FLOW CHARACTERISTICS OF FLUID-FINE PARTICLE MIXTURES

by

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Requirements for the Degree of
Master of Science
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Signature of Author
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Signature of
Head of Department

38

M.I.T. Graduate House,

Cambridge, Mass.

January 15, 1940

Professor G.W.Swett,
Secretary of the Faculty,
Massachusetts Institute of Technology,
Cambridge, Mass.

Dear Sir:

In accordance with the requirements for graduation with the degree of Master of Science, I herewith submit a thesis entitled "Flow Characteristics of Fluid-Fine Particle Mixtures."

Respectfully yours,

Scott W. Walker

ACKNOWLEDGMENT

The author gratefully acknowledges the help and suggestions of Professor Warren K. Lewis, under whose direction this thesis has been carried out.

The author also wishes to thank the Standard Oil Development Company, and Mr.W.P.Dooley, whose able assistance is greatly appreciated.

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The data and results are presented in four series of plots. The first is a diagram of the apparatus employed. There are three groups of data as plots. All plots marked "Series A" are based on the data obtained in the glass tube column, tabulated on pages 62-70. Series B plots are based on the brass tube data using air, found on pages 71-77. Series C plots are based on the hydrogen data in brass tube, pages 80-82.

The plots are inserted in the body at the points of their discussion. They can be located by the following table:

SUMMARY

The purpose of this investigation was to obtain data on the flow characteristics of a fluid-fine particle mixture transported in a vertical tube. This involved initiating a flow of a mixture of fine clay and gas in a 1-inch tube, and after flow was initiated, measuring the gas velocity, powder concentration within the tube, pressure drop over the height of the tube, and the rate at which solid was transported, vertically 100 inches.

It was the purpose to extend the range of data on this same subject obtained by Chambers*, using air as the fluid. It was further the purpose to use as the transporting fluid carbon dioxide and hydrogen in order to determine the effect of fluid density and viscosity.

The results of this thesis using clay and air have greatly extended the data of Chambers, especially in the range of low air velocities and high concentration of solid in the mixture. The results change slightly the correlations presented by Chambers but, in general, substantiate his work.

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*Chambers, J.M., "Flow Characteristics of Air-Fine Particle Mixtures in Vertical Tubes", S.M.Thesis, MIT (1939).

The resukts are presented as correlations between air velocity, feed rate, pressure drop over the height of column, clay concentration and the relative velocity of the fluid with respect to the solid, here called slip.

This thesis indicates from the use of carbon dioxide and hydrogen that under the conditions of this work, the gas density has no effect on the flow characteristics of gas-fine particle mixtures. It does show, however, that the slip of a given solid under identical conditions of feed rate and clay concentration is a function of the viscosity of the transporting gas. The ratio of slip for a gas to that of air under the same flow conditions is the inverse ratio of the gas and air viscosities, thus allowing the air curves to be used for estimation of the flow characteristics for any gas.

In the region of reasonably high feed rates and gas velocities a correlation has been developed from the theory which allows estimation of feed rate from air velocity and clay concentration, which checks the actual data to a marked degree.

Recognition of the complication due to elutriation at low transport rate has been made and no point other than the presentation of the actual data is made.

It is recommended that further work be done on the existing apparatus with solids of different density, size, and size distribution in order to determine the effect of these physical properties of the solid on the flow characteristics; concentration, gas velocity and feed rate. It is recommended that the apparatus be changed to allow the study of the effect of the variables, tube height and tube size on the relationships.

INTRODUCTION

The processing of powders and fine particles is an increasingly important operation in industry. As powders bear a close resemblance to liquids, they are conveyed, fractionated, and distilled just as are liquids and these operations are carried out in equipment similar to those employed for fluids. Thus, we find pigments, cement, grain, etc., elutriated and transported through pipes by a stream of air, and other fine particles, pumped, classified, and processed in a current of fluid. It is, therefore, obvious that a knowledge of the principles underlying these operations would be of value in design, estimation of power consumption, and control of equipment involved in the processing of fine materials.

The handling of fine particles with the aid of fluids can be divided into two groups: (1) Those which use liquids as the fluid carrier, and (2) those which use gases. Each of these groups can be sub-divided into two more groups: (a) those which aim to elutriate or fractionate the particles of different size, and (b) those which transport or carry the particles of the material as a heterogeneous mass. In this work only the transport or movement of particles by gases is considered and in particular the movement of particles under the influence of gases in a vertical tube.

Several principles which may apply to special cases of this problem should be considered. In the case of small particles moving in a fluid at low velocities the motion can be predicted by Stoke's Law (6). As the size of the body and its relative velocity increase the motion changes to a type which can be expressed by Newton's Law (4). For particles whose diameter is intermediate between the region where Stoke's and Newton's laws hold, the motion is correlated by a dimensionless friction factor f and the Reynolds number in a manner similar to fluid flow (7). These three principles apply to conditions where there is no interference of the moving particles with each other, commonly called "free settling conditions". Where the concentration of the solid in the fluid becomes so high that the motion of the particles is influenced by the presence of other particles, the "hindered" or "impeded settling" conditions are encountered. (7)

These principles, while holding at low concentrations of solid in the fluid, do not seem to be applicable to the conditions of high concentration encountered in the commercial transport of powdered materials. Some attempts have been made to correlate variables under these operating conditions (1,2,3,5). These investigators determined the relationships between air velocity, V_a, particle velocity, V_c, slip, S*, and constants which are characteristic of the size, shape, and specific gravity of the solid material. The work of these investigators is mainly preliminary and deals with the motion of a single particle in regard to its acceleration and slip or "floating velocity" under conditions where little interference of other particles is encountered. The several empirical formulas presented are, however, not applicable to many cases and may be subject to question as to their soundness.

Chambers (2) has worked with fine clay and air in a vertical tube and has determined correlations between air velocity, pressure drop, feed rate, and solid concentration, all in a 1-inch tube. He made both batch and continuous flow determinations and in the latter, measurements were made after flow was initiated. As his work shows promise, this investigation was carried out to add to and extend his contribution, and to study the effect of variables held constant by Chambers.

It seems probable that the flow characteristics of fluid-fine particle mixtures should be dependent

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*This is the difference between air velocity and particle velocity, $S = V_a - V_c$, and is called "terminal velocity", "floating velocity", and other terms by different authors.

on fluid velocity, feed rate, solid concentration and the physical properties of the solid. Furthermore, considering the Reynolds analogy of fluid flow, the diameter of the confining tube and the physical properties of the transporting fluid should be important factors. Therefore, in this investigation the three variables, fluid velocity, feed rate, and solid concentration were measured in a vertical column of constant height. Only one powder solid was used, that is, filtering clay, but the transporting fluid was varied.

The purpose of this investigation is to extend the range of the data obtained by Chambers for the flow of a fine clay in a vertical tube with air as the transporting fluid; to use carbon dioxide and hydrogen individually as the transporting fluid, thus giving a considerable range in fluid density and viscosity; and to attempt to correlate the flow characteristics of fine solid-fluid mixtures with the several variables involved, in the hope that these may serve to predict flow characteristics for other conditions.

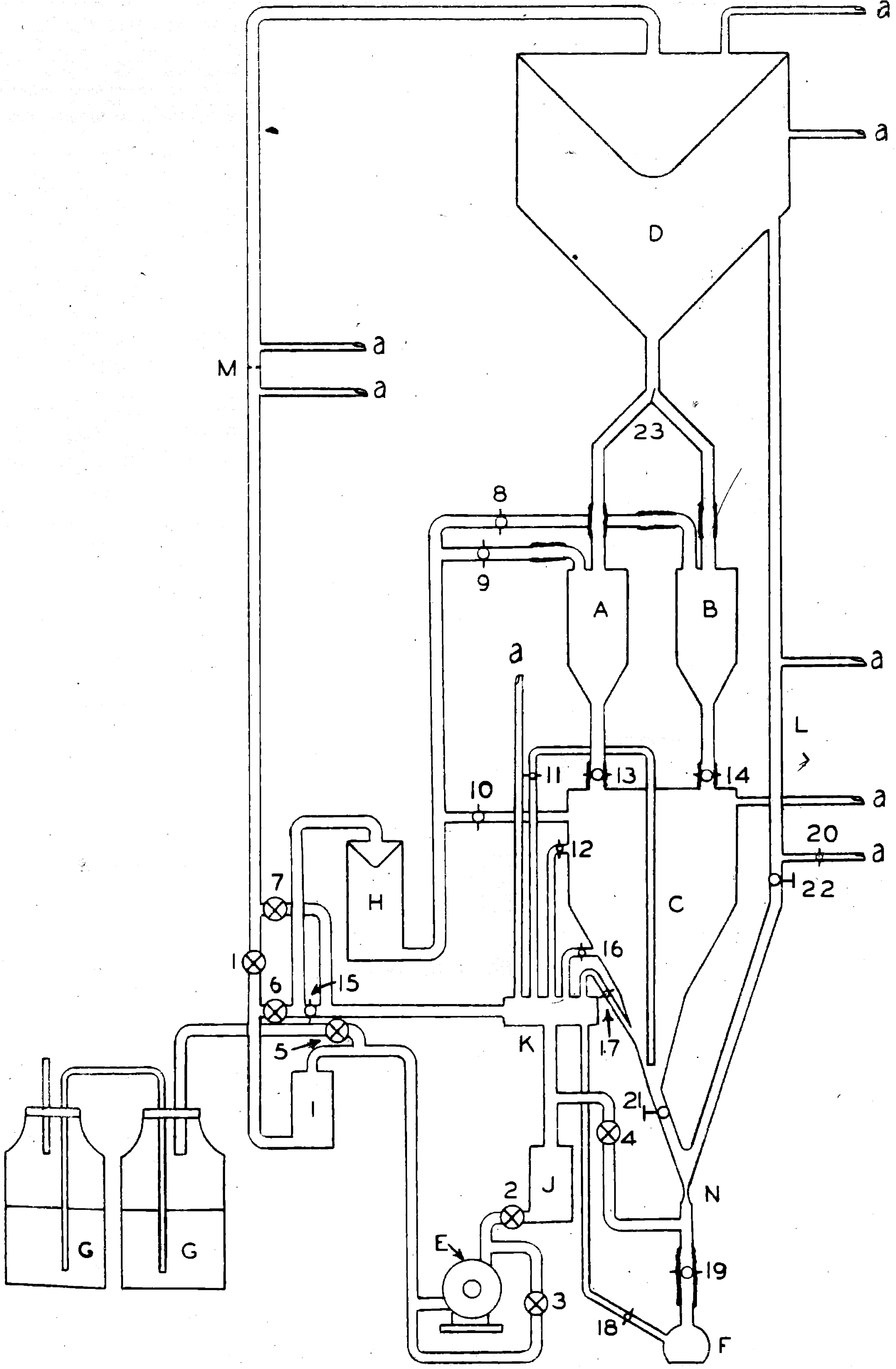
DESCRIPTION OF APPARATUS AND METHOD OF OPERATION

The apparatus used in this work is the same in principle as that used by Chambers. However, as Chambers used only air and felt that he might have errors in gas measurement, a new apparatus was built under his direction. This apparatus is a modification of the one used by Chambers and contains features which he found to be desirable during his previous work. It is a completely closed system, planned for use with gases other than air, the use of larger column diameters, and for greater capacity than could be reached in Chambers' original apparatus.

This is a description of the experimental apparatus, shown in the accompanying detailed sketch, and the method of operation. The apparatus consists of a vertical column of 1 in. tubing 100 in. in length, measured from butterfly valve 22 to the top, through which particles of solid from tank C are blown by gas from blower E.

Solid and gas are separated in separator D. The gas is filtered here and passes to a return tube where it is metered by means of orifice M. The solid falls into either of two weighing hoppers, A and B, selection being made by flapper valve 23. These hoppers are suspended from scales and as they are connected to the rest of the system by flexible

APPARATUS



W/D

rubber tubing, allow weighing of the contents. The solid is returned to the feed tank through pinch valves 13 and 14.

The gas from the return line passes through a dust filter I to the blower, which is equipped with by-pass and valve 3. The gas from the blower first passing through a filter to remove oil is distributed to a header K and also to the column through valve ~~1~~4. Lines from the header enter the feed hopper with pinch valves 11, 12, 16 and 17, this gas serving to agitate the solid and build up a pressure in the hopper.

Bottles G serve as a gas reservoir to compensate for pressure changes of the system during running conditions. Provisions for blowing the filter in separator D free from fine solid is made by reversing the air flow through it by means of valves 1, 6, 15 and 7. The dust laden air is returned to the blower through filter H which can also be blown free of solid by manipulation of the above valves. Manometers are connected to taps *a*.

Before beginning a run all valves except 1, 2, 3, 5 and 22 are closed. Then the motor which drives the blower E is started. The gas velocity is regulated by means of valve 4, and its magnitude is determined by the pressure drop across the sharp-edge orifice at M. Valve 3 on the blower by-pass is used to control the pressure in the header at K. The pressure in the feed chamber containing the solid particles is kept at the desired magnitude.

The feed rate at a particular gas velocity is controlled by adjusting valve 21. By means of the constriction at N the gas is given greater turbulence, and this results in a steadier flow of solid particles from the feed-chamber than would otherwise be obtained. In addition, the constriction serves to prevent the particles from sliding down into the dead space about valve 19 and partially stopping up the gas line, which, however, is only of secondary importance. The gas-fine particle mixture passes up the column L, to the separator D. The pressure drop is observed across 40 inches of the column at its bottom and also across the entire column.

Depending on the concentration of the clay in the column, the gas velocity drops off, and it becomes necessary to open valve 4 slightly more to restore the velocity to the magnitude at which it was initially set. By slightly opening valve 10, it is found that fluctuation in the gas velocity is decreased. However, if opened too far, the fluctuation is increased. Once adjusted, it is seldom necessary to change the setting of this valve for other gas velocities.

Until fairly steady conditions are obtained, the feed which passes up the column is allowed to fall in either hopper A or B by changing the position of valve 23. The initial weight is taken of the hopper into which the feed is to be passed during the run. When conditions become steady, the feed is switched to this hopper by flipping the valve. After an arbitrary time interval, measured by a stop-watch, the feed is switched back to the first hopper. The hoppers are connected to the apparatus by large rubber tubing and are suspended from scales in such a manner that these joints are always in compression. Hence the difference between the final and initial weight of the hopper is the correct weight of the clay which has passed over. This was determined by calibration.

After the final weight is taken, valves21 and 22 are closed and the motor stopped, all simultaneously. As soon as possible the valves leading to the feed-chamber from the header are closed to prevent these tubes becoming full of the solid. Valve 19 is then opened and the solid in the tube below valve 22 is run into the flask F and weighed. A length of thin-walled rubber tubing is used to attach the flask to the system in such a manner that the balance indicates the true weight. By opening valve 22, the solid trapped in the column is run into the flask sufficiently slowly to prevent any flowing up into the gas-line. This gives the weight of solid in the column of known dimensions, and from this the concentration can be obtained.

The solid is removed from the flask by starting the blower, opening valve 18, and turning the flask upside down. The removal is facilitated by preventing constriction in the flexible joint. Valves 13 and 14 are opened in order to return the solid from the weighing hoppers to the feed-chamber. By allowing the gas to bubble up through the solid in the hoppers, the dumping is hastened. The blower is again stopped, and all valves set as at the beginning of the run. At low feed rates it is possible to make a number of runs before it becomes necessary to empty the weighing hoppers.

The pressure drop across the filter in the tank D is occasionally noted, and its magnitude indicates the extent of the clogging of the filter. To unclog it, valves 2, 3, 5, 6, 7, 8 and 9 are opened and all others closed. The blower is started, and the gas is blown backwards through the filter snd unclogs it. It is also advisable to unclog the filter H from time to time. This is accomplished by opening valves 1,2,3, 5, 15, 8 and 9, all others being closed, and starting the blower.

The gas-holder G functions as a ballast to prevent too great a decrease in pressure in tank D when starting the blower. In a short time the pressure in the various parts of the system comes to equilibrium, and the water level in G becomes constant.

I and J are cotton-packed filters. The former serves to remove any solid particles that D and H fail to remove, whereas the latter removes oil droplets from the gas leaving the blower.

At low feed rates, such as two pounds a minute or less, the solid flows without the necessity of agitation. However, for high feed rates, gas is slowly bubbled through the fine particles by opening valve 17. In cases of very high feed rates it sometimes becomes necessary to open valve 11, producing further agitation near the feed valve.

It is found to be most convenient to weigh the weighing hoppers while the blower is running, and calibration showed that this did not produce any deviation from the true weight. In this manner it is possible to make checks on the constancy of the feed rate for a given set of conditions without shutting down by flipping valve 23, after an arbitrary time interval, and then weighing the hopper.

When running at high concentrations, it is found that the fine particles flow up the bottom pressure tap as soon as the blower is stopped. By closing valve 20 as soon as the blower is stopped, the gas in the line leading from the tap to the manometer is kept under pressure. When the column has been emptied, the solid is forced out of the top by opening this valve.

The pressure drop (ΔP) across the entire column at high concentrations is too large to be conveniently read on a manometer using water as the liquid. Instead, mercury is used. This has the disadvantage, however, of being inconvenient and not sufficiently precise at low concentrations. For these reasons close attention was given to the ΔP across 40 inches at the bottom of the column, and an occasional reading was noted during the run of the ΔP across the entire column.

When gas other than air is to be used as the transporting fluid, the system is filled with the desired gas. This is best accomplished by allowing the gas to flow slowly into separate parts of the system, displacing the air and sweeping it out with as little mixing as possible. Upflow is, of course, best for admitting carbon dioxide, and downflow is used for hydrogen. The system can be separated into smaller closed systems by the various valves which materially aids in building up a high gas concentration in each part independently of the others.

When it is believed that most of the air is displaced, the entire system is completely connected and run while gas is allowed to flow into the system at one point and purge at as great a distance from entrance as possible. In this way, if leaks are kept at a minimum, gas densities approaching that of the pure gas can be reached. Maintenance of this density under running conditions is not absolutely possible because of small leaks and occasionally the system must again be run while admitting gas and purging in order to keep the density within the desired range.

The density of the gas is determined by gas analysis in a high accuracy Orsat apparatus. Where carbon dioxide is the system fluid, the CO_2 is determined by adsorption in strong NaOH. In the case of hydrogen the oxygen is adsorbed in a solution of potassium pyrogallate and from this value the amount of air present is determined. The density found by gas analysis is occasionally checked by weighing a known volume of the gas.

All joints and rubber tubing in the system are kept gas tight and are carefully checked frequently to prevent leaks.

RESULTS

1. Glass Tube. Series A.

The column of the apparatus as originally built was made up of several sections of glass tubing held together by rubber connections. The approximate inside diameter was 1 inch, but did vary within a single piece and between different pieces from 0.972 inches to 1.032 inches.

In Series A a fine clay was transported by air in a vertical 1-inch glass column of 99 inches height. The clay, a filtering clay, bentonitic in character, was 70% through 200 mesh and 96% through 100 mesh. These runs were made in series of variable number at constant air velocity. During a run the pressure drop over the entire 99 inches of column and the bottom 37 inches was determined as were concentration within the column and the feed rate. Thus for a complete run three to five variables were measured, not all of which are independent as will later be seen.

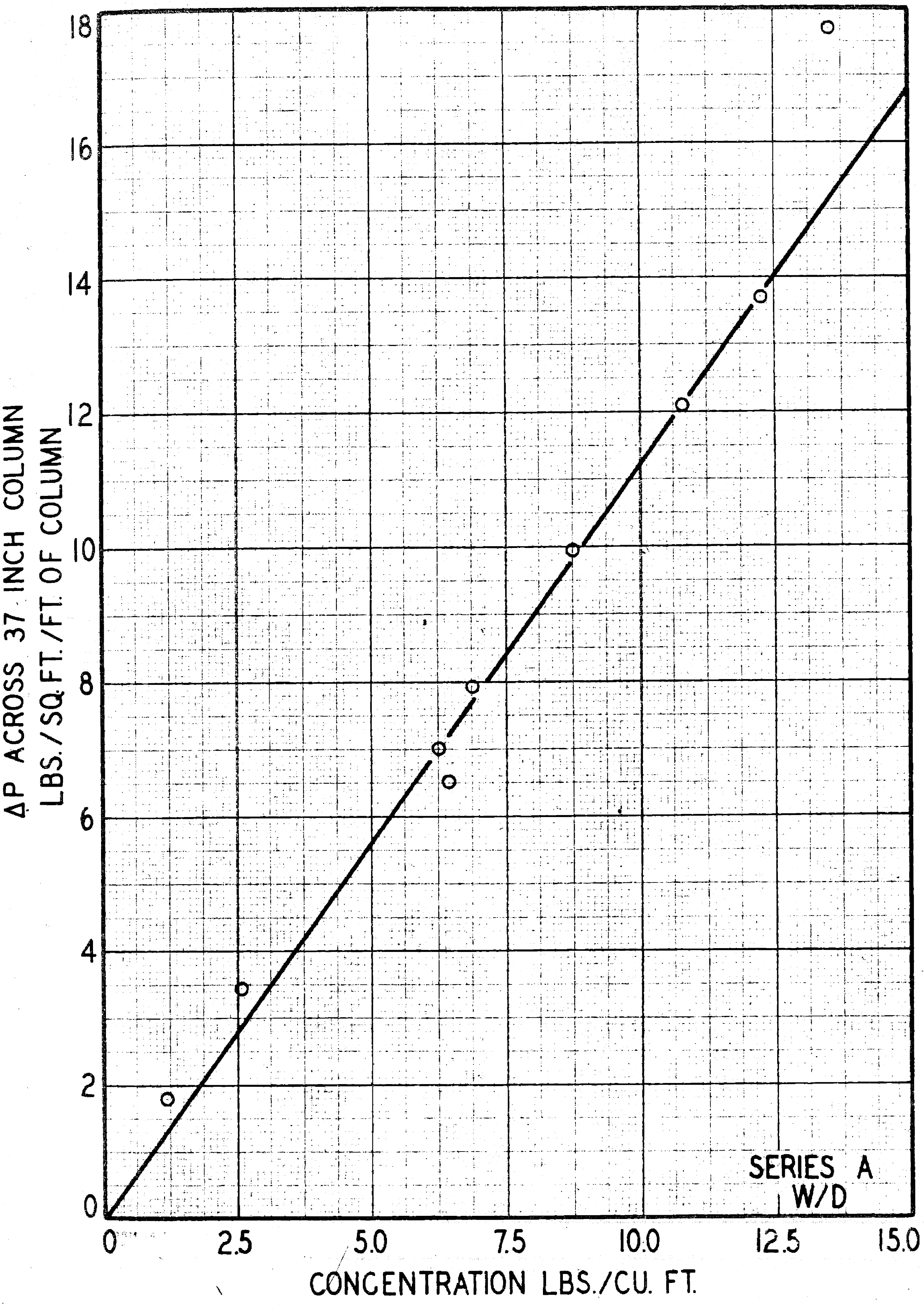
The pressure drops were measured by manometers and were expressed as pounds per square foot per foot of column height. Concentrations were measured by stopping a run instantaneously and trapping the solid within the column, then weighing the solid. From this weight and the known volumes of the column the concentration was found and expressed as pounds per cubic foot.

It is obvious that the pressure drop in a vertical column of mixed solid and fluid, where the solid is of much greater density than the fluid, should be a function of the solid concentration. Chambers (2) had found in a column of 5 ft. height that the pressure drop was approximately equal to the concentration. Because, if a correlation could be obtained the troublesome concentration determination for each run could be eliminated, a large number of the first runs were made to determine the relationship between pressure drop in the column and the concentration. These were made at the different air velocities employed in the later experiments. The tabulated data can be found in the Appendix. Runs which carry the same lower case letter are identical runs and have been used as averages.

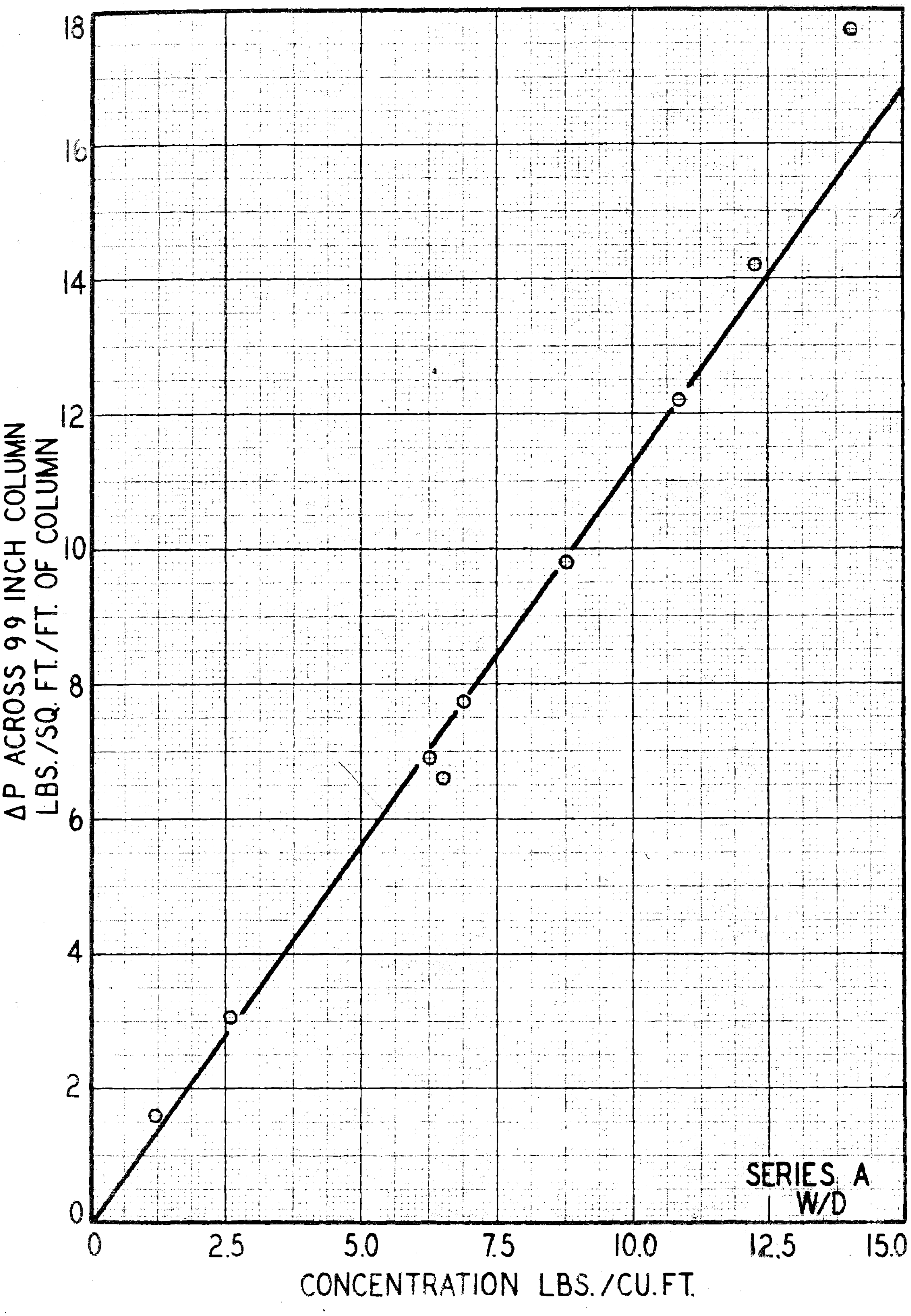
The data are presented in Plots I and II, Series A. Plot I is concentration (lbs./ft.^{3}) vs. pressure drop across the bottom 37 inches of column (lbs./ft.^{3}). Plot II is concentration vs. pressure drop across the entire 99 inches of column. It is to be noted that ΔP expressed as lbs. per square foot per foot of column height is in the same units as concentration, pounds per cubic foot.

The air velocity was measured by an orifice beyond the air-solid separator and is reported as feet per second of superficial air velocity in a 1-inch tube. Calibration of orifices can be found in the Appendix.

PLOT I-A


ΔP ACROSS 37 INCH COLUMN
LBS./SQ.FT./FT. OF COLUMN
0
2
4
6
8
10
12
14
16
18
0
2.5
5.0
7.5
10.0
12.5
15.0
CONCENTRATION LBS./CU. FT.
SERIES A
W/D

PLOT II - A



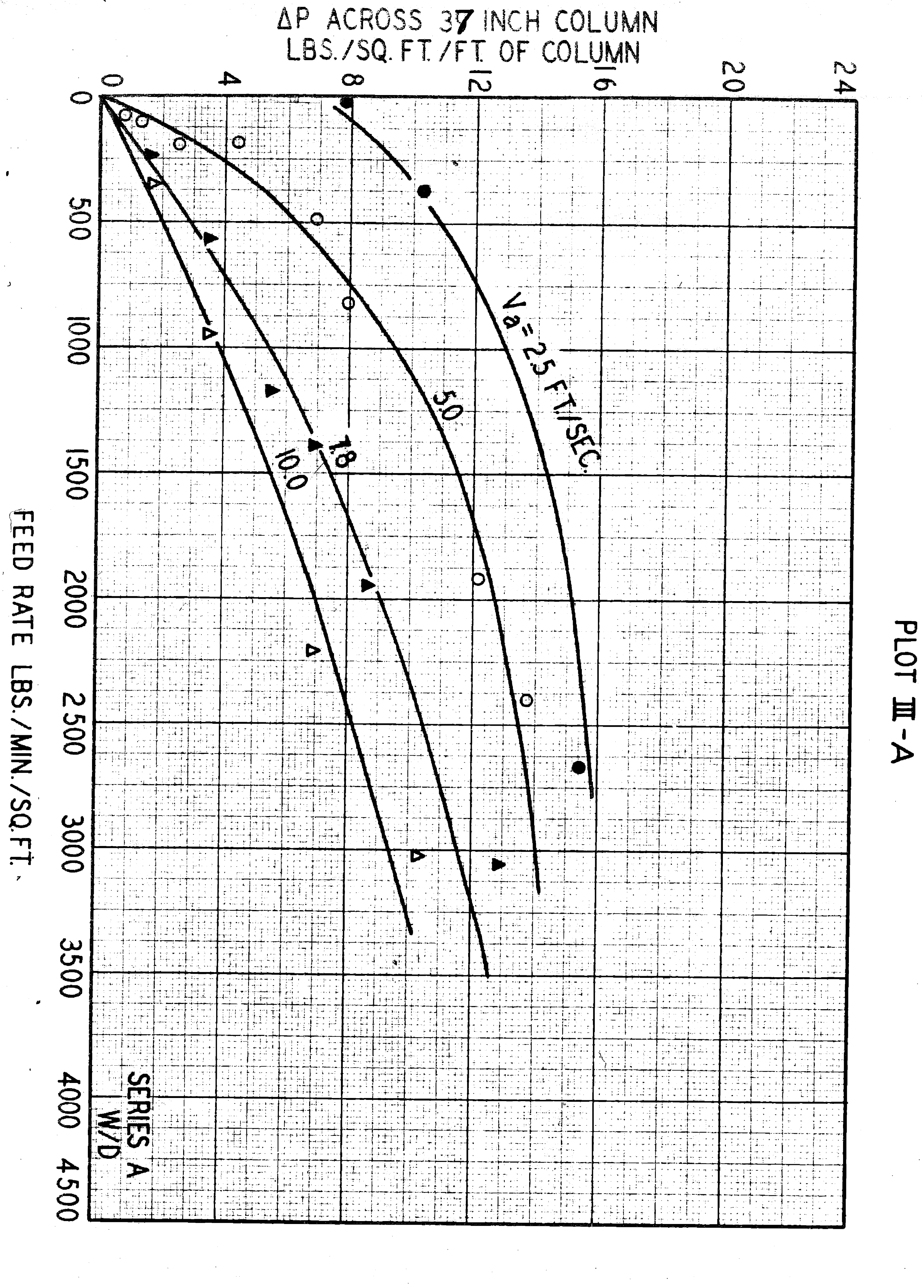
ΔP ACROSS 99 INCH COLUMN
LBS./SQ. FT./FT. OF COLUMN
0
2
4
6
8
10
12
14
16
18
0
2.5
5.0
7.5
10.0
12.5
15.0
CONCENTRATION LBS./CU. FT.
SERIES A
W/D

The feed rate was determined by weighing the solid transported in a given time. It is expressed as pounds per minute passing a square foot of cross section (lbs./min./sq.ft.). Several duplicate runs were made by switching the feed weighing hoppers while running. Thus pressure drops were measured on each run, but concentrations usually were determined on only one or two of these similar runs to serve as a check of the ΔP — concentration relationship.

The basic data tabulated in the Appendix are presented in Plot III, Series A. Here, pressure drop across 37 inches of column is plotted against feed rate giving curves at constant air velocity. Approximately the same results can be obtained by plotting concentration vs, feed rate, but as ΔP is expressed in the same units and more data are available they are presented in this manner. Concentration can be found by reference to Plot I. Most of the points on Plot III are averages of several runs.

2, Brass Tube. Series B.

From the results presented in Plots I and II, Series A it is seen that the pressure drop is somewhat greater than the concentration. This difference could not readily be explained by friction alone and the most logical explanation was that the constrictions and variations in the glass column were at fault. In order to eliminate these factors the glass tube was replaced by a brass tube of an exactly uniform



PLOT III-A

ΔP ACROSS 37 INCH COLUMN
LBS./SQ. FT./FT. OF COLUMN
0
4
8
12
16
20
24
FEED RATE LBS./MIN./SQ.FT.
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Va = 2.5 FT./SEC.
5.0
1.8
10.0
SERIES A
W/D

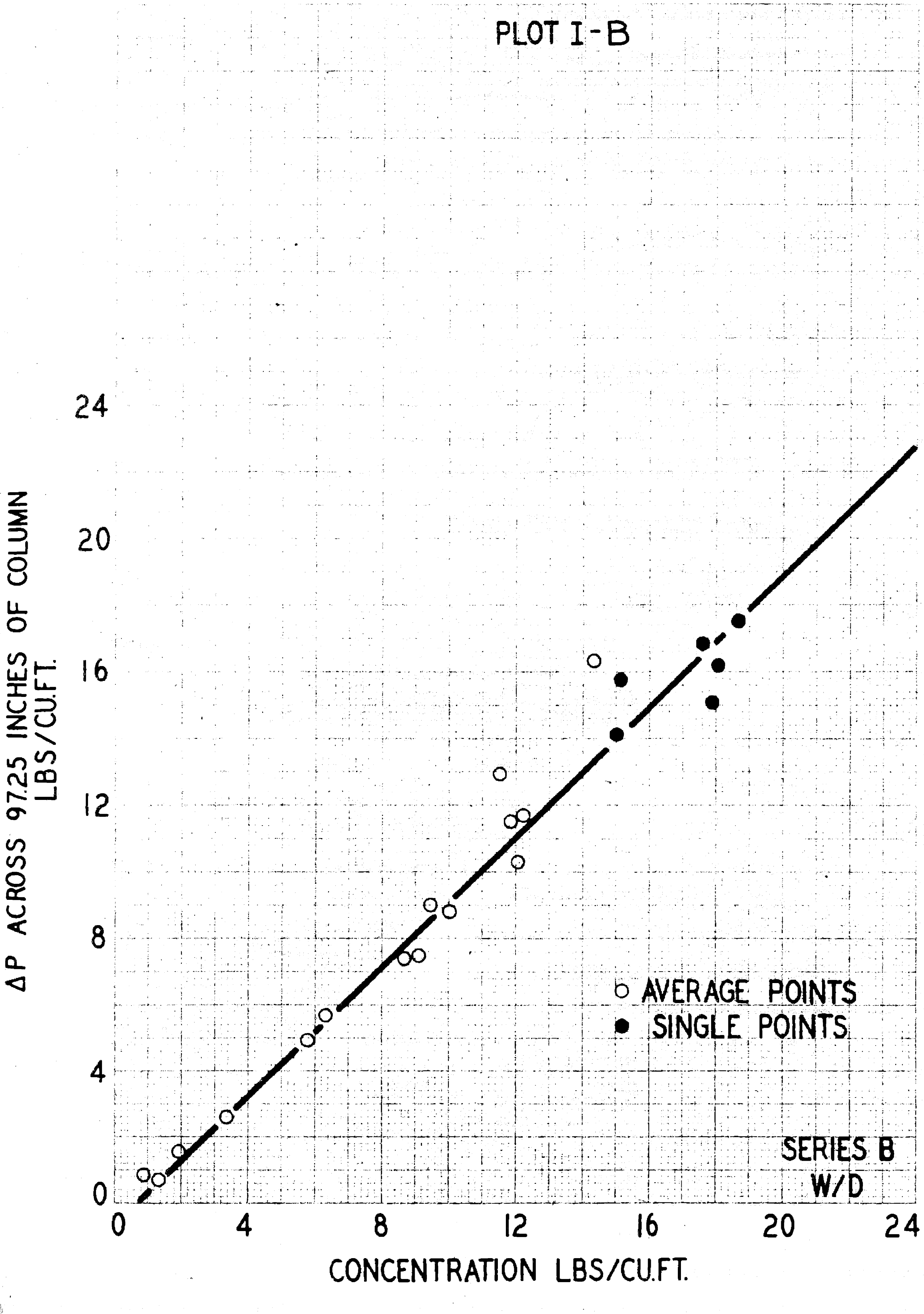
inside bore 1.011 inches i.d. At the top of this tube a short piece of glass tube was placed to serve as a sight glass. The inside diameter of this glass tubing was substantially equal to that of the brass tube.

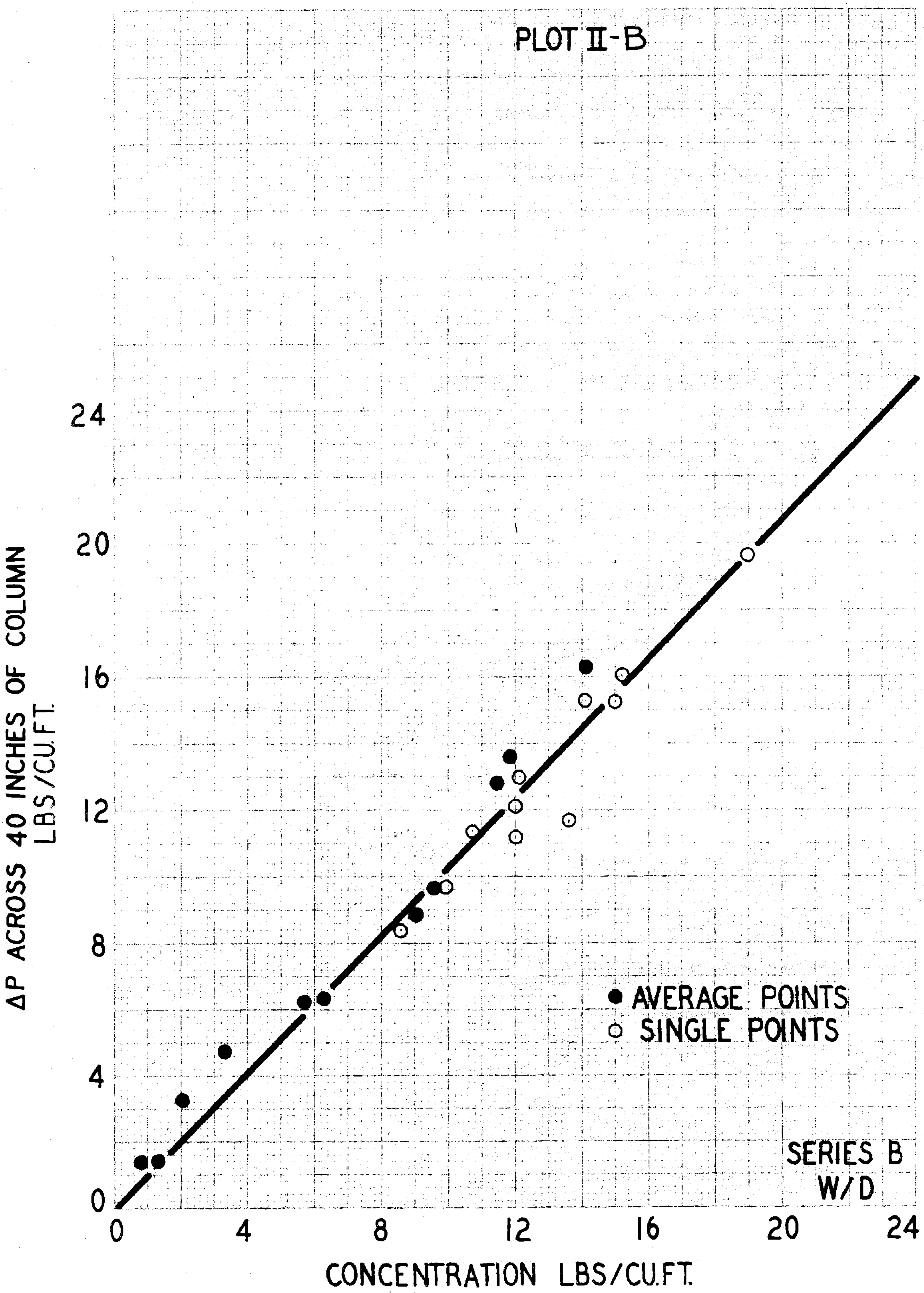
Again, as in Series A, a large number of points were determined to obtain the relationship between concentration and pressure drop across the entire column, now 97.25 inches, and the bottom 40 inches of the column. Concentrations, pressure drops, and feed rates were determined and expressed as in Series A. The tabulated data can be found in the Appendix, Table 1, Series B. Plots I and II, Series B present the relationship between pressure drops and concentration.

Plots IV and V, Series B present the basic data of pressure drop vs. feed rate at constant air velocity. In these it is to be noted that the air velocities are not the same as in Series A, but cover the range of low air velocities from 4 to 1 ft./sec. This gives regions of high concentration at lower feed rates, the regions considered the most important to study in this limited work.

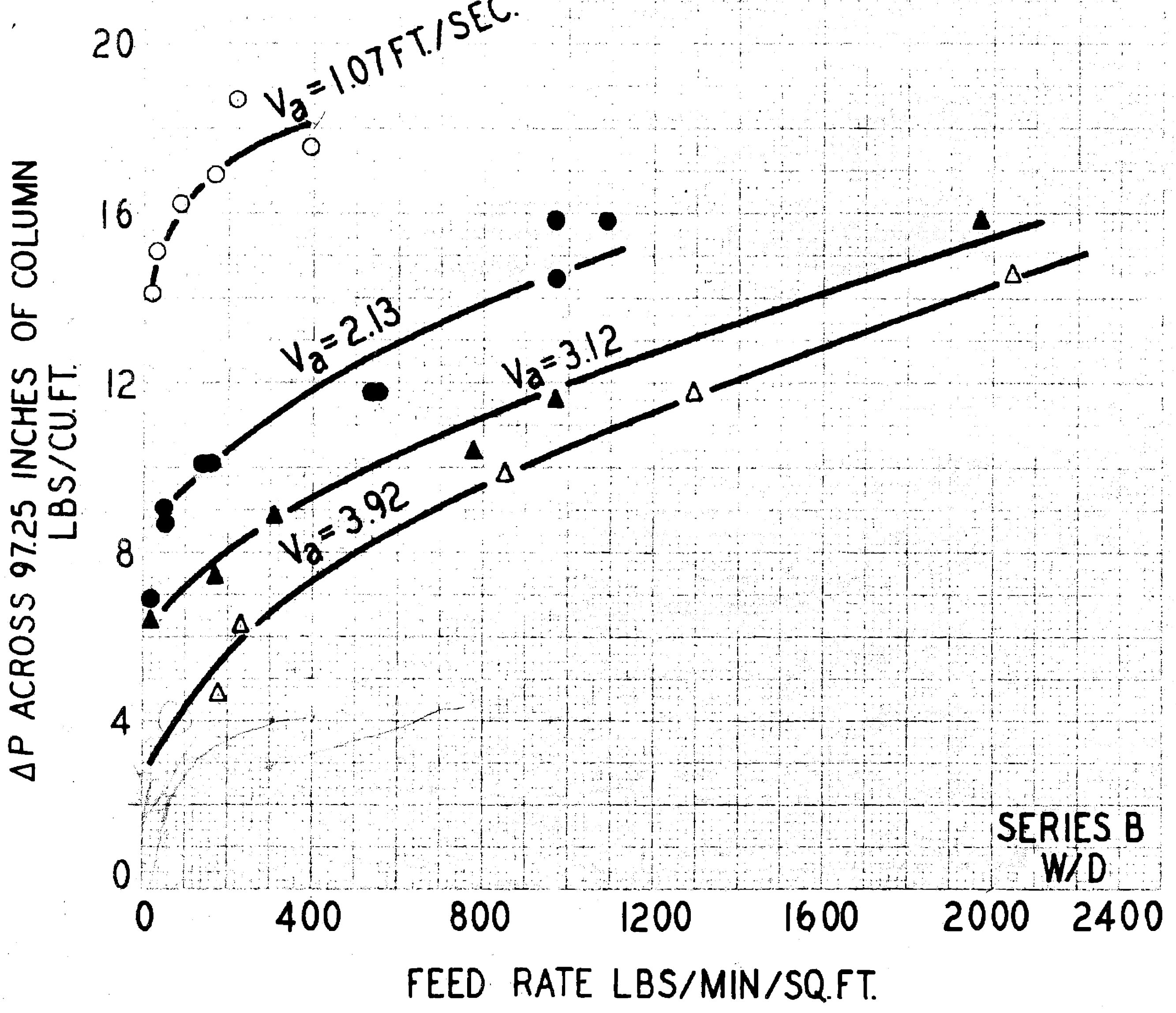
The curves of air velocity 2.13 and 1.07 feet per second are not to be extrapolated beyond the point drawn. It was observed in the runs at 1.07 feet per second, when feed rates are slightly greater than 400 lbs./min./sq.ft. were reached that the column concentration became so high that air ceased to flow through the mixture and the column became tightly

PLOT I-B


ΔP ACROSS 97.25 INCHES OF COLUMN
LBS/CU.FT.
24
20
16
12
8
4
0
0
4
8
12
16
20
24
CONCENTRATION LBS/CU.FT.
○ AVERAGE POINTS
● SINGLE POINTS
SERIES B
W/D

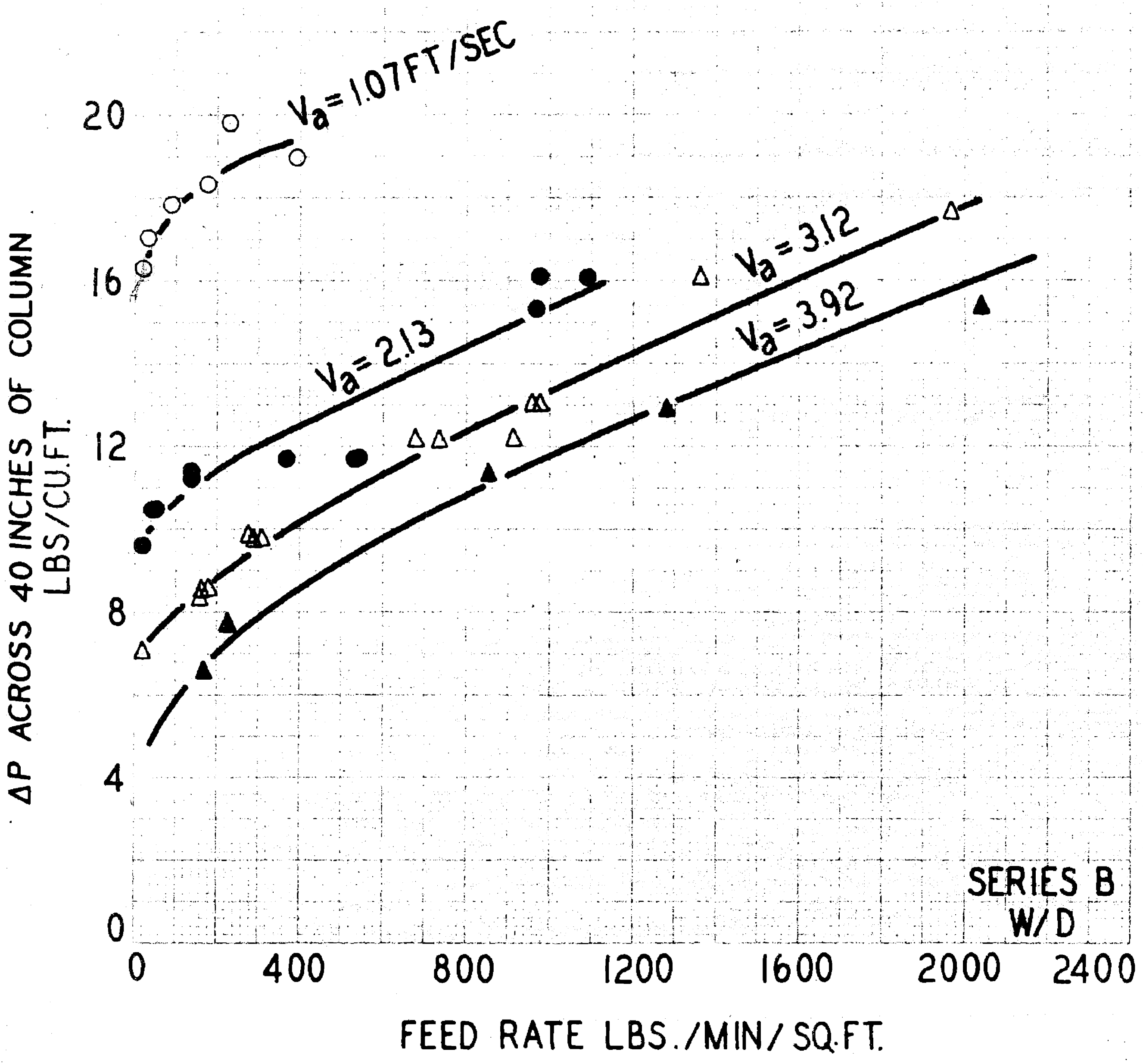

PLOT II-B
ΔP ACROSS 40 INCHES OF COLUMN LBS/CU.FT.
CONCENTRATION LBS/CU.FT.
0
4
8
12
16
20
24
0
4
8
12
16
20
24
● AVERAGE POINTS
○ SINGLE POINTS
SERIES B
W/D

PLOT IV -B



Va = 1.07 FT./SEC.
Va = 2.13
Va = 3.12
Va = 3.92
ΔP ACROSS 97.25 INCHES OF COLUMN
LBS/CU.FT.
20
16
12
8
4
0
0
400
800
1200
1600
2000
2400
FEED RATE LBS/MIN/SQ.FT.
SERIES B
W/D

PLOT V-B


Va = 1.07 FT/SEC
Va = 2.13
Va = 3.12
Va = 3.92
SERIES B
W/D
ΔP ACROSS 40 INCHES OF COLUMN
LBS/CU.FT.
0
4
8
12
16
20
0
400
800
1200
1600
2000
2400
FEED RATE LBS./MIN/ SQ.FT.

packed with clay and transport of solid ceased. Thus the upper end of this curve represents the maximum feed rate and concentration attainable at this air velocity in a 1 inch tube 97.25 inches high.

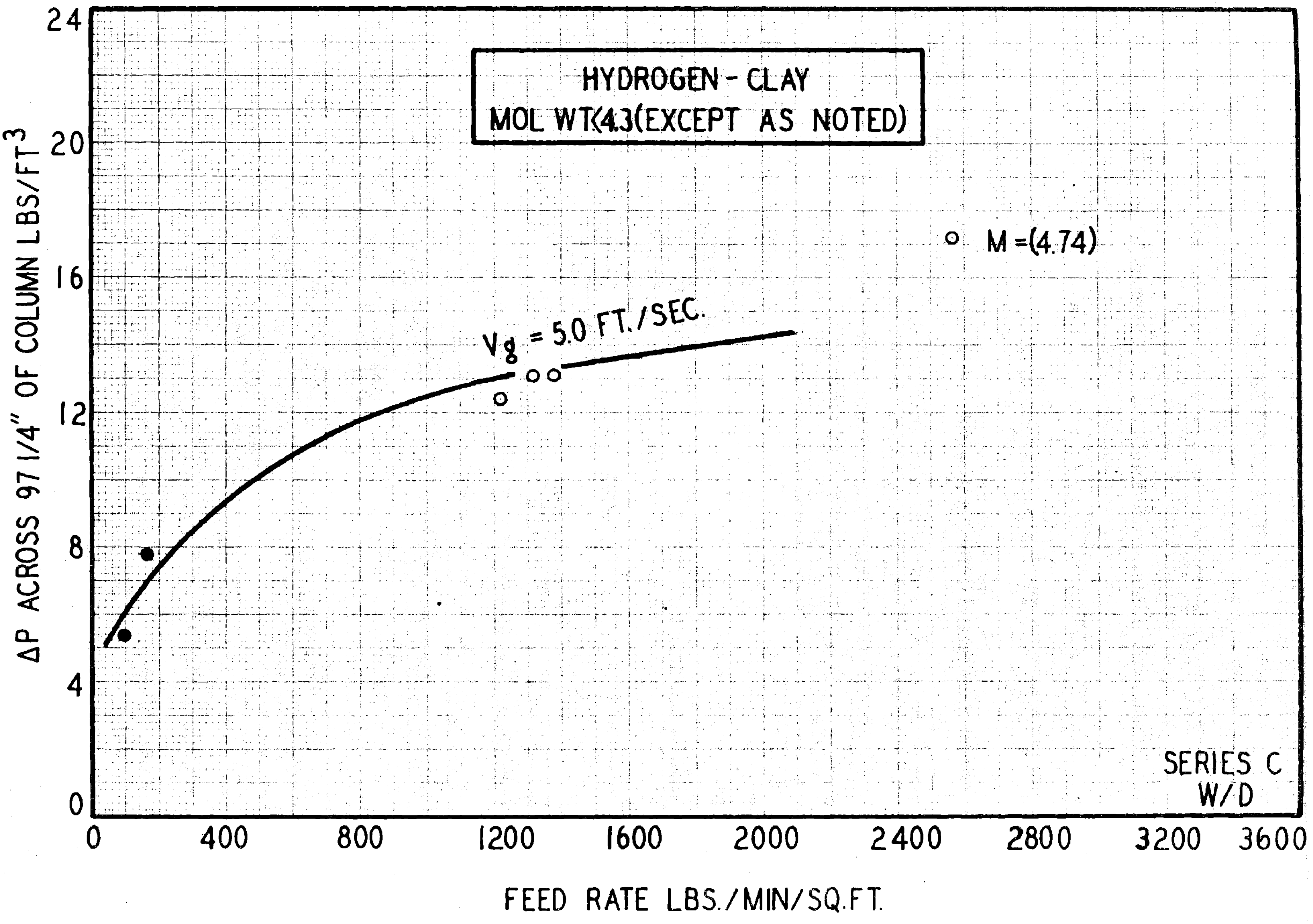
The lowest feed rate range of this curve, that is, the left end, is probably not representative of homogeneous transport conditions. It was observed that below this point the solid only filled the column to near the top with particles elutriating over into the separator. Under these conditions the clay in the column acts like a liquid with a definite liquid level, the solid passing over doing so by passing from this dense level to a dilute or vapor phase and blowing over. This level of concentrated solid did fluctuate over several inches of height and the left end of the curve while believed to be representative of the lowest range of true transport may be influenced by this variable level. The curve drawn represents the narrow range in which transport or homogeneous flow conditions are known to exist for the materials and conditions employed.

The data from the runs in the vertical brass tube using clay as the solid and CO_2 as the transporting fluid, are presented in the Appendix, Table I, CO_2 Runs.

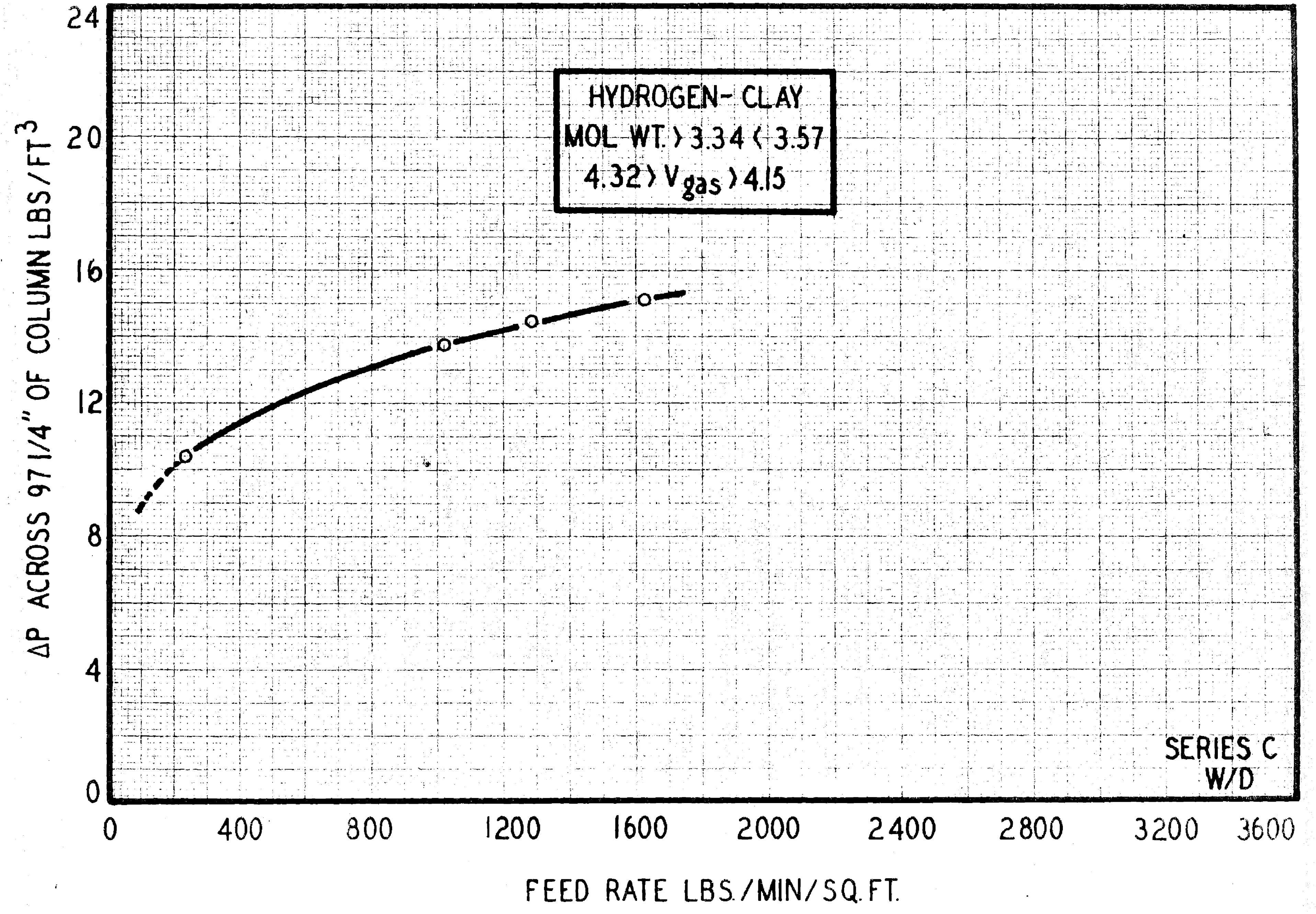
These data are not presented as curves as they fall almost on the corresponding air curves. A table of them with corresponding calculated data will be found in Discussion of Results. The gas velocities reported were calculated from gas density and the air orifice calibrations.

The Hydrogen-Clay Runs, Series C are reported as tabulated data in the Appendix, Table I, Series C. Here the gas velocities reported were calculated from gas density and air orifice calibrations. Concentrations, pressure drops and feed rates were determined as in Series B. The gas density varied from run to run and is reported as original data. The results are grouped into two sets of different gas velocities and molecular weight of transporting gas. These data are presented graphically in the customary manner in Plots I and II, Series C.

PLOT I-C


HYDROGEN - CLAY
MOL WT(4.3(EXCEPT AS NOTED)
M =(4.74)
Vg = 5.0 FT./SEC.
SERIES C
W/D
24
20
16
12
8
4
0
0
400
800
1200
1600
2000
2400
2800
3200
3600
ΔP ACROSS 97 1/4" OF COLUMN LBS/FT3
FEED RATE LBS./MIN/SQ.FT.

PLOT II - C


HYDROGEN- CLAY
MOL. WT. ⟩ 3.34 ⟨ 3.57
4.32 ⟩ V_{gas} ⟩ 4.15
SERIES C
W/D
ΔP ACROSS 97 1/4" OF COLUMN LBS/FT^3
0
4
8
12
16
20
24
0
400
800
1200
1600
2000
2400
2800
3200
3600
FEED RATE LBS./MIN/SQ.FT.

DISCUSSION OF RESULTS

Each point on the experimental diagrams presenting the data corresponds to a separate run or an average of several duplicate runs, generally in which five quantities were measured. These were total pressure drop across the column, which in this work was nearly 100 inches high; the pressure drop across the lower 40 inches of the column; the feed rate, i.e., the rate at which clay was being fed and discharged; the superficial gas velocity; and finally the average concentration of clay in the whole column. All these runs were conducted under steady conditions of flow where true transport of solid by fluid existed. Series A was run in a column of glass tubes; Series B, C, and CO_2 Runs were made with a brass tube.

In interpretation of the data it is imperative to keep in mind two facts: first, that there are surges in flow so that the significant factors are the average values of the quantities measured during a run, and second, that, while the methods of measurement of pressure and flow rates tend to give such average values, the measurements of concentration in the column inevitably are determinations of point conditions, any one of which is almost sure to be unrepresentative of average conditions. These facts do induce deviations in results, but it is felt that the general relationship obtained by drawing smooth curves among the data points are quite representative. Furthermore, it is believed that the order of deviations of the experimental points from the curves fairly well represents the probable errors.

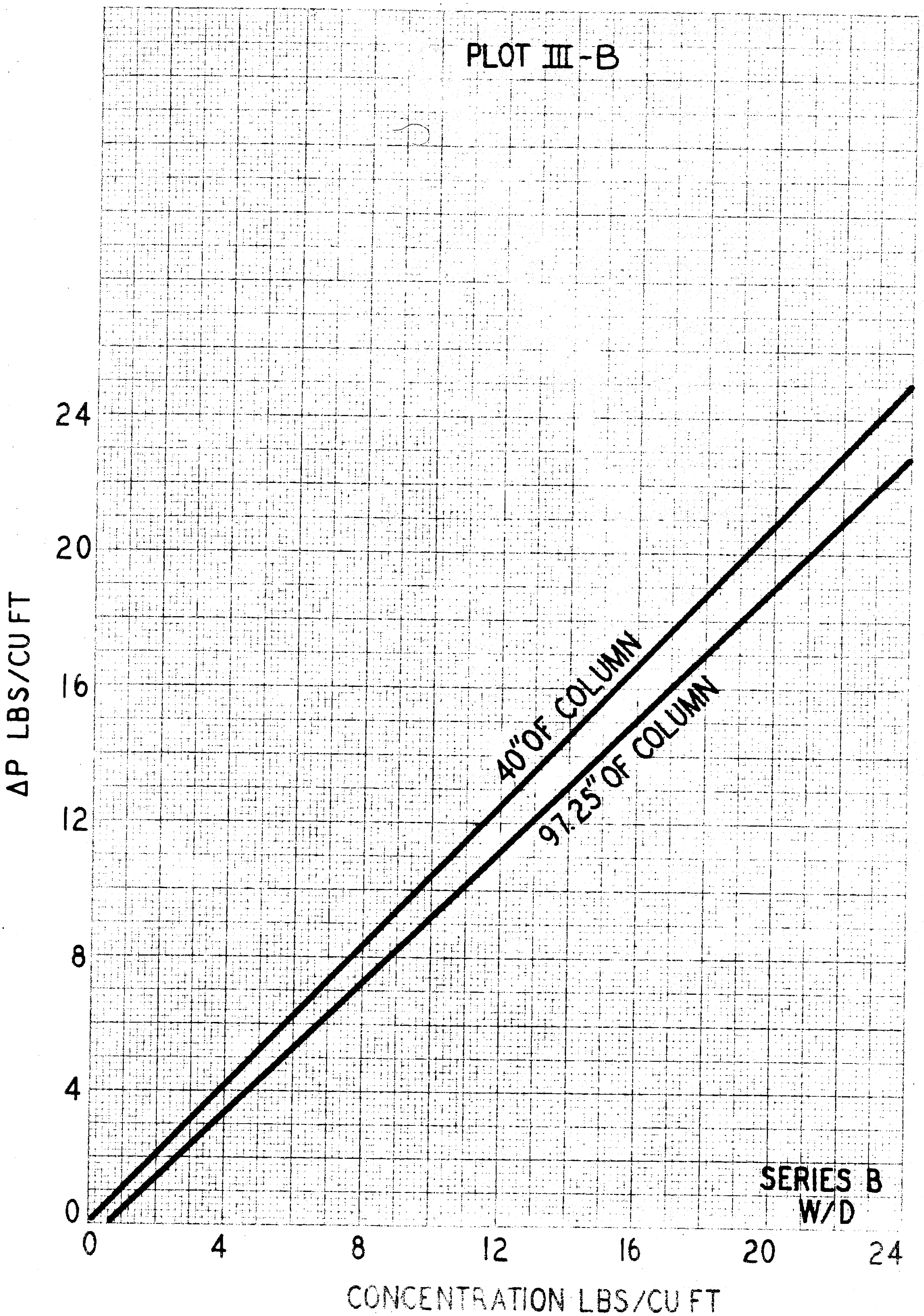
The pressure gradiant, as noted before, is expressed in lbs. per cu.ft., i.e., as lbs. per sq.ft. for each foot of column height. This makes it comparable, in the same units, with concentration, lbs. per cu.ft. Plots I and II, Series A representing the data on the glass tube, show that the pressure drop is considerably greater than the concentration. This difference is too large to be explained as a frictional drop along the tube. The glass tubes making up the glass column were later found not to be of uniform diameter and the excessive pressure drop was assumed to be due to the slight constrictions in the tube. Because of this fact, the data of Series A are considered to be less dependable, but are included as they extend the range of Series B.

Plot I, Series B shows that the measured pressure drop in the column as a whole is about 5% less than the measured concentration. The reason for the direction of the divergence is not clear, but it is concluded that it is probably due to the difficulty of elimination of disturbing effects at pressure taps. It is felt that the pressure gradient over the entire column is essentially equal to the concentration.

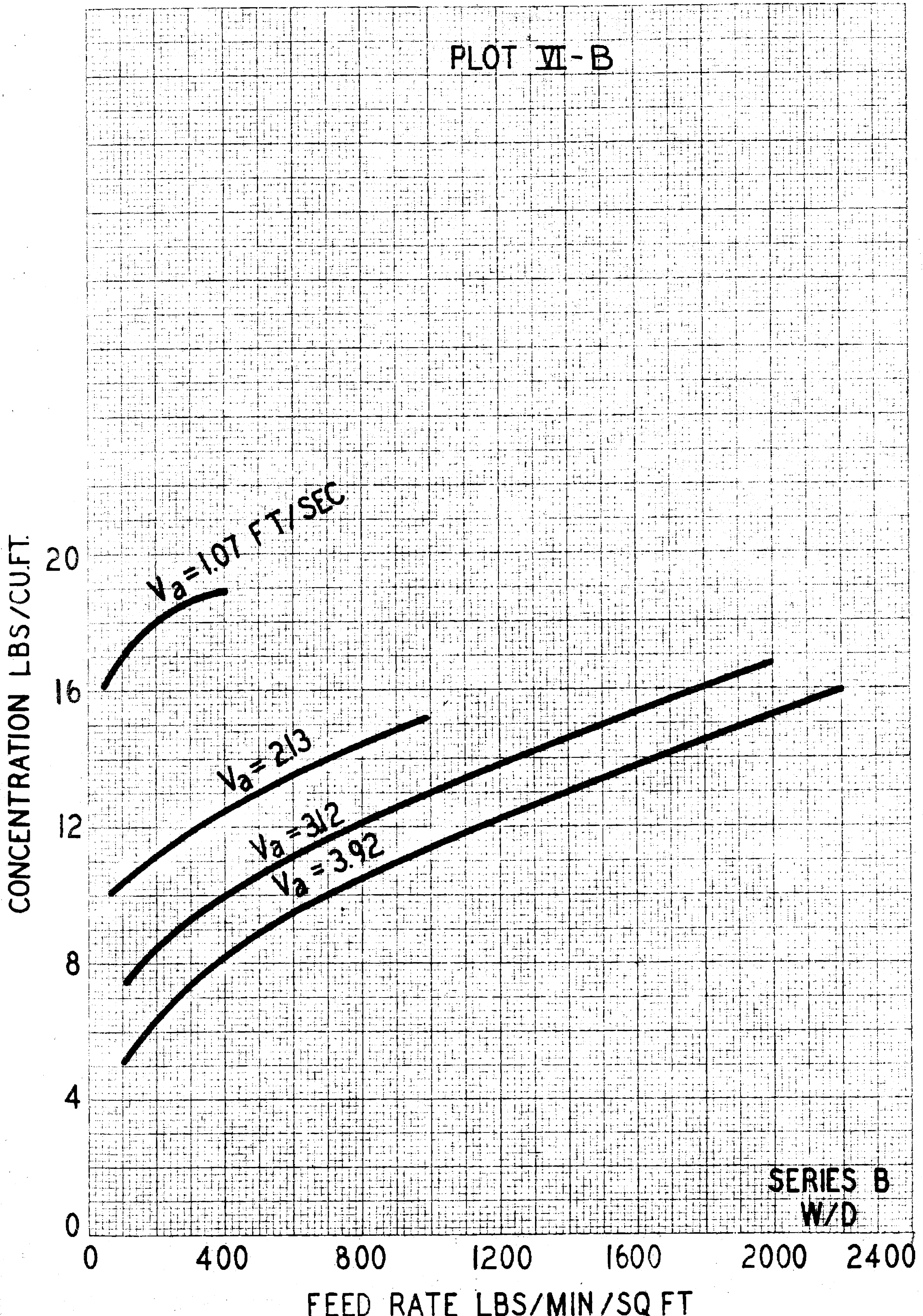
Plot II B shows that the pressure drop in the bottom 40 inches of the tube is about 5% higher than the average concentration in the whole tube. While this might be due to the lack of the same disturbing effects as over the entire column it is believed that the added pressure gradient is a "barometric" effect. The fluid-fine particle mixture consists of a solid and a gas and because the lower portion of the column must support that above it, it is reasonable to assume that the mixture is more dense, that is, greater concentration. The mixture becomes as if compressed, with more solid particles filling the voids of gas. This increased concentration obviously would cause a greater pressure drop per foot of height at the bottom of the tube than the average pressure drop per foot of height caused by the fluid whose concentration decreases from bottom to top.

Plot III B presented here reproduces the two preceding plots for use without the confusion of the experimental points.

The data in the glass tube are presented in Plot III A and for the brass tube and air in Plots IV and VB. Plot VI B is constructed from the preceding two together with IIIB. This is believed to be the best presentation of the relationship between concentration in the entire tube, and the feed rate at constant air velocity.


PLOT III-B

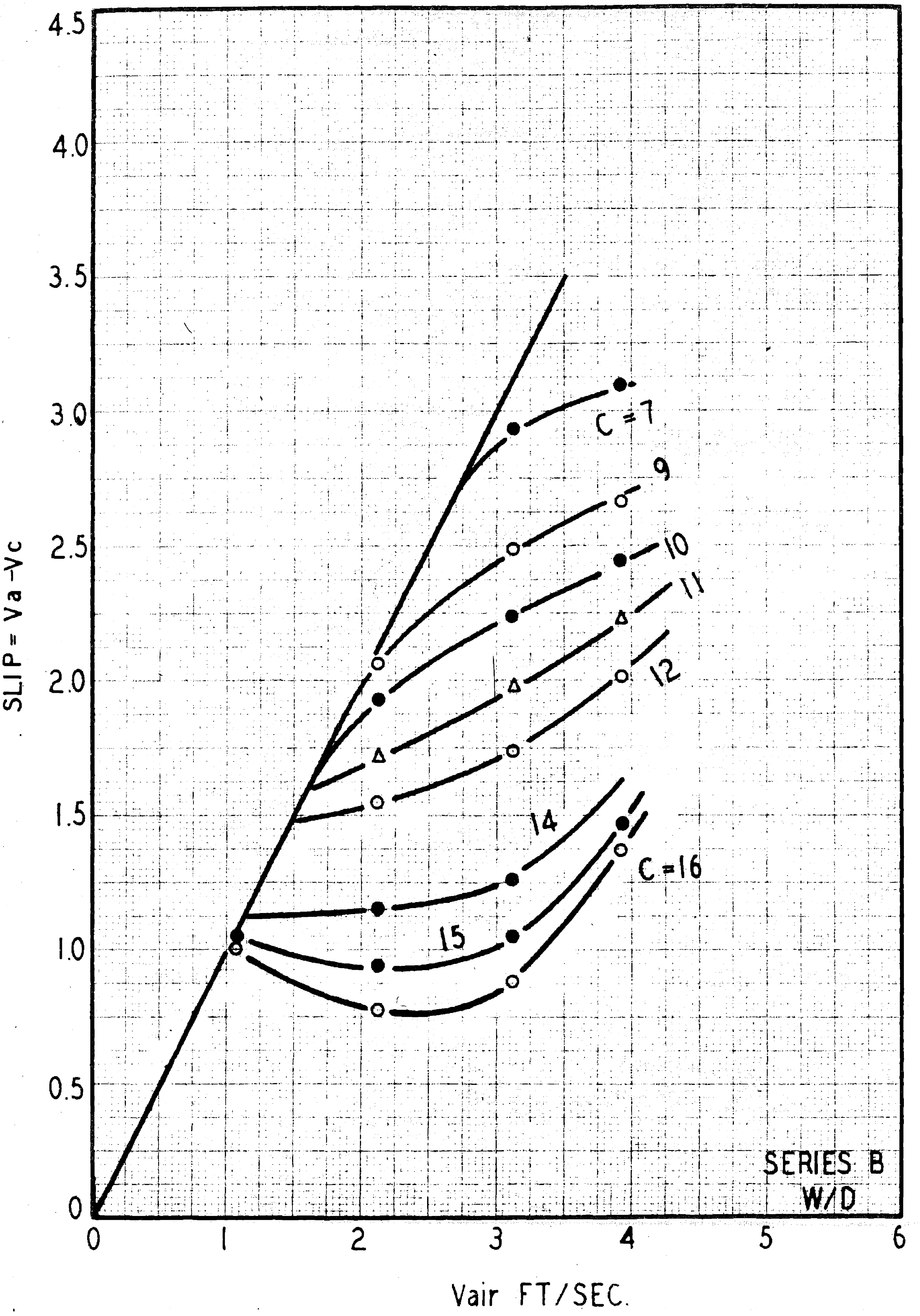
ΔP LBS/CU FT
0
4
8
12
16
20
24
CONCENTRATION LBS/CU FT
0
4
8
12
16
20
24
40" OF COLUMN
97.25" OF COLUMN
SERIES B
W/D


PLOT VI-B
CONCENTRATION LBS/CU.FT.
0
4
8
12
16
20
V_a=1.07 FT/SEC
V_a=2.13
V_a=3.12
V_a=3.92
SERIES B
W/D
0
400
800
1200
1600
2000
2400
FEED RATE LBS/MIN/SQ FT

The shape of these curves both in Series A and B are seen to be the same general shape as those found by Chambers. It is to be noted that at the same air velocity and same feed rate these curves show a higher concentration than is reported by Chambers. His curves are, however, for the transport in a column of 67 inches while those presented here are for a column 100 inches in height. The curve of 7.8 feet per second in Series A is the only one directly comparable with data by Chambers. Comparison of these two curves at 7.8 ft. per sec. shows that the curve for Series A is higher in concentration at the same feed rate. This increase after a feed rate of 1000 is a remarkably constant amount and expressed as ΔC/ΔF is equal to approximately 0.5/1000. That is, for every 1000 increase in feed rate the concentration of 7.8 ft./sec., Series A is 0.5 higher than the 7.8 ft./sec. determined by Chambers. The fact that this relation does not hold below a feed rate of 1000 is probably due to the error of extending the curve to the origin. As is seen in Series B the curves as they approach zero feed rate may become discontinuous for transport conditions, the actual conditions being those of elutriation. Thus, there may be a correlation between the height of column of mixture lifted and concentration at the same air velocity and feed rate. Obviously, data must be obtained on different heights of columns to substantiate this. However, it is easily seen that the "barometric" effect mentioned before would cause an increase in the average concentration for a column of greater height at the same conditions of feed rate and air velocity over that in a shorter column.

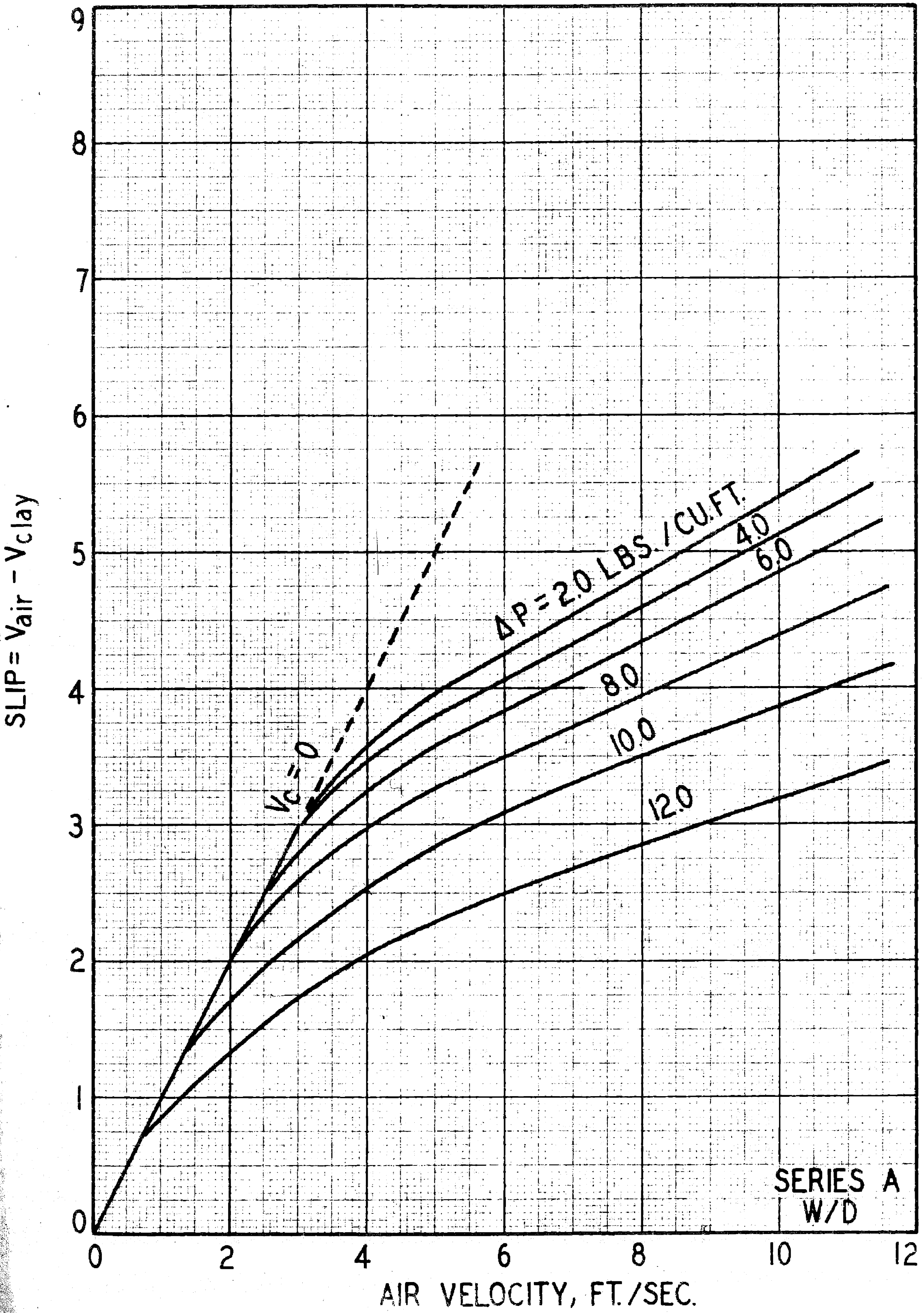
The actual mechanism by which a particle is supported and moved by a rising gas is the frictional force of the gas moving past the particle. Then, the variable which really determines the movement of particles suspended in a rising gas is certainly the difference in velocity between the gas and the particle, that is, the slip, S. It is perhaps best defined as $S = V_a - V_c$, gas velocity less clay velocity (ft./sec.). These velocities of necessity must be averages. As clay velocity can not be measured directly it is defined as $V_c = R/C$ where R is the clay feed (transporting) rate (lbs./sq.ft./sec.) and C is the clay concentration (lbs./cu.ft.). V_a is here taken as the superficial air velocity which in these experiments never differed from the actual velocity allowing for voids by even as much as 15%. Since R, C and V_a were measured, S is readily computed and is presented in Plot VIIB and IVA as a function of air velocity at constant clay concentration. These are constructed curves, VIIB being constructed from the curves of IVB, using the ordinates of IV

PLOT VII - B



4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
SLIP = Va - Vc
0
1
2
3
4
5
6
Vair FT/SEC.
C = 7
9
10
11
12
14
15
C = 16
SERIES B
W/D

PLOT IV -A

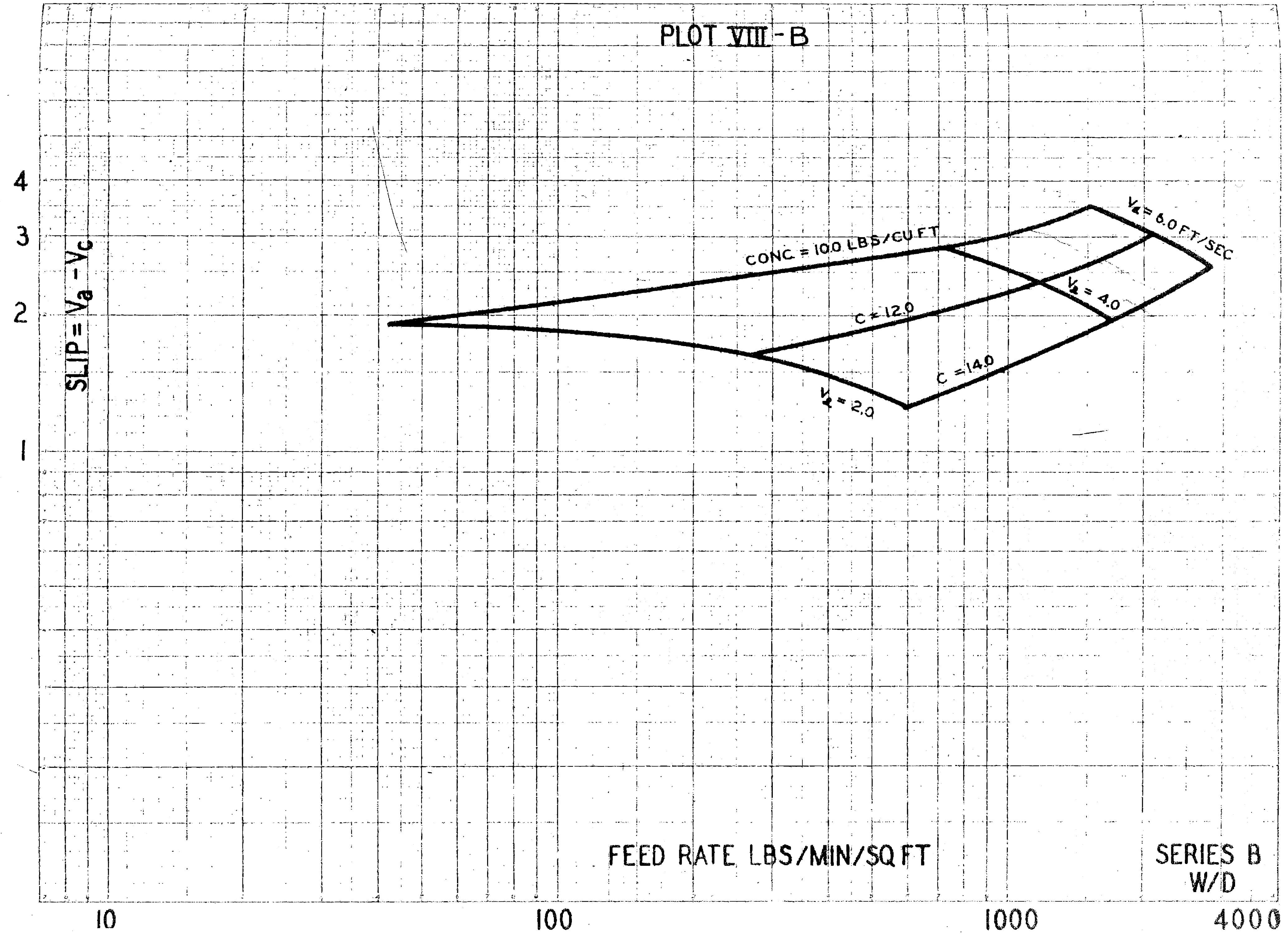

SLIP = $V_{air} - V_{clay}$
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
AIR VELOCITY, FT./SEC.
ΔP = 2.0 LBS./CU.FT.
4.0
6.0
8.0
10.0
12.0
$V_c = 0$
SERIES A
W/D

as concentrations, because it is felt that IVB represents the most dependable basic data at present available. The points on VIIB are construction points and not experimental. At S = V_a, V_c is zero, hence the curves have no physical meaning whatever to the left of the 45° line.

The curves of plot IVA are not considered to be fully representative of the actual condition. First, because of the error in Series A measurement and secondly, the curves close to the 45° line are extrapolated. It is presented, however, as the shape of the curves to the right are thought to represent the actual conditions. It does extend the range of VIIB and may prove of value in this respect.

Plots VIIIB and VA indicate another possible way of correlating relationships, but it is believed that the following plots are more helpful. These plots confirm the conclusions of Chambers that as concentration increases at constant air velocity, the slip decreases because of increased friction due to the gas flowing through the smaller voids. That this slip, while smaller, should produce a higher friction thus transporting solid at a high concentration is reasonable and the data confirm this postulate.

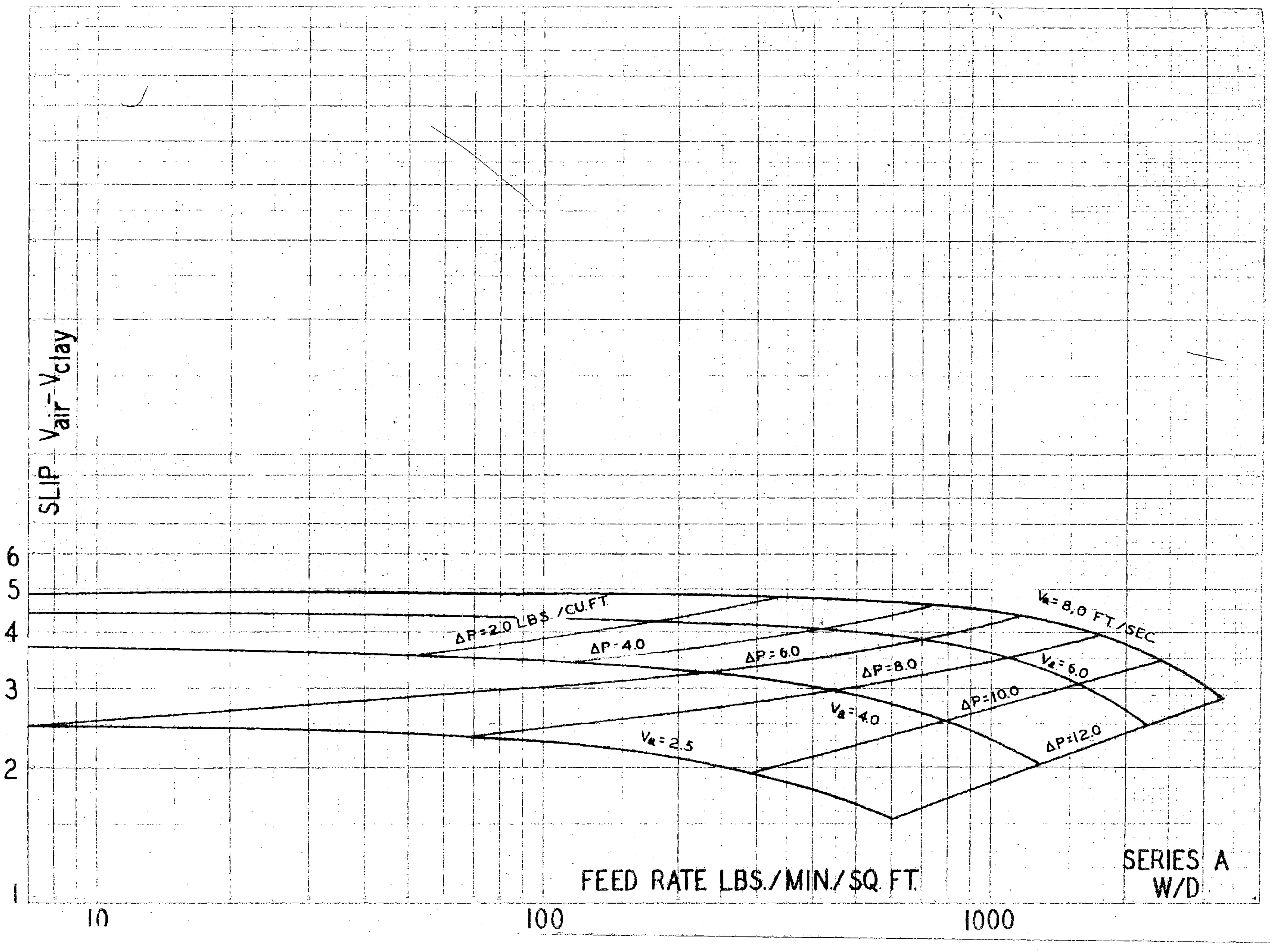
These plots do, however, show that at constant clay concentration, slip increases with increased feed rate. At very low feed rates, slip should be equal to the free falling velocity and



PLOT VIII-B

SLIP = $V_a - V_c$
4
3
2
1
10
100
1000
4000
FEED RATE LBS/MIN/SQ FT
SERIES B
W/D
CONC = 10.0 LBS/CU FT
C = 12.0
C = 14.0
V_a = 6.0 FT/SEC
V_a = 4.0
V_a = 2.0

PLOT V-A

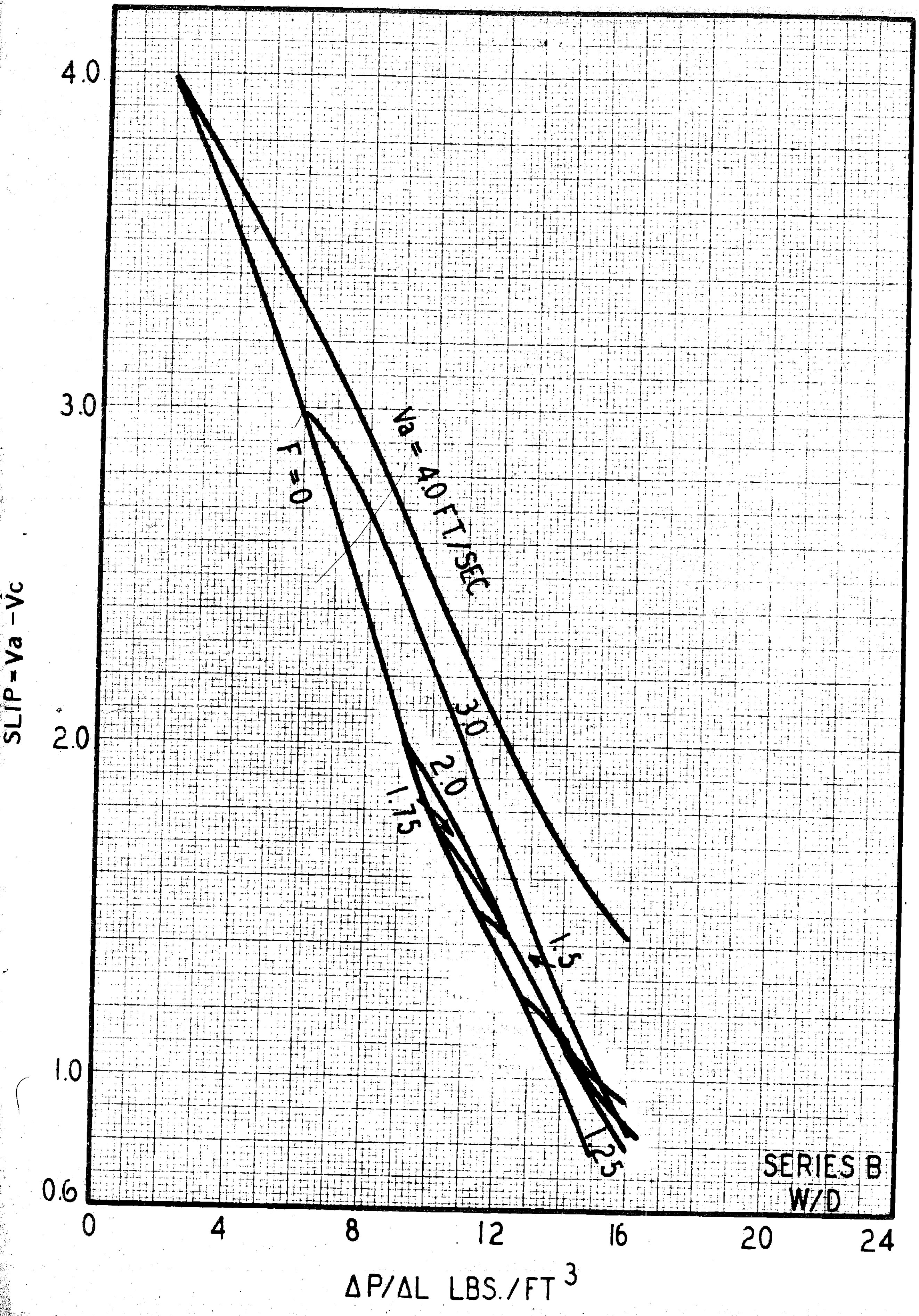

SLIP $V_{air} - V_{clay}$
6
5
4
3
2
1
10
100
1000
FEED RATE LBS./MIN./SQ. FT.
SERIES A
W/D
V_a = 8.0 FT./SEC
V_a = 6.0
V_a = 4.0
V_a = 2.5
ΔP = 2.0 LBS./CU.FT.
ΔP - 4.0
ΔP = 6.0
ΔP = 8.0
ΔP = 10.0
ΔP = 12.0

independent of the rate of feed. When conditions of higher feed rate and high concentrations are reached, slip increases probably due to the introduction of a greater amount of friction of the particles on each other, the overall frictional force being that of the mixture on the tube walls.

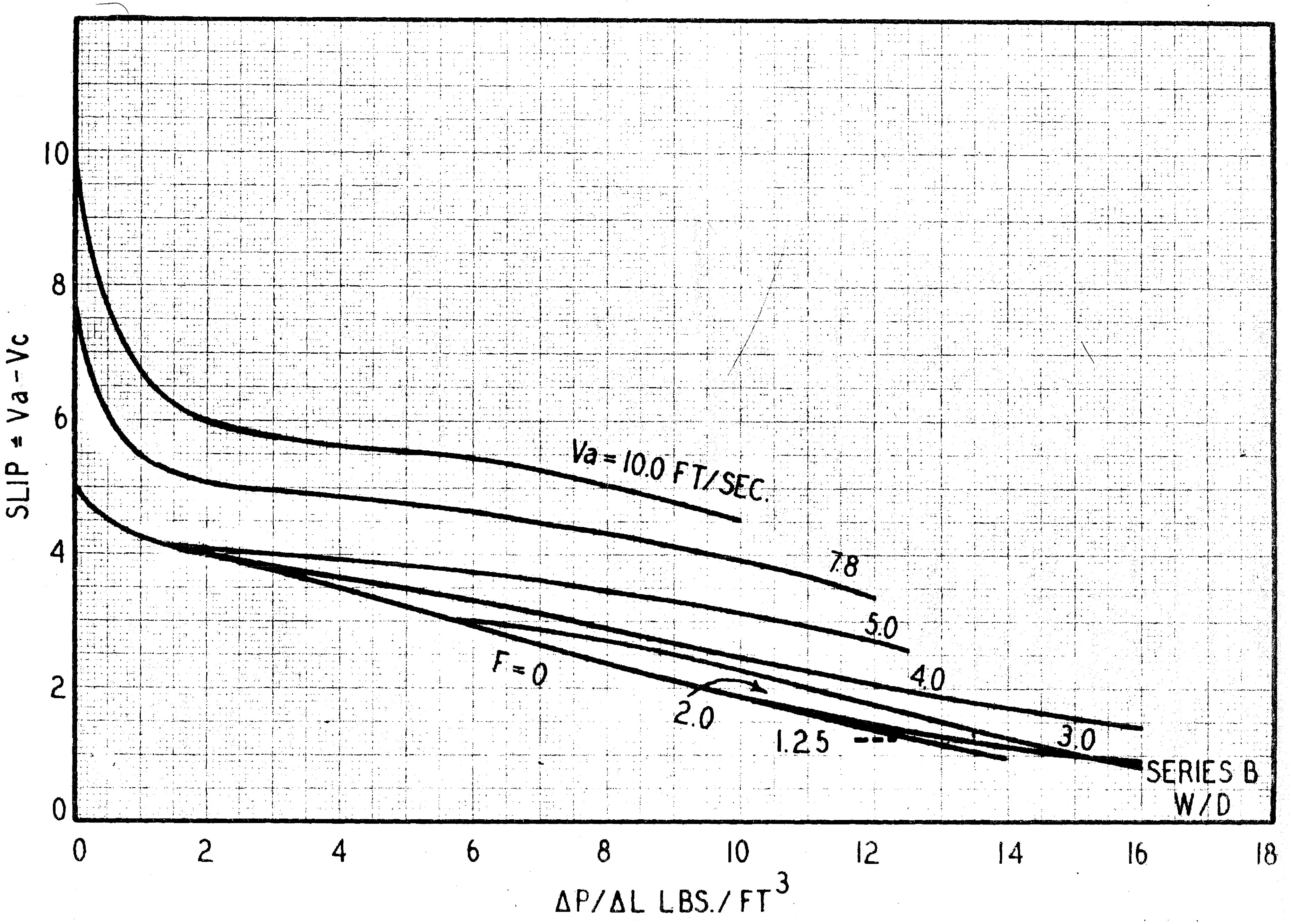
IX B is constructed from VII B. It will be noted that the slip in this range is not greatly influenced by air velocity so that interpolation of slip for intermediate air velocities is relatively dependable. The envelope curve at the left corresponds to conditions of zero feed rate, i.e., to the 45° line of VIIB. XB is identical with IX B except for scale and for the fact that high velocity curves, above $V_a=4$, have been inserted from Series A data. These high velocity lines should be looked on as tentative only. In both IX B and XB abscissae are given as pressure gradients, because the curves are in fact based on pressure measurements, but it is recommended that in using them pressure gradient be considered equivalent to concentration.

VII-B differs from the similar plots previously presented, based both on the work of Chambers and plot IV A of this program, particularly in the shape of the curves corresponding to high concentration and low slip. However, the curves of

PLOT IX-B


4.0
3.0
2.0
1.0
0.6
SLIP = Va - Vc
0
4
8
12
16
20
24
ΔP/ΔL LBS./FT 3
Va = 4.0 FT/SEC
F = 0
3.0
2.0
1.75
1.5
1.25
SERIES B
W/D

PLOT X-B


SLIP = Va - Vc
0
2
4
6
8
10
0
2
4
6
8
10
12
14
16
18
ΔP/ΔL LBS./FT³
Va = 10.0 FT/SEC.
7.8
5.0
4.0
3.0
2.0
1.25
F = 0
SERIES B
W/D

VII-B correspond to the present data and it is believed conform to the general character of the phenomena. It should be emphasized that the 45° line (allowing for scale) of VII-B corresponds to zero clay feed rate. This condition always involves fractionation of the clay, blowing out the finer particles before the coarser. The experiments here reported all correspond to steady conditions of flow so far as is experimentally obtainable. Consequently, there must be a discontinuity between the smooth curves of this figure and conditions existing at zero feed rate. At high air velocities, low clay concentrations and high slip, one can approach quite closely to the 45° line without getting much segregation. At low air velocities, low slips, and high concentrations far more segragation develops, even at considerable feed rates. In consequence, on the high concentration curves at low air velocities the clay in the column averages much coarser than the clay being pumped. Obviously, therefore, more friction and hence more slip is required to support the column of clay of given density. This is the reason for the minimum in the constant concentration curves at high concentrations and the rise in slip in these curves at the left of the minimum. In using these curves, one must always keep in mind the tendency toward segregation, remembering that it is large as the 45° line is approached, particularly at high concentrations. At low concentrations away from the 45° line, the data are convincing that segregation is inconsequential. Were it possible to realize conditions of steady flow without segregation (e.g., by pumping a powder of uniform particle size) it is felt that minima would not be encountered in the constant concentration curves of VII B.

Series C represents the results of flow experiments entirely similar to those of Series B, conducted in the same apparatus but using hydrogen instead of air. Under the conditions of operation it is impossible to avoid a small amount of air contamination of the hydrogen, but the molecular weight of the mixture, determined by analysis for oxygen (air) and confirmed by direct determination of gas density, ranged from a little above 3 to about 5. This means that the percentage of air goes down to almost 4%. IC and IIC correspond to two different gas velocities. Table I, constructed from IC, IIC and IVB, shows that the ratio of the slip with hydrogen to the slip with air, under identical conditions of feed rate and clay concentration, averages 2.17, with a maximum deviation of less than 15% and an average deviation of less than 7%. A number of runs with CO_2 gave slips which did not differ significantly from those obtained with air.

It seems extraordinary at first that a density variation in the lifting gas of ten-fold makes only a two-fold difference in the velocity of the slip. On the other hand, in view of the fact that this clay was approximately 70% thru 200 mesh, it turns out that the Reynolds number of a single clay particle

TABLE I

Slip of air and H_2 at equal C and F. (IC, IIC and IVB)

V_H	C	R	V_c	S_H	V_A	S_A	p
5.0	13.9	30	2.16	2.84	3.7	1.54	1.85
5.0	12.2	15	1.23	3.77	2.9	1.67	2.26
5.0	7.2	3	0.42	4.58	3.4	1.98	2.32
4.25	15.4	30	1.95	2.3	2.9	0.95	2.05
4.25	13.4	15	1.12	3.13	2.45	1.33	2.35
4.25	10.8	5	0.46	3.79	2.2	1.74	2.18
						Aver.	2.17

falling through the gas is so low that viscous rather than turbulent motion of the gas around the individual particle is indicated. Granting this fact, the friction of the gas against the particle should follow Stoke's Law, $R = 3\pi\mu DV$, where R is the frictional force, μ is the viscosity of the fluid, D the diameter of the particle, and V the relative velocity or slip. This would require that the friction, i.e., the slip, should be proportional to the viscosity of the gas and independent of the density. In fact, the viscosity of air at room temperature is approximately 2.1-fold the viscosity of hydrogen, whereas the viscosity of CO_2 is about 17% less than that of air. The viscosity ratio for air:hydrogen, 2.1, checks the slip ratio of the above table well within the experimental accuracy of the data. It is true that the ratio should be the viscosity for air vs. the viscosity of a mixture of air and H_2, but the error for a 95% H_2 mixture is only about 12% from 2.1. The relatively small difference between the viscosity of CO_2 and air, made still smaller by the fact that leakage of a little air into the CO_2 in the apparatus could not be avoided, explains the substantial check between the measured slip for CO_2 and air. In other words, it is concluded that the curves here presented for air, e.g., IVB, IXB, and XB, can be used for other gases by allowing for the fact that at identical values of concentration and feed rate, slip will be inversely proportional to the viscosity of the gas, i.e., inversely proportional to the viscosity of the gas relative to that of air at room temperature.

FLOW OF CLAY IN CO_2

Table 2 summarizes the data on the runs with CO_2, using the same clay as in the air runs. It was impossible to completely eliminate air leakage; however, the molecular weight was never less than 38.7, ranging up to 42.4. As in Plot IVB, in computation it is assumed that the values of pressure gradient over the whole length of the column given in Column 7 of the table can be treated as clay concentrations. The significance of the results is seen in comparing the CO_2 slip with the air slip obtained in the same apparatus, with the same brass tube and the same clay, at operating conditions giving the same feed rate and same concentration in the column. At the low air velocity, the CO_2 slip averages definitely higher than the corresponding air slip, which was obtained by reading off the air velocity equivalent to the same clay concentration and feed rate from plot IV-B. At the intermediate velocity, all air slips were higher than the corresponding CO_2 slips. but unfortunately, all these measurements were made at feed rates too low to secure maximum accuracy. At the highest CO_2 velocity it is unfortunate that the clay concentrations and feed rates correspond to points outside the range of IVB. However, from the last two of these measurements, which probably represent the most dependable data obtained on CO_2, the air slip is definitely below

TABLE 2

CO_2 Data Calculations

Runs	V_g	Mol.Wt.	P 97-1/4" Col.cm.Hg.	Conc. Obs.	Feed Rate	P/ L	V_c	Slip CO_2	V_a	Slip Air
300	2.14	39.1	3.1	12.5	97	10.7	.15	1.99	2.0	1.85
301	2.14	39.1	5.5	----	1925	18.9	1.7	.44	2.0	0.3
302	2.15	38.8	4.45	14.8	1030	15.3	1.12	1.03	2.05	0.93
303	2.09	38.7	3.3	12.4	247	11.3	.36	1.73	2.05	1.69
304	2.09	38.7	3.25	12.4	269	11.2	.40	1.69	2.1	1.7
305	2.09	39.5	2.5	10.4	11	8.6	.02	2.07	2.1	2.08
306	3.08	39.9	1.6	6.7	121	5.5	.37	2.71	3.65	3.28
307	3.08	40.7	2.55	9.7	376	8.8	.71	2.37	3.2	2.49
308	3.03	41.4	2.3	8.1	254	7.9	.54	2.49	3.25	2.71
309	3.08	41.4	2.35	8.9	367	8.1	.76	2.32	3.5	2.74
310	3.05	42.2	2.05	8.4	216	7.1	.51	2.54	3.4	2.90
311	4.18	42.4	1.02	----	168	3.5	.80	3.38		
312	4.18	42.4	1.02	4.0+	157	3.5	.75	3.43		
313	4.20	41.7	.45	----	99	1.6	1.03	3.17		
314	4.30	40.0	.40	----	85	1.4	1.01	3.29		
315	4.30	40.0	.40	1.6	90	1.4	1.07	3.23		
316	4.19	41.9	4.6	----	2640	15.8	2.79	1.40	4.0	1.2
317	4.22	40.9	4.6	14.5	2690	15.8	2.84	1.38	4.0	1.2

the corresponding CO_2 slip. Furthermore, the percentage difference in these last two runs is just about equal to that by which the viscosity of CO_2 is lessthan that of air. All measurements at high feed rates, corresponding to the most dependable conditions of measurement, show air slips less than CO_2 slips. In other words, these data confirm the conclusion that the rate of slip at given clay feed rate and concentration is inversely proportional to the gas viscosity.

SLIPS AT HIGH AIR VELOCITY.

If one will restrict one's-self to conditions of reasonably high feed rate, and high gas velocity where segregation is certainly small, one can extrapolate the corresponding portions of the curves of VIIB down to the 45° line and find a corresponding slip, S_o, which may be looked upon as the hypothetical slip for a zero feed rate, but no segregation. This slip is, of course, a function of concentration only, which, as elsewhere, will be considered as equivalent to pressure gradient. The relation is given in Plot XIB which, however, is really constructed, not from the intercepts of VIIB but from the high velocity data to make them check reasonably. At actual feed rates and correspondingly higher air velocities the slip is, of course, greater. This increase in slip should be that of translation or pumping and should be proportional to the energy of translation, i.e., $S-S_o \alpha \beta V_c^2$. It is found, however, that this increased slip due to pumping at the same concentration is more or less proportional to the square of the air velocity instead of the clay velocity. The constant of proportionality is approximately 0.052. This means that the actual slip at a given concentration is $S_o + 0.052 V_a^2$. The corresponding clay velocity is V_a minus this slip, since the feed rate is equal to clay concentration, C, times clay velocity. This means that feed rate should be $F = C (V_a - S_o - 0.052 V_a^2)$, where S_o is given by the adjoining plot as a function of the concentration. Clearly, at a given concentration and air velocity one can immediately compute the feed rate. The results of the use of this formula are compared with the experimental data in the columns of the following table. It is here seen that very good agreement with the data are obtained in the region of high air velocity where elutriation is negligible.

PLOT XI - B

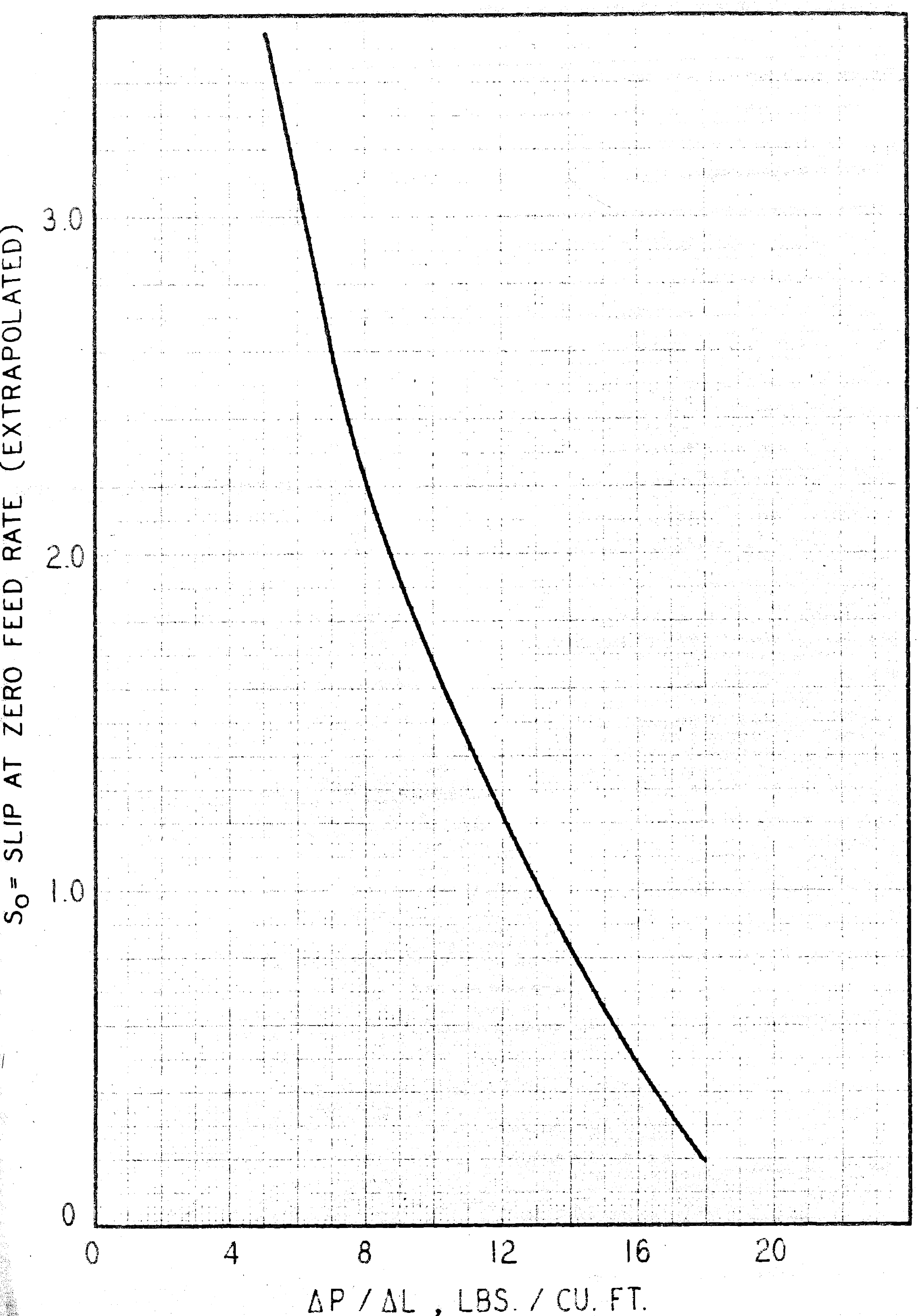

S_O = SLIP AT ZERO FEED RATE (EXTRAPOLATED)
3.0
2.0
1.0
0
0
4
8
12
16
20
ΔP / ΔL , LBS. / CU. FT.

TABLE 3

Runs	$F_{obs.}$	V_a	$\Delta P/\Delta L$	S_o	$F_{calc.} = \Delta P/\Delta L(V_a - S_o - .052\ V_a^2)$
242-244	171	3.12	7.4	2.44	76
245-247S	783	3.12	10.3	1.60	625
249	1970	3.12	15.8	.51	1990
251-252s	307	3.12	8.77	2.0	320
253	22	3.12	6.36	2.92	neg.
254-255t	969	3.12	11.7	1.30	920
258,260	141	2.13	9.98	1.68	126
259	539	2.13	11.7	1.30	414
261	18	2.13	6.88	2.68	neg.
262	58	2.13	8.95	1.94	neg.
264	970	2.13	14.45	.75	987
265	370	2.13	11.7	1.30	414
267-268U	1030	2.13	15.8	.51	1310
269	35	1.07	15.1	.64	333
270	92	1.07	16.15	.46	533
272	175	1.07	16.85	.36	657
273	390	1.07	17.55	.26	790
274	232	1.07	18.55	.12	990
275	176	4.23	4.47	3.82	neg.
276	224	3.92	6.19	3.0	45
277	853	3.92	9.8	1.72	824
278	1285	3.92	11.7	1.30	1280
279	2040	3.92	14.45	.75	2050
25-27c	182	5.0	4.4	3.85	neg.
35-37,39e	2400	5.0	13.7	.90	2300
94,95,97,98	491	5.0	6.94	2.64	441
114-118	1395	7.8	6.94	2.64	831
119-123	1940	7.8	8.62	2.02	1350
124-129	3060	7.8	12.85	1.06	2760
139-142	2210	10	6.93	2.64	900
148-150	2670	2.5	15.38	.59	1460
151-152	372	2.5	10.3	1.60	352

Runs 269-274, inclusive, are in brass tube.

Relation does not hold below 2 ft/sec.

CONCLUSIONS

It is concluded from the results of this thesis that, when a fluid-fine particle mixture is transported in a vertical tube, the flow characteristics of this operation can be correlated by relationships between fluid velocity, solid concentration, solid transport rate, pressure drop over the height of the column, and the relative fluid velocity, i.e., slip.

The average pressure drop per foot of height over the height of the column is substantially equal to the average concentration of the solid in the mixture.

The average pressure drop at the bottom of the column is greater than the average pressure drop over the entire column, the result of a "barometric" effect.

The best correlations of the data on the flow condition variables are curves of concentration vs. feed rate at constant gas velocity. These curves confirm those presented by Chambers (2). These results obtained on a 100 inch column when compared with those of Chambers obtained on a column of 67 inches height indicate a possible correlation between the other variables and column height.

A correlation of the data involving the variable, slip, gives the best insight into the mechanism of solid transport. Slip is defined as the relative velocity of the fluid with respect to the solid and is expressed as $S = V_a - V_c$, where V_a is fluid velocity and V_c is solid velocity.

Elutriation or fractionation of the solid occurs at low gas velocities, high concentration, and low feed rates. This changes the size distribution of the solid present in the column and changes the flow characteristics from these found at higher feed rates and higher gas velocities. If it were possible to transport a powder of absolutely uniform particle size it is almost certain that the flow characteristics at low feed rates would be similar to those at high feed rates where elutriation is now of no consequence.

The density of the transporting gas under the conditions here investigated has no observable effect on the flow variables. The slip, however, is proportional to the viscosity of the transporting fluid. Because of this, the curves presented for air and clay can be used for any gas and clay ?, by allowing for the fact that at identical values of concentration and feed rate, the slip for any gas will be inversely proportional to the viscosity of the gas relative to that of air at room temperatures.

inversely

A relationship has been developed which allows the feed rate to be calculated from concentration and air velocity. The relationships gives remarkable checks of the data at high feed rates and high air velocity where elutriation or segregation are not pronounced.

RECOMMENDATIONS

It is recommended that further work be done with the existing apparatus using solids of different density, size, and size distribution. This should enable the determination of the effect of these physical properties of the solid on the flow characteristics. When these solids are used, gas other than air should also be used to check the results of this work on clay. Of practical interest, a solid in the extremely small particle range would be Portland Cement.

It is recommended that the height and diameter of the column be changed to study the effect of those variables on the flow characteristic relationships.

When sufficient data are obtained involving all of these variables, the correlation by a type of Reynolds number suggested by Chambers(2) should be attempted.

If the apparatus is rebuilt the gas-solid separator should be changed to a cylindrical bag filter of the conventional type, thus reducing the volume of the filter from that used in this apparatus.

Study should be made of the solid feeding device. While the one used in this apparatus is satisfactory for the feed rates employed, it tends to give difficulties at extremely high feed rates.

APPENDIX

TABLE I. SERIES A.

Vertical glass tube column - air-clay runs

Nomenclature

A - Time; minutes

B - Air velocity; ft./sec. V_a

C - Δ P across 99 inches of column; cm. of Hg.

D - Feed weight; lbs.

E - Δ P across bottom 37 inches of column; in. of H_2O

F - Weight of clay in column; grams

G - Concentration; lbs./ft.^{3} = (F)/19.98

Symbol C

H - Column Δ P, 99 in.; lbs. per ft.^{2} per ft. of height

(#/ft.^{3}) = 3.38 x (C)

I - Column Δ P, 37 in.; lbs. per ft.^{2} per ft. of height

(lbs./ft.^{3}) = 1.69 x (E)

J - Feed rate; lbs. per min.per sq.ft.

= (D)/0.00525 x (A) Symbol F

K - Clay velocity; ft. per sec.

= (J)/60 x (G) V_c

L - Slip; ft.per sec. = (B) - (K)

Symbol $S = V_a - V_c$

M - Comments

Table 1 – Original Data – Series A

	A	B	C	D	E	F	G	H	I	J	K	L	M
Runs							=F/19.98	= 3.38C	=1.69F	=D/.00525A	=J/60G	=B-K	
1.		12.8	2.25					7.61					↑
2.	2.50	10.5	2.80	15.5		1.88.	9.4	9.46		1,180	2.09		
3.		6.7	1.95					6.59					Runs 1 – 6 off
4	5.25	7.8	2.20	8.5		166	8.3	7.44		308	0.62		because of Air leakage
5	1.00	11.3	2.40	6.5		89	4.45	8.11		1240	4.65		
6	1.00	14.0	0.90	9.5		52	2.60	3.04		1810	11.60		↓
7.	0.59	7.8	1.60	1.6	4.25	163	8.75	5.41	7.18	516	1.06	6.74	
8	0.75	10.2	0.10	0.81	0.25	56	2.80	0.34	0.42	206	1.23	8.97	
9.	13.08	7.8	0.05	1.25	0.20	2.7	0.14	0.17	0.34	18	2.14		F Questionable
10.	5.87	7.8	0.50	20.20	1.90	52	2.6	1.69	3.21	656	4.21	3.59	
11.	2.00	7.8	1.5	7.13	3.0	32	1.6	5.07	5.07	679	7.06	4.27	
12.	2.50	7.8	2.9	14.3	6.0	103	5.15	9.8	10.14	1090	3.53	4.27	
13.	1.00	7.8	3.0	9.25	6.0	83	4.15	10.12	10.14	1760	7.07	0.73	
14.	1.25	7.8	2.8	8.31	3.0	69	3.45	9.46	5.07	1268	6.12	1.68	
15.	2.00	7.8	1.15	5.69	3.0	62	3.10	3.89	5.07	541	2.91	4.89	
16.	1.00	6.95	1.80	5.31	3.75	85	4.25	6.09	6.34	1010	3.96		
17a	1.0	7.8	1.8	6.44	3.25	77	3.85	6.09	5.49	1225	5.3	2.5	
18 a	1.0	7.8	1.8	5.88	3.25	77	3.85	6.09	5.49	1120	4.85	2.95	
17a, 18a	1.0	7.8	1.8	6.16	3.25	77	3.85	6.09	5.49	1175	5.09	2.71	
19	1.0	5.0	2.3	3.25	5.0	156	7.8	7.78	8.45	620	1.32	3.68	{ Disregard. Feed
20	1.0	5.0	2.3	7.20	5.0	156	7.8	7.78	8.45	1370	2.93	2.07	Weights off.
21 b	1.0	5.0	2.3	4.44	4.7	143	7.15	7.78	7.95	845	1.97	3.03	
22 b	1.0	5.0	2.3	4.31	4.7	143	7.15	7.78	7.95	821	1.91	3.09	
23 b	1.0	5.0	2.3	4.0	4.7	135	6.8	7.78	7.95	763	1.87	3.13	
24 b	1.0	5.0	2.3	4.25	4.7	135	6.8	7.78	7.95	810	1.98	3.02	
21-24b	1.0	5.0	2.3	4.28	4.7	139	6.95	7.78	7.95	815	1.95	3.05	

Table 1 - Original Data - Series A

Runs	A	B	C	D	E	F	G	H	I	J	K	L	M
25c	1.0	5.0	1.1	0.813	2.5	81	4.05	3.72	4.22	155	0.64	4.36	
26c	1.0	5.0	1.05	1.31	2.4	64	3.20	3.55	4.05	250	1.30	3.70	
27c	1.0	5.0	1.05	0.75	3.0	64	3.20	3.55	5.07	143	0.75	4.25	
25-27c	1.0	5.0	1.065	0.958	2.6	70	3.50	3.59	4.4	182	0.87	4.13	
28d	2.0	5.0	0.15	0.875	0.45	10	0.50	0.51	0.76	84	2.8	2.20	
29d	2.0	5.0	0.15	0.875	0.45	10	0.50	0.51	0.76	84	2.8	2.20	
30d	2.0	5.0	0.15	0.75	0.45			0.51	0.76	71			
31d	2.0	5.0	0.15	0.69	0.45	14	0.70	0.51	0.76	66	1.57	3.43	
28-31d	1.0	5.0	0.15	0.40	0.45	11	0.55	0.51	0.76	76	2.30	2.71	
32	1.0	5.0	2.2	2.81	4.4	108	5.4	7.44	7.44	535	1.65	3.35	
33	1.0	5.0	3.4	4.56	7.0	208	10.4	11.50	11.82	870	1.40	3.60	
34	1.0	5.0	4.4	13.6	8.1	106	5.3	14.85	13.70	2590			Valve Leak. Conc. off.
35e	1.0	5.0	4.4		8.1	234	11.7	14.85	13.70				
36e	1.0	5.0	4.3	11.7	8.0	248	12.4	14.52	13.50	2230	3.0	2.0	
37e	0.77	5.0	4.3	9.88	8.1	199	9.95	14.52	13.70	2450	4.1	0.9	
38	1.0	5.0	4.2	12.75	8.1	140	7.0	14.18	13.70	2430			Conc. questionable.
39e	1.0	5.0	4.2	12.9	8.1	171	8.55	14.18	13.70	2460	4.8	0.2	
35-39e	1.0	5.0	4.3	12.6	8.1	213	10.65	14.52	13.70	2400	3.75	1.25	
40	1.0	5.0	2.5	4.38	4.8	177	8.85	8.45	8.11	835	1.57	3.43	
41f		5.0	4.4		8.1	279	13.95	14.85	13.7				
42f		5.0	4.1		8.1	234	11.70	13.85	13.7				
43f		5.0	4.1		8.1	204	10.2	13.85	13.7				Conc ?
44f		5.0	4.1		8.1	260	13.0	13.85	13.7				
41-44f		5.0	4.2		8.1	244	12.2	14.2	13.7				
45g		5.0	2.0		3.9	136	6.8	6.76	6.6				
46g		5.0	1.95		3.85	127	6.4	6.6	6.5				

Table 1 - Original Data - Series A

Runs	A	B	C	D	E	F	G	H	I	J	K	L	M
47g		5.0	1.95		3.85	113	5.65	6.6	6.5				conc. low.
48g		5.0	1.95		3.85	137	6.85	6.6	6.5				✓ ✓ valve leak.
45-48g		5.0	1.95		3.85	128	6.4	6.6	6.5				
49h		5.0	2.9		5.9	172	8.6	9.8	9.96				
50h		5.0	2.95		5.9	178	8.9	9.97	9.96				
49-50h		5.0	2.93		5.9	175	8.75	9.9	9.96				
51		5.0	0.71		1.75	41	2.05	2.4	2.96				
52i		5.0	2.2		4.1	141	7.05	7.44	6.93				
53i		5.0	2.2		4.1	123	6.15	7.44	6.93				ΔP may be low.
54i		5.0	1.8		4.0	125	6.25	6.08	6.76				
55i		5.0	1.9		4.0	114	5.7	6.42	6.76				conc. low valve leak.
56i		5.0	2.0		4.2	128	6.4	6.76	7.1				
57i		5.0	2.0		4.1	124	6.2	6.76	6.93				
58i		7.8	2.2		4.2	122	6.1	7.44	7.1				
52-58i			2.05		4.15	125	6.25	6.93	7.01				
59j		7.8	5.2		10.3	261	13.05	17.6	17.4				
60j		6.7	6.0		11.0	261	13.05	20.6	18.6				ΔP not exact.
61j		6.7	5.1		10.3	263	13.15	17.25	17.4				
62j		7.8	6.0		11.0	314	15.7	20.3	18.6				ΔP not exact.
63j		7.8	5.3		10.3	304	15.2	17.9	17.4				
64j		7.8	5.0		10.2	274	13.7	16.9	17.25				
59-64j			5.25		10.5	280	14.0	17.75	17.75				
65		7.8	2.0		4.1	134	6.7	6.76	6.93				
66k		7.8	0.9		2.05	50	2.5	3.04	3.46				
67k		6.35	0.85		2.0	52	2.6	2.87	3.38				
68k		6.7	0.9		2.05	52	2.6	3.04	3.46				

Table 1 - Original Data - Series A

Runs	A	B	C	D	E	F	G	H	I	J	K	L	M
69k		7.8	0.9		2.05	52	2.6	3.04	3.46				
66-69k			0.9		2.05	51	2.55	3.04	3.46				
70m		6.95	0.5		1.05	25	1.25	1.69	1.77				
71m		6.7	0.45		1.00	23	1.15	1.52	1.69				
72m		6.7	0.45		1.05	23	1.15	1.52	1.77				
73m		5.0	0.50		1.10	23	1.15	1.69	1.86				
70-73m			0.475		1.05	24	1.20	1.60	1.77				
74n	1.0	5.0	0.25	0.563	0.75			0.85	1.27	107			
75n	1.0	5.0	0.25	0.50	0.75			0.85	1.27	95			
76	1.0	5.0	0.25	1.00	0.6 - 1.4			0.85		190			ΔP varied widely
77n	1.0	5.0	0.25	0.563	0.75			0.85	1.27	107			
78n	1.0	5.0	0.25	0.375	0.75			0.85	1.27	72			
79n	1.0	5.0	0.25	0.563	0.75			0.85	1.27	107			
80n	1.0	5.0	0.25	0.50	0.75			0.85	1.27	95			
81n	1.0	5.0	0.25	0.563	0.75			0.85	1.27	107			
82n	1.0	5.0	0.25	0.438	0.75	17	0.85	0.85	1.27	83	1.63	3.37	
83n	1.0	5.0	0.25	0.438	0.75			0.85	1.27	83			
84n	1.0	5.0	0.25	0.375	0.75			0.85	1.27	72			
85n	1.0	5.0	0.25	0.563	0.75	18	0.90	0.85	1.27	107	1.98	3.02	
74-85n	1.0	5.0	0.25	0.495	0.75	18	0.90	0.85	1.27	94	1.74	3.26	
86p	1.0	5.0	0.45	1.06	1.5			1.52	2.54	202			
87p	1.0	5.0	0.45	1.00	1.5			1.52	2.54	190			
88p	1.0	5.0	0.45	0.75	1.5			1.52	2.54	143			
89p	1.0	5.0	0.45	1.00	1.5			1.52	2.54	190			
90p	1.0	5.0	0.45	0.94	1.5			1.52	2.54	179			
91p	1.0	5.0	0.45	1.19	1.5			1.52	2.54	227			

Table 1 - Original Data - Series A

Runs	A	B	C	D	E	F	G	H	I	J	K	L	M
92p	1.0	5.0	0.45	0.81	1.5			1.52	2.54	154			
93p	1.0	5.0	0.45	1.00	1.5	32	1.6	1.52	2.54	190	1.98	3.02	
86-93p	1.0	5.0	0.45	0.97	1.5	32	1.6	1.52	2.59	185	1.92	3.08	
94q	1.0	5.0	2.10	2.19	4.0	134	6.7	7.10	6.76	418	1.04	3.96	
95q	1.0	5.0	2.10	2.44	4.1			7.10	6.93	465			
96	1.0	5.0	2.1	3.63	4.1			7.10	6.93	691			Feed Weight Quest.
97q	1.0	5.0	2.1	2.63	4.1			7.1	6.93	501			
98q	1.0	5.0	2.1	3.06	4.1			7.1	6.93	583			
94-98q	1.0	5.0	2.1	2.58	4.1	134	6.7	7.1	6.93	491	1.22	3.78	
99r	1.0	5.0	3.6	11.13	7.15	217	10.85	12.15	12.08	2120	3.25	1.75	
100r	1.0	5.0	3.6	9.94	7.15			12.15	12.08	1890			
101	1.0	5.0	2.5		5.1			8.45	8.62				
102r	1.0	5.0	3.6	10.00	7.15			12.15	12.08	1905			
103r	1.0	5.0	3.5	9.19	7.15	214	10.7	11.80	12.08	1750			
99r - 103r	1.0	5.0	3.6	10.07	7.15	216	10.8	12.15	12.10	1920	2.96	2.04	
104	2.0	7.8			0.60				1.01				
105t	1.0	7.8		2.69	2.05	58	2.9		3.46	513	2.95	4.85	
106t	1.0	7.8		2.94	2.05				3.46	560			
107t	1.0	7.8		3.31	2.05				3.46	631			
108t	1.0	7.8		3.06	2.05				3.46	584			
105t - 108t	1.0	7.8		3.00	2.05	58	2.9		3.46	572	3.29	4.51	
109u	1.0	7.8		1.13	1.00	23	1.15		1.69	215	3.12	4.68	
110u	1.0	7.8		1.25	1.00				1.69	238			
111u	1.0	7.8		1.69	1.00				1.69	322			
112u	1.0	7.8		1.06	1.00				1.69	202			

Table 1 - Original Data - Series A

Runs	A	B	C	D	E	F	G	H	I	J	K	L	M
113u	1.0	7.8		1.12	1.00				1.69	214			
109u - 113u	1.0	7.8		1.25	1.00	23	1.15		1.69	238	3.45	4.35	
114v	1.0	7.8	2.1	8.00	4.1			7.1	6.93	1520			
115v	0.717	7.8	2.1	6.00	4.1	113	5.65	7.1	6.93	1595	4.7	3.1	
116v	1.0	7.8	2.1	6.81	4.1			7.1	6.93	1300			
117v	1.0	7.8	2.1	6.50	4.1			7.1	6.93	1240			
118v	1.0	7.8	2.1	6.94	4.1			7.1	6.93	1320			
114v - 118v	1.0	7.8	2.1	7.32	4.1	113	5.65	7.1	6.93	1395	4.11	3.69	
119w	1.0	7.8		9.94	5.1				8.62	1890			
120w	1.0	7.8		10.0	5.1				8.62	1905			
121w	1.0	7.8		9.75	5.1				8.62	1860			
122w	1.0	7.8		10.94	5.1				8.62	2090			
123w	0.417	7.8		4.38	5.1				8.62	2000			
119w - 123w	1.0			10.20	5.1				8.62	1940			
124x	1.0	7.8		16.63	7.6				12.85	3170			
125x	0.835	7.8	3.9	12.69	7.6			13.2	12.85	2890			
126x	1.0	7.8	3.9	15.63	7.6			13.2	12.85	2980			
127x	1.0	7.8	3.9	15.63	7.6			13.2	12.85	2980			
128x	0.917	7.8	3.9	14.81	7.6			13.2	12.85	3080			
129x	1.0	7.8	3.9	17.31	7.6	227	11.35	13.2	12.85	3300	4.85	2.95	Conc. High.
124x - 129x	1.0	7.8	3.9	16.09	7.6	227	11.35	13.2	12.85	3060	4.49	3.31	
130y	1.0	10.0		2.13	1.05				1.77	406			No Conc. Clay stuck to tube.
131y	1.0	10.0		1.69	1.05	26	1.3		1.77	322	4.13	5.87	
132y	1.0	10.0		1.88	1.05	29	1.45		1.77	358	4.11	5.89	
133y	1.0	10.0		2.06	1.05	28	1.40		1.77	393	4.68	5.32	
134y	1.0	10.0		1.50	1.05				1.77	286			

Table 1 - Original Data - Series A

Runs	A	B	C	D	E	F	G	H	I	J	K	L	M
135y	1.0	10.0		1.94	1.05				1.77	370			
130y -135y	1.0	10.0		1.87	1.05	28	1.4		1.77	356	4.24	5.76	
136a'	1.0	10.0		5.00	2.05				3.46	953			
137a'	1.0	10.0		4.69	2.05				3.46	894			
138a'	1.0	10.0		5.25	2.05				3.46	1000			
136a' -138a'	1.0	10.0		4.98	2.05				3.46	950			
139b'	1.0	10.0		12.44	4.1				6.93	2370			
140b'	1.0	10.0		12.00	4.1	113	5.65		6.93	2290	6.75	3.25	
141b'	1.0	10.0		10.63	4.1	112	5.60		6.93	2025	6.03	3.97	
142b'	1.0	10.0		11.38	4.1				6.93	2170			
139b' -142b'	1.0	10.0		11.61	4.1	113	5.65		6.93	2210	6.53	3.47	
143c'	0.67	10.0		10.31	6.1				10.30	2930			ΔP varied widely.
144c'	1.08	10.0		17.06	6.1				10.3	3010			
145c'	0.75	10.0		12.44	6.1				10.3	3160			
143c' -145c'	1.0	10.0		15.9	6.1				10.3	3030			
146d'	5.0	2.5	3.1	0.563	4.55			10.48	7.69	21.			
147d'	5.0	2.5	3.1	0.563	4.6			10.48	7.77	21.			
146d' -147d'	1.0	2.5	3.1	0.113	4.6			10.48	7.77	21.			
148e'	0.333	2.5		4.69	9.1				15.38	2680			ΔP of Runs 148 thru 150 are questionable
149e'	0.167	2.5		2.25	9.1				15.38	2570			
150e'	0.50	2.5		7.19	9.1	480	24.0		15.38	2740	1.9	0.6	
148e' -150e'	1.0	2.5		14.0	9.1	480	24.0		15.38	2670	1.85	0.65	
151f'	1.25	2.5		2.31	6.1				10.3	352			
152f'	1.0	2.5		2.06	6.1	219	10.95		10.3	392	0.6	1.9	
151f' -152f'	1.0	2.5		1.95	6.1	219	10.95		10.3	372	0.57	1.93	

Table 1 - Original Data - Series A

Runs	A	B	C	D	E	F	G	H	I	J	K	L	M
153	7.0	2.5		0.375	3.1	52	2.6		5.24	10.0	0.06	2.44	
154	2.0	2.5		4.06	6.4	217	10.85		10.8	387	0.59	1.91	
155	1.5	2.5		8.38	7.2	301	15.05		12.15	1060	1.17	1.33	Conc. slightly high.

TABLE I. SERIES B.

Vertical brass tube column - air-clay runs

Nomenclature

A - Time; minutes

B - Air velocity; ft.per sec. V_a

C - ΔP across 97.25 inches of column; cm. of Hg.

D - Feed weight; lbs.

E - ΔP across bottom 40 inches of column; in. of H_2O

F - Weight of clay in column; grams

G - Concentration; lbs. per ft.^{3} = (F)/21.25

Symbol C

H - Column ΔP, 97.25 in.; lbs.per ft.^{2} per ft. of height

(lbs./ft.^{3}) = 3.44 x (C)

I - Column ΔP, 40 in.; lbs. per ft.^{2} per ft. of height

(lbs./ft.^{3}) = 1.56 x (E)

J - Feed rate; lbs. per min. per sq. ft.

= (D)/0.005575 x (A) Symbol F

K - Clay velocity; ft. per sec.

= (J)/60 x (G) Symbol V_c

L - Slip; ft. per sec. = (B) - (K)

Symbol $S = V_a - V_c$

M - Comments

Table 1 - Original Data - Series B

Runs	A	B	C	D	E	F	G	H	I	J	K	L	M
							= F/21.25	= 3.44 C	= 1.56 E	= D/$\overset{\Delta x}{0.00515}$	= J/60G	= B − K	
156a			1.7		4.0	129	6.08	5.85	6.25	—			conc. questionable.
157a		2.4	1.6		4.0	139	6.55	5.50	6.25				conc. questionable
158		3.5	3.2		7.1	238	11.20	11.00	11.05				
159b			0.7		3.05	66	3.10	2.41	4.76				
160b			0.8		3.5	83	3.90	2.75	5.46				
161		3.97	3.6		8.15	209	9.85	12.40	12.70				conc. Low
162			0.75		0.45	14	0.66	0.26	0.70				
163		4.1	0.22		0.95	18	0.85	0.76	1.48				conc. questionable
164c		4.2	0.22		0.95	29	1.36	0.76	1.48				
165c		4.4	0.20		1.00	28	1.32	0.69	1.56				
166c			0.22		1.00	24	1.13	0.76	1.56				
167c		4.4	0.21		1.00	24	1.13	0.72	1.56				
168c			0.22		0.95	27	1.27	0.76	1.48				
164c -168c			0.21		0.98	26	1.24	0.72	1.53				
169~~c~~a			1.70		4.1	139	6.55	5.85	6.40				
170a			1.6		4.0	130	6.12	5.50	6.25				
171a			1.6		4.0	127	5.98	5.50	6.25				
172d			1.4		3.9	115	5.41	4.82	6.08				
173		3.0	0.9		3.0	74	3.48	3.10	4.68				conc. questionable
174			1.2		3.3	112	5.28	4.13	5.15				Disregard Runs
175			0.8		3.0	61	2.87	2.75	4.68				174 – 183; pressure
													tap broken.
184b		4.7	0.8		3.0	67	3.15	2.75	4.68				
185b		4.1	0.7		3.0	58	2.73	2.41	4.68				
186b		5.1	0.8		3.0	74	3.48	2.78	4.68				
187b		4.2	0.7		3.0	59	2.78	2.41	4.68				

Table I - Original Data - Series B

Runs	A	B	C	D	E	F	G	H	I	J	K	L	M
159b -187b			0.75		3.09	68	3.19	2.58	4.82				
188d			1.50		4.0	124	5.84	5.16	6.25				
189a			1.60		4.1	132	6.21	5.50	6.40				
190e		4.73	1.8		4.2	143	6.73	6.20	6.55				
191e		4.73	1.8		4.2	145	6.82	6.20	6.55				
190e -191e			1.8		4.2	144	6.78	6.20	6.55				
192a		4.73	1.7		4.1	135	6.35	5.85	6.40				
193a		4.45	1.6		4.1	130	6.12	5.50	6.40				
156a -193a			1.65		4.05	133	6.25	5.68	6.32				
194d		4.15	1.40		4.0	124	5.84	4.81	6.25				
195f		4.70	4.6		10.5	284	13.38	15.80	16.40				
196f		4.70	4.9		10.7	307	14.43	16.85	16.70				
197		4.70	5.4		11.2	462	21.70	18.55	17.50				
198f		4.73	4.6		10.7	301	14.15	15.80	16.70				
199		4.73	4.4		10.1	291	13.70	15.10	15.75				
200f		4.70	4.8		10.4	300	14.10	16.5	16.25				
201		4.7	4.7		10.2			16.15	15.90				
202f			4.7		10.4	303	14.25	16.15	16.25				
195f -202f			4.7		10.5	299	14.05	16.15	16.40				
203g			0.45		2.2	47	2.21	1.55	3.43				
204g			0.45		2.1	42	1.98	1.55	3.28				
205g			0.40		2.05	40	1.88	1.38	3.20				
206g			0.45		2.10	39	1.83	1.55	3.28				
203g -206g			0.44		2.11	42	1.98	1.51	3.29				
207		1.07	0.56		12.20	400	18.80	19.25	19.05				
208h			2.70		6.20	201	9.45	9.29	9.67				

Table 1 - Original Data - Series B

Runs	A	B	C	D	E	F	G	H	I	J	K	L	M
209h			2.6		6.3	212	9.97	8.95	9.82				
210h			2.7		6.2	198	9.36	9.29	9.67				
211h			2.6		6.2	200	9.41	8.95	9.67				
208h -211h			2.65		6.23	203	9.56	9.12	9.73				
212j			3.8		8.5	250	11.75	13.05	13.25				
213j			3.8		8.3	250	11.75	13.05	12.95				
214j			3.7		8.2	248	11.68	12.70	12.80				
215j			3.7		8.0	203	10.50	12.70	12.50				
212j -215j			3.75		8.25	243	11.42	12.90	12.85				
216			0.1		0.5	15	0.71	0.34	0.78				
217			0.2		0.6	10	0.47	0.69	0.94				
218			0.1		4.1	90	4.23	3.78	6.40				wt. uncertain
219d			1.42		4.1	122	5.75	4.88	6.40				
220d			1.5		4.0	123	5.79	5.16	6.25				
221d			1.42		4.0	122	5.75	4.88	6.25				
112d -221d			1.44		4.0	122	5.73	4.95	6.25				
222					8.0	223	10.50		12.50				conc. varying
223m			3.3		8.75	252	11.85	11.35	13.65				
224k			4.4		10.75	349	16.40	15.10	16.80				Column C questionab
225k			5.0		10.25	331	15.56	17.20	16.00				
224k -225k			4.7		10.50	340	15.98	16.15	16.40				
226m			3.35		8.75	262	12.32	11.50	13.65				
227n			2.25		5.90	203	9.55	7.75	9.20				
228n			2.1		5.6	182	8.56	7.22	8.74				
229			0.6		3.1	62	2.92	2.06	4.84				

Table 1 - Original Data - Series B

Runs	A	B	C	D	E	F	G	H	I	J	K	L	M
230			1.1		4.6	115	5.42	3.79	7.18				H + C ?
231n			2.2		5.7	189	8.9	7.57	8.90				
227n - 231n			2.18		5.7	191	9.0	7.50	8.90				
232					8.4	251	11.80		13.10				
233m			3.45		8.7	239	11.23	11.85	13.55				
223m - 233m			3.37		8.7	251	11.80	11.60	13.60				
234			3.05			248	11.67	11.48					
235			4.05		9.3	278	13.10	13.95	14.50				
236			1.5		4.2	123	5.79	5.16	6.55				
237			0.15		0.35	1	0.05	0.52	0.55				
238p			0.25		1.0	16	0.75	0.86	1.56				
239p			0.25		0.75	16	0.75	0.86	1.17				
238p - 239p			0.25		0.90	16	0.75	0.86	1.40				
240			0.50		2.3	54	2.54	1.72	3.59				
241	3.0	3.12	2.0	2.69	5.3	174	8.19	6.88	8.25	161	0.33		
242d	3.0	3.12	2.2	2.75	5.4			7.56	8.42	165			
243d	3.0	3.12	2.2	3.00	5.4			7.56	8.42	180			
244d	1.0	3.12	2.2	0.94		182	8.56	7.56		168	0.33		
242d - 244d	1.0	3.12	2.15	0.95	5.4	182	8.56	7.40	8.42	171			
245r	1.0	3.12	3.0	3.81	7.75			10.30	12.10	684			
246r	1.0	3.12	~~4.13~~	4.13	7.75				12.10	742			
247r	1.0	3.12		5.13	7.75	255	12.00		12.10	921	1.28 ~~0.128~~		
245r - 247r	1.0	3.12	3.0	4.36	7.75	255	12.00	10.30	12.10	783	1.09		
248	2.0	3.12		2.0	10.30				16.05	1800			conditions unsteady
249	1.0	3.12	4.6	11.0	11.30	416	19.6	15.8	17.65	1970	1.69		conc. High
250	1.5	3.12	2.5					8.6					wt. uncertain

Table 1 - Original Data - Series B

Runs	A	B	C	D	E	F	G	H	I	J	K	L	M
251s	1.5	3.12	2.5	2.5	6.3	222	10.43	8.6	9.83	278	0.48		
252s	1.5	3.12	2.55	2.63	6.2	200	9.41	8.77	9.67	292.	0.56		
251s -252s	1.5	3.12	2.55	2.57	6.25	211	9.92	8.77	9.75	307	0.48		
253	2.0	3.12	1.85	0.25	4.5	97	4.56	6.36	7.01	220	0.08		
254t	1.5	3.12	3.4	8.13	8.3			11.70	12.95	972			
255t	1.0	3.12	3.4	5.38	8.3	257	12.1	11.70	12.95	966	1.33		
254t -255t	1.0	3.12	3.4	5.40	8.3	257	12.1	11.70	12.95	969			
256		3.12	4.7		10.1	495	23.3	16.2	15.75				Conc. High; Leakage.
257	0.583	3.12		4.44	10.3	283	13.3		16.05	1365	1.71		Conc. questionable
258	5.0	2.13	2.9	3.94	7.2	255	12.0	9.98	11.23	142	0.20		
259	2.0	2.13	3.4	6.0	8.3	288	13.55	11.70	12.95	539	0.66		
260	5.0	2.13	2.9	3.88	7.3	227	10.68	9.98	11.4	140	0.22		
261	5.0	2.13	2.0	0.50	6.1			6.88	9.50	18.0			
262	6.0	2.13	2.6	1.94	6.7	222	10.45	8.95	10.45	58	0.09		
263	6.0	2.13	2.5	1.69	6.7	217	10.2	8.60	10.45	51	0.08		
264	2.0	2.13	4.2	10.81	9.8	319	15.0	14.45	15.30	970	1.08		
265	1.0	2.13	3.4	2.06	8.3	251	11.8	11.7	12.95	370	0.524 ~~5.24~~		
266	0.73	2.13	3.4	2.19	8.3			11.7	12.95	538			
267u	1.0	2.13	4.6	6.06	10.3			15.8	16.05	1088			
268u	1.0	2.13	4.6	5.44	10.3	322	15.15	15.8	16.05	975	1.07		
267u -268u	1.0	2.13	4.6	5.75	10.3	322	15.15	15.8	16.05	✓1030	1.13		
269	7.0	1.07	4.4	1.38	10.9	379	17.82	15.1	17.00	350	0.03		
270	5.0	1.07	4.7	2.56	11.4	382	18.0	16.15	17.80	92.	0.09		
271	5.0	1.07	4.1	0.56	10.4	321	15.1	14.1	16.20	20	0.02		
272	5.0	1.07	4.9	4.88	11.7	373	17.55	16.85	18.25	175	0.17		

Table 1 - Original Data - Series B

Runs	A	B	C	D	E	F	G	H	I	J	K	L	M
273	4.0	1.07	5.1	8.69	12.1	3.95	18.6	17.55	18.90	390	0.35		
274	3.0	1.07	5.4	3.88	12.6	4.04	19.0	18.55	19.65	232	0.20		
275	3.0	4.23	1.3	2.94	4.2	120	5.65	4.47	6.55	176	0.52		
276	3.0	3.92	1.8	3.75	4.9	161	7.59	6.19	7.64	224	0.49		
277	3.0	3.92	2.85	14.25	7.25	197	9.27	9.8	11.30	853	1.53		
278	2.0	3.92	3.4	14.31	8.25	260	12.22	11.7	12.85	1285	1.75		
279	1.0	3.92	4.2	11.38	9.8	300	14.10	14.45	15.30	2040	2.41		

TABLE I. CO_2 RUNS

Vertical brass tube column - CO_2 - clay runs

Nomenclature

A - Time; minutes

B - Gas velocity; ft.per sec. Symbol V_g

C - ΔP across 97.25 inches of column; cm. of Hg.

D - Feed weight; lbs.

E - ΔP across bottom 40 inches of column; in. of H_2O

F - Weight of clay in column; grams

G - Concentration; lbs. per ft.^{3} = (F)/21.25 Symbol C

H - Column ΔP, 97.25 in.; lbs. per ft.^{2} per ft. of height
(lbs./ft.^{3}) = 3.44 x (C)

I - Column ΔP, 40 in.; lbs. per ft.^{2} per ft. of height
(lbs./ft.^{3}) = 1.56 x (E)

J - Feed rate; lbs. per min. per sq.ft.
= (D)/0.005575 x (A) Symbol F

K - Clay velocity; ft. per sec.
= (J)/60 x (G) Symbol V_c

N - Molecular weight of gas in system

M - Comments

Table 1 - Original Data - CO_2 Runs

Runs	A	B	C	D	E	F	G	H	I	J	K	N	M
300	5.0	2.14	3.1	2.70	8.2	265	12.5	10.7	12.8	97	0.15	39.1	
301	2.0	2.14	5.5	21.40	12.75			18.9	19.9	1925	1.70	39.1	
302	2.0	2.15	4.45	11.5	10.50	314	14.8	15.3	16.4	1030	1.12	38.8	
303	3.0	2.09	3.30	4.1	8.5	263	12.4	11.3	13.3	247	0.36	38.7	
304	3.0	2.09	3.25	4.5	8.4	263	12.4	11.2	13.1	269	0.40	38.7	
305	3.0	2.09	2.50	0.2		220	10.4	8.6		11	0.02	39.5	
306	5.0	3.08	1.6	3.4	5.3	143	6.7	5.5	8.25	121	0.37	39.9	
307	4.0	3.08	2.55	8.4	6.7	207	9.7	8.8	10.50	376	0.71	40.7	
308	3.0	3.03	2.30	4.25	5.8	171	8.1	7.9	9.05	254	0.54	41.4	Leakage on Conc.
309	3.0	3.08	2.35	6.10	5.9	189	8.9	8.1	9.20	367	0.76	41.4	
310	5.0	3.05	2.05	6.00	5.4	178	8.4	7.1	8.42	216	0.51	42.2	
311	5.0	4.18	1.02	4.70	3.6			3.5	5.61	168	0.80	42.4	
312	5.0	4.18	1.02	4.4	3.6	86	4.0	3.5	5.61	157	0.75	42.4	Conditions good
313	5.0	4.20	0.45	2.75	1.5			1.6	2.34	99	1.03	41.7	
314	5.0	4.30	0.40	2.4	1.45			1.4	2.26	85	1.01	40.0	
315	2.5	4.30	0.40	1.25	1.45	33	1.6	1.4	2.26	90	1.07	40.0	
316	1.0	4.19	4.6	14.70	9.1			15.8	1.42	2640	2.79	41.9	
317	0.47	4.22	4.6	7.0	9.1	307	14.5	15.8	1.42	2690	2.84	40.9	

TABLE I. SERIES C

Vertical brass tube column - H_2 - clay runs

Nomenclature

A - Time; minutes

B - Gas velocity; ft.per sec. Symbol V_H

C - ΔP across 97.25 inches of column; cm. of Hg.

D - Feed weight; lbs.

E - ΔP across bottom 40 inches of column; in of H_2O

F - Weight of clay in column; grams

G - Concentration; lbs. per ft.^{3} = (F)/21.25 Symbol C

H - Column ΔP 97.25 in.; lbs. per ft.^{2} per ft. of height
(lbs./ft.^{3}) = 3.44 x (C)

I - Column ΔP 40 in.; lbs. per ft.^{2} per ft. of height
(lbs./ft.^{3}) = 1.56 x (E)

J - Feed rate; lbs. per min. per sq.ft.
= (D)/0.005575 x (A) Symbol F

K - Clay velocity; ft.per sec.
= (J)/60 x (G) Symbol V_c

N - Molecular weight of gas in system

M - Comments

Table 1 - Original Data - Series C - H_2 Runs

Runs	A	B	C	D	E	F	G	H	I	J		N	M
321	3.0	5.15	2.3	2.3	6.0			7.9	9.35	138.		5.3	
322	2.0	5.01	2.3	2.72	6.0			7.9	9.35	244		5.32	Conc. Doubtful
323	2.0	5.01	2.3	2.49	6.0	191.	9.0	7.9	9.35	224		5.32	
322 -323		5.01					9.0	7.9	9.35	234		5.32	
324	2.25	5.14	3.8	15.1	9.2	294	13.8	13.05	14.35	1203		4.82	
325	1.0	5.18	5.0	14.3	11.6	342	16.1	17.2	18.1	2570		4.74	Conc. Low, Leakage
326	1.25	5.07	3.8	9.19	9.1			13.05	14.2	1320		4.31	
327	1.25	5.07	3.6	8.55	9.0			12.4	14.02	1225		4.31	
328	1.50	5.32	3.8	12.0	9.1	272	12.8	13.0	14.2	1438		4.37	Conc. Low. Leakage
329	1.0	6.31	4.2	10.78				14.45		1935		3.78	Run unsteady
330	0.75	6.31	4.0	7.42				13.75		1775		3.78	〃 〃
331	1.58	5.32	4.4	17.4	10.75			15.1	16.8	1978		3.23	〃 〃
332	0.67	5.32	4.4	6.0	10.75			15.1	16.8	1608		3.23	〃 〃
333	2.0	5.25	1.6	1.085	6.2			5.5	9.68	97		3.11	Conditions good
334	2.0	5.13	1.55	1.127	6.1			5.33	9.51	101		3.11	〃 〃
335	2.0	5.25	1.55	1.085	6.1	1.38.	6.5	5.33	9.51	97		3.11	〃 〃
336	2.0	5.25	1.6	1.13	6.2	142	6.68	5.5	9.68	101		3.11	〃 〃
333 -336							6.6	5.4	9.6	99		3.11	
337	2.0	5.17	2.3	1.66	6.45			7.9	10.1	149		3.79	Manometer on
338	2.0	5.17	2.3	1.99	6.45			7.9	10.05	179		3.79	40" Column may
339	2.0	5.17	2.3	2.04	6.45	195	9.2	7.9	10.1	183		3.79	be in error.
337 -339							9.2	7.9	10.1	170		3.79	
340	1.0	5.04	4.0	6.81	9.2	276	13.0	13.75	14.35	1220		3.78	ΔP low. unsteady
341	0.975	4.94	3.8	5.83		253	11.9	13.05		1073		4.04	Cond. good.
342	1.0	5.13	3.8	7.69				13.05		1380		3.98	〃 〃
343	1.08	5.58	3.9	8.73				13.4		1450		3.98	〃 〃

Table 1 - Original Data - Series C - H_2 Runs

Runs	A	B	C	D	E	F	G	H	I	J		N	M
344	3.0	4.18	2.3	1.22	7.2?			7.9	11.25	73		3.53	Conditions good
345	3.0	4.18	2.3	1.06	7.2?			7.9	11.25	63		3.53	〃 〃
346	3.0	4.18	2.3	1.15	7.2?	193	9.07	7.9	11.25	68		3.53	
344 -346							9.1	7.9	11.25	68		3.53	
347	1.0	4.22	4.6	11.1				15.8	~~199~~	1990		3.47	
348	0.91	4.21	4.2	8.2				14.44		1620			
349	1.25	4.06	3.0	0.96	7.85			10.3	12.23	1370			
350	1.25	4.06	3.0	0.99	7.85			10.3	12.23	1430			
351	1.25	4.06	3.0	1.02	7.85	2.49	11.7	10.3	12.23	147			
349 -351								10.3	12.23	142			
352	1.67	4.18	3.0	2.61	7.85			10.3	12.23	280			
353	1.67	4.18	3.1	1.99	8.25			10.65	12.85	214			
354	1.67	4.29	3.0	1.79	7.85			10.3	12.23	192			
352- 354								10.41	12.44	229			
355	0.60	4.29	4.2	3.76				14.44		1124			
356	1.0	4.29	4.2	8.05	10.6?			14.44	16.53	1445			
357	0.55	4.15	4.1	10.3?				14.1					
355 - 356								14.44	16.53	1285			
358	0.50	4.15	4.0	2.95				13.75		1058			
359	0.50	4.15	4.0	2.85				13.75		1022			
358 -359								13.75		1040			
360	1.0	4.21	4.4	9.37	11.27			15.13	17.5	1680			
361	0.5	4.32	4.4	4.5	11.2?			15.13	17.5	1615			
362	0.5	4.32	4.4	4.4	11.2?	318	14.98	15.13	17.5	1580			
360 -362								15.13	17.5	1625			
363	0.92	4.30	3.8	5.56				13.07		1085			

CALCULATIONS - GLASS TUBE

SERIES A

1. Volume of Tube (cu.ft.) =

$$\frac{\text{Length (in.)} \times \text{diameter (in.)}^2 \times \pi}{12 \times 144 \times 4}$$

$$\frac{20.13 \times 0.972^2 \times \pi}{2 \times 144 \times 4} = \qquad 0.00864$$

$$\frac{39.7 \times 1.0^2 \times \pi}{12 \times 144 \times 4} = \qquad 0.01803$$

$$\frac{3.67 \times 0.993^2 \times \pi}{12 \times 144 \times 4} = \qquad 0.00164$$

$$\frac{34.25 \times 0.965^2 \times \pi}{12 \times 144 \times 4} = \qquad 0.01450$$

$$\frac{2.67 \times 0.99^2 \times \pi}{12 \times 144 \times 4} = \qquad \underline{0.00119}$$

Total = 0.04400 cu.ft.

2. Height of Glass Tube = 100.63 inches.

3. Average cross-sectional area of Glass Tube.

$$\frac{\text{Volume}}{\text{Height}} = \frac{0.04400 \times 12}{100.63} = 0.00525 \text{ sq.ft.}$$

4. Average inside diameter

$$= \frac{0.00525 \times 144 \times 4}{\pi} = 0.982 \text{ inches.}$$

SAMPLE CALCULATIONS

1. Weight in grams of clay in column to lbs./cu.ft.

$$= \frac{\text{wt. in grams}}{454 \times 0.044} = \frac{\text{wt. in grams}}{19.98}$$

2. Feed weight to feed rate lbs./min. x sq.ft.

$$= \frac{\text{wt. in lbs.}}{0.00525 \times \text{min.}}$$

3. Pressure drop to lbs./sq.ft. x ft. of column height.

(a) 37 Inch ΔP inches of H_2O

$$\Delta P \text{ in } H_2O \times \frac{25.4}{13.6} \times \frac{14.7}{760} \times \frac{144 \times 12}{37} = 1.69\ \Delta P (\#/\text{ft.}^3)$$

(b) 99" ΔP cm. Hg.

$$= \Delta P \times \frac{14.7}{76} \times \frac{144 \times 12}{99} = 3.38\ \Delta P\ (\#/\text{ft.}^3).$$

4. Concentration ($\#/\text{ft.}^3$)

Weight of clay in column in grams to $\#/\text{ft.}^3$

$$\frac{\text{Wt. in grams}}{454 \times 0.044} = \frac{\text{wt. grams}}{19.98}$$

5. Clay velocity (ft./sec.)

$$\frac{\text{Feed rate}}{\text{Concentration}} = \left(\frac{\#}{\text{min.} \times \text{ft.}^2}\right)\left(\frac{\text{ft.}^3}{\#}\right) \frac{1}{60} = \text{ft./sec.}$$

$$= \frac{\text{Feed Rate}}{60 \times \text{concentration}}.$$

CALCULATIONS - BRASS TUBE

SERIES B

Diameter 1.011 inches i.d.

Length brass tube 90.25 inches.

Sight glass tube 1.032 inches i.d.

Length glass tube 10.25 inches.

Cross sectional area of brass tube $= \frac{1.011 \times \pi^2}{144 \times 4} = 0.005575$ sq.ft.

Volume brass tube $= \frac{1.011^2 \times \pi \times 90.25}{4 \times 144 \times 12} = 0.0419$ cu.ft.

Volume sight glass $= \frac{1.032^2 \times \pi \times 10.25}{4 \times 144 \times 12} = \underline{0.00496}$ cu.ft.

0.04686 cu.ft.

Distance from bottom pressure tap to top = 97.25 inches.

Weight of clay in grams to concentration, lbs./ft.^{3}

$$= \frac{\text{grams}}{454 \times 0.04686} = \frac{\text{grams}}{21.25}$$

Feed weight to feed rate; lbs./min. x sq.ft.

$$= \frac{\text{lbs.}}{0.00557 \times \text{min.}}$$

ΔP across 40 inches of column in inches of water to lbs./ft.^{3}

$$= \frac{\Delta P \times 2.54 \times 14.7 \times 144 \times 12}{13.6 \times 76 \times 40} = 1.56\ \Delta P$$

ΔP across 97.25 inches of column in c.m. of Hg/ to lbs./ft.^{3}

$$\frac{\Delta P \times 14.7 \times 144 \times 12}{76 \times 97.25} = 3.44\ \Delta P$$

CHECK OF GAS DENSITY

Mixture of H_2 and Air in Apparatus

Method: A 530 c.c. glass bulb, the volume measured by filling with water, was evacuated by an air aspirator to 23 m.m. of Hg. The bulb was then filled with gas from the system, closed, and again evacuated to 23 m.m. of Hg. The bulb was again filled with the gas from the system, closed, placed in a small wire carriage, wiped free of dust, and placed in a desicator for one-half hour. It was then removed and weighed. The flask was then evacuated to 23 m.m. of Hg. placed in the desicator for one-half hour, removed, and weighed.

Wt. of gas and bulb	=	92.1431
Wt. of gas and bulb at 23 m.m.	=	92.0091
Wt. of gas added	=	0.1340

Volume of bulb corrected for presence of gas not removed $530 \times \frac{23}{737} = 16.6$ c.c.

Vol. = 530 - 16.6 = 513.4 c.c.

Therefore the molecular weight of the gas is

$$\frac{0.134 \times 22.4}{0.5134} = 5.85$$

The gas analysis before the taking of the weighed sample previously described was

$$O_2 = 3.07\%$$

Therefore $\text{Air} = 3 \times \frac{100}{21} = 14.3$

$H_2 = \underline{85.7}$

100.0

Molecular weight = $(14.3 \times 28.8) + (85.7 \times 2) = 5.83$

Molecular weight

1. By density = 5.85
2. Gas analysis = 5.83

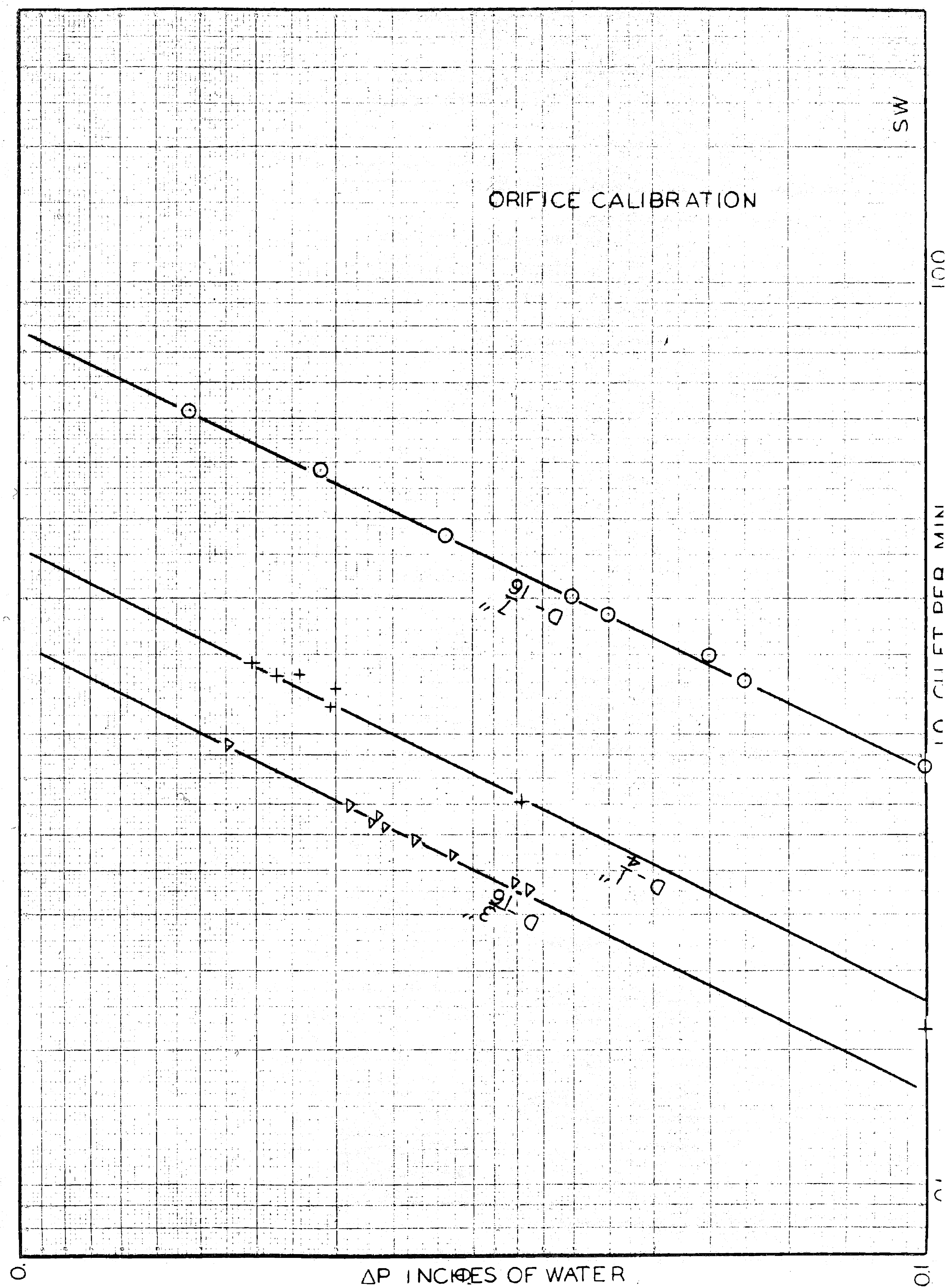
It is to be noted that there was considerable bubble formation in the pyrogallol used for absorption of the oxygen. It is believed that a maximum error of 0.2 c.c. in oxygen analysis is possible. This means that the air determination may be off by ± 1%.

CALIBRATION OF ORIFICES

Measurement by displacement of water from bottle of Vol. 0.678 cu. ft.

3/16" Orifice			1/4" Orifice			7/16" Orifice		
P in H_2O	Time Sec.	Cu.ft. per min.	P in.H_2O	Time Sec.	Cu.ft. per min.	P in.H_2O	Time Sec.	Cu.ft. per min.
0.75	90	0.452	2.0	31	1.26	0.6	20	2.03
1.10	75	0.542	2.4	30	1.35	0.3	27	1.50
0.75	90	0.452	2.7	30	1.35	0.25	31	1.31
0.80	87	0.467	0.1	182	0.223	0.25	30	1.35
1.85	59	0.689	0.4	160	0.254	0.10	48	0.845
1.55	65	0.625	0.5	130	0.313	0.60	20	2.03
1.60	62	0.656	0.78	*	0.71	0.50	22	1.85
1.32	70	0.581	2.05	*	1.15	1.15	*	2.75
1.65	*	0.640	3.05	*	1.45	2.15	*	3.85
3.45	*	0.940				4.2	*	5.2

* Points from Chambers calibration at higher rates.


SW
ORIFICE CALIBRATION
100
CU FT PER MIN
10
D - 7/16"
D - 1/4"
D - 3/16"
.1
ΔP INCHES OF WATER
1.0

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