part of the investigation reported herein deals with the effect of concentration on size analysis results.

The hydrometer provides a simple method of size analysis and has found wide use in this country in connection with the construction of earth dams, levees, highways, and in other applications of soil mechanics. Within the range where it is satisfactory, it is perhaps the simplest and most rapid method, although it is probably less accurate than the pipette. As in the case of the decantation and pipette, it is impractical to analyze sediment coarser than about 1/16 mm. The range of concentrations used in present routine analyses with the hydrometer is from 25,000 to 50,000 p.p.m.

Size analysis by settling rates for the coarser particles in suspensions has found wide use in India. In Report No. 4, pages 138-140, are described two forms of "siltometers" used for the analysis of coarse

material. The first of these, known as an "optical lever siltometer," was designed by Vaidhianathan (2) in 1933. A mercury manometer located near the bottom of a long sedimentation tube indicates the change in pressure with time after a concentrated sample has been introduced at the top of the tube. The movement of the top of the mercury column is greatly enlarged by reflecting a beam of light upon photographic paper on a revolving drum. The apparatus was designed for a size range of 0.07 to 0.30 mm. diameter particles.

In 1934 Puri (3) designed a "siltometer" for analyzing sediment samples with particle diameters between 0.06 and 0.6 mm. in which the sample is introduced at the top of a long tube of water and fractions withdrawn from the bottom. Since Puri's apparatus is about 200 cm. long it probably can be used to analyze particles as coarse as 1.0 or even 2.0 mm. in diameter.

For the coarser particles in suspended sediment samples the U. S. Soil Conservation Service at their laboratory in Greenville, South Carolina, have developed a microscopic method of size analysis in which a microprojector is used. This has proven satisfactory because the weight of coarse material above about 1/16 mm. in diameter is very minute for the particular samples being analyzed there and because only the total weight and not the grading of the finer material is being determined. A paper describing this method and entitled "Use of the Microprojector in the Analysis of Small Samples of River Sand" has been prepared by Mr. R. G. Grassy and has been accepted for publication in an early issue of the Journal of Sedimentary Petrology.

Sieves and the siltometer are adapted only to sands or the coarser

material. The decantation, pipette, and hydrometer methods are satisfactory for the analysis of silts and clays only. Fig. 2 illustrates the particle size limitations of each method just discussed.

Where sufficiently large samples can be obtained, the existing methods of analysis are reasonably satisfactory. However, the concentrations in suspended sediment samples are frequently so low that huge quantities would be required in order to obtain enough solids for the analysis by existing convenient methods. The additional work required to concentrate light samples for analysis in the laboratory, and the increased time, effort, and expense involved in field sampling and transporting the large number of samples necessary, all combine to make the determination of size distribution difficult where low concentrations are involved.

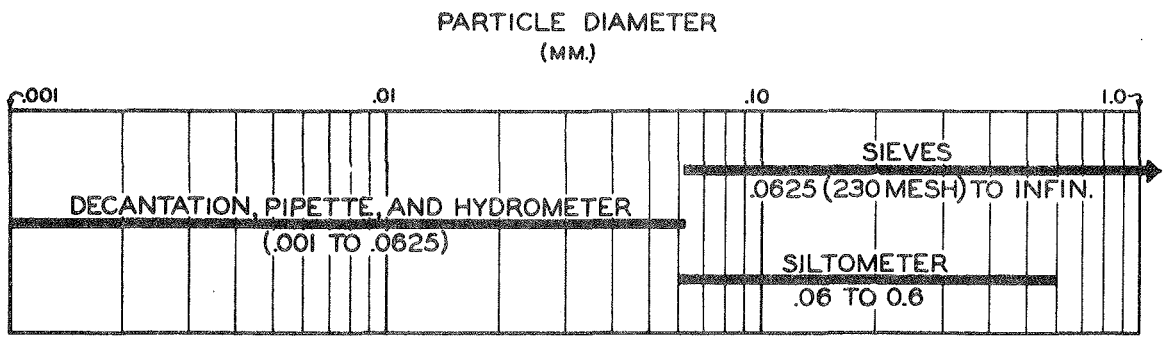


Fig. 2 - Particle size limitations of present common methods of size analysis.

The settling rate methods are dependable for analyzing concentrations below a certain limit only. In greater concentrations such factors as changes in the apparent density of the suspension and the mutual interference of particles with different fall velocities disturb the normal settling process. Furthermore, the particles do not settle in a slender

vessel in the same manner as they would in a fluid of unlimited extent, due to the unavoidable effects of the side walls. Krumbein and Pettijohn (4) state, "The authors know of no quantitative data on the subject, but it is perhaps best to use suspensions containing not more than about 25 gm. of solid to the liter".

The present known ranges of concentrations and particle sizes which can be handled satisfactorily by the various common methods of sediment analysis now employed are shown in Fig. 3.

The range of the hydrometer is shown for the usual concentrations of from 25,000 to 50,000 p.p.m. employed in routine analysis. No attempt is made in this investigation to explore the possibility of using lighter concentrations because studies along this line have already been made without marked success. Assuming that 0.5 gm. is needed for the decantation process in a 1,000 cc. suspension, a lower limit of 500 p.p.m. is indicated. From the experience of the U. S. Waterways Experiment Station at Vicksburg, Mississippi, a concentration as low as 1,000 p.p.m. can be used with the pipette in a suspension of 500 cc. The upper limit of both the decantation and pipette methods has been placed at 25,000 p.p.m. A 10.0-gm. sample was used by Puri (3) in a 200-cm. tube having a volume of 5650 cc. Taking this as the upper limit, a lower limit of 10 p.p.m. might be indicated using a sample of about 0.05 gm. For sieves a minimum weight of 0.05 gm. in 1,000 cc. would give a lower limit of 50 p. p. m. while the upper limit would be as high as any encountered in suspended sediment samples.

These limitations as to particle size and concentration are based on present published articles. From the results of this investigation, however, different limitations are indicated as discussed in Section 25 and

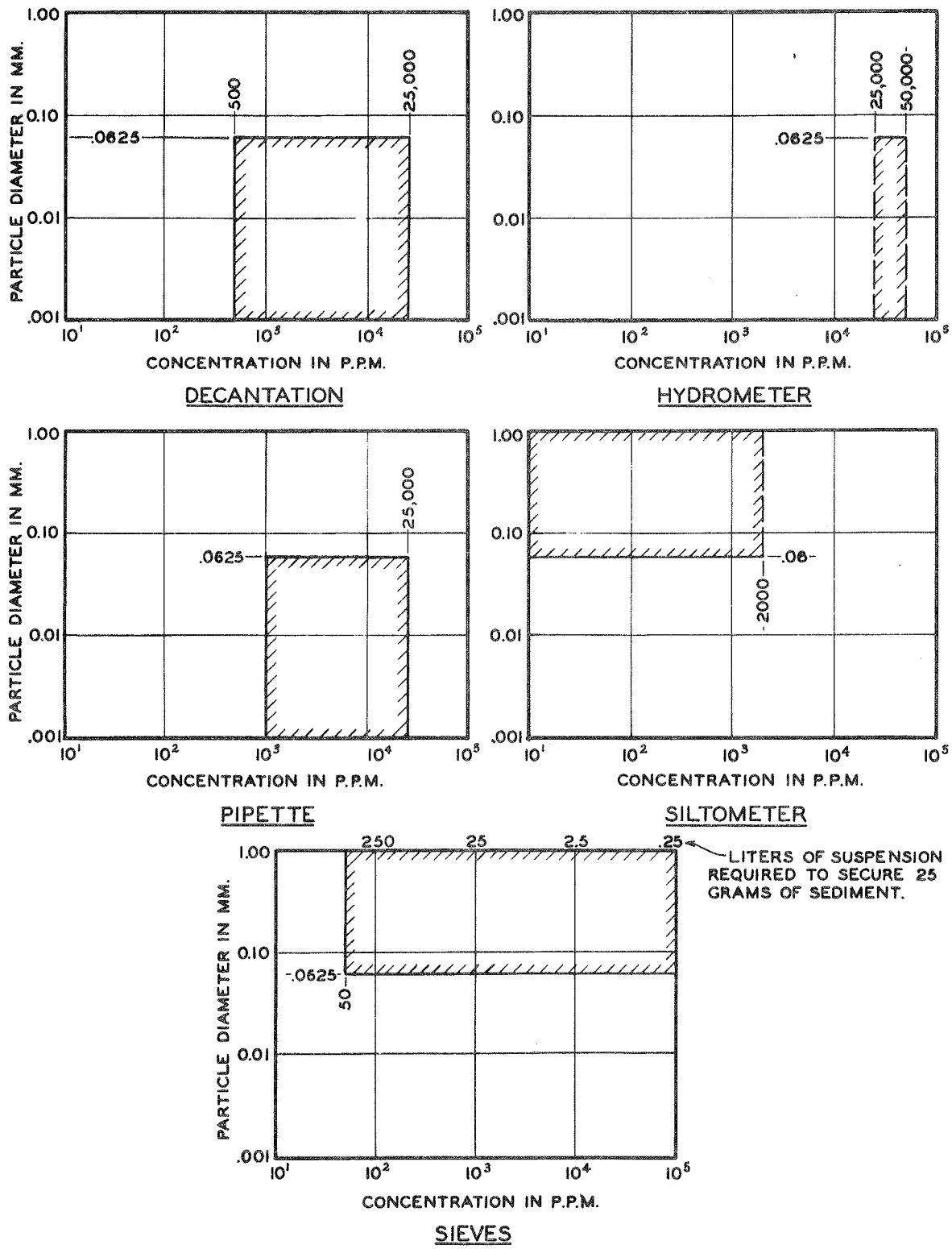


FIG.3-RANGE OF PARTICLE SIZES AND CONCENTRATIONS COVERED BY PRESENT SIZE ANALYSIS METHODS

AS INDICATED IN PUBLISHED LITERATURE

shown in Table 4.

8. Limitations of present methods of size analysis--The ideal method for making size analyses should be fast, accurate, and adaptable to mass production output. It should be capable of covering the complete range of concentrations and particle sizes encountered in suspended sediment samples. Since the actual settling rate of a particle is generally of more importance in sediment studies than an exact measure of volume or diameter, it is advisable to analyze the complete sample by settling methods without resorting to sieves or other devices. The sedimentation diameters indicated by the settling rates in water form the basis for the grading curve.

The most sensitive hydrometer yet devised is Puri's "chainomatic" which is described in Report No. 4, page 94. The concentration of a suspension at a point is measured from the buoyancy weight of a hydrometer having a displacement volume of about 100 cc. The weighing apparatus is sensitive to one milligram (0.001 gm.). In the pipette analysis the volume of each pipetted fraction is usually 20 cc., and the sediment in each fraction is ordinarily weighed on an analytical balance to one-tenth of a milligram (0.0001 gm.). These two methods, when compared to some method which utilizes the complete sample, would have the comparative sensitiveness shown in the following tabulation:

Method	Sensitiveness of weighing device, gm.	Volume of sample used in test, cc.	Sensitiveness gm./cc.	Sensitiveness p.p.m.
Puri Hydrometer	0.001	100	0.00001	10
Pipette	0.0001	20	0.000005	5
Total sample	0.0001	1,000	0.0000001	0.1

Due to the practical difficulties encountered in their operation, these comparative values for the hydrometer and pipette are never attained. It has been the experience of others that when hydrometers are built sensitive enough to handle concentrations lighter than about 25,000 p.p.m. it becomes increasingly difficult to obtain consistent results. In regard to the pipette method, laboratory tests reported herein indicate that accurate results cannot be obtained with concentrations lighter than about 3,000 p.p.m. The decantation method utilizes the entire sample but it has been eliminated from consideration because of the labor and time required to make an analysis. Furthermore, the hydrometer, pipette, and decantation methods are unsatisfactory for analyzing particles larger than a 1/16 mm. diameter.

Since some method by which the total sample can be analyzed seemed to offer the best possibilities it was decided to investigate one in which a concentrated sample is introduced into the top of a long column of water. If such a tube were divided into chambers which could be closed off at will, then the material trapped in each chamber could be weighed and the grading determined.

III. INVESTIGATION OF THE CHAMBERED TUBE

9. Description of method and apparatus--The type of analysis where a concentrated sample is introduced into the top of a long, chambered tube seemed to have several advantages over other methods. If the particles would settle individually this method would provide a grading based on settling rate, it would probably handle all sizes likely to be found in suspended sediment samples, and lower concentrations could be more accurately analyzed since the entire weight of the sample would be used. Such an apparatus would require an adequate method for introducing the concentrated sample, some way of dispersing the sample just before the introduction, and a system of slides or other devices whereby the tube could be separated into sections. Dividing the tube into sections, or fractions, would separate the sediment directly into fractions just as a set of sieves. An apparatus of this type will be referred to as a chambered sedimentation tube.

Subdividing the sedimentation tube does two things; it separates the size grading directly into fractions, as stated above, and it reduces the time required to separate the finer particles. As an example of the time element consider the Vaidhianathan optical lever siltometer which measures the hydrostatic pressure of a suspension at a fixed opening near the bottom of a long tube. The time required for the very fine particles to settle as far as the manometer opening would be prohibitive. The value of dividing the tube into sections is at once apparent when one considers the fact that the time required for an analysis would then be for a fall of only 10 or even 5 cm. for the finest particle desired.

Fig. 4 is a sketch of a chambered tube, designed with demountable sections and having a slide at each section. With the tube filled with distilled water and all except the top slide "J" in an open position, the concentrated sample could be dispersed with a stirring device. The upper

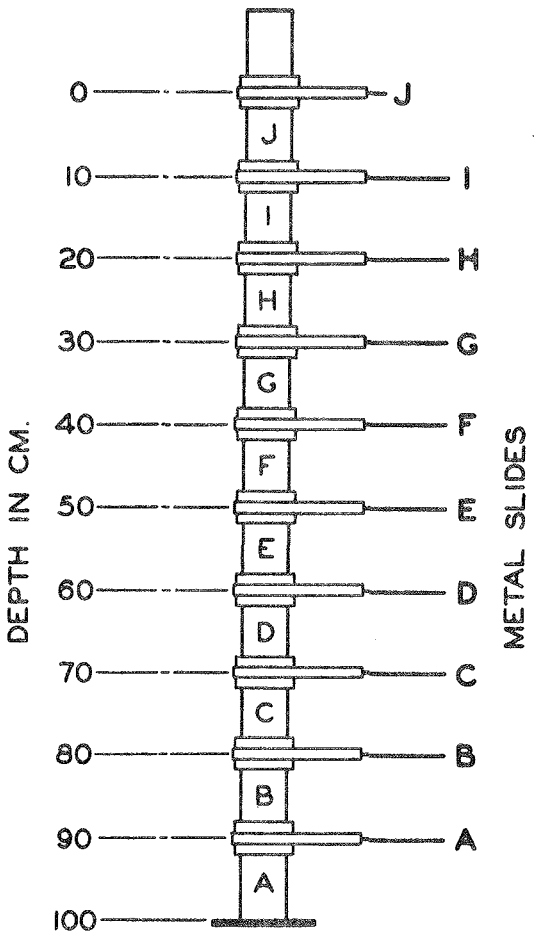


Fig. 4 - Chambered Sedimentation Tube

slide would then be withdrawn quickly to an open position, allowing the sample to settle in the clear water. If the coarsest fraction desired was of particles larger than the 1.0 mm. diameter then slide "A" should be inserted, or closed, at the instant that a 1.0 mm. particle would have had time to fall from the top of the water column to the elevation of slide

"A". If slide "B" was inserted at the proper time to separate the 0.5 mm. particle, then section "B" would contain all the particles between 0.5 and 1.0 mm. in diameter. Slide "C" might then be inserted to separate the 0.25 mm. particle and thus trap all the particles between 0.25 and 0.5 mm. in Section "C". This could be continued until the finest fraction desired was trapped in the top section. Since the top sections would be used to catch the fine particles, the distance they would fall would be small and therefore the time required would be reasonable. The time for inserting the slides would have to be adjusted to take into account the effect that temperature has upon the settling velocity of particles in water. The suspension in each section would then be evaporated, the dry weight of the sediment determined, and the grading computed. It was recognized that the introduction of the concentrated sample was the critical thing. For that reason the top slide for introducing the sample was built first and tested.

10. Test results--Silt and clay samples were used as well as coarse, or sandy material. It was found that when a concentrated sample containing fine material was introduced at the top of a column of water density currents were setup which made it impossible for the finer particles to settle at their own individual velocities. Cloudy sections would settle as a body down either side of the tube. Others would settle diagonally across the tube and some sections would be forced in an upward direction in a swirling current. Coarser particles of about 1/16 mm. in diameter or larger would settle out of these density currents as individual particles in a manner susceptible to this form of analysis. Samples of varying degrees of concentration were tried with like results. Metal vanes or baffles were inserted near the top of the tube in an attempt to eliminate these density

currents, as were various types, sizes and systems of screens. Variation in the size of the tube did not seem to alter the situation when less elaborate forms of sample introduction were tried on 2 cm. and 7 cm. diameter tubes.

Mechanical difficulties were also experienced. It was not possible with this design to make the apparatus water-tight without making the slide too hard to work. Also sandy material would jam the slides so that the device would have to be dismantled and cleaned before it could be used again.

Some work was done on the design of what might be called a Tait-Binckley type chambered tube (patterned after the Tait-Binckley sediment sampler described in Report No. 1, page 139) where the metal slide was replaced by a short section of rubber tubing which had about the same diameter as the tube. Separation into chambers was accomplished by twisting adjacent sections of tubing. Work on this type of apparatus was abandoned before completion on account of the difficulty in obtaining suitable materials and because of the development of the "bottom withdrawal" tube (see Chapter V), which seemed more promising.

IV. THEORY OF SEDIMENTATION OF UNIFORM DISPERSIONS

11. Relation of the theory to the present problem--The difficulties experienced with density currents when the sediment was introduced at the top of a column of water prompted a study of the possibility of eliminating the trouble by using a uniform dispersion in the chambered tube. However, no method was found which could be used to determine the particle size distribution from the weight of sediment in the chambers and it was therefore necessary to develop one. This involved a thorough study of the theory of sedimentation of uniform dispersions. In the following sections the development of this method will be discussed.

12. Behavior of particles settling from a uniformly dispersed suspension--Fig. 5 shows a sedimentation tube containing a suspension of particles all of the same settling rate.

Fig. 5 (a) shows the particles uniformly dispersed just as they begin to settle in water. Since all the particles will settle at the same velocity, the uniform spacing shown will be maintained and the concentration at some point, such as at the 40-cm. depth, will remain constant because particles which have passed this point will be continually replaced by those from above. However, when the particles have had time to fall 40 cm., as shown in Fig. 5 (b), the concentration above that point will become zero, and the water will become clear. The number of particles which have settled out of the suspension will just equal the number that were in suspension above the 40-cm. mark at the beginning of the time period. Furthermore, the particles will settle out of the suspension at a constant rate.

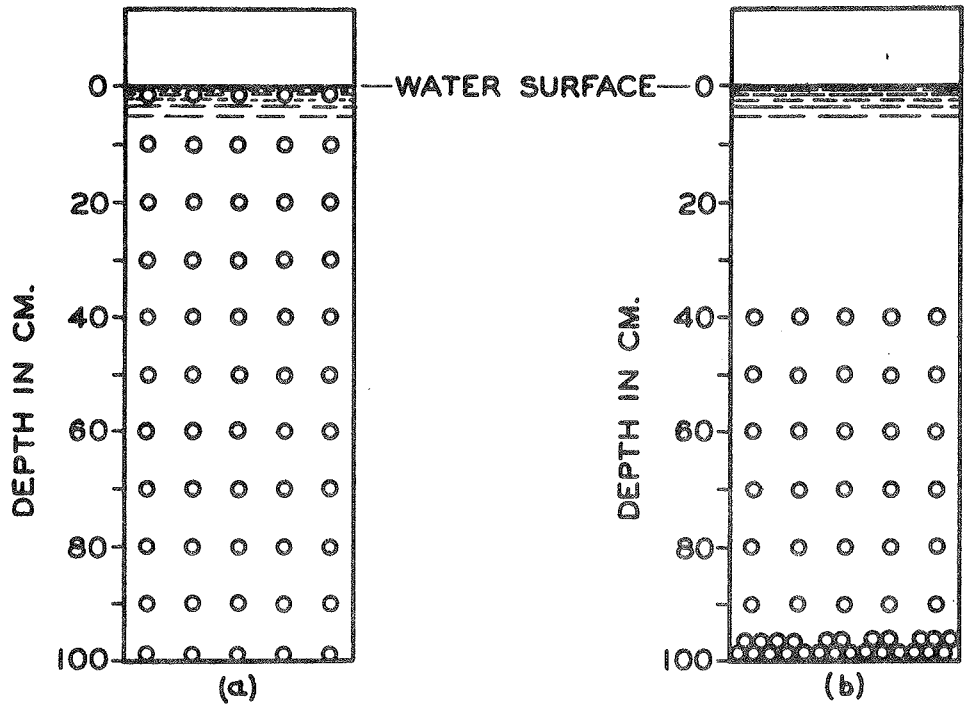


Fig. 5 - Uniform particles in suspension.

In order to study the behavior of a system of particles starting with a uniformly dispersed suspension, Fig. 6 has been prepared using particles of three different diameters such that the settling velocities are 4v, 2v and v, respectively. Fig. 6 (a) shows a uniform dispersion at time T_0 just as the particles begin to settle.

If the largest particles, with diameter d_1, settled 40 cm. in time T, then the medium-sized particles, diameter d_2, would have settled 20 cm. and the smallest particles, d_3, 10 cm. In time T, then, the particles would have arranged themselves as shown in Fig. 6 (b). During this time the concentration at the 40-cm. point would remain constant because particles passing that point are being continually replaced by those from above. This illustrates the fact that the concentration at any point in the suspension is constant until the coarsest particle present has had time to

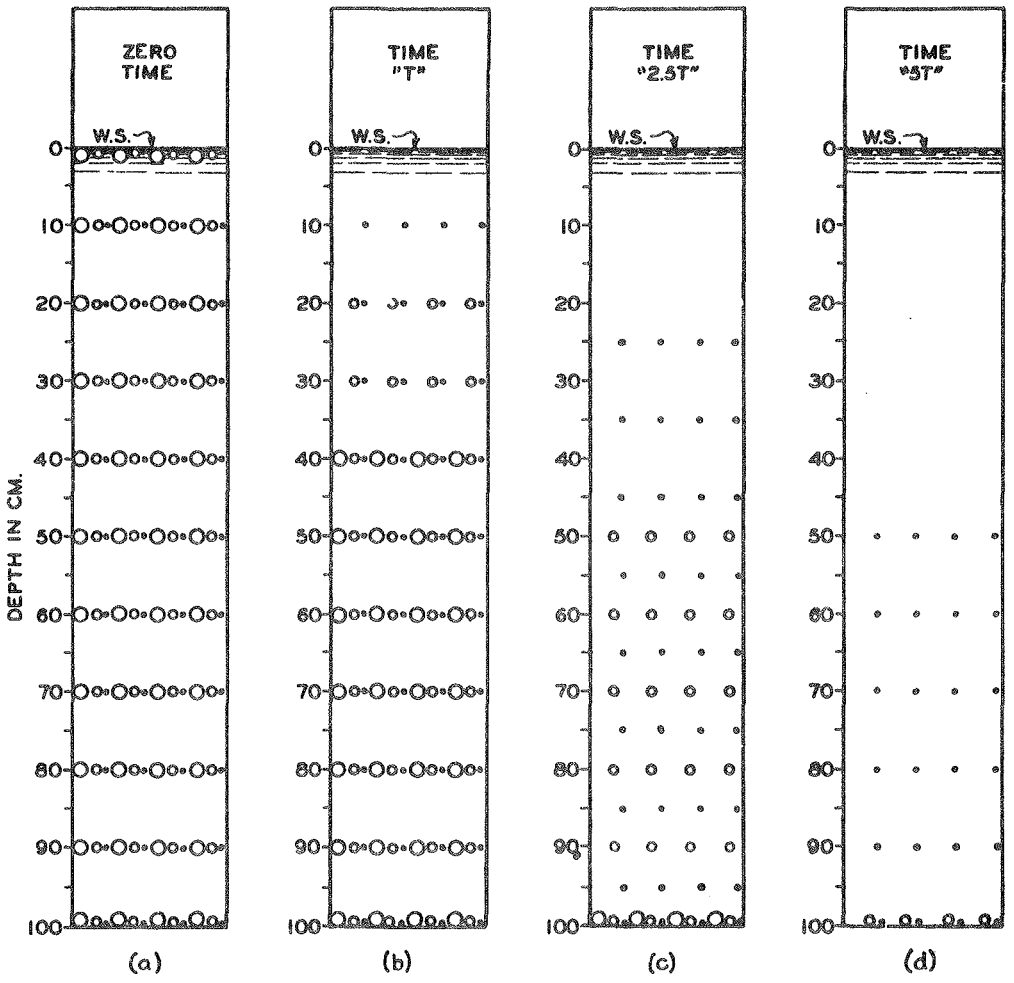


Fig. 6 - A System of Particles in Suspension

fall from the surface of the suspension to the point in question. At the 100-cm. depth, therefore, the rate of deposition will be constant until time 2.5T when the particles would be in the position shown in Fig. 6 (c).

At the instant the last d_1 particle reaches the 100-cm. depth the total number of particles passing this point will immediately become less but the total number of size d_2 particles and smaller passing this point will continue constant until the instant that the last d_2 particle has reached the 100-cm. depth. Fig. 6 (d) shows the condition of the suspension at this instant. Deposition will now continue at a constant but

much slower rate until time 10T when the last d_3 particle has reached the 100-cm. depth.

The behavior of the particles shown in Fig. 6 can be conveniently shown on a graph. Assuming that facilities were available for periodically weighing the amount of sediment deposited on the bottom of the tube, a graph like that shown in Fig. 7 could be constructed. Beginning at zero

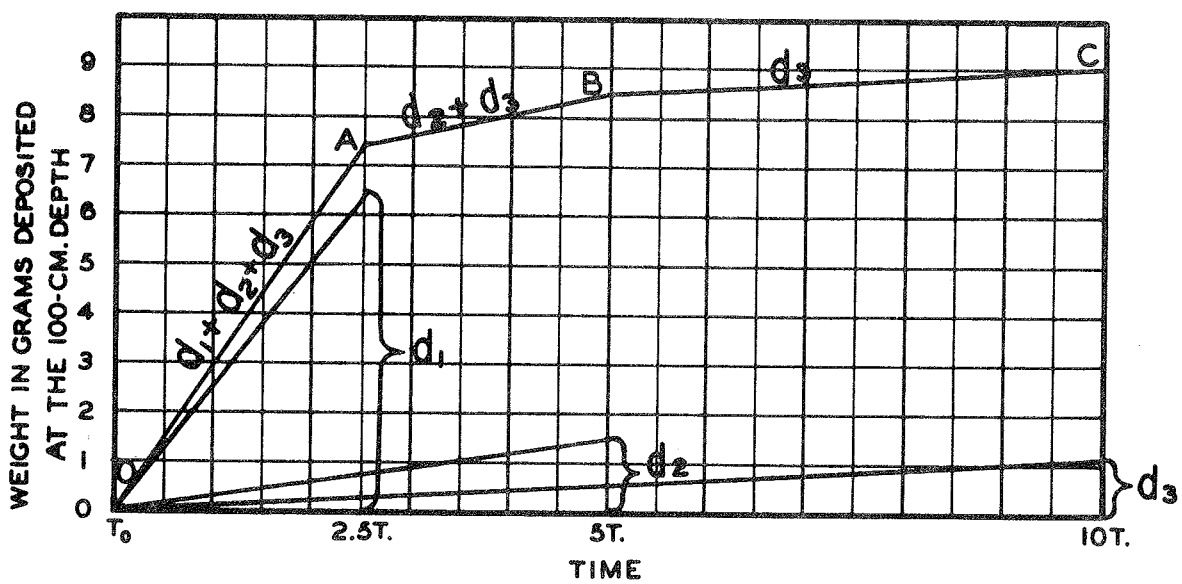


Fig. 7 - Rate of Sediment Deposition

time, T_0, deposition proceeds at a comparatively fast and constant rate until time 2.5T, when all of the d_1 particles, plus some d_2 and d_3 particles, will have settled out of the suspension. Since the ordinate of the point A is the weight of sediment which has settled on the bottom and its abscissa is the time, the slope of the line OA represents the rate at which the sediment was depositing from time T_0 to time 2.5T. A lower but also constant rate of deposition indicated by the line AB then

continues until time 5T when all of the d_2 particles, plus some additional d_3 particles, will have settled out. The graph then assumes the flattest slope BC which indicates the lowest rate of deposition until all of the d_3 particles have settled out in time 10T.

The slope of each of the three lines is a measure of the rate of deposition during the respective time intervals. The particles which are settling during any one of these three periods are those equal to or smaller than the size which will fall from the surface to the bottom of the tube in the time elapsed to the end of the period.

13. Odén theory of sedimentation systems--In 1915 Dr. Sven Odén (5) published his first article on the fundamental theory of uniformly dispersed sedimenting systems, having direct application to the size analysis of suspended sediments. It was the first sound mathematical approach solving the difficult problem of reducing accumulative sedimentation data to direct size fractions. In collaboration with Fisher, Oden (6) published a generalization of his theory in 1923 which included several methods of obtaining the size frequency or size analysis of soils and suspended sediments by indirect methods. In 1925 Odén (7) summarized the general theory.

As particles in a uniform dispersion settle, the density and hydrostatic pressure at any point in the suspension decrease with time. Odén showed that his theory could be applied in two ways. The condition of the suspension could be determined, with respect to either density or hydrostatic pressure at various points throughout the depth of the vessel at some particular instant of time, or at a single point at various times. In other words, the density or pressure could be studied at various depths

at a fixed time or at a fixed depth with time as the variable. If the vessel containing the suspension were divided into ten sections, for instance, either the hydrostatic pressure or the density could be measured simultaneously at each section. This, then, would be determining the situation at a fixed time with depth as the variable. If the pressure or density were measured at one of these sections at a number of different times, this would be a study with a fixed distance and variable time.

The Odén mathematical approach resulted in equations for the ordinate of the frequency function. Owing to the difficult mathematics involved, however, no one has made it a practice to obtain the frequency function by substituting directly into these formulas. A simpler graphical solution is used more generally.

As a practical application of his theory, Odén constructed his continuous sedimentation balance, the essential features of which are shown in Fig. 8. At various time intervals the accumulative weight of the sedi-

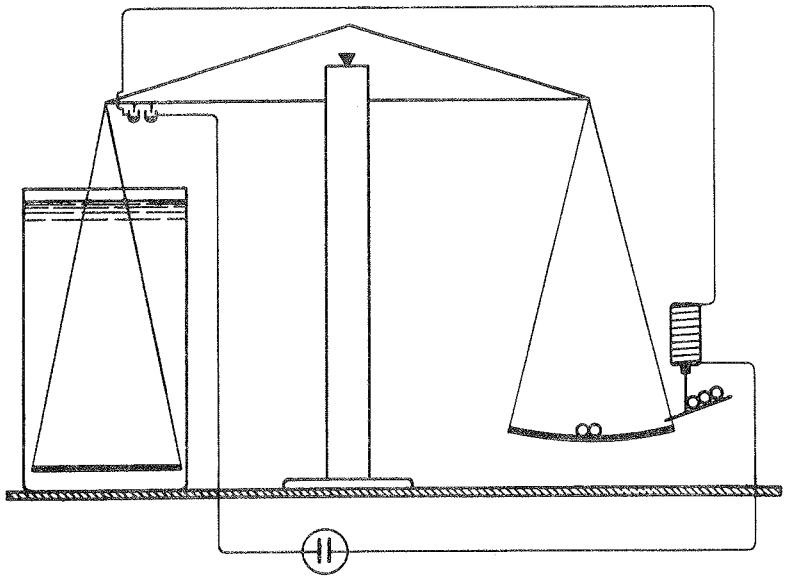


Fig. 8 - Original Odén Sedimentation Balance

ment falling on the pan is determined. An "Odén" curve is then plotted with time as the abscissa and accumulative weight as the ordinate. Fig. 9 shows this type of curve by means of which the grading of the material can be obtained, as will be explained in the following paragraphs.

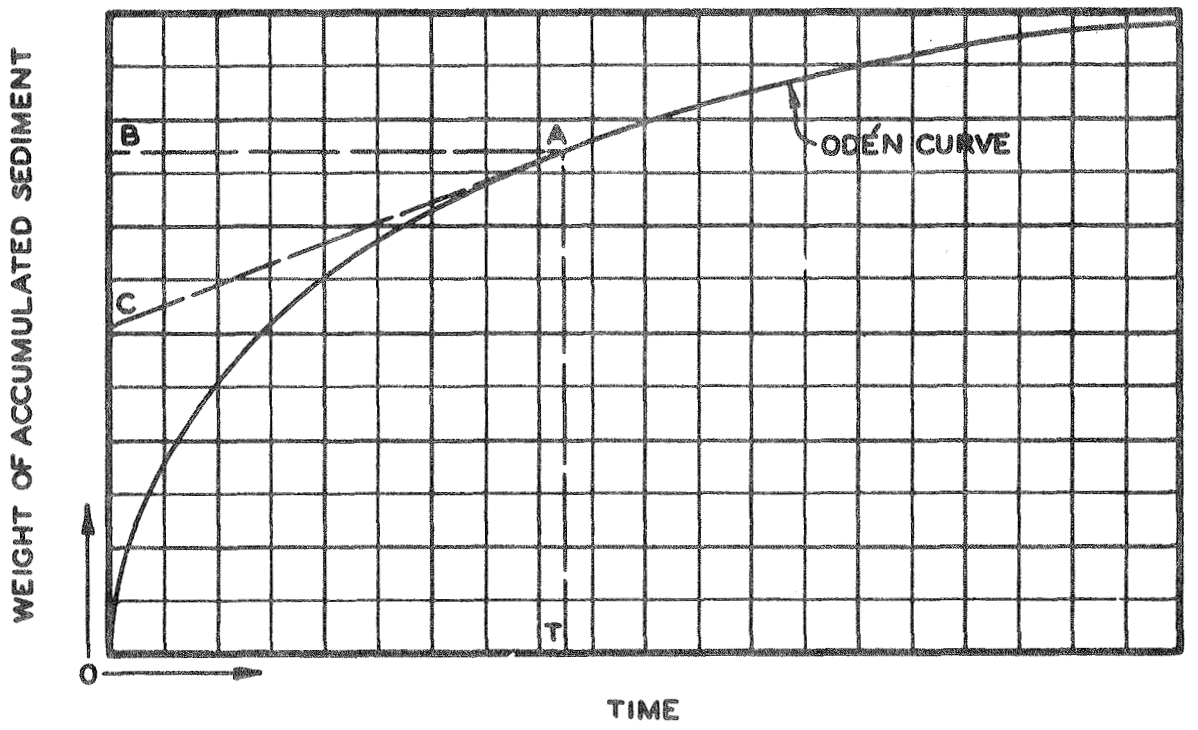


Fig. 9 - Odén Curve

14. Graphical analysis of the Odén curve--Successive particles in an ordinary suspended sediment sample differ from each other in size by infinitesimals. The graph showing the rate of deposition of a sediment will therefore be a smooth curve composed of straight lines of infinitesimal length as shown in Fig. 9 instead of a series of straight lines like those shown in Fig. 7. The rate at which particles are settling on the bottom at any time is the slope of the infinitesimal straight line in the curve at that time or the tangent to the curve at that point. The particles

that are settling at any instant T are of a size d equal to, or smaller than, those which will settle the entire depth of the vessel in the total elapsed time represented by the corresponding abscissa. Thus the slope of the tangent CA to the curve of Fig. 9 gives the rate at which particles are settling on the bottom, of sizes equal to or smaller than d, the size which will settle from the surface of the water in the tube to the bottom in the time T represented by the abscissa OT.

Since the slope of line CA represents the rate of deposition of the particles of size d or smaller at the time T and since, as has been previously shown, the rate of deposition of particles of these sizes on the bottom is uniform up to the time T, when the particles of diameter d which start at the surface reach the bottom, the slope of the tangent CA represents also the rate of deposition of particles of sizes d and smaller during the whole period T, represented by the abscissa OT. Since the slope of the line CA represents the rate of deposition and the time of deposition is BA = OT, the weight deposited of sizes d and smaller for the time represented by BA, is equal to the weight given by the distance CB. Since CB represents the weight of sediment of sizes d and smaller that have settled on the bottom in time T, and OB is the total weight that has settled in this time, the weight of particles larger than d which have settled, is the difference between OB and CB, or OC. Since all the material of size d has reached the bottom in time T, and all of the larger sizes have also reached the bottom, the amount OC represents the weight of sediment in the entire sample with sizes greater than d. To find the weight of the sample composed of particles larger than any desired size it is, therefore, necessary only to find the time required for a particle of that size to fall the entire

depth of the vessel, and draw a tangent to the Odén curve at the point whose ordinate represents this time. The distance corresponding to OC in Fig. 9 will represent the desired quantity.

This explanation of the graphical solution has been simplified as much as possible. Odén (5, 6, 7) gives both a mathematical and geometric proof of the meaning of the tangent intercepts and Krumbein and Pettijohn (4) give an excellent, easily understood mathematical proof.

V. DEVELOPMENT OF THE BOTTOM WITHDRAWAL TUBE AND THE METHOD OF ANALYZING ITS RESULTS

15. Method of operating the chambered tube--Since introduction of the sediment at the top of the sedimentation tube proved unsatisfactory for analyzing fine material and the uniform distribution method was to be investigated, consideration was given to which of the two systems mentioned in Section 13 could be used, variable distance with fixed time, or fixed distance and variable time. With the chambered tube the first method was physically possible, but the method was suitable for only a limited range of sizes and the procedure of analysis by the Odén curve was difficult. The only method which could be found for uniformly dispersing coarse sediment in a tube was to invert the tube a number of times at frequent intervals. This rapid reversal could not be done conveniently with a tube much longer than 1.0 m. Since the time for a 1.0-mm. particle to fall the length of this tube was only about 6 sec., and since this is about as soon as the first sample could conveniently be cut off, a tube much less than 1.0 m. long could not be used. With a tube 1.0 m. long, in order to determine the portion over 1.0 mm. diameter, if the variable distance-fixed time method was used, it would be necessary to close all the slides simultaneously at about 6 sec. If all were closed at this time, particles of 0.125 mm. or smaller would be uniformly dispersed throughout the lower 90 per cent of the length of the tube. If ten equal chambers were used, the largest particle found in the upper chamber would therefore be 0.125 mm. and since all smaller particles would be uniformly dispersed throughout the remainder of the tube only sizes between 1.0 and 0.125 mm. could be determined from the weight of material deposited in the nine other chambers.

In other words, such an operation would give a mechanical analysis curve extending only between the 1.0 and 0.125 mm. sizes. The water containing only particles smaller than 0.004 mm. would be contained in the upper 0.008 cm. of the tube. Therefore, to obtain the proportion of the total particles smaller than this size, it would be necessary to have a chamber closing off the upper 0.008 cm. of the tube. This would be impracticable from a mechanical standpoint and the amount of solids contained in so small a chamber would be conducive to inaccuracy in weighing. The method of measuring the variation of concentration over a variable distance at a fixed time using this tube, therefore, did not appear feasible, since it provided for too limited a range of particle sizes.

The chambered tube, however, does not permit the use of a fixed distance of settlement with a variable time, since the closing of the lowest chamber changes the distance of settlement for the particles remaining in suspension. For example, in a 100-cm. tube of ten equal chambers, the fall distance for the fraction in the lowest chamber would be 90 cm., for the fraction in the next chamber 80 cm. and correspondingly less for subsequent fractions. The Odén curve could not, therefore, be used without modification. As will be described later, a method was developed by which the data from the chambered tube could be transformed to give the ordinary form of Odén curve for the fixed distance and variable time. Thus the theoretical basis for the use of the chambered tube with uniform distribution was solved, but there remained the practical difficulty of making such a tube which would be water tight and without trouble from sticking slides. Moreover, such a tube would be quite expensive to construct. Further thought was therefore given to developing a simpler tube, and a

very simple, inexpensive form, called a bottom withdrawal tube, was evolved which seemed to meet the needs.

16. Development of the bottom withdrawal tube--The matter of size of sample was given considerable thought preparatory to the design of the bottom withdrawal tube. It is noted in Report No. 1 of this series that the Straub, U.S.G.S. Colorado, Anderson-Einstein time-integrating, Frazier and Omaha samplers use a container of one pint capacity. Also, the Tait-Binckley sampler obtains about a 400-cc. sample.

In designing a sampler that would incorporate many of the better features of former samplers, the time-integrating type was recommended in Report No. 6. It contains a pint bottle and was designed to be light enough to be used from a hand line if necessary. It was streamlined as much as possible in order to reduce downstream drag. The action of the integrating sampler requires that the sampling be completed before the pint bottle is entirely full in order to prevent circulation. While several samples may be taken at any one stream vertical, the action of the integrating sampler is such that a representative portion of the stream concentration is obtained in each sample taken so that actually only one sample is required.

In line with these field requirements the size analysis apparatus was designed to analyze samples of about 400 cc. in volume. Such an apparatus would permit the minimum amount of work in that only one sample need be secured and analyzed for each vertical selected for sampling.

The bottom withdrawal tube consists of a transparent tube of large diameter which is open at one end and contracted at the other to a short

section of small tube, on which is slipped a short piece of rubber tube which can be opened or closed with a pinch-clamp. The tube used for the studies described herein, which is shown in Fig. 10, was 48 in. long, and

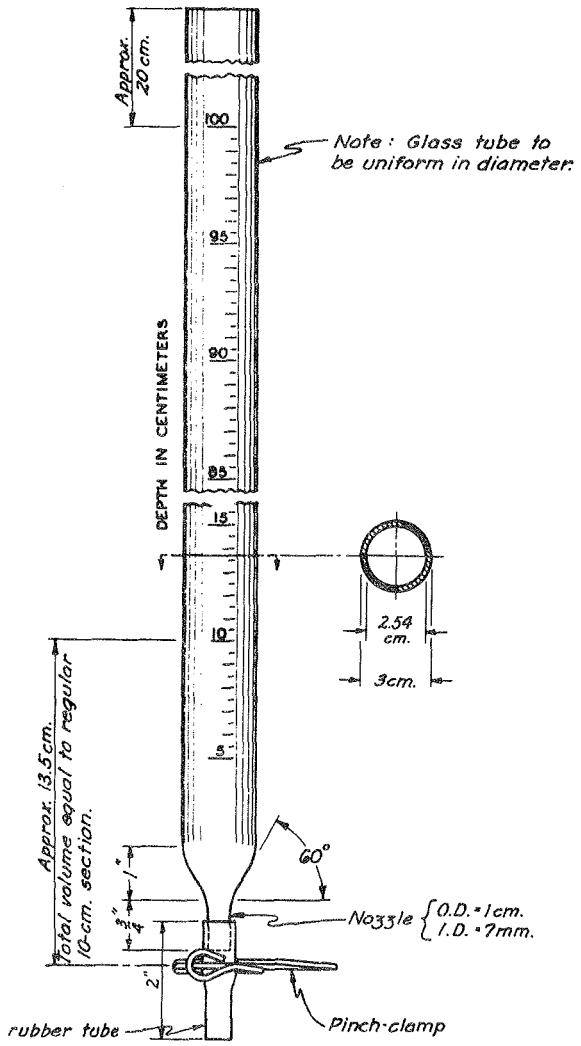


Fig. 10 - Proposed Bottom Withdrawal Sedimentation Tube

1.0 in. inside diameter, large enough to hold a pint sample. It was drawn down at the lower end to 1/4 in. inside diameter on which was slipped a 2-in. length of rubber tube closed by a pinch-clamp. Studies were also made with a larger tube, 1-7/16 in. inside diameter and 27

in. long drawn down to the same outlet size as the other tube. Scales were placed on these tubes to indicate the depth and calibrations were made to establish the relation between the scale reading and the volume.

A detailed description of the procedure to be used in order to obtain the best results in analyzing material with this tube is given later in this report. Briefly stated it consists of uniformly dispersing the material in the tube, placing the tube in an upright position and withdrawing samples of predetermined volumes from the bottom of the tube by temporarily opening the pinch-clamp, at predetermined intervals of time. The volume and time for the samples is selected so that the values determined will give plotted points which will accurately define an Odén curve for the material used.

Two possible sources of error in using this apparatus were evident; (a) that some of the material analyzed would settle on and adhere to the surface of the tube in the cone-shaped transition section between the two sizes of tube, and (b) that the release of the suspension from the bottom of the tube would set up turbulent currents in the tube which would interfere with the quiet settlement of the particles. Neither of these possible objections proved to be material. Sediment does deposit in the cone-shaped section, but it is practically all washed out by the rush of water which occurs when the bottom of the tube is opened. Comparisons of the weight of solids introduced with that recovered from the tube showed that after the operators had sufficient practice to do accurate weighing, the difference between the weight of the solids put in and that recovered was negligible. Several different cone angles were tried and although there was little difference between them, an apex angle of 60° seemed to give best

results. Experiments were made to investigate the possibility of the introduction of turbulence into the tube when withdrawing the suspension at the bottom. Streaks of color were introduced into water in the tube and the position of these streaks was noted as water was withdrawn at the bottom. No change in the position of the streaks was noted except that they moved vertically in the tube, showing that no turbulence was introduced.

Since no turbulence is introduced in the tube by withdrawing water from it, the taking out of a sample from the bottom into a vessel beneath the tube has exactly the same action as closing off a bottom chamber of a chambered tube, since the suspension in the bottom of the tube is removed without disturbing that above it. Drawing successive samples from the bottom therefore secures the same samples as would be obtained by successively thrusting in slides in the tube, beginning at the bottom, if each slide enclosed a volume equal to that removed from the bottom. In other words, the action of the bottom withdrawal and chambered tubes is practically the same. The only differences are that the bottom withdrawal tube is more flexible in that the size of sample withdrawn can be varied at will, and that with the bottom withdrawal tube the volumes withdrawn have to be measured each time while in the chambered tube the sample has the same volume as the chamber, which only has to be measured once.

17. <u>Analysis of the results obtained with the bottom withdrawal tube</u>--In the bottom withdrawal tube, as in the chambered tube when the chambers are closed successively, both the fall distance and the time are variables. In order to transform the results thus obtained to a form

suitable for analysis by the Odén method it is necessary to convert them into the equivalents with either the time or the fall distance constant. Either of these can be done by a conception which considers the amounts left in suspension rather than the amount deposited, as in the ordinary Odén method, and the average concentration above a point rather than the concentration at a point. The following paragraphs give an explanation of this conception.

In a suspended sediment sample successive particles or successive groups of particles will differ by infinitesimals from each other as to size. Furthermore, if the proper conditions are satisfied, each particle will settle unhindered at its own particular constant terminal velocity. With these facts in mind it follows directly that the average density of a suspension above a depth D at a time T will be the same as the average density above a depth X(D) at a time X(T). A simple diagram will be used to illustrate this point.

As in the case of Fig. 6, Fig. 11 shows the behavior of three differently-sized particle groups settling from a uniformly dispersed suspension. The particle diameters are such that the fall velocities would have the following relation: $v_1 = 2v_2 = 4v_3$.

If the particles d_1 are of such size as to fall 40 cm. in time T, then the particles d_2 will fall 20 cm. and the particles d_3, 10 cm. in the same time, as shown in Fig. 11 (b). In time 2T each particle will have fallen twice as far as it did in time T and they would have arranged themselves as shown in Fig. 11 (c).

The tube being of uniform diameter, the volume above the 80-cm. level is just twice that above the 40-cm. level. It will be noticed that the

number of particles of each size in suspension above the 80-cm. level in Fig. 11 (c) at time 2T is also just twice the number of each size in suspension above the 40-cm. level in Fig. 11 (b) at time T. Therefore the density above 40 cm. in time T is the same as the density above 80 cm. in time 2T, or in other words the average density above a depth D at time T is the same as the average density above a depth X(D) at time X(T).

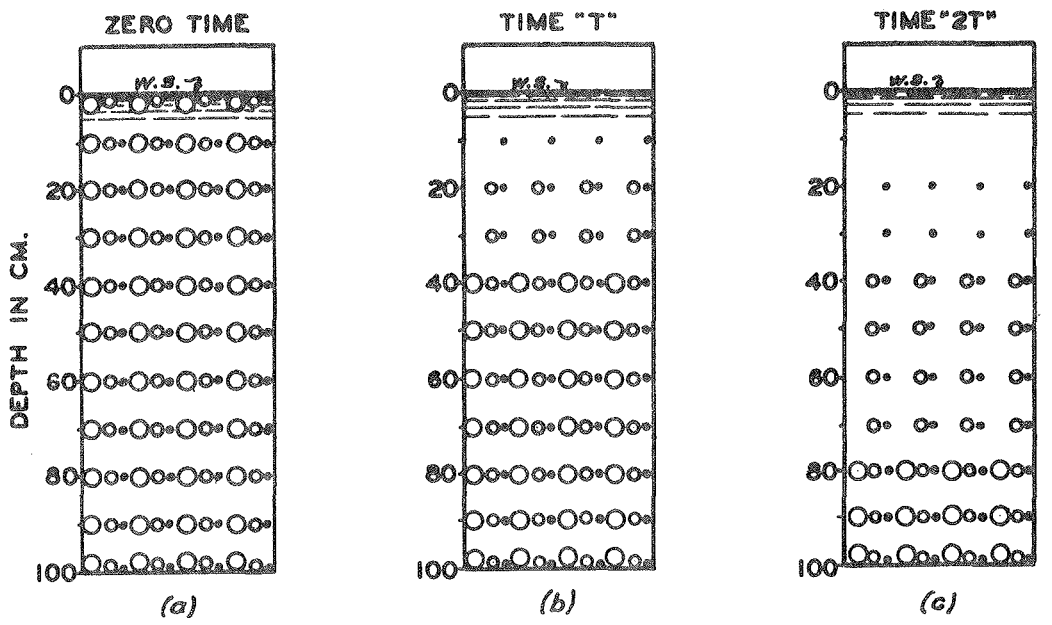


Fig. 11 - Various-sized particles in suspension.

This means that if the weight of the particles above the 40-cm. level were determined at time T and designated as w_1, then the weight of the particles above the 80-cm. level at time 2T by computation is equal to 80/40 times w_1 or $2w_1$. Knowing the average density above any point at any time, it is possible to compute either the time at which the average density above any other known point would reach this value, or the position of the point above which the average density would be the same at any other known time.

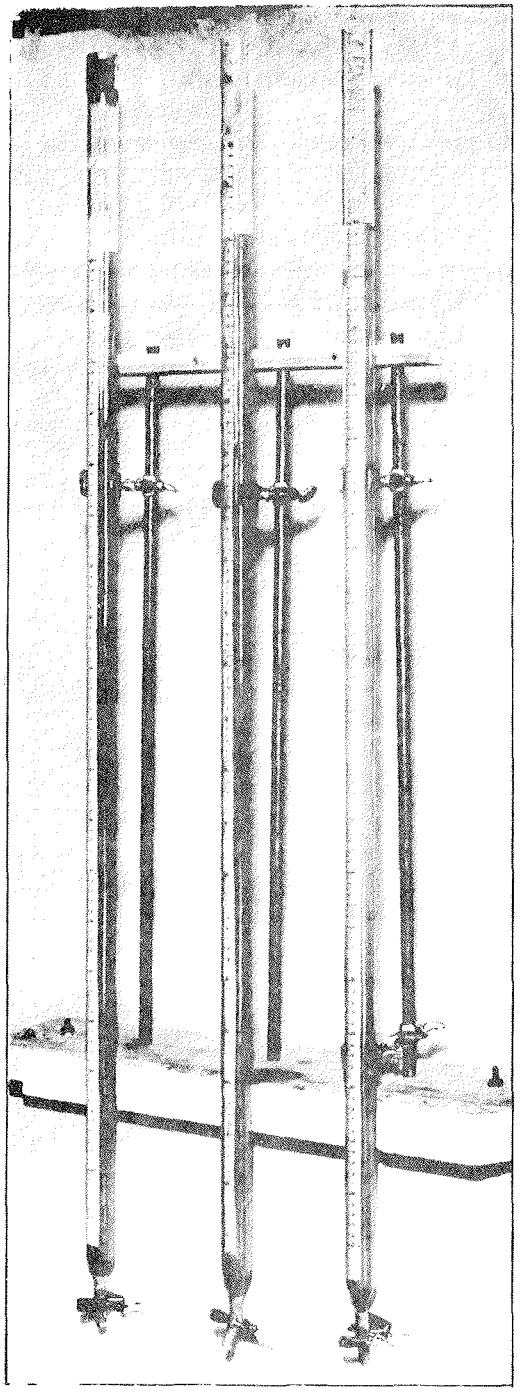


Fig. 12 - Bottom withdrawal sedimentation tubes and stand.

18. Basic data collected in bottom withdrawal tube--To illustrate the collection of the basic data from the bottom withdrawal tube, the following illustration is given for a tube using a height of column of suspension of 100 cm. The sample was uniformly dispersed and the tube set vertically in a rack, as shown in Fig. 12. The first fraction was withdrawn at the time when the coarsest particle desired would have had time to fall 90 cm. from the top of the tube. In the case of a 1.0 mm. particle, the first withdrawal would be at 6 sec. (in water at 20°C.) and for a 0.5-mm. particle, 12 sec. If the finest fraction desired were 0.0039 mm., then it would require about 2 hrs. for it to settle 10 cm. Having set the time for withdrawing the coarsest and finest fractions, the intervening time intervals were chosen in such a way as to accurately define the Odén curve as explained in Section 14.

The temperature of the suspension was assumed to be constant. Ten samples were withdrawn and the weight of sediment in each determined.

The data for an actual test, which are typical of the results obtained, are tabulated below.

Fraction No.	Elapsed Time min.	Fall cm.	Weight of Sediment in Fraction gm.	Cumulative Weight in Suspension gm.
1	2	3	4	5
	0	100		0.5619
1			0.0753	
	8	90.3		0.4866
2			0.0847	
	24	80		0.4019
3			0.0771	
	40	69.6		0.3258
4			0.0632	
	54	60		0.2616
5			0.0639	
	69	49.5		0.1977
6			0.0509	
	82	40		0.1468
7			0.0488	
	96	30		0.0980
8			0.0423	
	110	20		0.0557
9			0.0338	
	124	9.9		0.0219
10			0.0219	
		0		
		Total weight	0.5619 gm.	

The data show that the first fraction was withdrawn at 8 min. leaving an observed column of suspension 90.3 cm. in height. Column 3 then records a total fall of 90.3 cm. for the first fraction, 80 cm. for the second fraction, etc. Column 4 gives the weight of the sediment found in each fraction and Column 5, the cumulation of the values in Column 4, beginning

at the bottom. Column 5 then represents the total weight of sediment remaining in the tube at the indicated total elapsed time, which is also the amount which would have remained in suspension above the indicated depth had the fractions not been withdrawn.

With this basic data it is possible, by applying appropriate factors, to obtain coordinates for two types of Odén curves: constant time with depth as the variable and constant depth with time as the variable.

19. Reduction of basic data to constant time with depth as the variable--One solution would be to reduce all data to a constant time of 8 min. The first fraction, withdrawn at 8 min., would then stand as is. The second fraction, withdrawn at 24 min., has 0.0847 gm. of sediment (dry weight). We know from the summation of data obtained that at 24 min. there were 0.4019 gm. of sediment in suspension above the 80-cm. depth. If this were the condition at 24 min., then at 8 min. there would have been 8/24 x 0.4019 or 0.1340 gm. in suspension above a depth of 8/24 x 80 or 26.7 cm. In a similar way any and all fractions can be reduced to the situation at 8 min. or any other settling time desired. In these tests an attempt was made to withdraw ten equal-volume fractions. Each fraction would then lower the water column 10 cm. It was found that a variation of as much as 0.5 cm. in 10 cm. did not materially affect the results. In this reduction no correction was made for variation from the desired 10-cm. depth, and the glass tube was assumed to have a uniform diameter throughout its entire length. The completed computations for Test No. 32 are shown in the following tabulation.

Fraction No.	Elapsed Time min.	Fall cm.	Weight of Sediment gm.	Cumulative Weight in Suspension gm.	Factor $\frac{8}{Col.\ 2}$	Effective Weight in Suspension (5x6) gm.	Effective Per Cent in Suspension	Effective Depth (3 x 6) cm.
1	2	3	4	5	6	7	8	9
	0	100		0.5619	--	--	--	--
1			0.0753					
	8	90.3		0.4866	1.0	0.4866	86.5	90.3
2			0.0847					
	24	80		0.4019	0.333	0.1340	23.8	26.7
3			0.0771					
	40	69.6		0.3258	0.2	0.0650	11.6	13.9
4			0.0632					
	54	60		0.2616	0.148	0.0387	6.9	8.9
5			0.0639					
	69	49.5		0.1977	0.116	0.0229	4.1	5.74
6			0.0509					
	82	40		0.1468	0.0975	0.0143	2.5	3.9
7			0.0488					
	96	30		0.0980	0.0833	0.0082	1.45	2.5
8			0.0423					
	110	20		0.0557	0.0727	0.0041	0.73	1.45
9			0.0338					
	124	9.9		0.0219	0.0645	0.0014	0.25	0.64
10			0.0219					
		0						
			0.5619					

The values in Column 8 are plotted as ordinates against those in Column 9 as abscissas, to obtain the curve shown in Fig. 13. This curve is too flat to draw tangents accurately at all of the desired points and, furthermore, the points are not spaced so as to define the curve accurately. The tangent intercepts are not obtained as simply as in the Odén curve shown in Fig. 9. A graphical solution was developed for this method of analysis but it is much more complicated than that for a variable time, and since it appears to have little use, will not be included here.

Of all the size analysis methods studied in Report No. 4, only one,

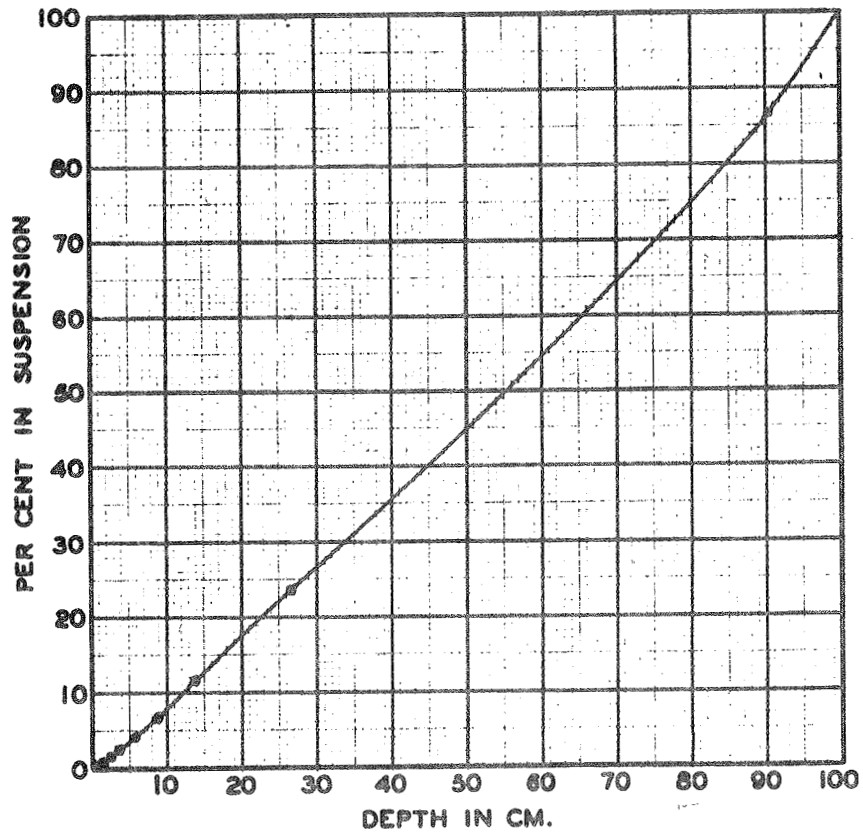


Fig. 13 - Odén Curve
Constant Time, Variable Depth

the Cole and Edlefsen fractional sedimentation tube, obtains the grading by measuring the density at some instant of time with depth as the variable. Evidently the same difficulties with this method in obtaining the grading of soil, as described in the above paragraph, have been encountered by other investigators.

20. Reduction of basic data to constant depth with time as the variable--To reduce the data to the results which would occur using a constant distance and variable time, the problem is approached in a similar manner. Taking the basic data of Test No. 32 a depth of 100 cm. is used. At 24 min. there were 0.4019 gm. of sediment in suspension above the

second fraction, or above the 80-cm. depth. The time at which the average density above the 100-cm. depth would be the same above the 80-cm. depth at 24 min. is (100/80)(24) or 30 min. and the weight of sediment above 100 cm. at 30 min. would be (100/80)(0.4019) or 0.5024 gm. In like manner all the other readings may be referred to the constant depth of 100 cm. The completed computations are shown in the following tabulation.

Fraction No.	Elapsed Time min.	Fall cm.	Weight of Sediment gm.	Cumulative Weight in Suspension gm.	Factor $\frac{100}{\text{Col. 3}}$	Weight above 100 cm. (5x6) gm.	Cumulative per cent above 100 cm.	Time to Settle 100 cm. (2 x 6) min.
1	2	3	4	5	6	7	8	9
		100		.5619	1.0	.5619	100	
1			.0753					
	8	90.3		.4866	1.107	.5387	95.9	8.85
2			.0847					
	24	80		.4019	1.25	.5024	89.3	30
3			.0771					
	40	69.6		.3248	1.435	.4661	83.0	57.4
4			.0632					
	54	60		.2616	1.667	.4361	77.6	90
5			.0639					
	69	49.5		.1977	2.02	.3994	71.0	139.4
6			.0509					
	82	40		.1468	2.50	.3670	65.3	205
7			.0488					
	96	30		.0980	3.33	.3263	58.0	320
8			.0423					
	110	20		.0557	5.0	.2785	49.5	550
9			.0338					
	124	9.9		.0219	10.1	.2212	39.3	1252
10			.0219					
		0						

The method of computing Columns 5, 6, 7, and 9 is indicated in the column headings and is self-explanatory. Fig. 14 is the Odén curve for Test No. 32, plotted from the values in Columns 8 and 9 in the table.

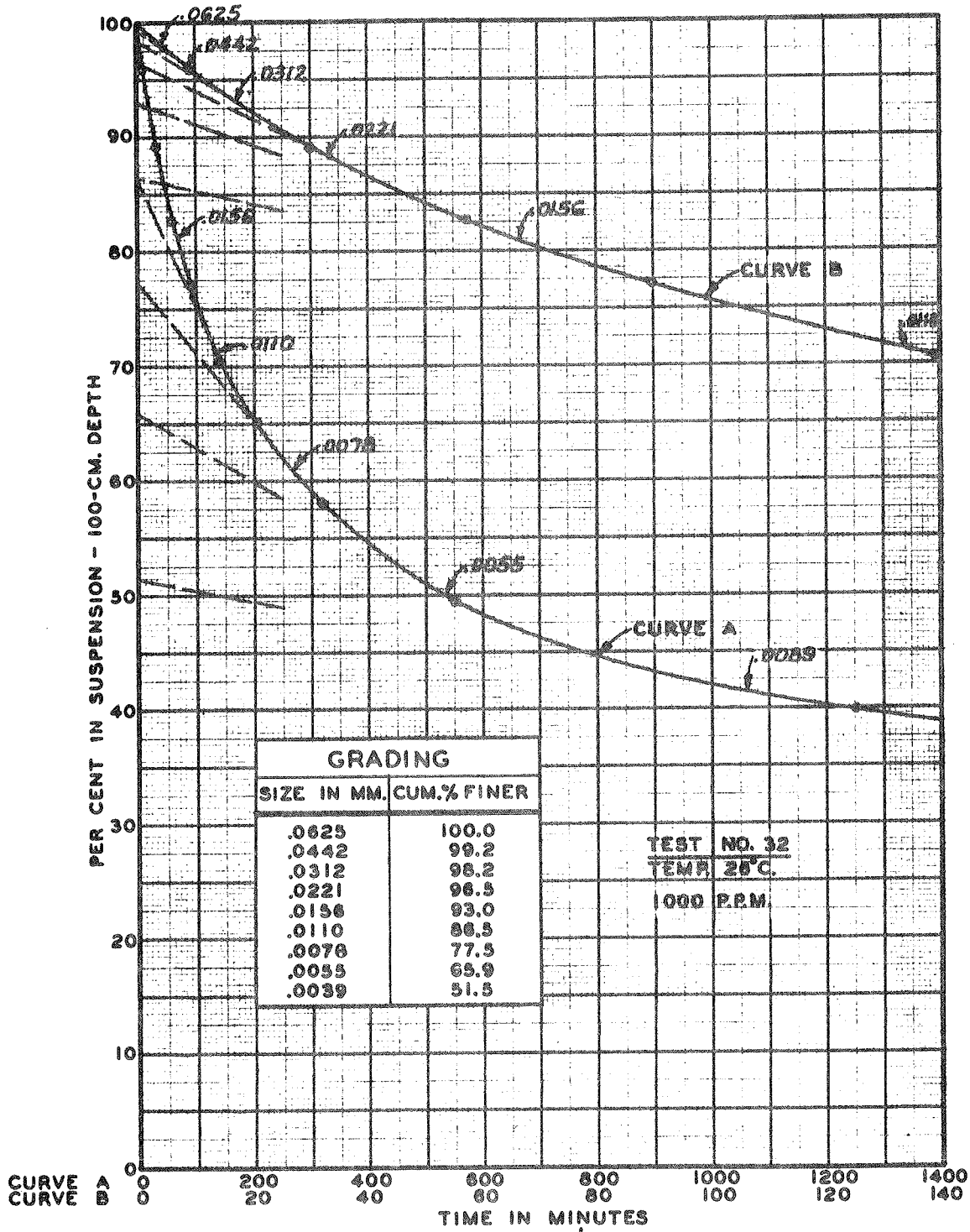


FIG 14 - ODEN CURVE

CONSTANT DEPTH, VARIABLE TIME

The range of time covered is so great for the size of paper used that the upper part of the curve has been replotted to an enlarged scale. The material tested consists of a silt-clay sediment.

In another study the Odén curve was plotted on semi-logarithmic paper, in which case the tangent intercept, instead of being a straight line, was curved. A family of curved tangent intercept lines was drawn on transparent paper and used as templates to locate points of tangency. Any advantages of this method were offset by the fact that values had to be interpolated between the lines of the template and because the grading of the coarser particles was not so clearly defined due to there being no definite point of origin on semi-logarithmic paper.

Variations in temperature have a decided effect upon the settling velocity of soil particles. Table 1 has been prepared to show the time required for different sized particles to fall 100 cm. at varying temperatures. It is used to locate points of tangency on the Odén curve. Test No. 32 was run at a temperature of 26° C. Table 1 shows that a particle 0.0055 mm. in diameter would require 534 min. to fall 100 cm. at 26° C. This is located on the Odén curve and a tangent drawn at that point. The intercept on the ordinate axis shows that 65.9 per cent of the sample is finer than 0.0055 mm. Similar values can be obtained for any size particle desired between the indicated limits.

Fig. 15 shows the cumulative grading curve for Test No. 32.

In the appendix to this report will be found a detailed description of the laboratory testing procedure developed as a result of this investigation and a recommended test procedure and data sheet for routine size analysis and total concentration tests.

TABLE 1

BOTTOM WITHDRAWAL SEDIMENTATION TUBE ANALYSIS

TIME TABLE TO BE USED WITH THE ODÉN CURVE

Time in min. required for spheres having a specific gravity of 2.65 to fall 100 cm. in water at varying temperatures. Terminal fall velocity for particles 0.00195 to 0.0625 mm. computed according to Stokes' Law; terminal fall velocity for coarser particles taken from curves prepared at The California Institute of Technology.

Temp. °C.	Particle Diameter in mm.														
	1.00	0.50	0.25	0.125	.0625	.0442	.0312	.0221	.0156	.0110	.0078	.0055	.0039	.00276	.00195
10	0.115	0.243	.592	1.73	6.22	12.4	24.9	49.7	99.6	200	399	802	1594	3182	6380
11	0.114	0.240	.577	1.68	6.03	12.1	24.2	48.3	96.9	195	388	780	1551	3095	6206
12	0.113	0.237	.568	1.65	5.87	11.7	23.6	46.9	94.2	189	377	758	1507	3007	6031
13	0.112	0.233	.562	1.62	5.72	11.4	22.9	45.7	91.6	184	367	737	1466	2927	5868
14	0.111	0.232	.552	1.59	5.57	11.1	22.3	44.5	89.2	180	357	718	1428	2850	5715
15	0.110	0.228	.543	1.56	5.42	10.8	21.7	43.3	86.9	175	348	698	1391	2776	5566
16	0.109	0.227	.538	1.53	5.27	10.6	21.2	42.2	84.6	170	339	681	1354	2703	5421
17	0.108	0.225	.528	1.50	5.15	10.3	20.6	41.1	82.5	166	330	664	1320	2969	5285
18	0.107	0.222	.522	1.48	5.02	10.0	20.1	40.1	80.5	162	322	647	1288	2570	5154
19	0.107	0.220	.515	1.45	4.88	9.77	19.6	39.1	78.5	158	314	631	1256	2507	5026
20	0.106	0.218	.508	1.41	4.77	9.53	19.2	38.2	76.6	154	306	616	1225	2445	4904
20.5	0.106	0.217	.505	1.40	4.72	9.43	19.0	37.8	75.8	153	303	609	1212	2418	4849
21	0.105	0.217	.503	1.39	4.67	9.32	18.7	37.3	74.9	151	299	602	1198	2391	4794
21.5	0.105	0.215	.500	1.38	4.61	9.21	18.5	39.9	74.0	149	296	600	1179	2362	4735
22	0.104	0.213	.497	1.37	4.55	9.10	18.3	36.4	73.0	147	292	587	1168	2332	4675
22.5	0.104	0.213	.492	1.36	4.50	8.99	18.1	36.0	72.2	145	289	580	1155	2305	4621
23	0.104	0.212	.488	1.34	4.45	8.88	17.8	35.5	71.3	143	285	574	1141	2277	4566
23.5	0.104	0.210	.487	1.33	4.39	8.78	17.6	35.1	70.5	142	282	567	1128	2251	4514
24	0.103	0.210	.485	1.32	4.33	8.67	17.4	34.7	69.6	140	279	560	1114	2225	4461
24.5	0.103	0.210	.480	1.31	4.29	8.58	17.2	34.3	68.9	139	276	554	1102	2200	4411
25	0.103	0.208	.478	1.30	4.25	8.48	17.0	33.9	68.1	137	273	548	1090	2175	4361
25.5	0.102	0.208	.475	1.29	4.20	8.38	16.9	33.6	67.4	136	270	541	1078	2151	4312
26	0.102	0.207	.472	1.28	4.15	8.28	16.7	33.2	66.6	134	266	534	1065	2126	4263
27	0.101	0.205	.467	1.26	4.05	8.10	16.3	32.4	65.1	131	260	524	1042	2076	4169
28	0.101	0.203	.462	1.24	3.97	7.93	15.9	31.7	63.7	128	255	512	1019	2034	4079
29	0.100	0.202	.455	1.22	3.88	7.77	15.6	31.1	62.3	125	249	501	997	1990	3991
30	0.0998	0.200	.450	1.20	3.80	7.60	15.3	30.4	61.0	123	244	491	976	1948	3907
31	0.0991	0.198	.445	1.18	3.71	7.43	14.9	29.8	59.7	120	239	481	956	1908	3825
32	0.0987	0.197	.442	1.17	3.65	7.28	14.6	29.2	58.5	118	234	471	936	1869	3747

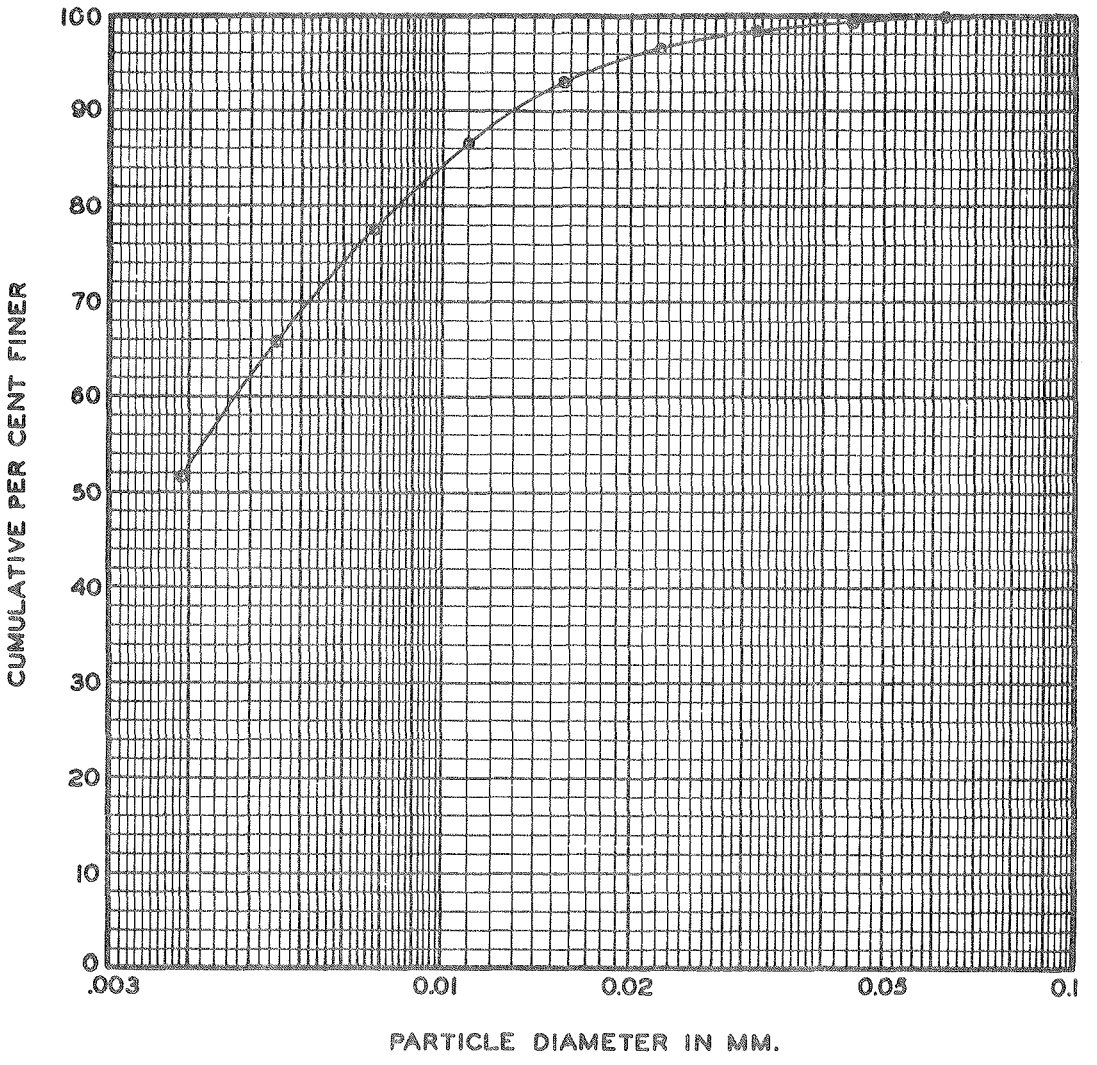


Fig. 15 - Cumulative Grading Curve

Test No. 32

Some work was done using a bottom withdrawal tube of only 50 cm. height and holding about 500 cc. of suspension and although the results were not conclusive they indicated that this length of tube can be used for suspensions having particles 0.25 mm. in diameter or smaller.

VI. RESULTS OF TESTS WITH THE BOTTOM WITHDRAWAL TUBE

21. Comparison with other methods--In order to evaluate test results obtained with the bottom withdrawal tube, comparison with some accepted method of obtaining the correct size grading was considered necessary. For particles 1/16 mm. in diameter and finer, the pipette method of size analysis is considered by many to be the most accurate method and, therefore, it was selected for sediments in this size range. For particles coarser than 1/16 mm., the grading adopted as a standard was obtained by introducing the sample at the top of the bottom withdrawal tube with a double cone device similar to the Puri siltometer (3) and drawing off fractions from the bottom of the tube, as this appeared to be the best method available.

Because of the possibility that the concentration of the sediment used might be a factor in the size analysis obtained by means of the pipette analysis, which was taken as a standard, as well as in the analysis obtained by other methods, a study was made of the effect of the concentration of the suspension used on the size analysis results. The results of this study were not conclusive, but it is believed that a sufficient program was carried out to indicate the practicability of the bottom withdrawal tube.

22. The effect of concentration on results of pipette analysis--In order to determine the effect of concentration on the analysis results, two types of material were tested, the first of which was a clay composed of particles 1/16 mm. in diameter or smaller and the second a silty loam with a size range up to 1.0 mm. In analyzing the clay, samples were taken

from a master sample with no attempt at splitting. The material being very fine-grained, little or no segregation was anticipated.

Several tests were run at various concentrations ranging from 100 p.p.m. to 100,000 p.p.m. The average grading from the tests run at each concentration was then obtained. These average gradings for the various concentrations were then referred to the average grading at 10,000 p.p.m. The method of referencing is shown in Table 2 for some of the concentrations used.

TABLE 2

DEVIATION FROM THE AVERAGE SIZE GRADING FOR 10,000 P.P.M.
PIPETTE ANALYSIS OF CLAY

Size in mm.	Per Cent Finer Than Given Size and Deviation From Standard						
	10,000 p.p.m.	20,000 p.p.m.	Deviation	30,000 p.p.m.	Deviation	60,000 p.p.m.	Deviation
.0625	100.0	100.0	0	99.5	-0.5	99.8	-0.2
.0442	99.0	99.3	+0.3	99.8	+0.8	99.2	+0.2
.0312	98.0	98.3	+0.3	99.3	+1.3	98.4	+0.4
.0221	96.0	96.4	+0.4	97.2	+1.2	96.9	+0.9
.0156	93.0	93.0	0	93.8	+0.8	94.2	+1.2
.0110	86.7	88.3	+1.6	88.3	+1.6	90.4	+3.7
.0078	78.0	79.7	+1.7	80.5	+2.5	83.6	+5.6
.0055	65.4	67.9	+2.5	70.2	+4.8	73.8	+8.4
.0039	51.4	54.0	+2.6	56.3	+4.9	59.9	+8.5

This deviation in cumulative per cent finer from the size grading at 10,000 p.p.m. for the various concentrations used is plotted on the graph

shown in Fig. 16.

From Fig. 16 it is evident that the grading obtained using concentrations of 100 and 1,000 p.p.m. are too erratic to be of value. Although the results at 2,000 p.p.m. compare quite well, the individual tests used to obtain this average grading vary so greatly that a lower limit of about 3,000 p.p.m. is indicated, below which consistent results were not obtained with the pipette.

The grading obtained from the samples taken from the same master sample became finer as the concentration was increased so that an upper limit of about 10,000 p.p.m. was indicated as the maximum concentration at which an analysis should be made.

Another computation was made for the purpose of showing the actual grading that would be obtained if the clay material is analyzed at different concentrations. Using the grading at 10,000 p.p.m. as correct, the cumulative per cent finer for the various fractions obtained from analyses run at other concentrations were shown as a per cent of the correct grading. That is to say, if the cumulative per cent finer than the 0.0039-mm. particle were 51.4 at 10,000 p.p.m., then the value of 54.0 obtained for this size at 20,000 p.p.m. would be 105.0 per cent of the correct grading. These percentages were then plotted and smooth curves drawn to correct for any individual deviations from the general trend. Values were taken from these smooth curves and reconverted into the indicated grading in cumulative per cent finer and plotted on Fig. 17.

As shown on Fig. 17, for this particular clay the tests indicate that consistent results can be obtained with the pipette when concentrations between 3,000 and 10,000 p.p.m. are used but that when higher concentra-

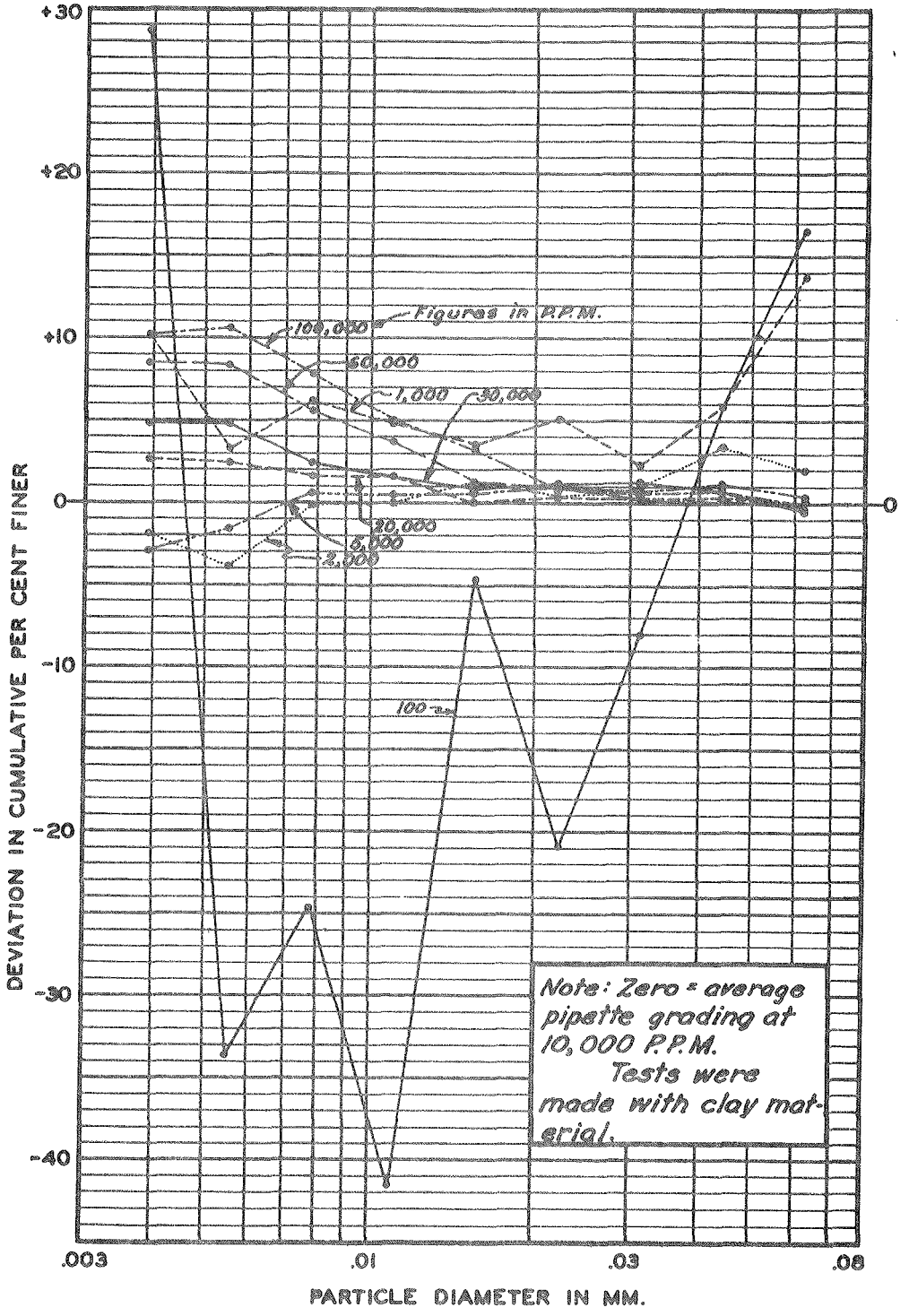


FIG. 16-PIPETTE

EFFECT OF CONCENTRATION ON SIZE ANALYSIS RESULTS

CLAY MATERIAL

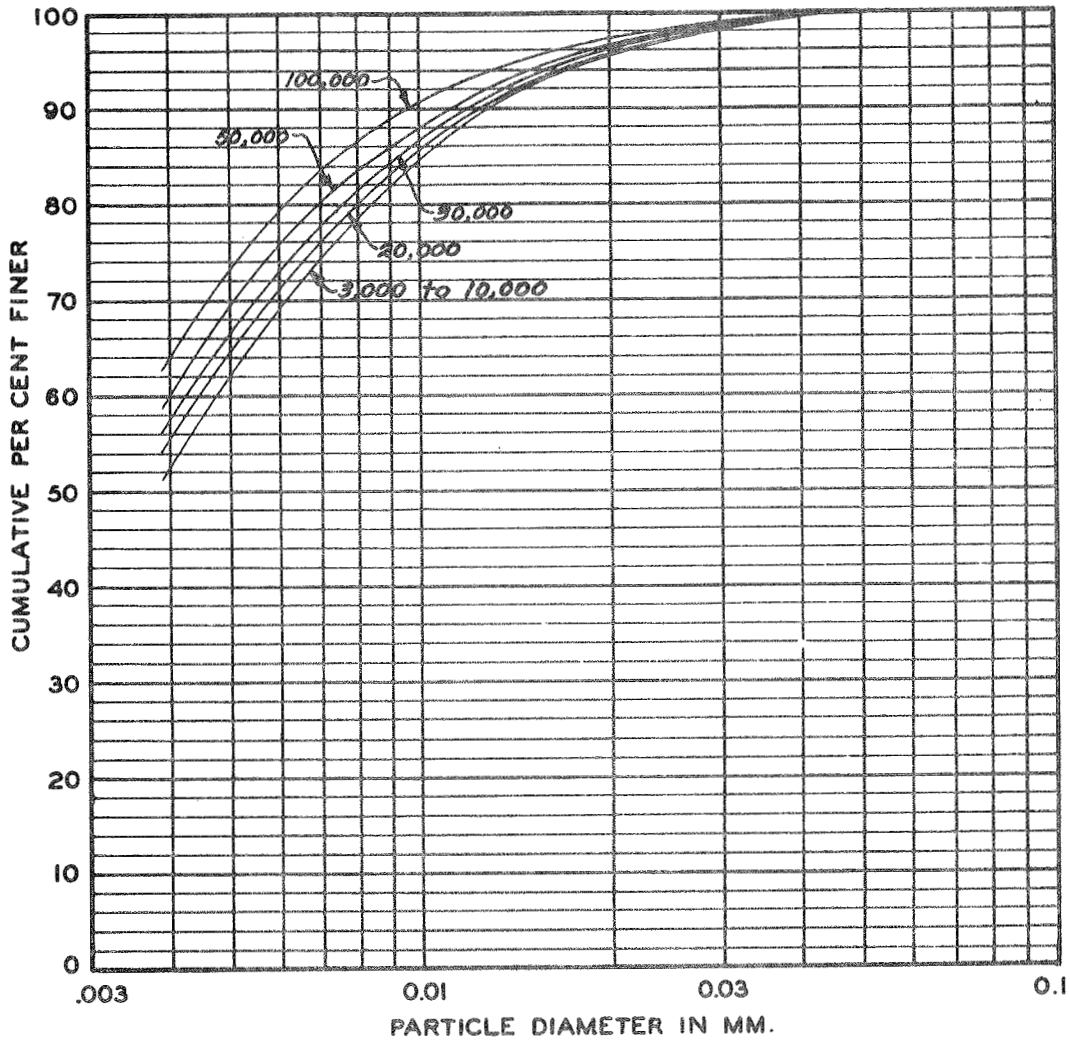


Fig. 17 - Pipette Analysis of a Clay

Actual Grading at Various Concentrations

tions are employed an increasingly finer grading is indicated.

The other type of material tested was a silty loam which graded from 1.0 mm. in diameter down to clay particles. Samples were taken from a master sample without the use of a sample splitter. Although very little work was done on the silty loam material with the pipette, several tests were run at 10,000 and 20,000 p.p.m. The same trend was noted as in the case of clay material, the grading at 20,000 p.p.m. being from 1.7 to 4.9

per cent finer than the grading at 10,000 p.p.m.

23. The effect of concentration on results of bottom withdrawal tube analysis--Clay samples were taken from the master sample from which pipette samples were run and average gradings obtained for tests run at various concentrations.

In using a bottom withdrawal tube with a water column 100 cm. in height and a capacity of about 500 cc. the weight of material required to give the lighter concentrations is as follows:

Volume of Tube cc.	Desired Concentration p.p.m.	Sample Required gm.
500	2,000	1.0
500	1,000	0.5
500	500	0.25
500	100	0.05

In order to insure that the small samples were truly representative, a method of splitting was used in this investigation which consisted of withdrawing a pipette sample of the proper volume from a uniformly dispersed suspension of a known concentration. Standard pipettes having volumes of 5, 10, 20 and 50 cc. were available for this procedure. A specific example will suffice to explain the method of splitting.

If, for example, a pipette analysis was to be run at 10,000 p.p.m. and three tube tests at 1,000 p.p.m., all from the same material, then a master suspension was prepared in the pipette jar containing 11.5 gm. of material. This would be enough to allow 10.0 gm. for the pipette analysis and 0.5 gm. for each of three tube tests. If the master suspension was brought to a volume of 1,150 cc. and uniformly dispersed it would have a

concentration of 10,000 p.p.m. and each cubic centimeter of suspension would contain 11.5/1,150 or 0.01 gm. of sediment. After uniform dispersion was obtained a 50-cc. pipette sample was withdrawn quickly at a depth below which the largest particle present had not yet had time to fall from the water surface. In a suspension having a temperature of 20° Centigrade, a 1/16-mm. particle will fall 20 cm. in 57 sec. If this were the largest particle present then the pipette sample would have to be taken at a 20-cm. depth within 57 sec. after settling had started from the uniformly dispersed condition. Proof that such a sample would be representative of the true grading of the master sample lies in the fact that the concentration at any point in the suspension remains constant until the largest particle present has had time to fall from the surface of the suspension to the point in question. An inspection of Fig. 6 will bear this out. It can be seen that a pipette sample taken at any point below the upper row of d_1 particles would be representative of the original uniform dispersion. Therefore the 50-cc. pipette sample would contain 50(0.01) or 0.5 gm. of sediment. The master suspension was redispersed before each of the three pipette samples was taken. Each pipette sample was washed into a tube and the suspension brought to a volume of 500 cc. so that it would have the desired concentration of 1,000 p.p.m. The master suspension would then have left 10.0 gm. of sediment and a volume of 1,000 cc. All four tests would then be ready to run.

This description of the method employed to secure small representative samples within the particle size range of the pipette (1/16 mm. or smaller) has been given in some detail because it has a wide application in the field of sediment transportation.

Average tube gradings for clay obtained at various concentrations were referred to the pipette grading at 10,000 p.p.m. and the graph shown in Fig. 18 was prepared corresponding to Fig. 16 for the pipette. Fig. 18 shows that size analysis results with the tube from clay samples taken from the same master sample agree very closely with the pipette analysis

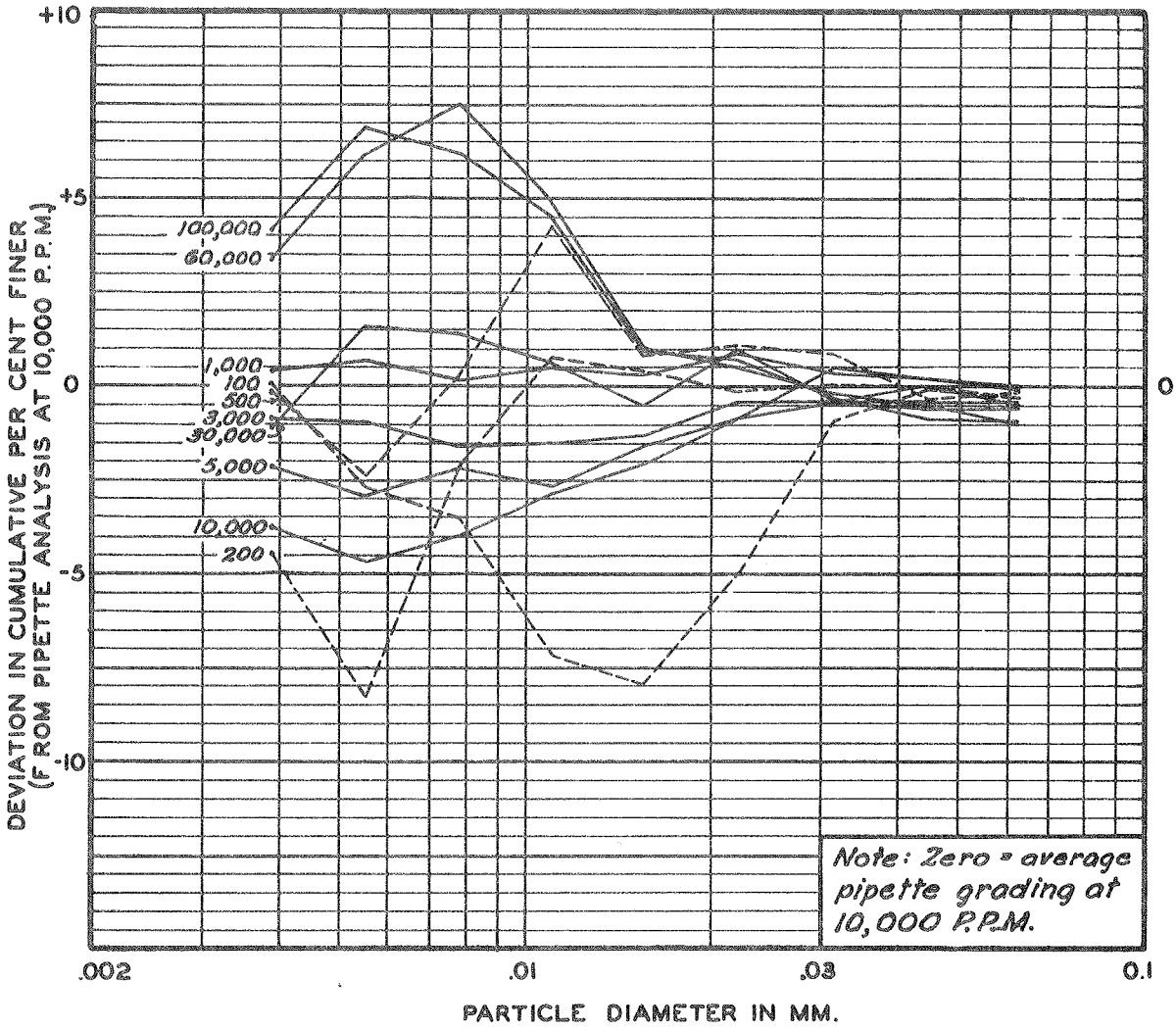


Fig. 18 - Bottom Withdrawal Tube
Effect of Concentration on Size
Analysis Results
(Clay Material)

at 10,000 p.p.m. when concentrations between 300 and 30,000 p.p.m. were used. Concentrations higher than 30,000 p.p.m. resulted in finer gradings just as in the case of the pipette (Fig. 16).

The fact that consistent results were obtained with concentrations as high as 30,000 p.p.m. may warrant further investigation. One is inclined to believe that the tube method would have about the same limit as the pipette method as regards the highest concentration that could be handled; namely, 10,000 p.p.m. The lower limit of 300 p.p.m. is a conservative estimate below which test results may not have the same high degree of accuracy.

Tests made with the bottom withdrawal tube on silty loam material were averaged and the graph shown in Fig. 19 was prepared to bring out the effect of concentration on size analysis results. It is similar in construction to Figs. 16 and 18. Although fewer tests were run on this type of material, there are enough shown on Fig. 19 to indicate that higher concentrations do not affect the grading as much as with the clay material. No attempt was made to split samples such as with a sand splitter. Since very small quantities are required to make up a concentration of 500 or 1,000 p.p.m. this may explain in part the variation in the grading obtained at these two concentrations.

24. Consistency of size analysis results--Up to this time consideration has been given to the manner in which size gradings obtained at various concentrations agree with the pipette grading at 10,000 p.p.m. In doing this the average grading of all the tests run at each concentration has been used and certain concentration limits have been indicated within

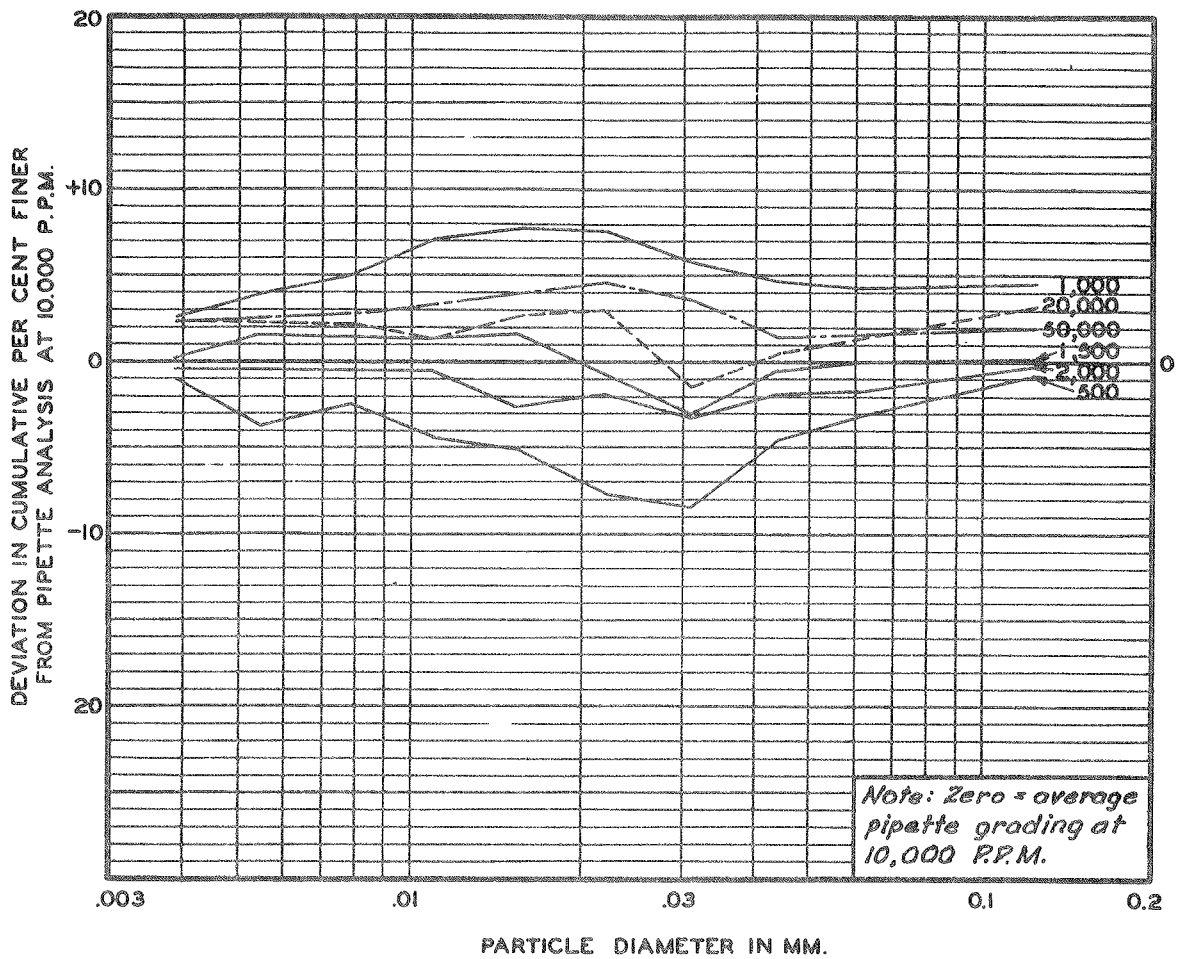


Fig. 19 - Bottom Withdrawal Tube
Effect on Concentration on Size
Analysis Results
(Silty Loam Material)

which consistent size analysis results were obtained.

An important aspect of the analysis of test results obtained is the consistency of the individual tests with the computed average or mean grading. Each individual test was therefore referred to the mean grading at each concentration used and the deviation determined. Fig. 20 has been plotted from these data to show the deviation from the mean grading in cumulative per cent finer at the various concentrations in testing clay

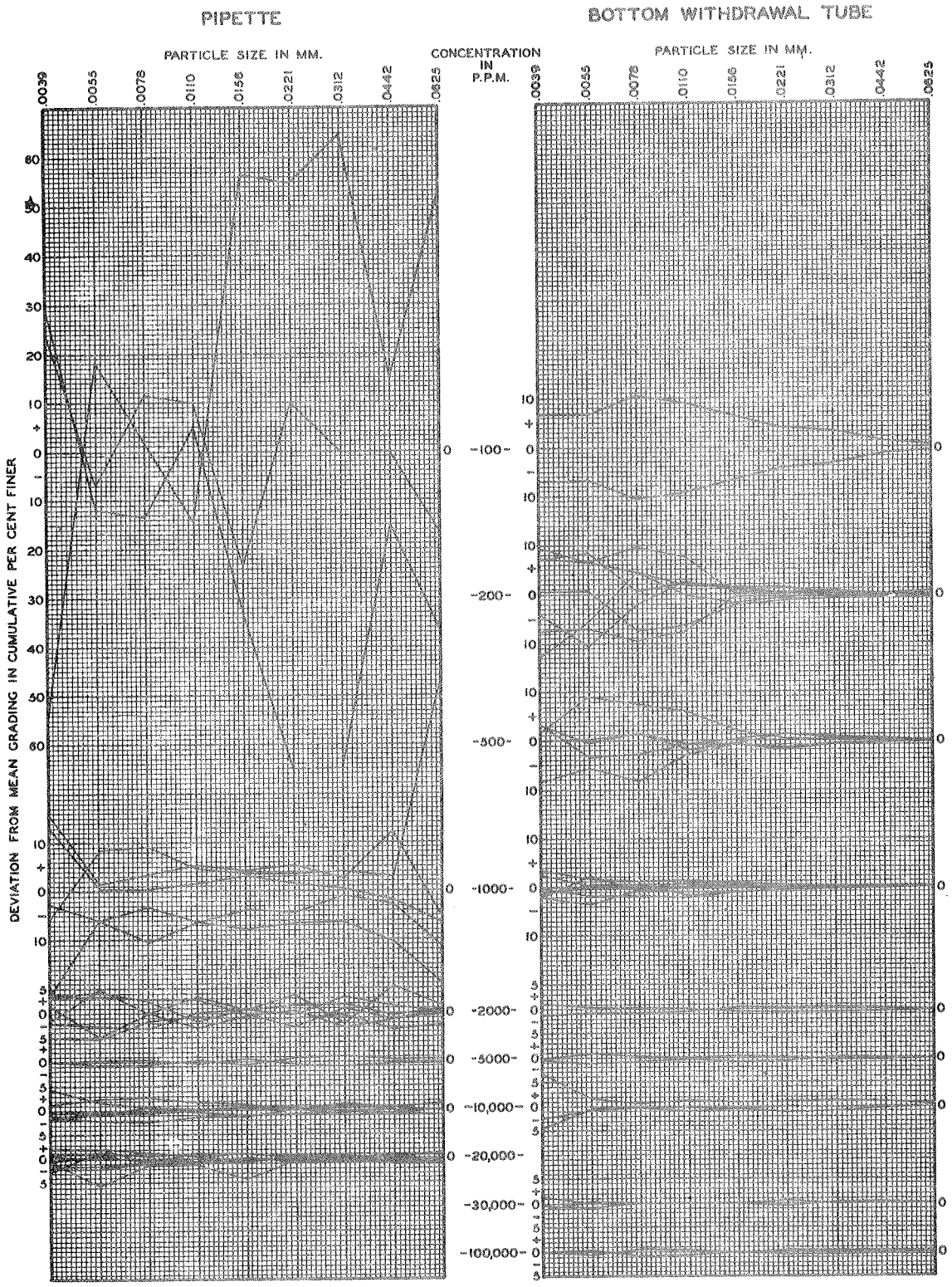


FIG. 20-CONSISTENCY OF SIZE ANALYSIS RESULTS

CLAY MATERIAL

material.

Fig. 20 indicates that for concentrations of 5,000 p.p.m. or greater, both the pipette and bottom withdrawal tube give very consistent results. It must be remembered, however, that the actual size grading of clay obtained with concentrations of 20,000 p.p.m. or greater may not agree with the pipette grading at 10,000 p.p.m., however consistent they might be.

For concentrations lighter than 5,000 p.p.m. the tube has much more consistent results. This is to be expected because the pipette grading is obtained from a very small sample of the suspension. Although the pipette analysis shown on Fig. 20 at 2,000 p.p.m. gives results within plus or minus 5 per cent, as has been stated, the actual grading obtained does not compare favorably with the accepted standard grading at 10,000 p.p.m. For that reason a lower limit of about 3,000 p.p.m. is indicated for the pipette. The individual tube tests have about the same consistency at 100, 200, and 500 p.p.m. when compared to their respective mean gradings, but when the mean grading is compared to the correct grading, as was done in Fig. 18, concentrations below about 300 p.p.m. may not have the same degree of accuracy. It will be noted on Fig. 20 that the tube tests at 1,000 p.p.m. give results as consistent as the pipette at 10,000 p.p.m.

A graph similar to Fig. 20, prepared for tests made on silty loam, is shown in Fig. 21. Very consistent results were obtained with both methods for the few tests run.

25. Particle size range of the bottom withdrawal tube--It has been shown that the bottom withdrawal tube gives accurate results within the

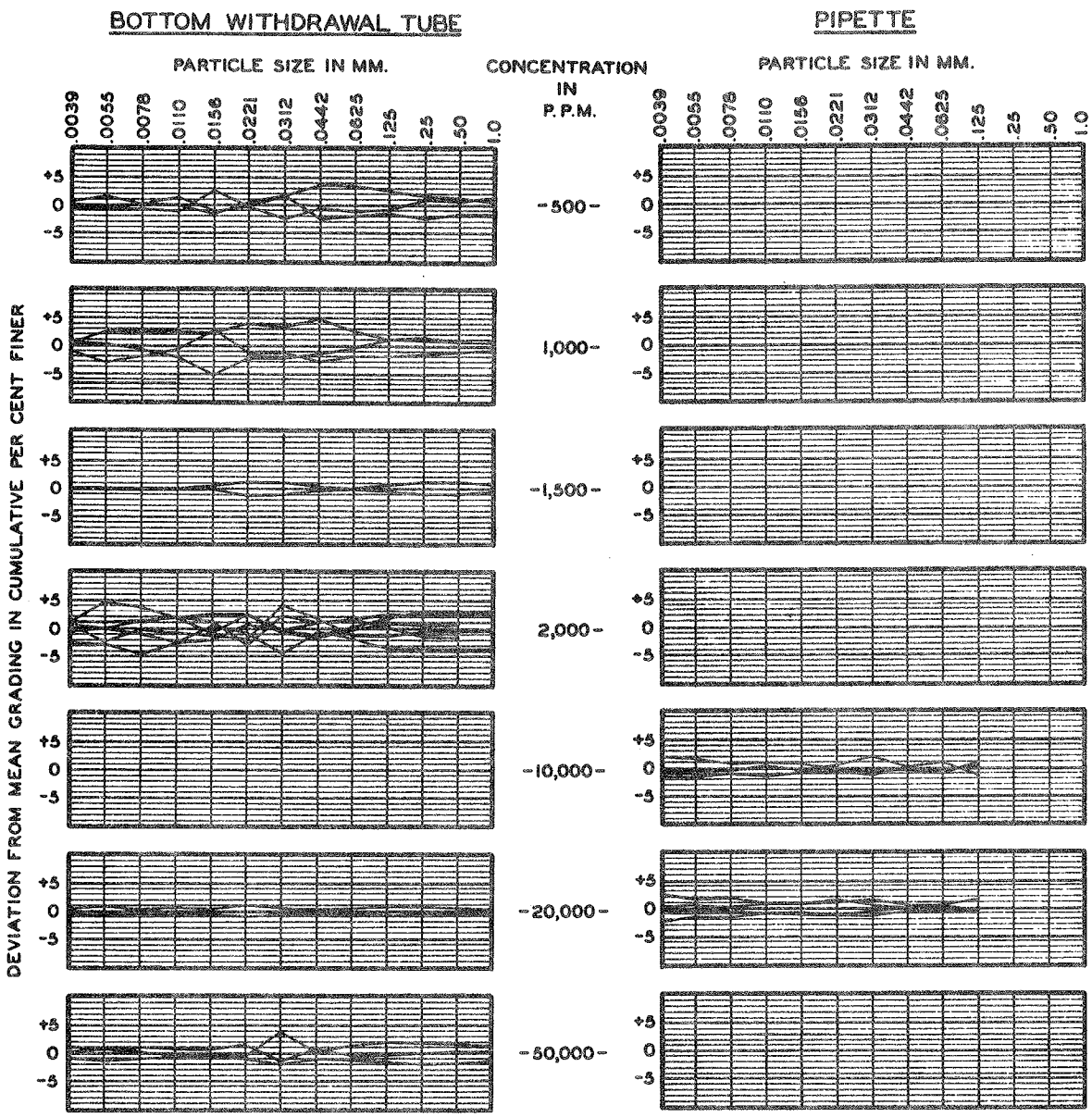


FIG. 21-CONSISTENCY OF SIZE ANALYSIS RESULTS

SILTY LOAM MATERIAL

particle size range of the pipette; namely, 1/16 mm. or finer. There follows a record of the test results obtained with the bottom withdrawal tube on prepared samples of sand, silty loam, and clay, which were made for the purpose of determining whether the tube would analyze particles as coarse as 1.0 mm. in diameter. Master samples of each of the three types of material were prepared and the standard grading of each determined with either the pipette or the top introduction methods or a combination of both. Having obtained the standard grading, analyses were then made with the bottom withdrawal tube for comparison. Also, two or more of the materials were mixed in different proportions by weight from which it was possible to compute the combined grading for comparison with the tube analysis.

In order to insure that representative samples of the sand and silty loam material were used in the tests, a Jones miniature sample splitter was used. It is called a microsplit and was designed by George H. Otto (8). The microsplit was designed for particles grading from 1/16 mm. to 1.0 mm. in diameter. It was not possible to use it in securing representative samples of clay as that material was all finer than 1/16 mm. and would stick to the sides of the splitter. The next best expedient therefore was merely to use reasonable care in obtaining representative samples of the clay material.

Several samples of the silty loam material of about 2.0 gm. each were split from the master sample. Since this material contained some particles which were coarser than the pipette could handle, the correct grading was obtained by combining results obtained with both the pipette and top introduction methods and a smooth average grading curve drawn. This smooth

curve and the points used to obtain it are shown in Fig. 22.

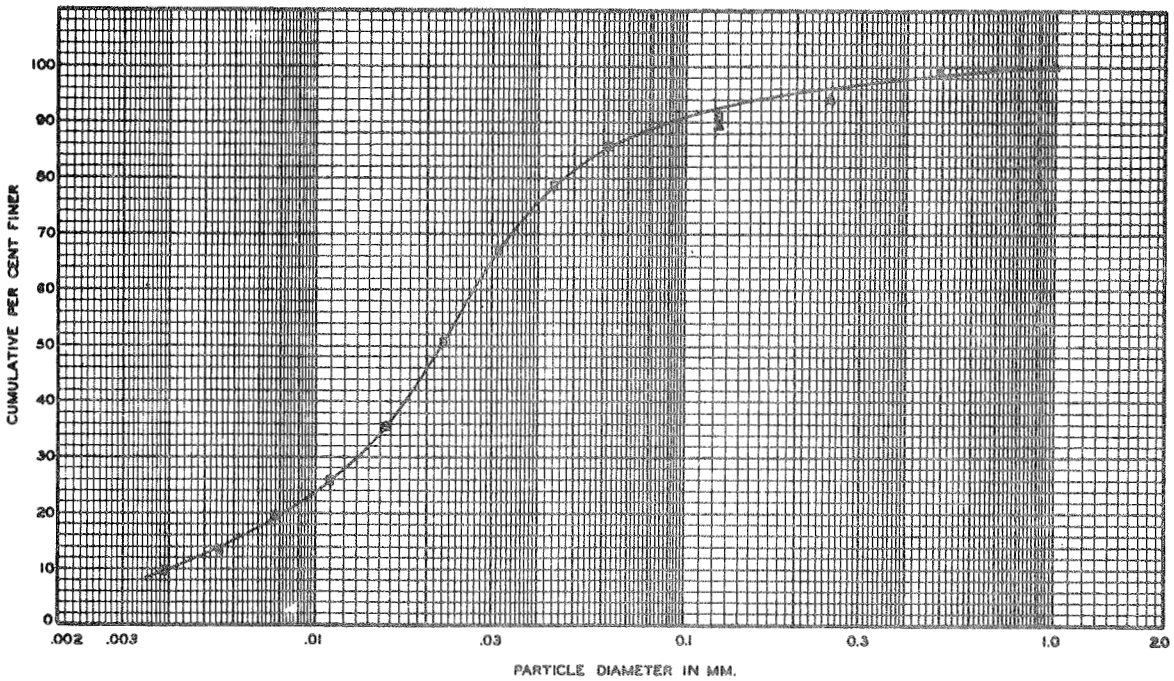


Fig. 22 - Combined Grading of Silty Loam
▲ Top Introduction Analysis
■ Pipette Analysis

The experience gained in investigating the chambered tube has been recorded in Section 9 of this report. It was found that even though fine particles were present in samples introduced into the top of a long column of water, coarse particles above 1/16 mm. in diameter would settle out ahead of the density currents as individual particles in a manner susceptible to this form of analysis. The method of obtaining the size grading of a sample introduced into the top of a long column of water in the proposed chambered tube has been described in detail in Section 9. Also, it was shown in Section 15 that the action of the bottom withdrawal tube is similar to that of the chambered tube. It was therefore felt that a reasonably accurate size analysis was obtained of the coarser particles in

the silty loam material when samples were introduced into the top of the bottom withdrawal tube and fractions withdrawn from the bottom until such a time as the cloudy density currents were encountered. A double cone device for introducing samples was built of galvanized sheet iron and patterned after the Puri siltometer. When these results were plotted on the same graph (Fig. 22) with pipette results on split samples of the same material, and a smooth curve drawn, it was felt that the grading obtained was reasonably accurate and was adopted as standard for the complete range of particle diameters. Tests were then run on other 2.0-gm. split samples of silty loam with the bottom withdrawal tube in the regular manner for comparison. The standard grading is drawn on Fig. 23(A) as a smooth curve and the tube results of individual tests are shown as dots.

Several samples of the sand of about 2.0 gm. each were also split from the master sample. Samples were introduced into the top of the bottom withdrawal tube with the double cone device and fractions withdrawn from the bottom at predetermined time intervals. Other samples were dispersed uniformly in the tube and the regular bottom withdrawal size analysis run. The standard average grading, obtained with the top introduction device, is shown plotted as a smooth curve on Fig. 23(B) while the test results with the tube are shown as dots for easy comparison.

At this time another master sample was prepared which included 90 per cent of silty loam by weight and 10 per cent of sand. Having previously determined the standard grading of these two materials it was possible to compute the combined grading by proper weighting. This standard grading was then plotted on Fig. 23(C) as a smooth curve and test results with the bottom withdrawal tube on split 2.0-gm. samples are shown as dots.

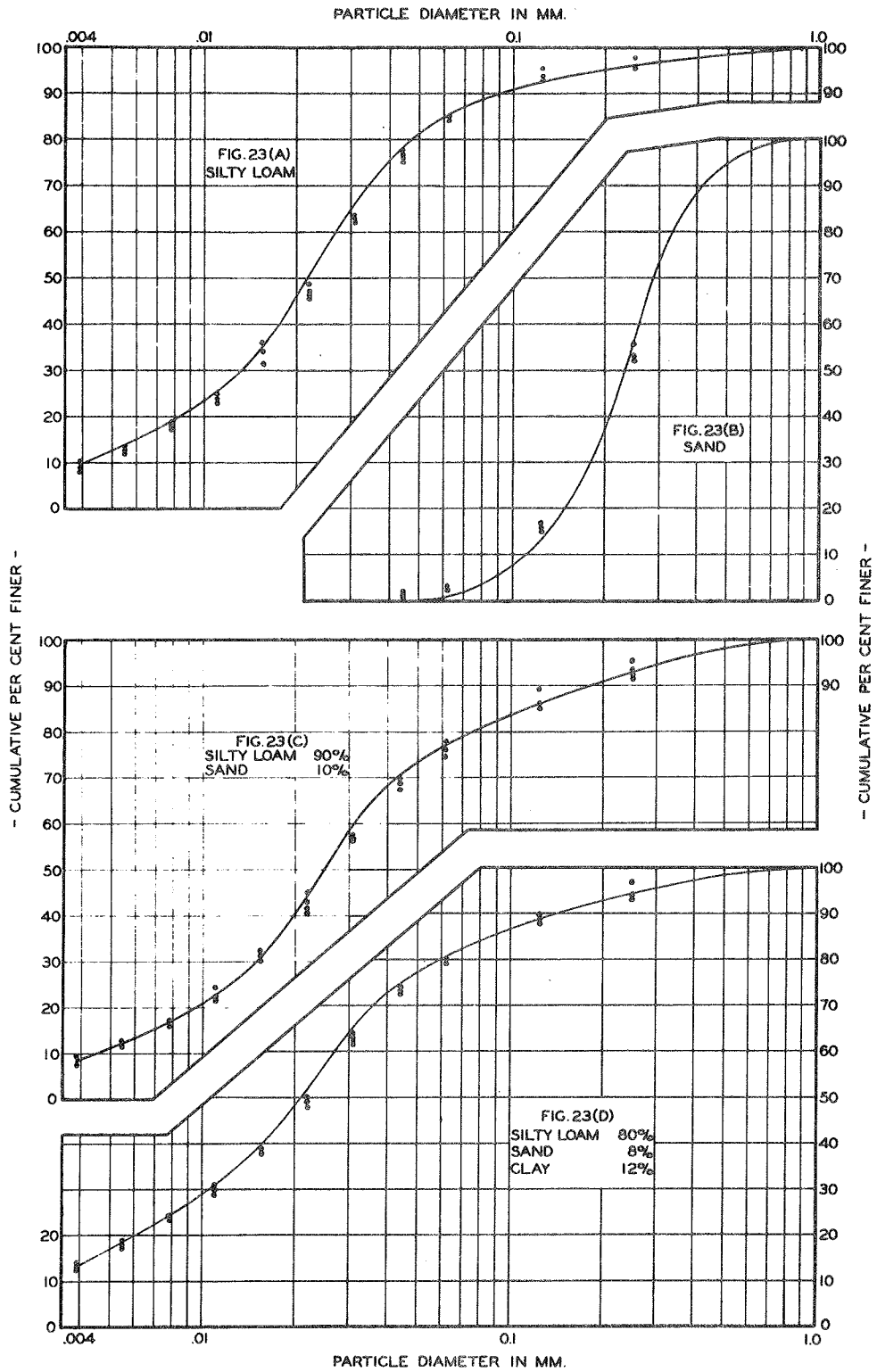


FIG. 23-PARTICLE SIZE RANGE OF BOTTOM WITHDRAWAL TUBE

NOTE:- SMOOTH CURVES = CORRECT GRADING
DOTS = INDIVIDUAL TUBE TEST RESULTS

Another master sample was then prepared having the following proportions by weight: sand, 8 per cent; silty loam, 80 per cent; and clay, 12 per cent. Again the standard grading was computed and compared to that obtained with the bottom withdrawal tube as shown in Fig. 23(D). Split samples weighing about 2.0 gm. were used in running the analysis.

26. Conclusions--The accuracy of size grading results obtained with the bottom withdrawal tube for particles 1/16 mm. in diameter or smaller has been determined by comparison with pipette analysis results on split samples of the same material. The standard pipette grading was obtained using a suspension having a concentration of 10,000 p.p.m. For particles between 1/16 mm. and 1.0 mm. the standard grading has been obtained with a double cone top introduction device similar to the Puri siltometer. This method was adopted because of the success had by Puri (3) and Vaidhianathan (2) in analyzing sand particles by introducing samples into the top of a long column of water. Puri used a 10.0-gm. sample in a tube having a diameter of 6.0 cm. Experiments reported herein were made with 2.0-gm. samples in a 2.54 cm. diameter tube. The effect of the nearness of tube walls on the fall velocity of sand particles was not taken into account. It is hoped that a study can be made of wall effects in some future investigation.

An extensive program has been carried out in determining that the bottom withdrawal tube will give results as accurate and consistent as the pipette for particles 1/16 mm. in diameter or smaller. From the few tests made on particles coarser than 1/16 mm. it has been concluded that the tube range can be extended to particles as coarse as 1.0 mm. This

means that in one operation the tube can be used in analyzing the complete range of particle sizes likely to be encountered in suspended sediment samples.

The range of concentrations within which the correct grading can be obtained has been found to be between 3,000 and 10,000 p.p.m. with the pipette and between 300 and 30,000 p.p.m. with the bottom withdrawal tube. The fact that much smaller samples are used would explain why the pipette will not handle concentrations as light as the tube, but theoretically there is perhaps no reason why both methods would not have the same limitation as to the highest concentration that could be used. For that reason an upper limit of 10,000 p.p.m. has also been placed on the tube until further tests can be made.

The bottom withdrawal tube has been designed for a maximum length of 100 cm. because it would be hard to obtain uniform dispersion in a tube much longer than this. This limitation as to length makes it impractical to analyze particles larger than about 1.0 mm. in diameter. It is suggested that a large number of tests be made on several different streams to determine if 1.0 mm. is high enough to go with the analysis. If it develops through further study that the analysis should go further up the grade scale it might be well to suggest certain procedures in the light of experience gained in this investigation.

Fall velocities for the coarser particles are as indicated in the following tabulation. If these values for the different water temperatures are plotted and smooth curves drawn, then the values for the intermediate temperatures can be read and a table prepared similar to Table 1, page 54.

If particles as coarse as 2.0 mm. were desired the first fraction

withdrawn in the regular analysis could be introduced into the top of the tube with the Puri double-cone device. If particles as large as 8 mm. in diameter were desired the first fraction would have to be introduced into a tube 200 cm. in length.

FALL VELOCITIES IN CM./SEC.						
Particle Diameter mm.	Sieve Number	0°C.	10°C.	20°C.	30°C.	40°C.
1	18	13	14.5	15.7	16.7	17.5
2	10	25.5	27	28.5	29.5	30.2
4	5	44	45	45.5	45.8	46
8		67	67	67	67	67

When field samples are obtained having concentrations as high as 50,000 to 100,000 p.p.m. by weight they can be split down with the pipette as described on page 61 if the particles are not larger than about 1/16 mm. in diameter. No attempt was made in this investigation to split samples from a suspension containing particles larger than 1/16 mm. It has been indicated, however, that concentrations as high as 30,000 p.p.m. by weight may be analyzed with the bottom withdrawal tube. Further study along this line will no doubt be desirable when such problems arise in the field.

Comparative size analysis results with a standard soil hydrometer were not obtained. The pipette analysis method is limited apparently to a concentration of 10,000 p.p.m., whereas hydrometer analyses can be made with concentrations as high as 50,000 p.p.m. An explanation of this circumstance may be found in the manner in which a hydrometer is calibrated. It is known, for instance, that the hydrometer measures the average density of a suspension over the depth of the bulb. In order to reduce this to a measure of the density at a point, a factor is applied to the total depth

of immersion so that the hydrometer will give size analysis results that agree with the pipette. If this factor takes into account the effect of concentration then it is probable that a correct analysis of concentrations as high as 50,000 p.p.m. can be obtained with the hydrometer.

The purpose of this investigation has been to develop a new size analysis method for suspended sediment samples and has resulted in the completion of the bottom withdrawal tube. It might be well at this point to summarize and orient the scope of the present common methods of size analysis with regard to their usefulness in the study of sediment transportation in order better to show the possibilities of this new device.

The usual suspended sediment sample is brought to the laboratory in a pint bottle and may have an average volume of about 400 cc. Since the smallest-sized sample that can be satisfactorily analyzed with 3-in. sieves is about 0.05 gm., and assuming that all of the particles are coarser than 1/16 mm., then the lightest concentration that could be handled by this method would be (0.05/400)(1,000,000), or 125 p.p.m. The heaviest concentration that could be handled would of course be unlimited. The particle size range for sieves is from 1/16 mm. to as large as may be encountered in suspension. Little is known about the siltometer except that Puri (3) designed for a particle size range of 0.06 to 0.6 mm. and used a 10.0-gm. sample. Assuming that 10.0 gm. is the upper and 0.05 gm. the lower limit of material that could be analyzed and that all particles are coarser than 1/16 mm., the corresponding concentration range would then be from 125 to 24,600 p.p.m. From the experience gained in this investigation it appears possible that the siltometer would handle particles from 1/16 mm. in diameter to as coarse as 2.0 mm., using a tube 200 cm. in

TABLE 3

SCOPE OF VARIOUS SIZE ANALYSIS METHODS

Method	Approximate Range in Particle Size, mm.	Approximate Range in Concentration, p.p.m. required in Single 400-cc. Sample
Sieves	Boulders to 1/16	125 to no limit
Siltometer	2 to 1/16	125 to 25,000
Hydrometer	1/16 to 0.001	60,000 to 116,000
Pipette	1/16 to 0.001	3,000 to 10,000
Decantation	1/16 to 0.001	1,250 to 19,000
Bottom Withdrawal Tube	1.0 to 0.001	300 to 10,000

length. The pipette will analyze particles 1/16 mm. in diameter or smaller, and from a maximum of 10,000 to a minimum of 3,000 p.p.m. in concentration. The hydrometer, limited to 1/16 mm. particles or smaller, is perhaps best suited for concentrations between 25,000 and 50,000 p.p.m. This would require about 25 to 50 gm. of sediment for the standard 1,000-cc. hydrometer jar which means that the 400 cc. suspended sediment sample would require a concentration of from 60,200 to 116,000 p.p.m. For this reason the hydrometer has very little if any use in the study of suspended sediment samples, it being confined to studies in which the amount of material available is unlimited. From previous experience with the decantation method of size analysis at the Iowa Institute of Hydraulic Research it was found that a minimum of 0.5 gm. of sediment was required in a decantation jar containing 750 cc. of suspension. In a 400-cc. suspended sediment sample 0.5 gm. of sediment would be a concentration of 1249 p.p.m. for the lower limit by decanting. If it is assumed that 10,000 p.p.m. is the maximum concentration that can be used in the 750-cc. decantation jar this

would require 7.5 gm. of sediment. A 400-cc. suspended sediment sample containing 7.5 gm. of sediment would have a concentration of 18,600 p.p.m. which would therefore be the upper limit for the decantation method.

The scope of present size analysis methods has been discussed on the basis of their ability to analyze a 400-cc. suspended sediment sample. The limitations found are shown in round numbers in tabular form in Table 3 and graphically in Fig. 24.

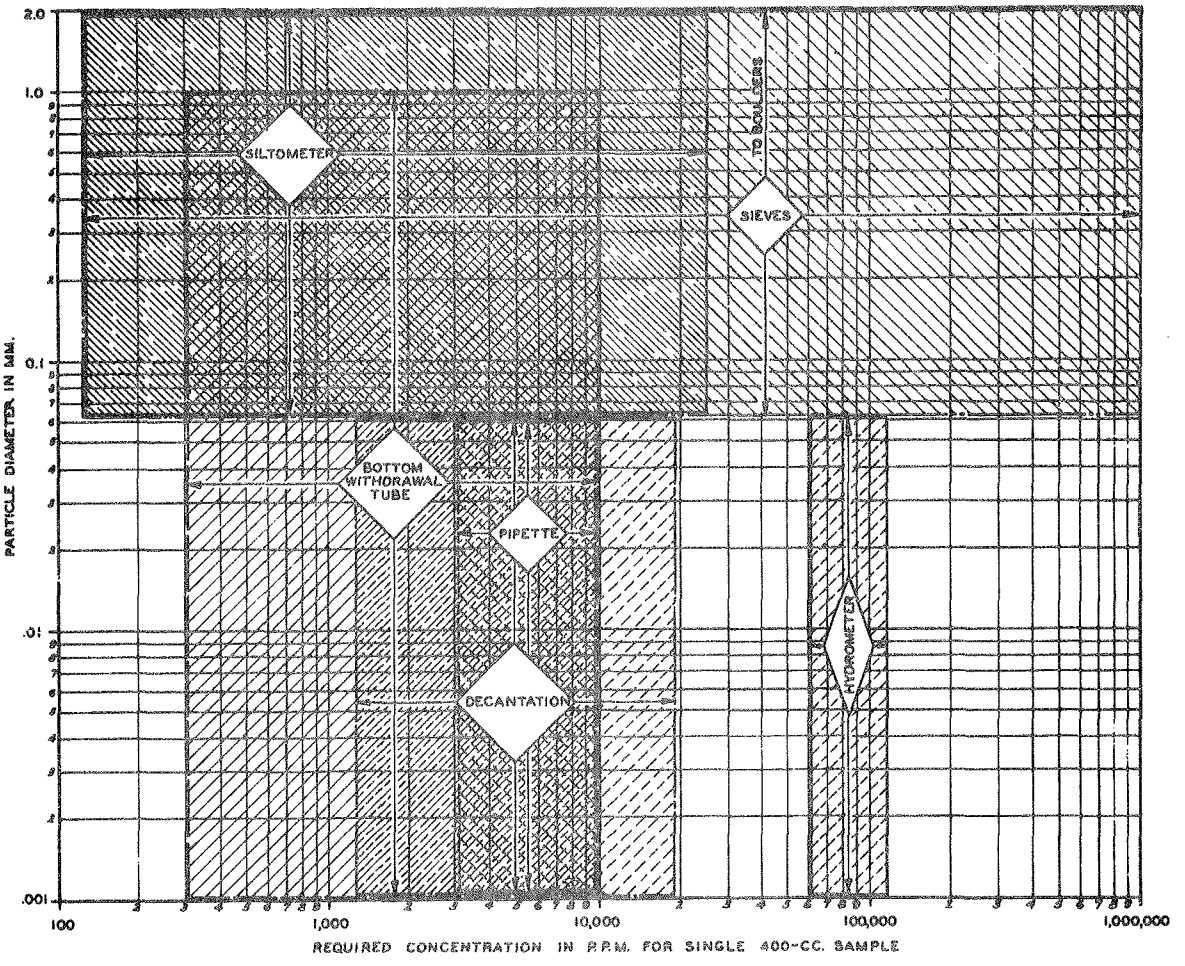


Fig. 24 - Scope of Size Analysis Methods
(As Indicated by this Investigation and Based on 400-cc. Sample)

It is believed that the bottom withdrawal tube method can be developed for mass production analysis by placing several tubes in a rack and securing a uniform dispersion by handling the rack in a manner similar to a single tube. A single lever could be arranged to open and close simultaneously all the tubes in the rack, and a set of vessels in another rack could be held below the outlets to receive the samples.

APPENDIX A

DETAILED TEST PROCEDURE

FOR BOTTOM WITHDRAWAL TUBE

APPENDIX A
DETAILED TEST PROCEDURE FOR BOTTOM WITHDRAWAL TUBE

27. Test procedure for bottom withdrawal tube--A complete list of equipment and a comprehensive and detailed description of the test procedure and computations necessary is given below for determining the size grading of a sediment sample, together with notes and observations designed to aid in obtaining a correct analysis. The test procedure is based upon the analysis of suspended sediment samples submitted to the laboratory in pint bottles and containing approximately 400 cc.

Equipment

Beakers, capacity 400 cc.
Drying oven
Desiccators
Analytical balance, sensitivity 0.1 mg., capacity 200 gm.
Evaporating dishes, pyrex, capacity 100 cc.
Graduates, capacity 100 cc.
Distilled water
Bottom withdrawal tubes, similar to that shown in Fig. 10
Stop watch or timer
Thermometer, 1° subdivisions, -10° to $+110^{\circ}$ C.
Rubber tubing, 5/16 in. bore
Stand for holding bottom withdrawal tube during test
Bottle brush
Pinch-clamps
Corks, size No. 9

Step by step procedure

a. If samples are to be stored in the laboratory for a period of several weeks before analysis they should be placed in a dark room or in subdued light in order to retard the growth of algae, or a few drops of formaldehyde may be added to prevent growth of algae. Samples in which algae have grown or which give off a strong odor of decaying organic matter or of hydrogen sulfide probably should be discarded.

Discussion: It is strongly recommended that samples be taken to the laboratory as soon as possible after being secured and the analysis run immediately in order to simulate actual stream conditions. If this is done it is believed that the turbulence set up in bringing the suspension

to a uniformly dispersed condition, as described in step c, will probably more nearly approach the condition found in natural streams. If a sample is stored over a prolonged period of time before an analysis is made, and it appears that some additional mechanical dispersion is necessary, caution should be observed in determining the severity of the mixing process. Conglomerates or clusters of particles which appear in the natural stream should not be broken down if a true picture of sedimentation is to be obtained.

b. Pour the sample into the bottom withdrawal tube and note the height of water column in order that the volume of the sample may be determined and recorded. Wash the sample bottle into the tube with a stream of clear native water and bring the suspension to the 100-cm. height.

c. In the 2 or 3 min. required to transfer the sample into the tube, all of the particles of 1/8 mm. diameter or greater will have had time to collect at the bottom of the tube. Placing one hand over the open end, or with a cork closing the open end, raise the tube to an inclined position so that the bottom of the tube is at a slightly higher elevation than the top end. With the tube in this position execute a backward and forward motion to wash the coarser particles out of the constricted or bottom end and continue this motion until it is observed that the coarser particles are distributed quite uniformly over the total length of the tube. The coarser particles can be seen by the eye along the bottom of the tube if it is held before a light. When this has been accomplished the tube will still be in an inclined position with the air bubble at the constricted end. Place the tube in an upright position. Invert the tube from end to end, allowing the air bubble to travel the full length of the tube (this takes about 5 sec.) before each inversion. Uniform dispersion is obtained when the suspension has become uniform in color throughout. This may take from 2 to 5 min. The tube is held vertical in both the upright and inverted positions. Once the inverting of the tube is started the process should be continuous. Should a break in the dispersion procedure occur, a fresh start should be made with the tube in an inclined position as described above. After uniform dispersion is obtained the stop watch is started when the tube is inverted to an upright position preparatory to placing in the stand. At this instant the air bubble is at the bottom of the tube. The tube is then securely fastened in the stand in a vertical position. If a cork is used it must be removed before the first fraction is withdrawn.

Discussion: This method of dispersion and the time for starting the stop watch differs somewhat from the pro-

cedure used in the preliminary tests. It is based upon further study of the behavior of the coarser particles made as a result of suggestions received from the cooperative agencies in reviewing the preliminary report and represents a refinement in the test procedure. It is felt that these improvements will result in a better analysis.

d. In this investigation, ten equal volume fractions were withdrawn for each test. Time intervals were chosen in such a way as to accurately define the Odén curve. Since the tube was 100 cm. in length, each fraction corresponded to a column height of 10 cm. The first fraction had a total fall of 90 cm. A 1.0-mm. particle will fall 90 cm. in about 6 sec. and a 1/16 (0.0625)-mm. particle will fall that distance in a little less than 5 min. In the former case the first fraction would have to be withdrawn in from 6 to 10 sec. but in the latter case it need not be withdrawn until after about 5 min. have elapsed. In general, for material containing particles as coarse as 1.0 mm., the withdrawal times used were at 10 sec., 30 sec., 1, 3, 7, 16, 40, 80 and 120 min. For samples containing particles in the neighborhood of 1/16 mm. or smaller the time intervals were spaced at 4, 15, 40, 54, 69, 82, 97, 110 and 124 min. The last fraction had a fall of 10 cm. and particles as fine as 0.0039 mm. were caught in a total elapsed time of 120 min. Deviations from any certain set time will do no harm if the actual time of withdrawal is noted.

e. About 1.0 sec. before the chosen withdrawal time, the pinch-clamp is quickly opened to full width and then closed slowly as the last of the sample is being withdrawn. A full opening is required at the start in order that the rush of water will clear the cone of any deposited sediment. Once this has been accomplished the pinch-clamp may be closed as slowly as desired in order to gage the sample height more accurately. With a little practice one becomes quite expert at withdrawing fractions. It must be remembered, however, that the total elapsed time is not taken at the time the pinch-clamp is opened, but at the time that it is closed. The method is entirely flexible in that fractions of any desired depth and volume may be withdrawn as long as the particle size range is covered and enough points are obtained to accurately define the Odén curve. Seven is probably the minimum for satisfactory results. The column height must be read after the withdrawal of each fraction.

f. Samples are withdrawn into a 100-cc. graduate in order to eliminate the possibility of losing any of the sample from splashing. They are then poured into the evaporating dishes, the graduate being washed with a stream of distilled water. Each evaporating dish should be numbered and the tare weight

determined frequently. Preference was given to pyrex evaporating dishes rather than porcelain because the glass containers are lighter in weight. Care should be taken in cleaning the tubes, evaporating dishes, and graduates before each test. This is especially important when light concentrations are being analyzed.

g. The evaporating dishes are placed in the oven to dry overnight at a temperature of from 105° to 110° C.

h. The evaporating dishes are transferred directly from the oven to a desiccator and allowed to cool about 40 min. to room temperature. They are then weighed to 0.1 mg. The desiccator should remain closed except when removing a sample.

i. Using ordinary precautions in maintaining a constant room temperature, a temperature determination of the suspension at the middle or latter part of the test has been taken as the average for the entire test. If there is considerable temperature variation more frequent readings will be necessary.

j. A sample of the clear water from one of the pint bottles evaporated to dryness should give the amount of dissolved solids present. For the sake of the time saved, it is recommended that one or more dissolved solids determinations be made in this manner for each set of sediment samples so that it will not be necessary to filter through filter paper or Gooch or alundum crucibles. Experience should dictate the number of determinations necessary. Having determined the weight of dissolved solids per cc. of suspension, a correction can be made to each fraction withdrawn according to its volume.

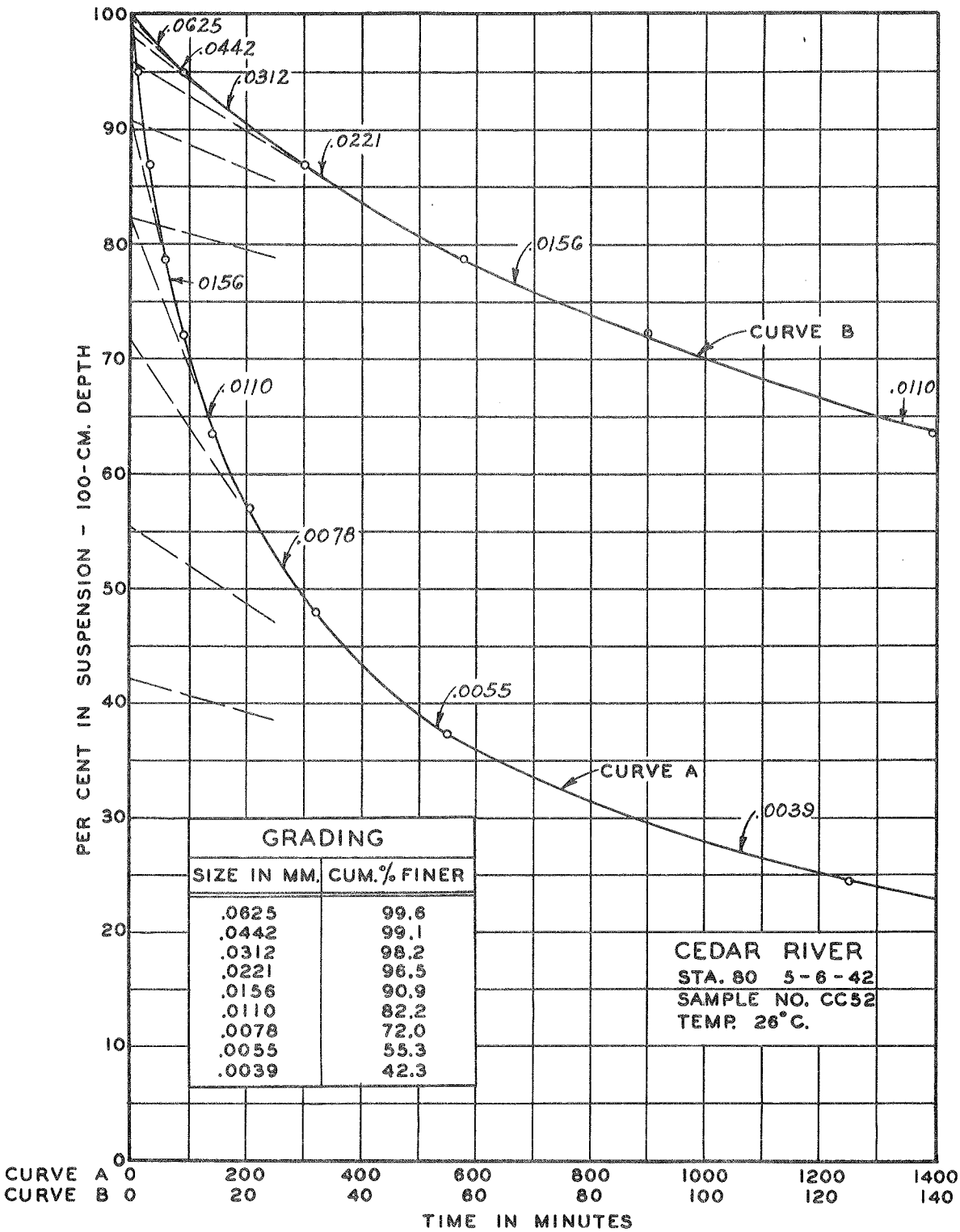
k. The recorded data together with the computation required to obtain the coordinates of the Odén curve are shown in Table 4. Columns 1 to 6, inclusive, are recorded during the analysis. The weight of sediment in each fraction is obtained by subtracting the tare from the gross and is recorded in Column 7. Column 8 is the net weight of sediment after subtracting the proportionate weight of dissolved solids from the weights in Column 7. By adding the net weights cumulatively, as is done in Column 9, the total sediment weight in suspension above each indicated depth is obtained. A depth factor is then computed in Column 10 by dividing the observed column heights in Column 3 into the total depth of 100 cm. Applying this factor to the weights in Column 9 reduces them to the weight that would obtain in a 100 cm. depth at the same average density. In Column 12 these weights for a 100 cm. depth are expressed in percentages of the total sediment weight. Column 13 is the result of applying the

depth factor to the elapsed time in Column 2 and is the time required for the average density above each observed height in Column 3 to be reached at 100 cm. In effect, then, these computations reduce the observed times of settling and weights in suspension to a constant depth of 100 cm.

1. The Odén curve is plotted on rectangular coordinate paper as shown in Fig. 25. The lower curve of Fig. 25 is the complete curve plotted from Columns 12 and 13 of Table 4. The upper curve is the upper portion of the complete curve plotted to an enlarged horizontal scale to facilitate the determination of the grading of the coarser particles. The choice of horizontal scales is arbitrary so long as smooth curves are drawn through the plotted points. Points of tangency are located from the temperature of the suspension (26°C.) and the use of Table 1. It will be noted that the "square root of two" grade scale is used. Once the Odén curve is defined any grade scale may be used, because as many or as few grade points as desired may be determined by merely drawing tangents at the proper points and reading the tangent intercepts on the vertical axis.

Discussion: The construction of the Odén curve and the drawing of tangents is a matter of vital importance in the analysis of sediment samples. In order to better show the method of drawing the curve, several typical examples are given in Appendix B. In suspended sediment samples where sedimentation takes place from a uniformly dispersed condition, the settling of particles will continue for several hours or even days before all particles have completely settled out of suspension. Since the Odén curve as here used shows the amount of sediment remaining in suspension with respect to time it is evident that the slope of the curve will probably never become zero over the period of time covered by the size analysis test. Furthermore, the curve will never have a negative slope. These facts are used as a guide in drawing a curve such as that shown on Fig. 30, Appendix B. No involved or refined method was used in arriving at smooth average curves or in the drawing of tangents. Curves and tangents were drawn with the aid of french curves, ship curves, and triangles. No study was made of the extent of error to be expected as a result of the variation in drawing of tangents by the same or different workers.

A tangent at a point is difficult to draw on a curve having too flat or too steep a slope. The horizontal scales used have been chosen in such a way that this difficulty is minimized. It may be desirable to change scales to fit different materials. If it is felt



GRADING

SIZE IN MM.	CUM. % FINER
.0625	99.6
.0442	99.1
.0312	98.2
.0221	96.5
.0156	90.9
.0110	82.2
.0078	72.0
.0055	55.3
.0039	42.3

FIG. 25 - ODÉN CURVE

CONSTANT DEPTH, VARIABLE TIME

> that the tangent intercept for the 0.0039-mm. fraction is too indefinite on Fig. 26, Appendix B, for instance, the curve can be redrawn to a horizontal scale of 200 min. to the cm. instead of the 100 min. to the cm. as shown. This would increase the slope of the curve and make the drawing of the tangent more positive. Any of several different french and ship curves may be used for drawing the curves, but particular use was made of a ship curve similar to Dietzgen catalogue No. 2217-48 in drawing the flatter portion of the curves. It becomes difficult to maintain continuity with the use of ordinary french or ship curves if the horizontal scale is expanded much beyond that used in the curves shown in this report.

This recommended test procedure differs in some respects from that used in the testing of the bottom withdrawal tube. It was not practicable to attempt to obtain actual suspended sediment samples with the desired size range from nearby rivers. Oven dry material was used instead, because any desired concentration and volume of suspension could easily be made up. The dry material was weighed, placed in a beaker, covered with distilled water, a deflocculant added if necessary, and allowed to soak overnight. The sample was then washed into a dispersion cup, placed in a milk shake mixer, and dispersed for 10 min. The dispersion cup and machine were similar to those specified in A. S. T. M. Designation D422-38T. The suspension was then ready to be transferred to the bottom withdrawal tube and the step by step procedure followed as outlined above. Since distilled water was used, no correction was necessary for dissolved solids.

In the tests the fractions were withdrawn into a 100-cc. glass graduate and then transferred to an evaporating dish, since some of the water would splash out if taken directly into the evaporating dish. In order to eliminate the necessity of making this transfer, and to speed up the analysis, it is believed that a way can be found of taking the fraction

from the tube directly into the vessel in which it is evaporated.

Test results of a few analyses made on actual suspended sediment samples emphasize the likelihood that concentrations as light as 100 p.p.m. may be handled with the bottom withdrawal tube with an accuracy comparable to the field conditions under which they are usually taken. Test results of one field sample of higher concentration is shown in Table 4 and Fig. 25.

The foregoing procedure is not entirely based upon extensive experience, as it was necessary to complete the project before many actual suspended sediment samples were analyzed. It can no doubt therefore be improved upon as the result of further experience.

Care should be exercised in attaching the scale to the bottom withdrawal tube. The scale should cover only the cylindrical portion of the tube and the volume below the lowest reading on the scale down to the pinch-clamp should be the same as would exist if the cylindrical portion of the tube was extended down to, and the tube ended at, the zero of the gage. Thus, if the lowest reading on the scale is 10 cm., the volume of the tube below this graduation down to the pinch-clamp should be the same as in any 10-cm. section of the cylindrical portion of the tube above the 10-cm. mark.

TABLE 4

DATA FOR BOTTOM WITHDRAWAL TUBE SIZE ANALYSIS

Description: Depth-integrated sample, Cedar River near Conesville--Station 80 Date taken 5-6-42 Date run 5-7-42
Sample No. CC52 Run by F. W. P. Computed by L. A. D. Checked by P. C. B. Tube No. 14 Temp. °C. 26
Column height 77.5 cm. Volume 422.4 cc. Sediment 0.45 gm.

Wt. of Suspension 422.85 gm. P.P.M. 1,060 Dissolved solids 0.00022 gm./cc.

Note: Clear native water used in washing sample into tube and in bringing suspension to 100 cm. height at start of test.

Clock Time	Elapsed Time min.	Fall Ht. cm.	Dish No.	Weight					Depth Factor 100/(3)	Sed. in Susp. 100 cm. fall (9)x(10) gm.	Per Cent in Susp.	Time to Settle 100 cm. (2)x(10) min.
				Gross gm.	Tare gm.	Sediment (5) - (6) gm.	Net (7) - Dis. Solids gm.	Cum. (Read up) gm.				
1	2	3	4	5	6	7	8	9	10	11	12	13
	0	100						.4519	1.0	.4519	100	
	8	90.3	20	61.6420	61.5667	.0753	.0643	.3876	1.107	.4291	95.0	8.85
	24	80	10	65.8947	65.8100	.0847	.0737	.3139	1.25	.3924	86.9	30.0
	40	69.6	3	60.5398	60.4627	.0771	.0661	.2478	1.435	.3556	78.7	57.4
	54	60	38	58.3563	58.2931	.0632	.0522	.1956	1.667	.3261	72.2	90.0
	69	49.5	12	62.3001	62.2362	.0639	.0529	.1427	2.02	.2883	63.5	139.4
	82	40	50	70.7378	70.6869	.0509	.0399	.1028	2.50	.2570	56.9	205
	96	30	25	60.9525	60.9037	.0488	.0378	.0650	3.333	.2166	47.9	320
	110	20	24	64.0510	64.0087	.0423	.0313	.0337	5.0	.1685	37.3	550
	124	9.9	43	64.9908	64.9570	.0338	.0228	.0109	10.1	.1101	24.4	1252
		0	45	63.7403	63.7184	.0219	.0109					

Dissolved Solids: Gross Weight 42.3844 Volume of Sample 50 cc.
Wt. of dish 42.3734
Net 0.0110 gm.; dissolved solids = 0.0110/50 = 0.00022 gm./cc.

APPENDIX B

LABORATORY RESULTS

APPENDIX B
LABORATORY TEST RESULTS

28. Typical tests--Tube test results, computations, and Odén curves are presented in this appendix for six typical tests covering a range of concentrations from 100 to 100,000 p.p.m. by weight. Test results are also shown for two typical pipette tests.

Columns 4, 5, and 11 in Tables 5 and 6 do not appear in the recommended data sheet shown in Table 4. The so-called "density factor" in Column 11 was introduced to correct for any variation in the diameter of the tube that might exist. From a study of this variation it was determined that no appreciable error occurred when the density factor was eliminated because, for all practical purposes, the diameter of the glass tubing used was uniform throughout.

The Odén curves plotted from Columns 13 and 14 show the manner of construction and indicate the tangent intercepts obtained. The curve for Test No. 32 is shown on Fig. 14 and is not here reproduced. Curves for the heavier concentrations follow the plotted points very closely. When concentrations as light as 100 p.p.m. by weight are analyzed, however, the plotted points may scatter somewhat, with the result that average curves must be drawn.

Table 7 shows results and computations for two typical pipette tests run at a concentration of 10,000 p.p.m. Pipette tests run at this concentration were used as a basis for determining the accuracy of tube tests run on split samples. As an example the size grading for Tests No. 32 and P6, and for Tests No. 39 and P17 are directly comparable as these two sets of tests were run on split samples.

The experimental and supporting data for all tests run are on file at the Hydraulic Laboratory of the University of Iowa at Iowa City, Iowa, and are available for loan to any interested parties.

TABLE 5

TYPICAL TEST RESULTS WITH BOTTOM WITHDRAWAL TUBE

Clock Time	Elapsed Time min.	Ht. after Withdrawal = Dist. of Fall cm.	Vol. in Section Withdrawn cc.	Cumulative Volume from (4) cc.	Evaporating Dish No.	Evaporating Dish Gross gm.	Evaporating Dish Tare gm.	Net Wt. = Wt. in Sample Withdrawn = (7)-(8) gm.	Cumulative Wt. in Suspension from (9) gm.	Density Factor = 100 cm. Vol. ÷ (5)	Wt. in Suspension for Fall of 100 cm. (10)x(11) gm.	Per cent in Suspension for Fall of 100 cm.	Time Factor = 100 cm. / (3)	Time to Settle 100 cm. (2)x(14) sec.
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Test No. 32 Tube No. 1 Date: 11-7-41 Temp.: 26°C. Concentration: 1,000 p.p.m. Material: Englewood Dam No. 1														
2:00	0	100.0		546.0					.5619	1.0	0.5619	100.0	1.0	
2:08	8	90.3	52.4	493.6	20	61.6420	61.5667	0.0753	.4866	1.108	0.539	95.9	1.107	8.85
2:24	24	80.0	55.6	438.0	10	65.8947	65.8100	0.0847	.4019	1.246	0.501	89.1	1.25	30.00
2:40	40	69.6	56.2	381.8	3	60.5398	60.4627	0.0771	.3248	1.432	0.465	82.7	1.435	57.4
2:54	54	60.0	52.3	329.5	38	58.3563	58.2931	0.0632	.2616	1.660	0.434	77.1	1.667	90.0
3:09	69	49.5	57.8	271.7	12	62.3001	62.2362	0.0639	.1977	2.012	0.3975	70.6	2.02	139.4
3:22	82	40.0	52.2	219.5	50	70.7378	70.6869	0.0509	.1408	2.49	0.366	65.1	2.50	205.0
3:36	96	30.0	55.0	164.5	25	60.9525	60.9037	0.0488	.0980	3.32	0.3255	57.9	3.333	320.0
3:50	110	20.0	55.0	109.5	24	64.0510	64.0087	0.0423	.0557	4.99	0.278	49.4	5.00	550.0
4:04	124	9.9	56.0	53.5	43	64.9908	64.9570	0.0338	.0219	10.21	0.224	39.8	10.1	1252.0
4:11		0	53.5		45	63.7403	63.7184	0.0219						
							Total Weight	0.5619						
Test No. 39 Tube No. 2 Date: 11-26-41 Temp.: 27°C. Concentration: 500 p.p.m. Material: Englewood Dam No. 1 Starting Wt.: 0.2500 gm.														
2:00	0	100.0		520.0					0.2514	1.00	0.2514	100.0	1.00	0
2:08	8	90.3	50.0	470.0	26	62.3766	62.3447	0.0319	0.2195	1.11	0.2430	96.8	1.11	8.88
2:24	24	79.9	54.6	415.4	32	67.8600	67.8214	0.0386	0.1809	1.25	0.2260	90.0	1.25	30.0
2:40	40	68.7	58.2	357.2	46	59.6953	59.6589	0.0364	0.1445	1.46	0.2105	83.9	1.46	58.4
2:54	54	60.5	43.1	314.1	6	58.4232	58.3967	0.0265	0.1180	1.66	0.1950	77.7	1.65	89.4
3:09	69	50.5	52.5	261.6	8	63.5393	63.5130	0.0263	0.0917	1.99	0.1825	72.6	1.98	137.
3:22	82	39.8	54.6	207.0	16	62.3489	62.3248	0.0241	0.0676	2.51	0.1700	67.7	2.52	206.
3:36	96	30.5	48.4	158.6	43	64.9773	64.9564	0.0209	0.0467	3.28	0.1530	60.9	3.28	315.
3:50	110	17.5	67.6	91.0	25	60.9250	60.9016	0.0234	0.0233	5.71	0.1330	53.0	5.72	629.
4:04	124	10.2	38.0	53.0	27	64.4485	64.4380	0.0105	0.0128	9.82	0.1255	50.0	9.80	1220.
4:20	140	0	53.0		5	72.1700	72.1572	0.0128						
							Total Weight	0.2514						
Test No. 70 Tube No.2 Date: 12-27-41 Temp.: 26.5°C. Concentration: 30,000 p.p.m. Material: Englewood Dam No. 1 Starting Wt.: 15.2 gm.														
9:06	0	100.0		520.0					15.2151	1.000	15.21	100.0		0
9:014	8	89.5	54.1	465.9	18	64.9049	62.6848	2.2201	12.9950	1.115	14.49	95.2	1.117	8.94
9:30	24	78.8	56.1	409.8	35	63.4250	61.1077	2.3173	10.6777	1.270	13.57	89.2	1.269	30.45
9.46	40	69.9	46.3	363.5	32	69.6349	67.8214	1.8135	8.8642	1.428	12.65	83.1	1.430	57.20
10:00	54	60.0	52.0	311.5	22	61.6023	59.8523	1.7500	7.1142	1.668	11.85	77.9	1.667	90.0
10:14	68	50.0	52.5	259.0	45	65.4383	63.7192	1.6291	5.4851	2.002	11.00	72.4	2.00	136.0
10:28	82	40.0	51.0	208.8	5	73.6452	72.1583	1.4869	3.9982	2.500	10.00	65.7	2.50	205.0
10:42	96	29.9	52.5	155.5	41	61.3980	60.0339	1.3641	2.6341	3.345	8.82	57.9	3.34	321.0
10:56	110	20.0	51.5	104.0	19	64.0900	62.9190	1.1710	1.4631	5.000	7.33	48.2	5.00	550.0
11:10	124	10.0	52.0	52.0	6	59.3111	58.3966	0.9145	0.5486	10.000	5.49	36.1	10.00	1240.0
11:15		0	52.0		42	62.3922	61.8436	0.5486						
							Total Weight	15.2151						

TABLE 6

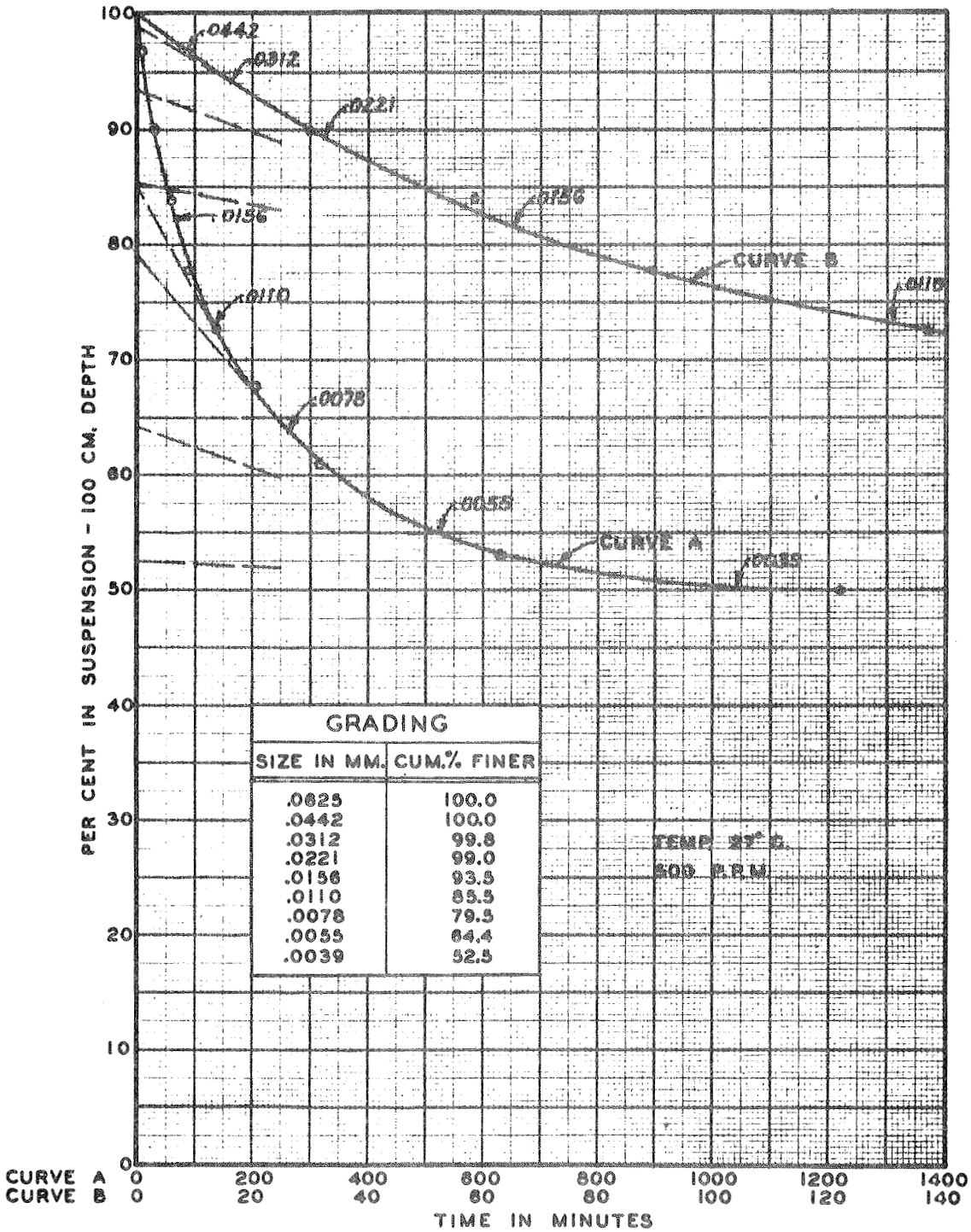
TYPICAL TEST RESULTS WITH BOTTOM WITHDRAWAL TUBE

Clock Time	Elapsed Time min.	Ht. after Withdrawal = Dist. of Fall cm.	Vol. in Section Withdrawn cc.	Cumulative Volume from (4) cc.	Evaporating Dish No.	Evaporating Dish Gross gm.	Evaporating Dish Tare gm.	Net Wt. = Wt. in Sample Withdrawn = (7)-(8) gm.	Cumulative Wt. in Suspension from (9) gm.	Density Factor = 100 cm. Vol. ÷ (5)	Wt. in Suspension for Fall of 100 cm. (10)x(11) gm.	Per cent in Suspension for Fall of 100 cm.	Time Factor = 100 cm. / (3)	Time to Settle 100 cm. (2)x(14) sec.
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Test No. 73 Tube No. 2 Date: 12-30-41 Temp.: 25°C. Concentration: 100,000 p.p.m. Material: Englewood Dam No. 1 Starting Wt.: 52.0 gm.														
9:20	0	101.5		527.7					52.1179	0.985	51.4	100.0	0.986	0
9:24	4	87.0	74.7	453.0	5	80.5447	72.1583	8.3864	43.7315	1.147	50.2	97.9	1.150	4.6
9:28	8	80.0	36.8	416.2	37	66.1416	61.9122	4.2294	39.5021	1.25	49.4	96.1	1.250	10.0
9:36	16	70.1	51.5	364.7	33	66.8056	60.7223	6.0833	33.4188	1.425	47.7	92.9	1.425	22.8
9:52	32	59.5	55.6	309.1	39	68.6988	61.8462	6.8526	26.5662	1.681	44.6	87.0	1.680	53.7
10:10	50	49.5	52.5	256.6	10	71.7943	65.8099	5.9844	20.5818	2.025	41.6	81.1	2.02	101.0
10:32	72	40.0	48.5	208.1	46	65.1183	59.6589	5.4594	15.1224	2.50	37.8	73.5	2.50	180.0
10:56	96	30.1	51.5	156.6	14	68.4478	63.2323	5.2155	9.9069	3.32	32.9	64.1	3.32	319.0
11:10	110	20.0	52.5	104.1	41	64.2786	60.0339	4.3447	5.5622	4.99	27.8	54.1	5.0	550.0
11:24	124	10.2	51.0	53.1	45	67.1775	63.7192	3.3583	2.2039	9.79	21.6	42.1	9.81	1217.0
11:25		0.0	53.1		8	65.7169	63.5130	2.2039						
							Total Weight	52.1179						
Test No. 86 Tube No. 2 Date: 1-31-42 Temp.: 24°C. Concentration: 200 p.p.m. Material: Englewood Dam No. 1														
9:06	0	100.0		520.0					.0968	1.00	.0968	100.0	1.00	0
9:14	8	89.8	52.5	467.5	22	59.8656	59.8528	0.0128	.0840	1.111	.0934	96.5	1.12	8.91
9:30	24	80.3	49.9	417.6	30	67.3435	67.3310	0.0125	.0715	1.243	.089	92.0	1.246	29.9
9:46	40	70.5	51.0	366.6	17	60.4055	60.3932	0.0123	.0592	1.419	.084	86.7	1.418	56.7
10:00	54	60.0	55.1	311.5	26	62.3562	62.3438	0.0124	.0468	1.670	.0782	80.7	1.665	90.0
10:14	68	50.0	52.5	259.0	20	61.5773	61.5668	0.0105	.0363	2.01	.0729	75.4	2.00	136.0
10:28	82	40.0	51.0	208.0	45	63.7294	63.7193	0.0101	.0262	2.50	.0655	67.6	2.50	205.0
10:42	96	30.0	52.0	156.0	51	46.1426	46.1343	0.0083	.0179	3.33	.0596	61.6	3.33	320.0
10:56	110	20.0	52.0	104.0	4	46.3917	46.3839	0.0078	.0101	5.0	.0505	52.2	5.00	550.0
11:10	124	10.0	52.0	52.0	2	31.2983	31.2919	0.0064	.0037	10.0	.037	38.2	10.0	1240.0
11:12		0	52.0		77	45.8149	45.8112	0.0037						
							Total Weight	0.0968						
Test No. 135 Tube No. 3 Date: 4-6-42 Temp.: 23.5°C. Concentration: 100 p.p.m. Material: Englewood Dam No. 1 Starting Wt.: 0.052 gm.														
12:06	0	100.0		531.0					.0516	1.00	.0516	100.0		0
12:14	8	90.2	51.9	479.1	13	60.2123	60.2052	0.0071	.0445	1.109	.0494	95.6	1.11	8.88
12:30	24	79.9	54.6	424.5	8	63.5099	63.5023	0.0076	.0369	1.250	.0461	89.3	1.251	30.05
12:46	40	70.0	52.5	372.0	33	60.7023	60.6956	0.0067	.0302	1.429	.0431	83.5	1.429	57.1
1:00	54	59.9	53.5	318.5	40	59.6967	59.6919	0.0048	.0254	1.667	.0424	82.2	1.67	90.1
1:14	68	50.0	52.5	266.0	20	61.5531	61.5474	0.0057	.0197	1.996	.03935	76.2	2.0	136.0
1:28	82	39.7	54.6	211.4	28	66.9674	66.9622	0.0052	.0145	2.51	.0364	70.5	2.52	206.5
1:42	96	30.0	51.4	160.0	26	62.3332	62.3283	0.0049	.0096	3.32	.0319	61.7	3.33	320.0
1:56	110	19.9	53.5	106.5	19	62.9102	62.9066	0.0036	.0060	4.99	.02995	57.9	5.02	552.0
2:10	124	10.0	53.0	53.5	29	63.0324	63.0294	0.0030	.0030	9.92	.0297	57.5	10.0	1240.0
		0	53.5		11	62.3483	62.3453	0.0030						
							Total Weight	0.0516						

TABLE 7

TYPICAL TEST RESULTS WITH PIPETTE

Size mm.	Fall cm.	Temp. °C.	Time hrs. min. sec.	Clock Time	Evaporating Dish No.	Evaporating Dish Gross gm.	Evaporating Dish Tare gm.	Net Weight gm.	Net Wt. x 50 gm.	Cum. Per Cent Finer
Test No. P6	Material: Englewood Dam No. 1			Concentration: 10,000 p.p.m.				Starting Wt.: 10 gm.		
.0625	20	23	0-53		26	62.5470	62.3442	0.2028	10.00	100.0
.0442	20	23	1-47		48	61.9477	61.7486	0.1991	9.95	99.5
.0312	10	23	1-47		32	68.0187	67.8219	0.1968	9.84	98.4
.0221	10	23	3-34		29	63.2460	63.0531	0.1929	9.64	96.4
.0156	10	23	7- 9		33	60.9102	60.7229	0.1873	9.36	93.6
.0110	10	22.5	14-33	2:23:00 2:37:33	44	59.1537	58.9805	0.1732	8.66	86.6
.0078	10	22.5	28-43	3:42:00 4:10:43	28	67.1403	66.9851	0.1552	7.76	77.6
.0055	10	22	58-54	4:15:00 5:13:54	40	59.8311	59.7008	0.1303	6.51	65.1
.0039	10	22	1-56- 0	5:18:00 7:14:00	14	63.3344	63.2326	0.1018	5.09	50.9
Test No. P17	Material: Englewood Dam No. 1			Concentration: 10,000 p.p.m.				Starting Wt.: 10 gm.		
.0625	20	25.5	0-50		11	62.5545	62.3552	0.1993	9.97	99.7
.0442	20	25.5	1-41		18	62.8829	62.6852	0.1977	9.89	98.9
.0312	10	25.5	1-41		44	59.1764	58.9795	0.1959	9.80	98.0
.0221	10	25.5	3-22	12:55:00 12:58:22	47	60.0149	59.8224	0.1925	9.62	96.2
.0156	10	26	6-39	2:15:00 2:21:39	37	62.0994	61.9124	0.1870	9.35	93.5
.0110	10	26	13-23	2:24:00 2:37:24	31	67.9472	67.7736	0.1736	8.68	86.8
.0078	10	26	26-38	2:40:00 3:06:38	14	63.3867	63.2323	0.1544	7.72	77.2
.0055	10	26.5	52-58	3:11:00 4:03:58	15	60.4772	60.3472	0.1300	6.50	65.0
.0039	10	26.5	1-45-20	4:07:00 5:52:20	24	64.1069	64.0079	0.0990	4.95	49.5



GRADING

SIZE IN MM.	CUM.% FINER
.0625	100.0
.0442	100.0
.0312	99.8
.0221	99.0
.0156	93.5
.0110	85.5
.0078	79.5
.0055	64.4
.0039	52.5

FIG. 26 - ODÉN CURVE - TEST NO. 39

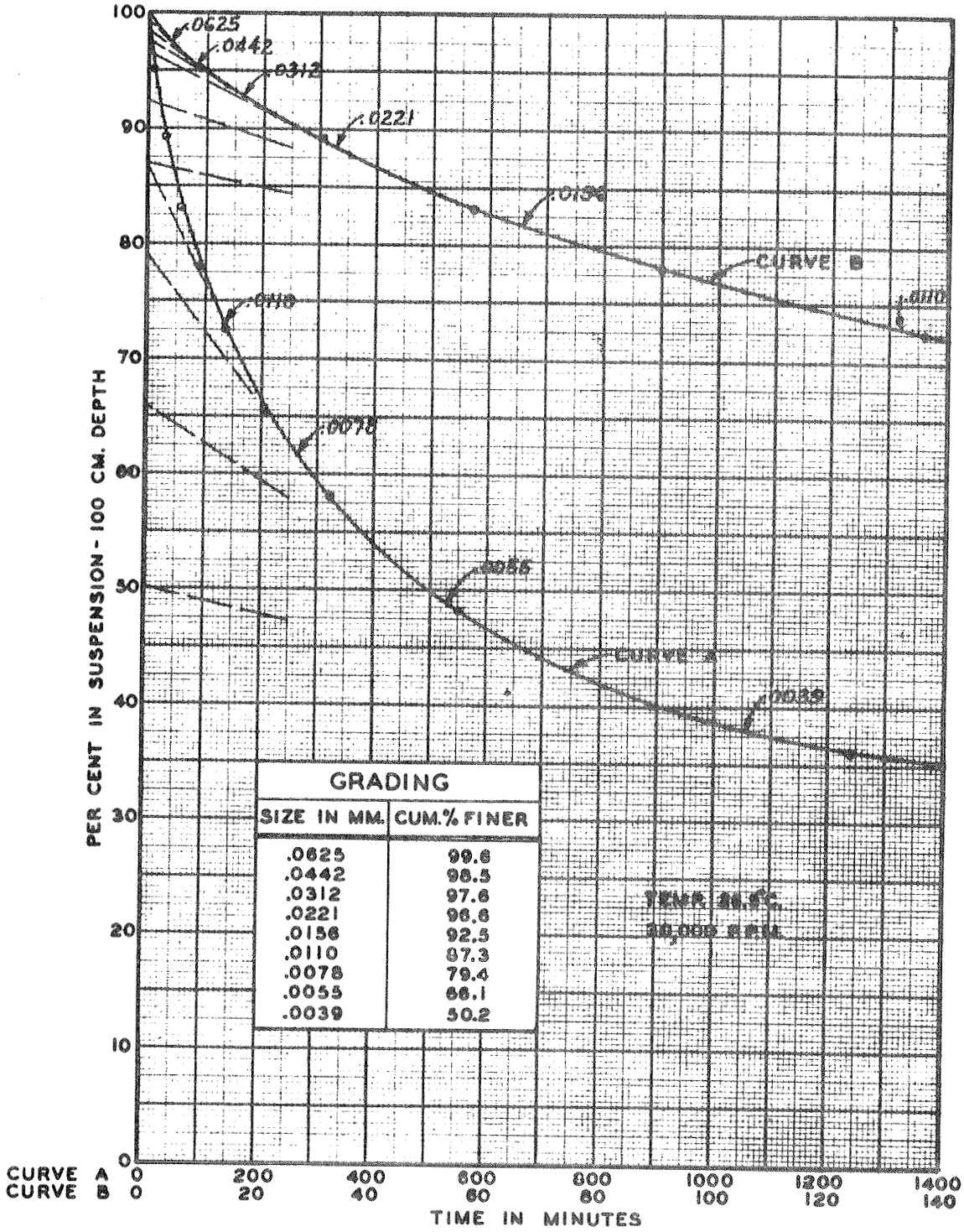
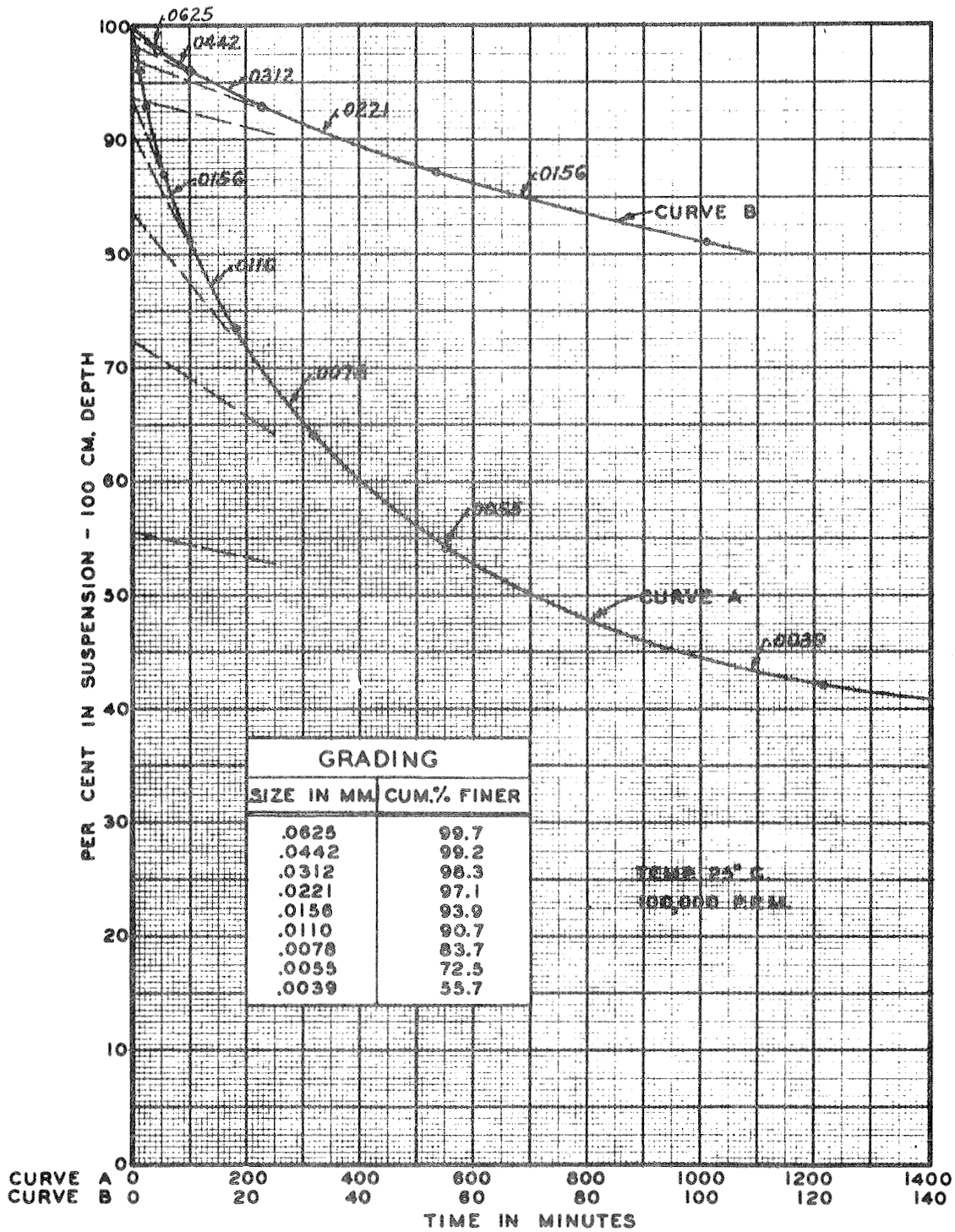
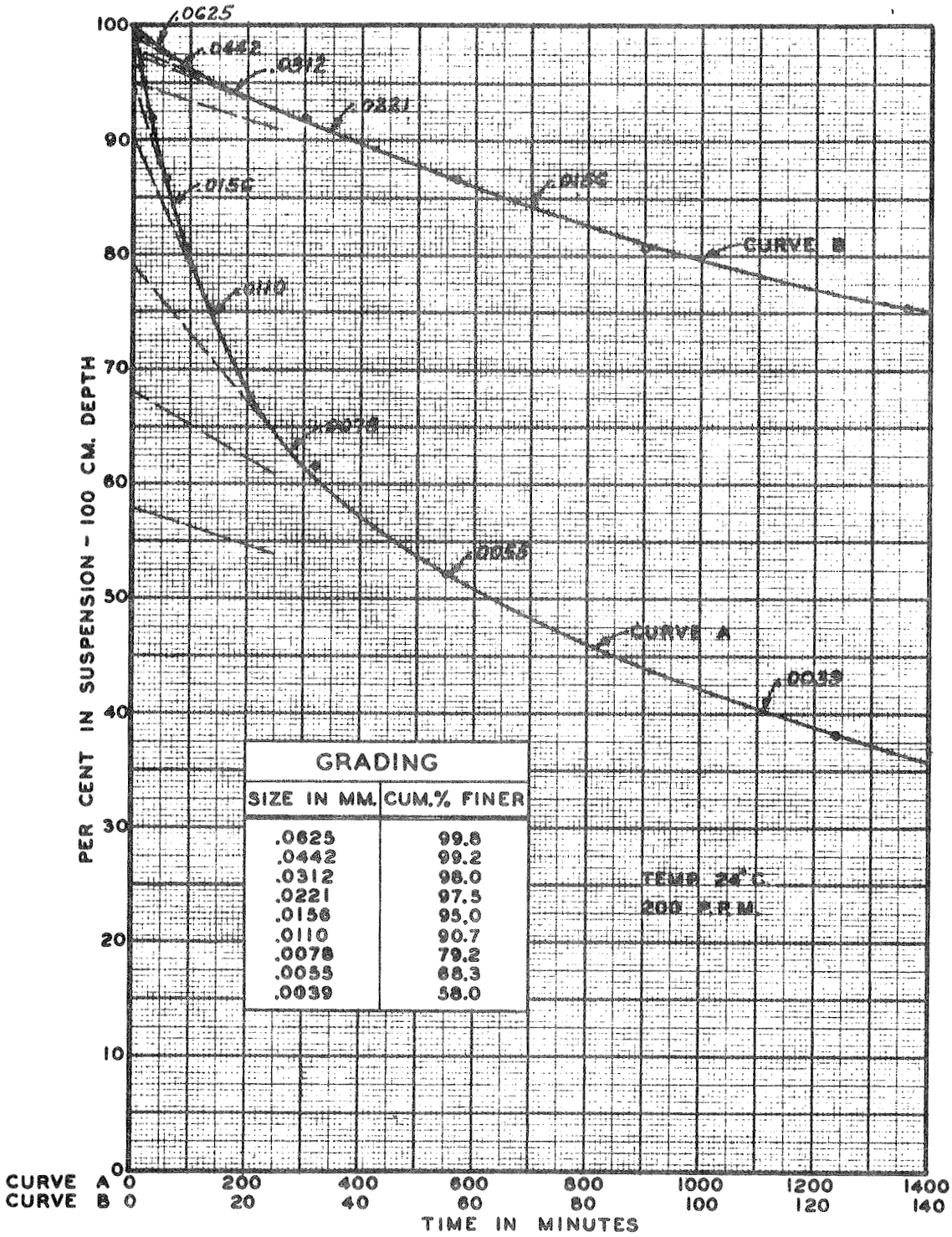


FIG. 27 - ODÉN CURVE - TEST NO. 70



GRADING	
SIZE IN MM	CUM.% FINER
.0625	99.7
.0442	99.2
.0312	98.3
.0221	97.1
.0156	93.9
.0110	90.7
.0078	83.7
.0055	72.5
.0039	55.7

FIG. 28 - ODÉN CURVE - TEST NO. 73



GRADING	
SIZE IN MM.	CUM.% FINER
.0625	99.8
.0442	99.2
.0312	98.0
.0221	97.5
.0156	95.0
.0110	90.7
.0078	79.2
.0055	68.3
.0039	58.0

FIG. 29 - ODÉN CURVE - TEST NO. 86

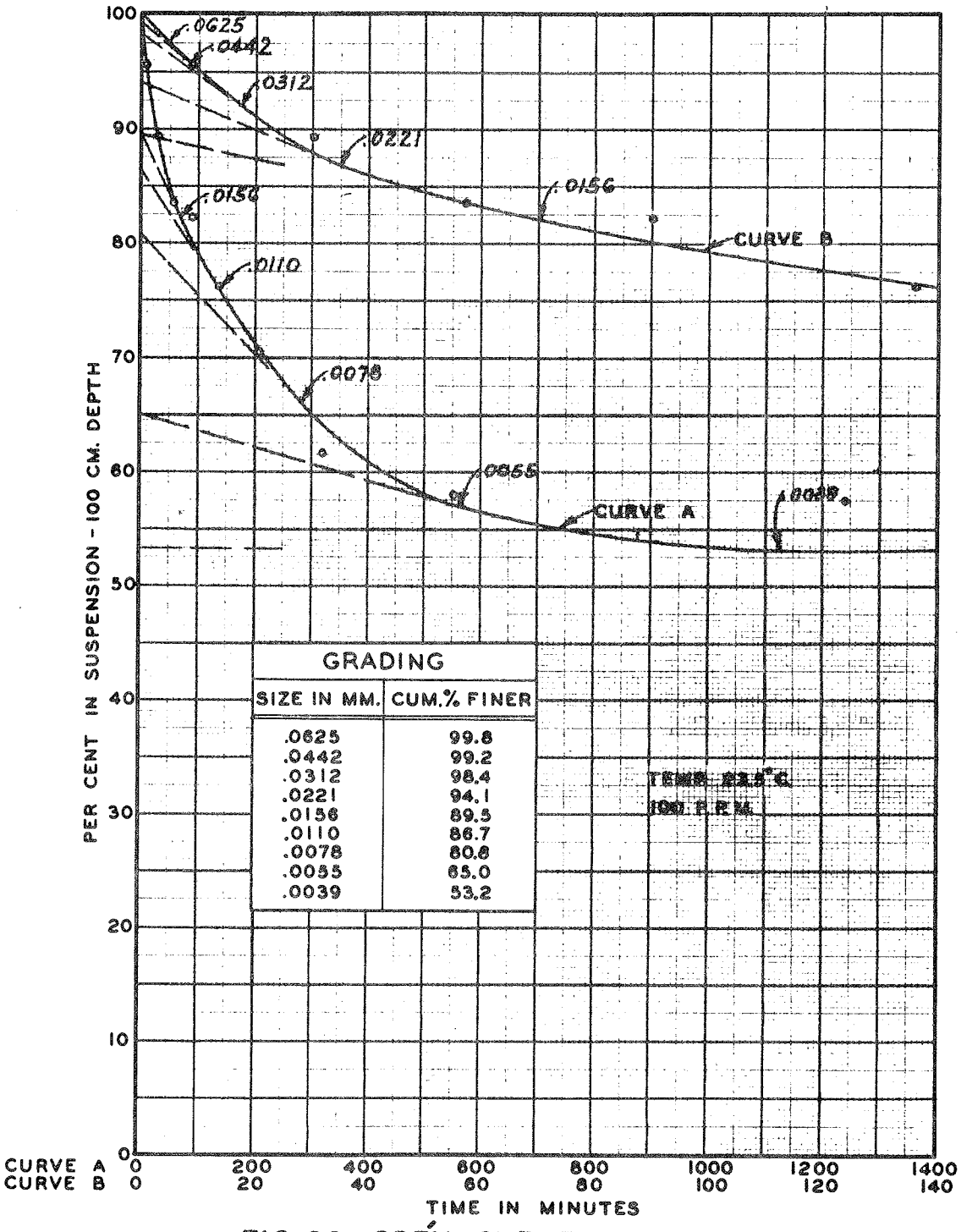


FIG. 30 - ODÉN CURVE - TEST NO. 135

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