WADC TECHNICAL REPORT 54-100
PART 2
ASTIA DOCUMENT No. AD 97302

BOUNDARY LAYER RADIOACTIVE TRACER TECHNIQUE

Part 2. Application

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SEPTEMBER 1956

AERONAUTICAL RESEARCH LABORATORY
CONTRACT AF 33(616)-31
PROJECT 1363
TASK 70159

WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Carpenter Litho & Prtg. Co., Springfield, O.
700 - October 1956

FOREWORD

This report was prepared by the Department of Engineering Research, North Carolina State College, describing the work carried out under Task 70159, "Boundary Layer Radioactive Tracer Technique," Project 1363, "Wind Tunnel Studies", on Contract AF 33(616)-31 from September 1953, to December 1955. The task scientist was Mr. K. E. Kissell, WCRRD, Aeronautical Research Laboratory, of Wright Air Development Center. Work carried out from the contract initiation to September 1953, has been reported in WADC TR 54-100, "Boundary Layer Radioactive Tracer Technique, Part 1, Instrumentation", August 1954. The present report, Part 2, Application, is the final report on the above contract.

Special acknowledgement is given to Mr. H. A. Lamonds who designed and supervised the construction of nearly all of the electronic equipment. Mr. J. D. Logan has also made important contributions to the success of the work.

All of the experimental work was carried out in the laboratories of the Department of Chemical Engineering, North Carolina State College, and the cooperation of this department is gratefully acknowledged.

ABSTRACT

The tracer displacement technique has been applied to fluid-dynamic studies with aqueous solutions in tubes of one-half and one-inch diameter under conditions of (a) turbulent flow in smooth tubes, (b) laminar flow in artificially roughened tubes, (c) laminar flow with superposed fluid vibration, (d) non-Newtonian flow at low velocities, and (e) flow accentuating mass transfer effects. Laminar flow studies in smooth tubes and a detailed description of the technique and instrumentation have been given previously in Part I of this report.

Turbulent flow observations have been made on fluids starting initially from rest and also under dynamic conditions where flow velocity and pattern were fully established prior to any tracer displacement. All data showed a high degree of reproducibility and marked similarity of general pattern over a Reynolds number range of 2500 to 7000. Within the limits of the sensitivity of the equipment, turbulent fluctuations of velocity were shown to exist in a region much closer to the tube wall than the thickness of the so-called laminar sublayer.

To determine the effects of roughness, flow studies were made in a one-half inch diameter aluminum tube with eighteen 0.039-inch deep internal threads per inch of length and in a one-half inch diameter glass tube, internally "frosted" by grinding with carborundum powder. Results of these runs indicate that the effect of the roughness does not extend more than a very short distance into the main fluid stream.

The effect of vibration was observed by superposing a pulse of 1200 to 1500 cycles per minute on the flowing fluid in the column. Results of the runs were inconclusive; except for minute fluctuations in the transmission data, there was no visible effect on the parabolic velocity pattern.

Several runs were attempted in which the mass transfer effects were enhanced by a high concentration gradient between the displaced and the displacing fluids. In these runs, a modified plug-type flow was obtained due to density differences, heat effects, and interfacial tension as well as to mass transfer.

Data on non-Newtonian flow were obtained using a 3% aqueous bentonite suspension. Evidence was obtained of anomalous behavior very close to the tube wall, but the data on the fluid properties are inadequate to permit quantitative interpretation. The application of the radio-tracer displacement technique to non-Newtonian flow will probably prove to be a most important one since other techniques for measuring local velocities are almost useless with these materials.

An appendix is included listing the various runs which have been made in each of the several categories of tests.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

Nathan L. Krisberg

NATHAN L. KRISBERG, Colonel, USAF
Chief, Aeronautical Research Laboratory
Directorate of Research

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INTRODUCTION

The tracer displacement technique provides a highly sensitive method of measuring relative fluid motion in a conduit without the necessity of introducing a sensing element into the fluid stream itself. The principle of the technique, the basis for its evaluation, the instrumentation constructed for its realization, together with the results of its application to fluids in laminar flow are reported in some detail in WADC-TR-54-100, Boundary Layer Radioactive Tracer Technique, Part 1, Instrumentation (August, 1954).

Here, in Part 2, are reported the results of applications of the technique to turbulent flow, flow of non-Newtonian fluids, flow in rough tubes, flow with vibration, and flow with mass transfer. Before describing these results, it will be convenient to outline briefly the principle of the tracer displacement technique and to summarize the results of the laminar flow runs referred to above.

The fluid entering a given section of a conduit is continuously displacing the fluid presently in that section. Because of the variations in fluid velocity across the cross section of the conduit, the rate of this displacement is not uniform but is a function of the velocity distribution. If a suitable tracer is added to the fluid in a given section of conduit, the rate of displacement may be observed externally to the conduit and may be used as a measure of the relative fluid motions within the section. Radioactive elements are suitable tracers in most cases, and dyes may be used if the fluid and the conduit are transparent.

In true streamline flow, where all fluid motion is parallel to the axis of the conduit, there is a direct and simple relationship between the observed rate of displacement and the velocity distribution. The photograph of Figure 1 shows a clear fluid being displaced by laminar flow of a dye solution. Measurements made by the tracer displacement technique in a 1/2-inch diameter glass tube with fluids in laminar flow have shown nearly perfect agreement between tracer displacement observations and the predicted velocity distribution down to within 0.002 inch of the tube wall. Measurements in the region closer to the wall need to be corrected for the effects of molecular diffusion of the tracer element in the direction normal to the tube axis. To date it has appeared more desirable to minimize the diffusion by appropriate choice of solvent and tracer rather than to depend on a mathematical correction for the effect of diffusion on the data. It is anticipated that suitable choice of tracer and fluid will permit accurate laminar flow measurements to within 0.0005 inch from the wall without significant diffusional error.

Although laminar flow measurements, particularly in the extreme wall-adjacent region, are of considerable interest, there are a number of much more important problems in relative fluid motion. Consequently, as soon as the apparatus and procedure had been worked out with laminar flow, a series of tests were made to determine the applicability of the tracer displacement procedure to some of these other problems.

The two outstanding advantages of this new technique are its high sensitivity and the absence of disturbing probes in the flowing fluid. The principal disadvantage, one which is always its ultimate limitation, is the difficulty of quantitative interpretation of the data obtained when the flow pattern is complex.

The remaining sections of this report describe the procedures used and results obtained in applying the tracer displacement method to the observation of Newtonian fluids in turbulent flow, non-Newtonian fluids in laminar flow, and Newtonian fluids undergoing mass transfer, vibration, and passage through conduits with rough walls.

Complete tabulation and presentation of the data for every run made is not feasible because of the nature of the data. However, there are tables presented in the appendix of this report in which the runs are listed, together with the more pertinent facts regarding conditions which were used in each run.

Manuscript released by the authors in March 1956 for publication as a WADC Technical Report.

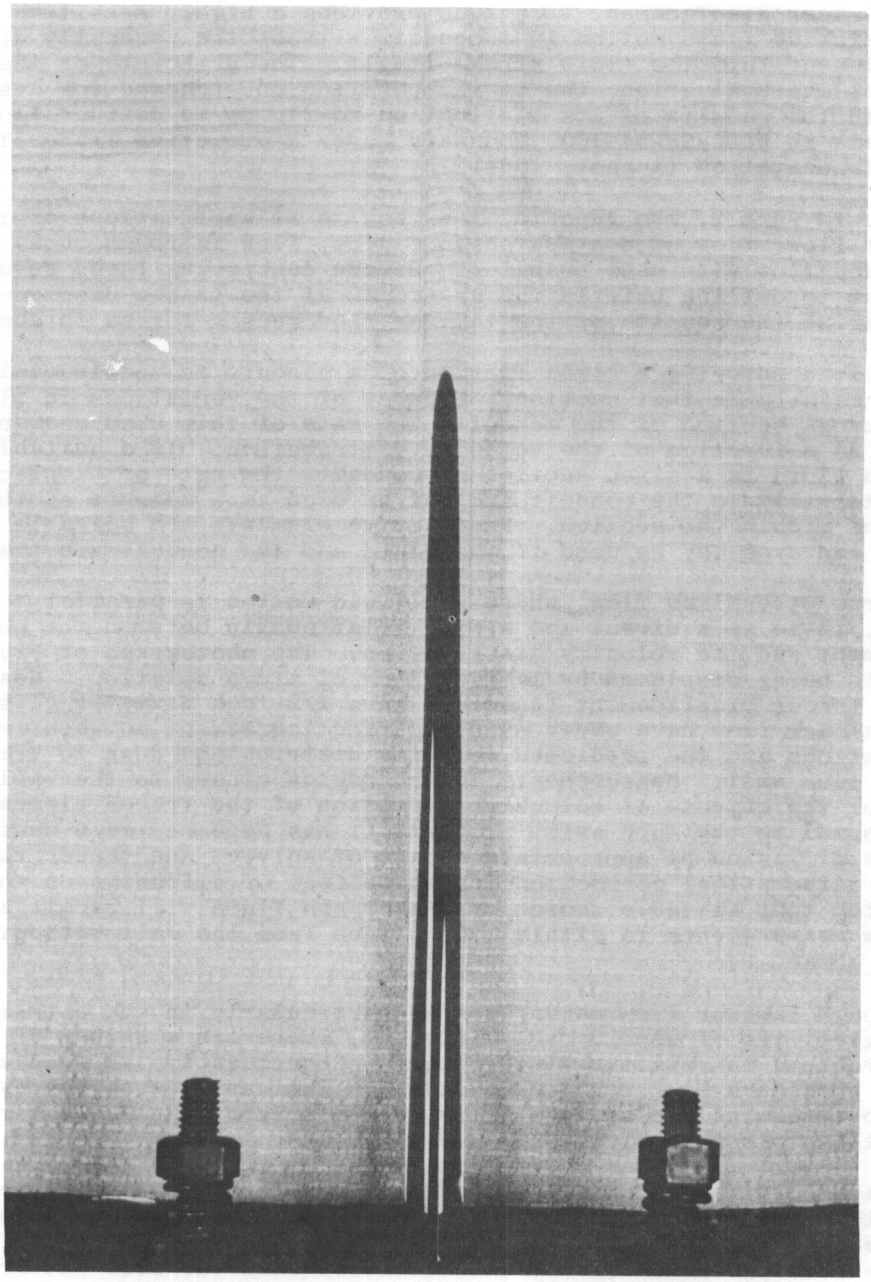


Figure 1. Parabolic Velocity Pattern Made Visible by Dye Tracer

I. TURBULENT FLOW

The phenomenon of turbulence in flow is one commonly observed and extensively studied. Whenever a critical value of the dimensionless Reynolds number is exceeded, the possibility of stable turbulence exists. The essential characteristic of turbulence is the existence of components of velocity normal to the axis of net flow. For incompressible fluids (or for those experiencing negligible changes in density over the region in question), the continuity of flow requires that the time average of such components shall be zero in the direction normal to that of net flow. Actually turbulence appears as a time variant phenomenon, and elements of the fluid may possess velocity components in all three directions. The magnitude of these components varies from instant to instant both when observed at a fixed position or when following a particular fluid element. The instantaneous magnitudes of the component velocities normal to the direction of flow may be an appreciable fraction of the mean net flow velocity. The velocity in the net flow direction also has superposed upon it fluctuations which may be appreciable fractions of the mean velocity.

Turbulence may be studied in a free stream well removed from any confining wall or other fixed surface. Under these conditions considerable progress toward a suitable theoretical treatment may be made by the assumptions of homogeneity of the turbulence and of the applicability of normal statistical distribution. Unfortunately, in the regions adjacent to bounding walls, assumptions of homogeneity are definitely invalid. In these wall-adjacent regions there are extremely steep velocity gradients which result in high shear even in fluids with relatively low viscosity. This wall-adjacent region is important in flow around submerged bodies such as the various surfaces on an aeroplane or ships, and they are of equal importance near the confining walls in conduits, as for example, flow in pipes. Any intelligent study of this important region requires good experimental data as well as adequate theoretical treatment.

There are many experimental difficulties inherent in carrying out measurements of the motion in this region. With liquids the entire thickness of the high shear region rarely exceeds a few thousandths of an inch. With gases it may be extended by use of large ducts and other expedients to a matter of several inches. Even here, however, the conditions within a few hundredths of an inch from the wall are of great importance. The most successful methods to date have been those using hot-wire anemometers in air streams (12). By special design and elaborate recording equipment it has been possible to measure the fluctuating components of velocity in all three directions in regions very close to the wall. Although such data have done much to better our description of the conditions existing in this region, its principal effect has been to prove the complexity of the situation. The hot-wire techniques have been highly developed but suffer from certain inherent characteristics which will always limit the information which may be obtained by their use.

Preliminary experiments on the present project, using the tracer displacement technique with fluid in turbulent motion, showed definitely highly reproducible results. The data taken are complex and there is severe question regarding interpretation in terms of the flow pattern. Despite this, it was felt that the great importance of any contribution to a knowledge of conditions in the wall-adjacent region warranted further measurements in the belief that some interpretation would be forthcoming. It should be pointed out here that the dye displacement technique and the radiotracer displacement technique are not expected to give identical results in turbulent flow although they do in laminar flow. In the previous report it was pointed out that the dye displacement technique makes a measurement of the totalamount of tracer (dye) in a diametrical path across the tube. The radiotracer procedure measures the total tracer (radioactive material) in a volumetric element encompassed in a short length of the tube. Where displacement is a unique function of the radius, i.e., independent of the circumferential position, the two measurements are readily converted one to the other by simple consideration of the relative geometries.

In turbulent flow the time-average rate of displacement at a given position along the length of a tube may be approximately independent of circumferential position, but the instantaneous value will be a function both of radius and circumferential angle. The effect of the radioactive tracer procedure is to average the rate of displacement over the entire circumference of the tube; the dye tracer procedure gives an average of only two circumferential positions at opposite ends of a single diameter. This means that the two techniques give supplementary data one to the other rather than mere complementary confirmation as is the case in laminar flow. Since major concern appears to be with the magnitude and extent of local fluctuation, it was felt appropriate that major emphasis in turbulence be given to studies using dyes. The decision to use dyes was also influenced by the greater simplicity of this technique and the possibility for a much greater number of runs.

A. Equipment and Procedure

Observations of turbulent flow were made in both the one-half inch column described in Part 1 of this report and in a one-inch column which was essentially similar in construction and operation. During runs made in the first column, flow was initiated and maintained by the same procedures employed in laminar flow runs, namely, first joining the tracer and non-tracer sections of the column carefully, then activating a solenoid valve to start flow, and regulating the flow rate by means of a fixed orifice calibrated to give a flow rate corresponding to a Reynolds number greater than 2000. In all the preliminary work on turbulence, dye solutions were used as the tracer solutions. These contained Pontamine Blue dye and were introduced into the lower portion of the glass section of column up to the height of either the upper or lower liquid junction device. Tracer observations were carried out spectrophotometrically, using the modified Coleman spectrophotometer previously described mounted 25-1/4 inches below the lower liquid junction device. The current output from the phototube of the spectrophotometer was recorded on a Brown recording potentiometer.

The larger diameter, one-inch, flow column was designed, after the preliminary turbulent flow runs had been completed, to increase the range of attainable Reynolds numbers and to facilitate more convenient operation of the column. A sketch of the one-inch column is shown in Figure 2. As in the first column, fluid entered the system from a constant head tank located approximately 28-1/2 feet above the active section. Flow regulation and metering were carried out by valves, a Maisch metering pump, and a weigh tank installed at the bottom of the column. Because there was some unavoidable leakage past the pump gears even at zero pump speed, a solenoid valve was also installed in the line to assure positive shut-off. The procedure for starting flow consisted of opening the solenoid valve and starting the pump simultaneously. A by-pass line around the pump made simple gravity flow runs also possible.

The working section of the column consisted of two six-foot sections of one-inch gauge-glass tubing selected for straightness and uniformity of bore. These were located about 22-1/2 feet below the constant head tank. The upper section, separated from the lower by a liquid junction-forming device, acted as a calming section, and the lower, as an observation section. A second junction-forming device was inserted at the bottom of the observation section. A Model B, Beckman Spectrophotometer was mounted around the lower section of column so that its light beam passed through the center of the observation section.

The upper junction-forming device was constructed from three one-inch thick Plexiglas blocks. It is identical in design to the device installed in the one-half inch column (16), scaled up to accommodate the one-inch tube. The operation of this component may be followed from the sketch in Figure 2. Briefly, the device is a sliding block valve having a center block which slides between two outer stationary blocks thereby bringing the valve to either the flow position or the filling position. Solution is placed in the column while the block is in the latter position after which the center block can be moved slowly to the flow position to form a sharp interface between the tracer and non-tracer sections of fluid. The holes in the blocks and in the adjoining sections of glass tube were carefully aligned in both the filling and flow positions. Because the increased surface area of the blocks made this large device prone to warpage and subsequent leakage, the whole device was sandwiched between two 1/4-inch steel plates.

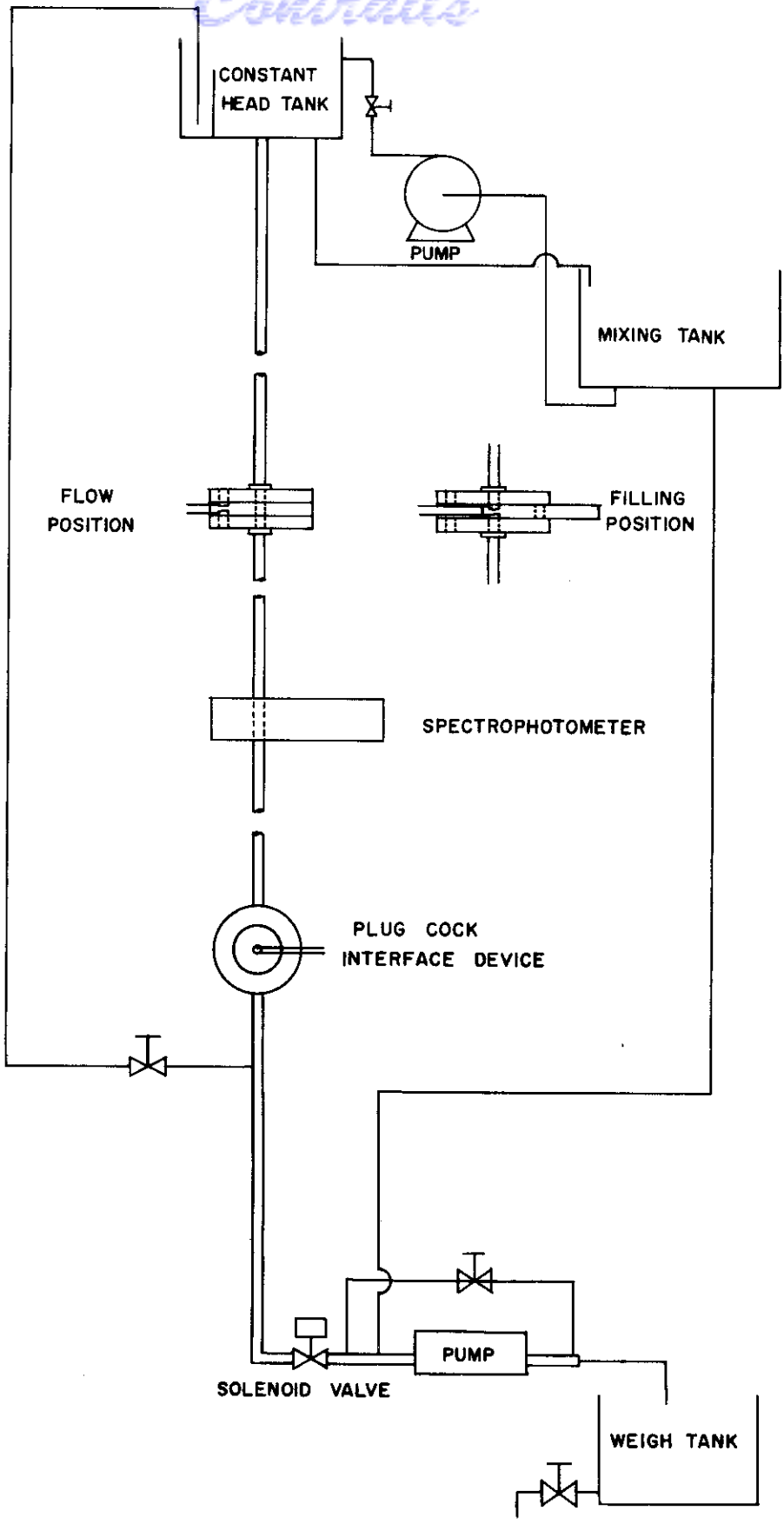


Figure 2. Schematic Diagram of Flow System 1

Since it was not necessary to obtain a carefully made interface at the lower entrance to the observation (tracer) section, a special plug-cock valve was installed here to function as a junction-former. Very precise alignment of valve and tubing was not as necessary in this case. A second line of small diameter copper tubing was installed from the constant head tank, around the working section to a spot slightly below the plug-cock to provide a means of equalizing the pressure above and below the interface prior to forming the junction.

The tracer measuring instrumentation consisted of the Model B, Beckman Spectrophotometer, a current amplifier, and a Brown Recorder. The spectrophotometer was mounted around the glass column by means of a light-tight adapter so that the tube was positioned in the space ordinarily occupied by a sample couvette. The spectrophotometer itself is equipped with an accurate meter registering per cent transmittance, a dark current compensator, and a sensitivity adjustment for four ranges each differing by a factor of $\sqrt{10}$. The amplifier and recorder were adjusted to give readings corresponding to the meter-registered transmittance for a given output of the phototube. More accurate analysis and more flexible operation were achieved with this instrumental arrangement than had been possible with the modified Coleman instrument previously described.

The procedure used for making a run was also very similar to that previously described for flow runs made in the one-half inch column. The entire column was initially filled with clear water. This was allowed to stand in the column for several hours during which time the instruments were warmed up and at the end of which the slit width was adjusted so that the transmittance read 100% on clear water. The two interface devices were then moved to the filling position and the section of column between them drained. This section was then rinsed with the dye solution to be used and finally filled with this solution. After allowing the solution to stand in the column for several minutes to permit eddy currents to damp out, the lower junction-forming device was changed to the flow position, pressure above and below the interface was equalized, the upper junction-forming device was moved to the flow position, and flow was started immediately.

An observation of turbulent flow made by the foregoing procedure was subject to an unknown error in interpretation caused by the unavoidable acceleration of fluid motion at the beginning of a run. At the start of flow, the various elements of fluid in the column are at rest and must accelerate from zero velocity to a final steady-state velocity. In laminar flow observations, this acceleration is also present but, as has been discussed previously (4), this has been shown to have little influence on the observed parabolic flow pattern. When the final flow velocity is in the turbulent flow region, however, the static start becomes a point of considerable significance. As the flow builds up from zero velocity, there is always a brief period in which the flow is laminar, followed by transition to turbulent flow, and finally to the steady state, fully developed turbulent flow. The duration of the initial laminar period depends on the presence or absence of turbulence-promoting disturbances and their location with respect to the observation section. In the particular system we used the "natural" point of turbulence initiation appeared to be the junction between the column proper and the constant head tank. At the beginning of a normal run, a turbulent "front" was generated and carried down the column at a rate approximately equaling the mean velocity of flow.

Visual as well as spectrophotometric observation confirmed the fact that the fluid in advance of this turbulent front was in substantially pure laminar flow. Our experimental conditions were such that a considerable amount of dye remained in the wall-adjacent portion of the column above the measuring device at the time the turbulent "front" passed down the column. The initial effect of the turbulence break was to sweep much of this dye toward the center of the tube into a relatively small volume wherein the dye appears to the detector as a fast-moving "slug" of concentrated solution. After the passage of this "slug," turbulent flow quickly removed the remaining tracer. A facsimile of a chart record shown in Figure 7 illustrates these occurrences in the dotted-line trace of run 1-25. In the initial portion of the trace a smooth increase in transmission occurs for about 7 seconds after which the per cent transmission returns sharply to zero, indicating the passage of the deeply dyed volume of fluid immediately ahead of the turbulent fluid. The remainder of the dye passed the detector in an erratic manner characteristic of turbulent runs, as it speedily disappeared.

It is obvious that any information concerning fully developed turbulent flow would be difficult to obtain at reasonable dye concentrations in this system unless the initial acceleration period and associated disturbances were eliminated or drastically reduced. Attempts were made to achieve the second alternative by introducing turbulence promoters into the column at points nearer the observation section and by adding a pump to the system. To check the observation that turbulence was initiated at definite points upstream from the interface and to hasten the turbulence transmission, a turbulence promoter consisting of a four-inch long roll of screen wire was inserted in the column at several locations above the junction-forming device. As was expected the turbulent front reached the detector at times nearly proportional to the distance of the promoter from the point of observation. While the turbulence development occurred nearer the spectrophotometer location when promoters were used, the reduction of the acceleration period was not sufficient to assure observation of fully developed turbulence at a reasonable dye concentration. Also, there are added uncertainties as to the effect of the promoter on the turbulence pattern when the wire is placed quite near the observation point.

The effect of adding a turbulence promoter is shown in Figure 3 where the distance from the promoter to the spectrophotometer divided by the time for turbulence to reach the spectrophotometer is plotted as a function of the average velocity of flow. If turbulence may be considered to begin at the promoter, the ordinate here becomes the velocity of the turbulent front moving down the tube. It may be noted that at low velocities, the velocity of the turbulent front coincides with the mean velocity of flow. At higher values, however, there is a considerable variance of the front velocity with different promoter distances probably due to the simultaneous growth of instability from more than one point in the tube.

A second procedure used in an attempt to reduce the transition flow period to a minimum value was to accelerate the fluid very rapidly by means of an auxiliary pump so that the ultimate volumetric flow rate could be reached almost instantaneously. For this purpose, a positive displacement pump was installed at the downstream end of the column. The pump chosen was a Maisch variable capacity metering pump with a rated capacity of zero to 150 ml. per sec. and a continuously variable speed transmission. This arrangement was not completely effective in shortening the transition period because of excessive leakage past the pump gears and because of mechanical difficulties encountered with the transmission.

Because of the uncertainty inherent in any observation of turbulence which must interpret acceleration effects, it seemed mandatory to attempt to eliminate these entirely by designing a flow system in which steady state flow was established prior to the formation of an interface between tracer and non-tracer solutions. A number of schemes for accomplishing this were worked on and one involving the establishment of flow through a short by-pass line around a specially devised diaphragm arrangement was chosen as the most workable way to carry out the displacement technique under dynamic flow conditions.

A sketch of the final design of this flow system is shown in Figure 4. The general arrangement of the column remained essentially the same as the original and all of the auxiliary equipment such as the constant head tanks, pumps, valves, etc., are those used in the static column. The working section of column consisted of two six-foot sections of one-inch glass tubing connected around and/or through the diaphragm "valve." The Beckman spectrophotometer was mounted as previously on the lower portion of the glass tubing. The valve-to-spectrophotometer distance was 39 inches. The by-pass line around the junction-forming device joins the column close to the "valve" on each side, as shown in Figure 5, a pictorial sketch of the valve and spectrophotometer mounting.

Prior to the initiation of a run the diaphragm is closed and liquid is circulated through the column by way of the by-pass line. Concentrated dye solution is injected into the stream in the by-pass line. Under steady flow conditions of both the main stream and the injected dye stream, good mixing occurs in the by-pass line. Dye concentrations are adjusted so that the volume of the injected dye stream is negligible compared to the principal flow. A few seconds after the dye injection begins, an equilibrium dye concentration is reached as indicated by a steady photometer reading. The value of this concentration is determined by

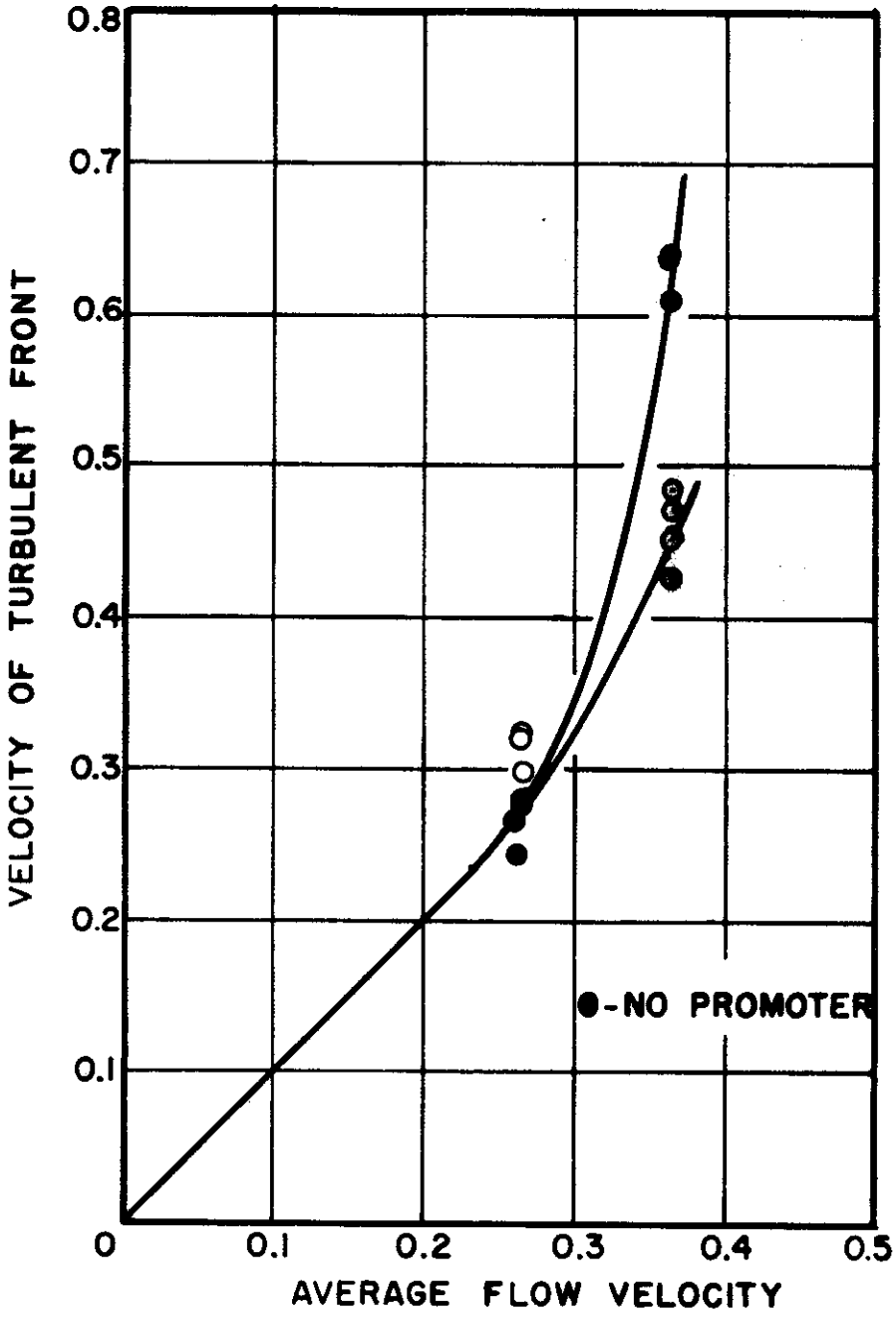


Figure 3. Effect of Turbulence Promoter on Turbulent Front Movement.

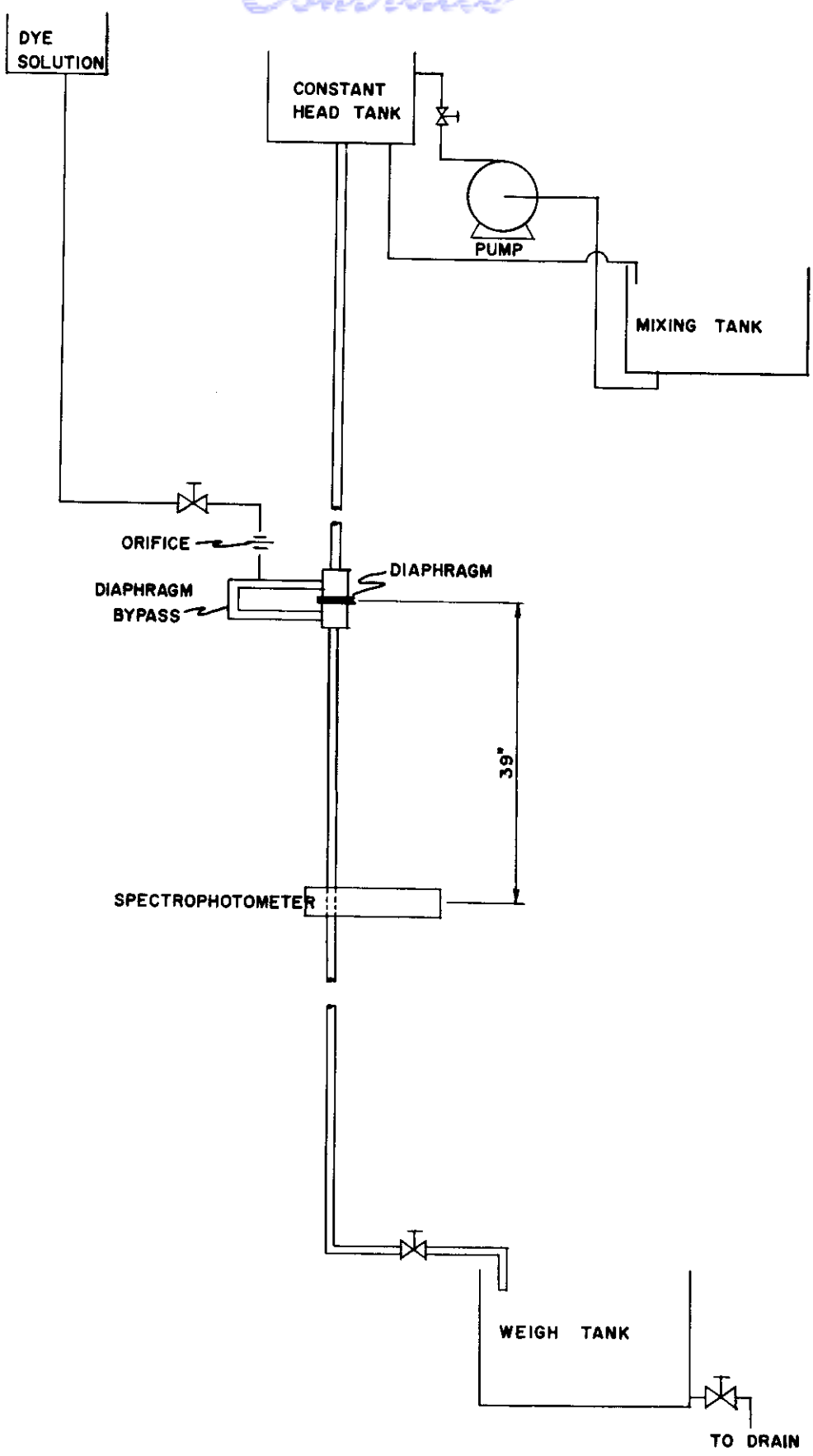


Figure 4. Schematic Diagram of Flow Column

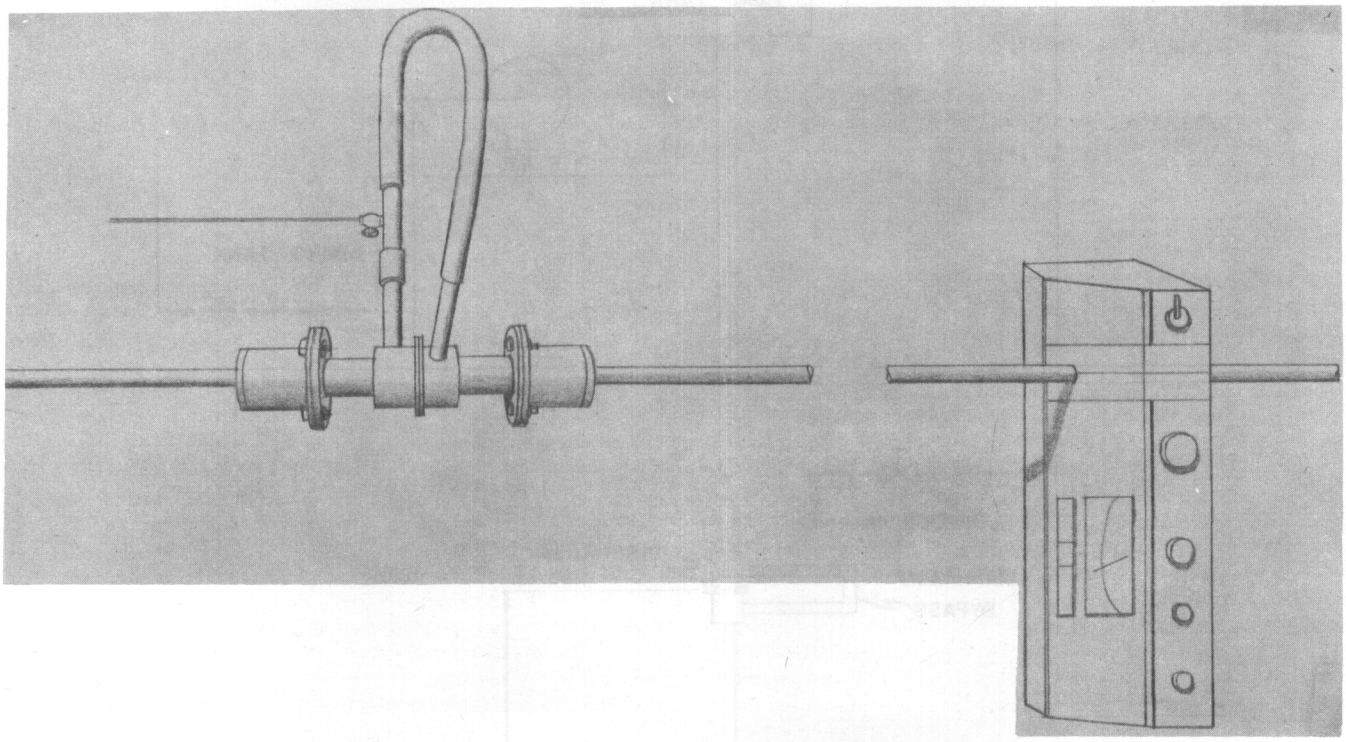


Figure 5

Sketch of "Valve," showing by-pass line and spectrophotometer mounting.

sampling the equilibrium dye flow and analyzing it colorimetrically. To begin a run the diaphragm is opened and the by-pass line is closed simultaneously. Since the size of the latter is large, the pressure drop through the by-pass is no greater than that through the main column. Whenever the diaphragm opens completely, flow rates before and after the opening are the same.

The interface-forming device itself is designed for smooth and rapid connection of the two straight sections of column and at the same time to block the by-pass line in such a way that a reasonably sharp interface is formed between the two flowing columns. The details of this design are shown in Figures 6 and 7. In the first drawing, the upper half of the valve which connects to the upper section of column is shown in an exploded view along with the diaphragm itself. The latter consists of a thin rubber sleeve about four inches long and one inch in diameter which has been stretched across two Plexiglas rings. In this position the diaphragm is open and ready for flow as shown in Figure 7A. Because the rubber is stretched in this position, the opening is slightly larger than the one-inch inside diameter of the flow column. To close the diaphragm, one of the plastic rings can be rotated through approximately 120° with respect to the other to form the iris closure shown in Figure 7B.

The rubber diaphragm is mounted between two stainless steel sleeve-flanges which are free to rotate around the tube axis. By rotating these sleeves in opposite directions approximately 60° each, the diaphragm may be opened and closed. Rotation of the sleeves turns the diaphragm and Plexiglas rings by friction. As may be seen in the drawing, this rotation also provides for opening and closing of the connections between the flow column and the by-pass line. The sleeve-flanges are made to fit tightly in the brass body of the valve. Although there is no positive seal between the sleeves and the body, leakage under full column pressure is negligible. Both upper and lower parts of the valve are clamped together on both sides of the closed diaphragm which also acts as a gasket.

The rubber sleeves, although made of very thin latex rubber, seldom tear or move far out of place during the opening of the iris; however, they are removed and replaced after each run to prevent possible sticking and leakage. This is carried out by lifting the entire upper part of the column a fraction of an inch above the lower part and inserting a new diaphragm in the closed iris position. The lower portion of the column contains a short length of flexible tubing connected in the horizontal outlet line which allows considerable freedom of movement in the lower column also. A set of counterbalancing weights holds the bottom section in alignment while the two parts are separated.

The operation of opening the diaphragm when making a run requires from one to two seconds, a procedure which does not produce a completely flat interface between the two solutions. In effect this causes the junction in the center portion of the tube to be somewhat blurred and to extend over a short length of tube. However, the spectrophotometer is located far enough downstream so that the effect of a blurred interface is damped out in the wall-adjacent region at the point of observation. The valve operating procedure was tested by making several runs in which the flow was laminar and checking the velocity distribution. One such curve appears in Figure 8 where the effect of a badly distorted interface can be seen as a small variance of the velocity distribution in the center of the tube from a parabolic pattern. Velocities near the wall, however, remain unaffected. The small internal irregularities in the tube wall caused by the by-pass line connections and sleeve cause negligible error.

B. Presentation of Results

A series of runs was made in turbulent flow using Pontamine Blue dye in water with Reynolds numbers from 3000 to 7000 for the mainstream flow. A facsimile of the current recorder chart record showing the typical forms of two of these runs is given in Figure 9 where flow runs from the "static" and "dynamic" arrangements are compared for approximately the same Reynolds number of flow and dye concentration. The dotted line representing a run made in the static column shows the laminar start-up interrupted by a sharp break into turbulence and irregular removal of dye immediately following. The solid trace shows the characteristic turbulent removal of dye occurring where two halves of the turbulent mainstream are suddenly joined and no acceleration takes place.

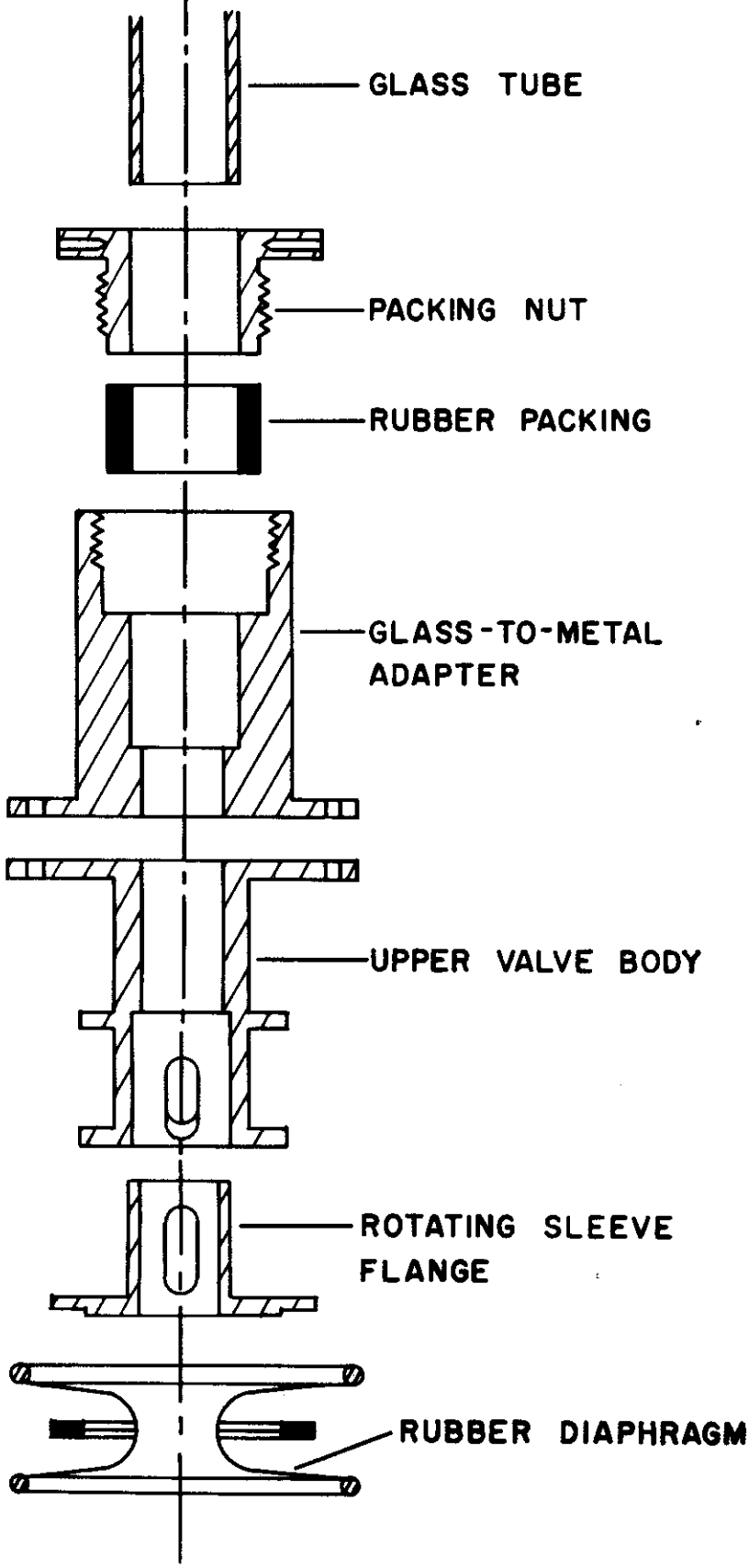


Figure 6. Exploded Cross Section of Diaphragm Valve

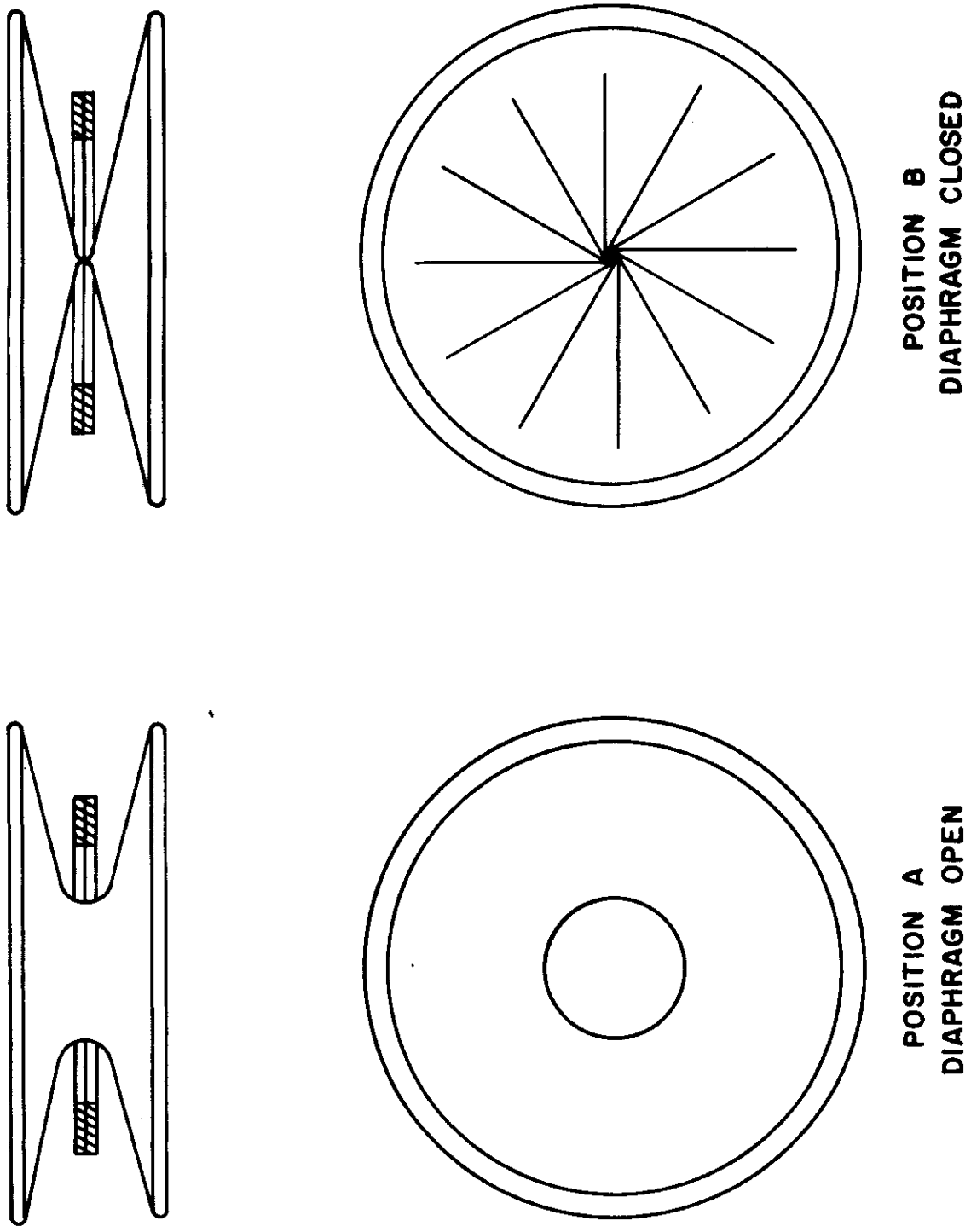
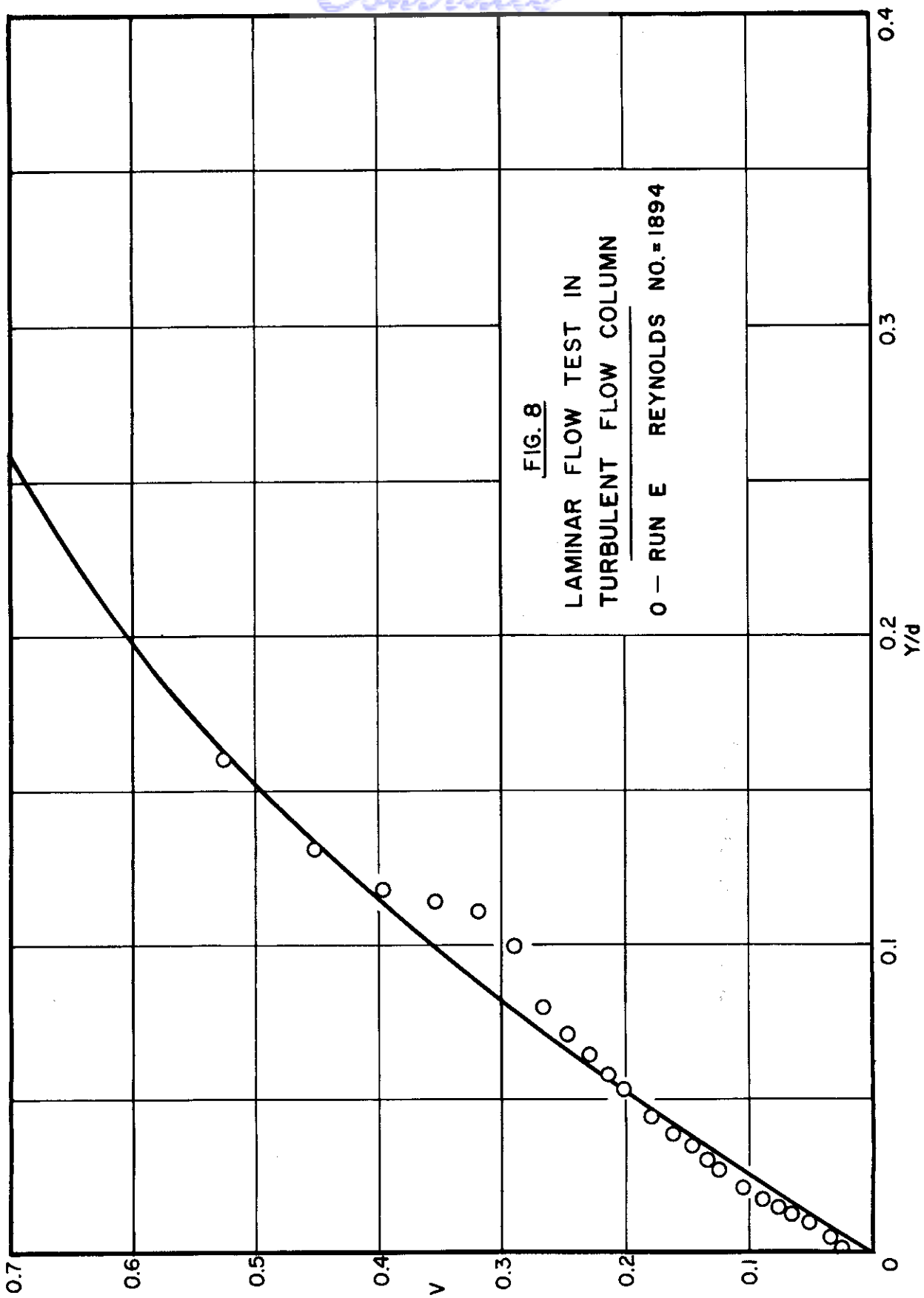


Figure 7. Details of Open and Closed Diaphragm



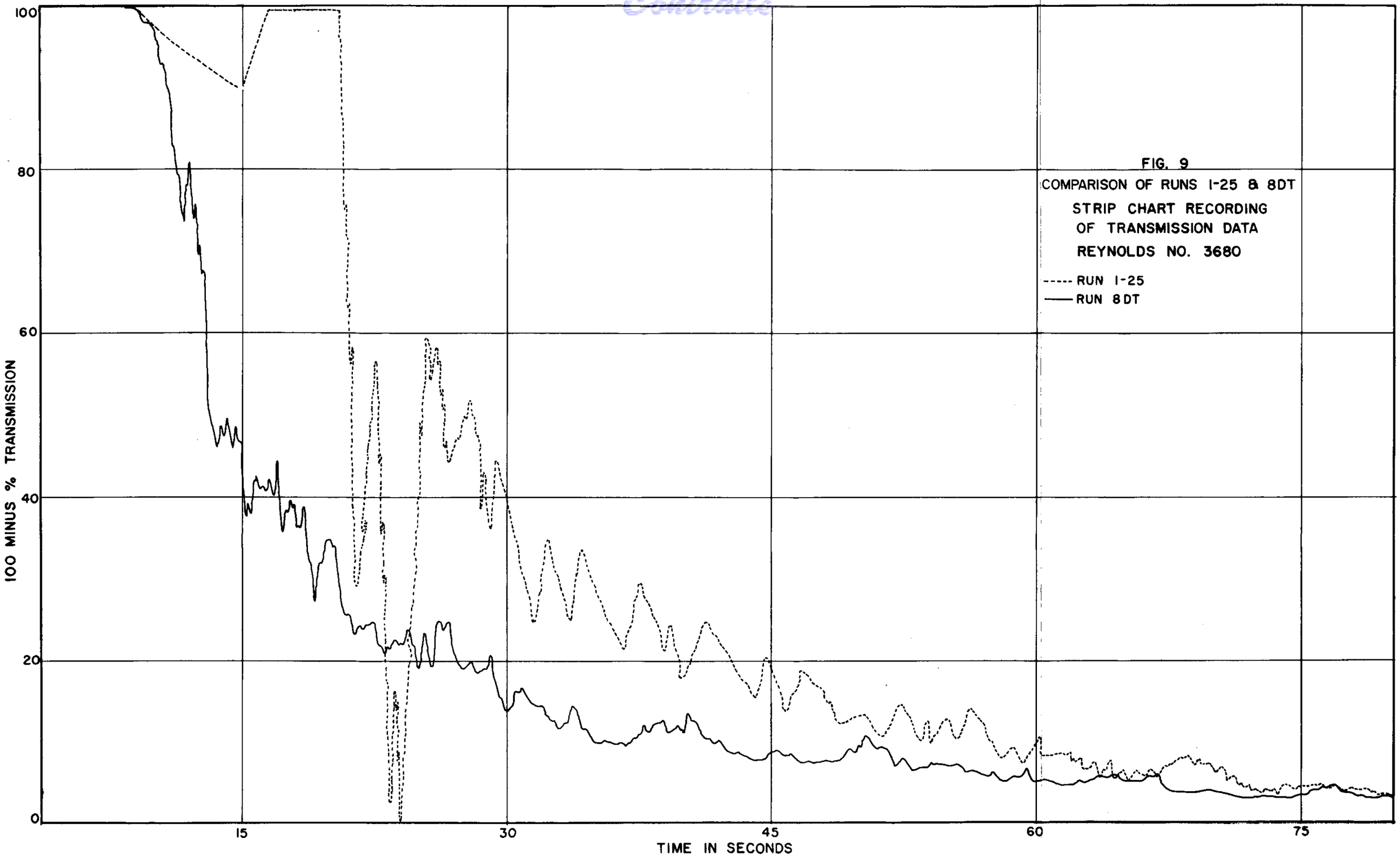


FIG. 9

COMPARISON OF RUNS 1-25 & 8DT

STRIP CHART RECORDING
OF TRANSMISSION DATA
REYNOLDS NO. 3680

----- RUN 1-25
—— RUN 8DT

It should be noted here that a relatively sharp washout occurs at the beginning of the run followed by a more gradual dye removal as the wall-adjacent region is reached. For practical purposes the two arrangements give results very nearly approaching each other in the very low dye region. Only the dynamic runs, however, can give an accurate picture of the entire pattern from the center outward.

A second chart facsimile, shown in Figure 10, compares the washout record of two runs made in the dynamic column of approximately the same dye concentration and Reynolds number. Here a very striking reproducibility of value and over-all pattern is demonstrated. While occasionally the patterns show some variance, particularly when the interface had been badly disturbed on opening the valve, the reproducibility is generally very good. Any obstruction to the juncture between the two main sections of column caused by improper opening of the iris is immediately apparent from the appearance of the chart record and change in flow rate measured after junction has been formed. It is very unlikely then that poor interface formation went undetected during a run.

The observational advantage gained by having the flow initially turbulent is again illustrated in Figure 11 where three runs made in the original column and one made under dynamic conditions are shown as Y/D plotted as a function of a normalized velocity, V/V_{avg}, where Y is the radial distance from the wall, D is the diameter of the tube, V is the velocity at the distance Y from the wall and V_{avg}, the average velocity.

Each of these runs was made at a velocity corresponding to a Reynolds number of about 3600. The solid line through the origin is the predicted distribution for pure streamline flow. For the runs 1-13, 1-21 and 1-23, the turbulence was initiated from three different positions. For 1-13, no artificial turbulence promoter was introduced and hence turbulence was initiated at the entrance to the column from the constant head tank, a distance of about 28-1/2 feet above the interface. For runs 1-21 and 1-23 a rolled-up piece of screen wire was placed in the column 23-1/2 inches and 67 inches above the interface respectively. In each case the general flow behavior is the same. The flow downstream from the turbulence initiator starts out as a streamline and only becomes turbulent after the "turbulent front" has moved down through the tube. The effect of this turbulence front is to wash out the tracer at an increasingly rapid rate. With the turbulence initiated close to the original interface, this increased rate of displacement starts while there is still a large amount of dye left in the tube.

With run 4-DT, also shown in Figure 11, the flow is in full turbulence prior to the start of displacement. This run was made in the dynamic column previously described and consequently the velocity distribution curve is much flatter and extrapolation would give a satisfactory turbulent flow pattern having an area under the curve corresponding closely to the observed average velocity.

A similar set of curves is shown in Figure 12 where the average flow velocity is lower and corresponds to a Reynolds number of about 2600. Here the runs 1-15, 1-19 and 1-26 correspond to no artificial promoter, promoter at 67 inches, and promoter at 23-1/2 inches above the interface respectively. The shape of the curves indicates that passage of the turbulent front has caused a marked increase in rate of dye displacement but that the front itself is in more violent turbulence than is the fluid following it. Since a Reynolds number of 2600 is definitely in the transition region, this type of effect is to be expected. This is one of the important factors which led to the decision to build the dynamic flow column because of such a column no "front" marking a transition from streamline flow to turbulence can exist.

Figure 13 shows the typical data from four dynamic column runs presented on Prandtls co-ordinates so that they may be readily compared with the so-called "universal velocity profile." The curves shown are typical of all the data and these particular runs were selected to show the general reproducibility of the data and the shift of data accompanying change in velocity.

Runs 7DT and 8DT were both made at Reynolds numbers of about 3600. The data, although convex upward, would fit reasonably well with an extrapolation of the straight line portion of the universal velocity distribution plot. Close

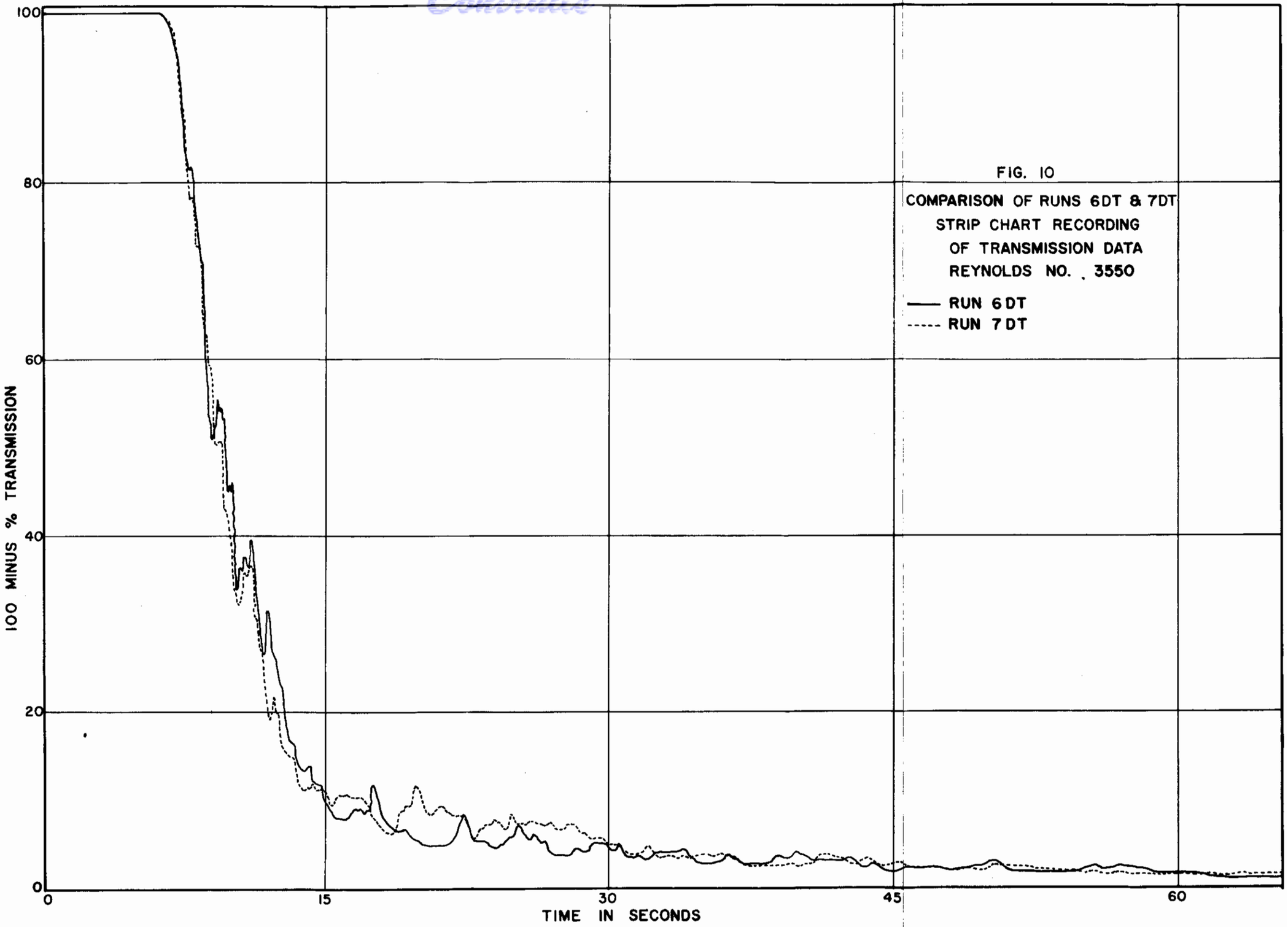
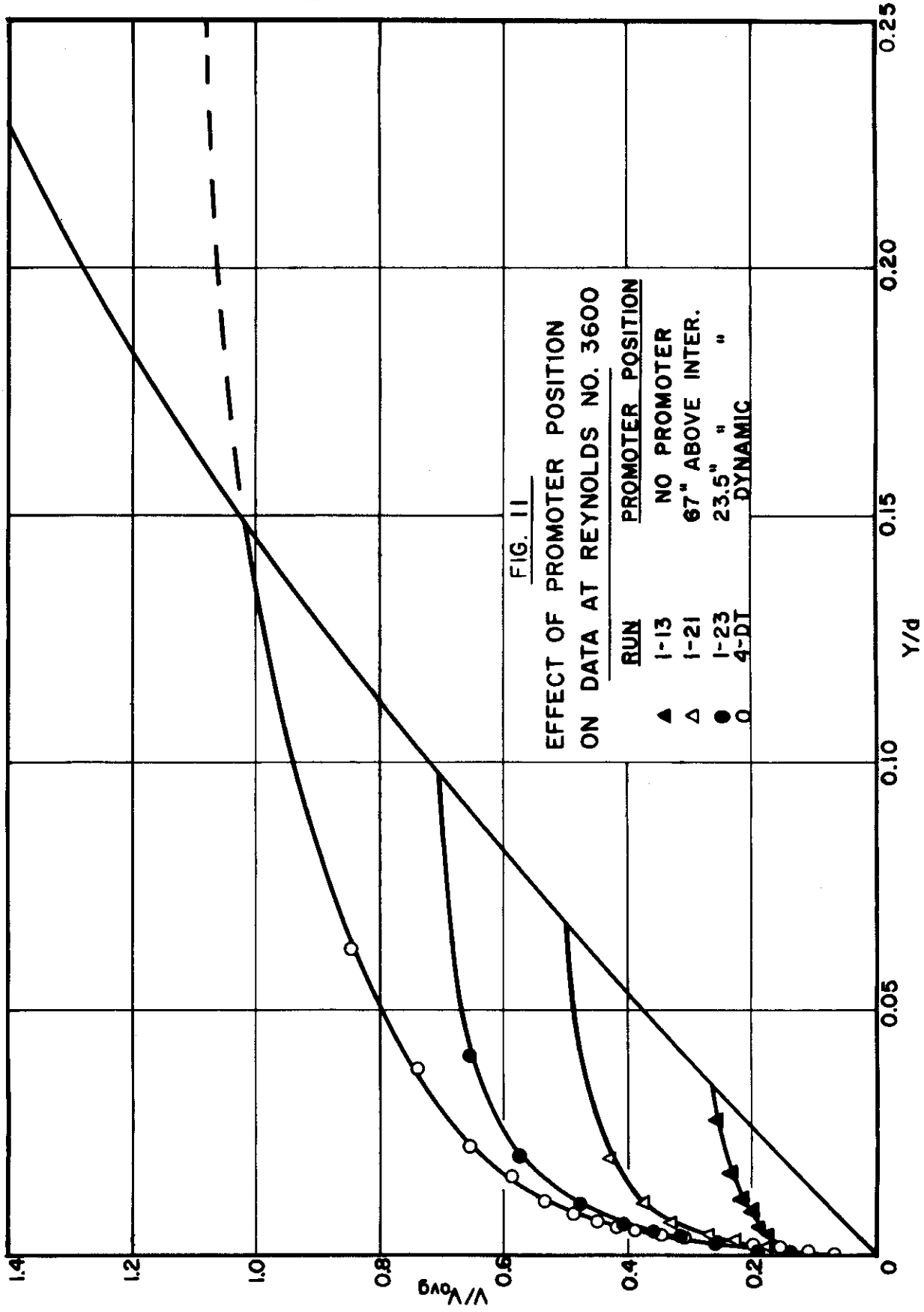
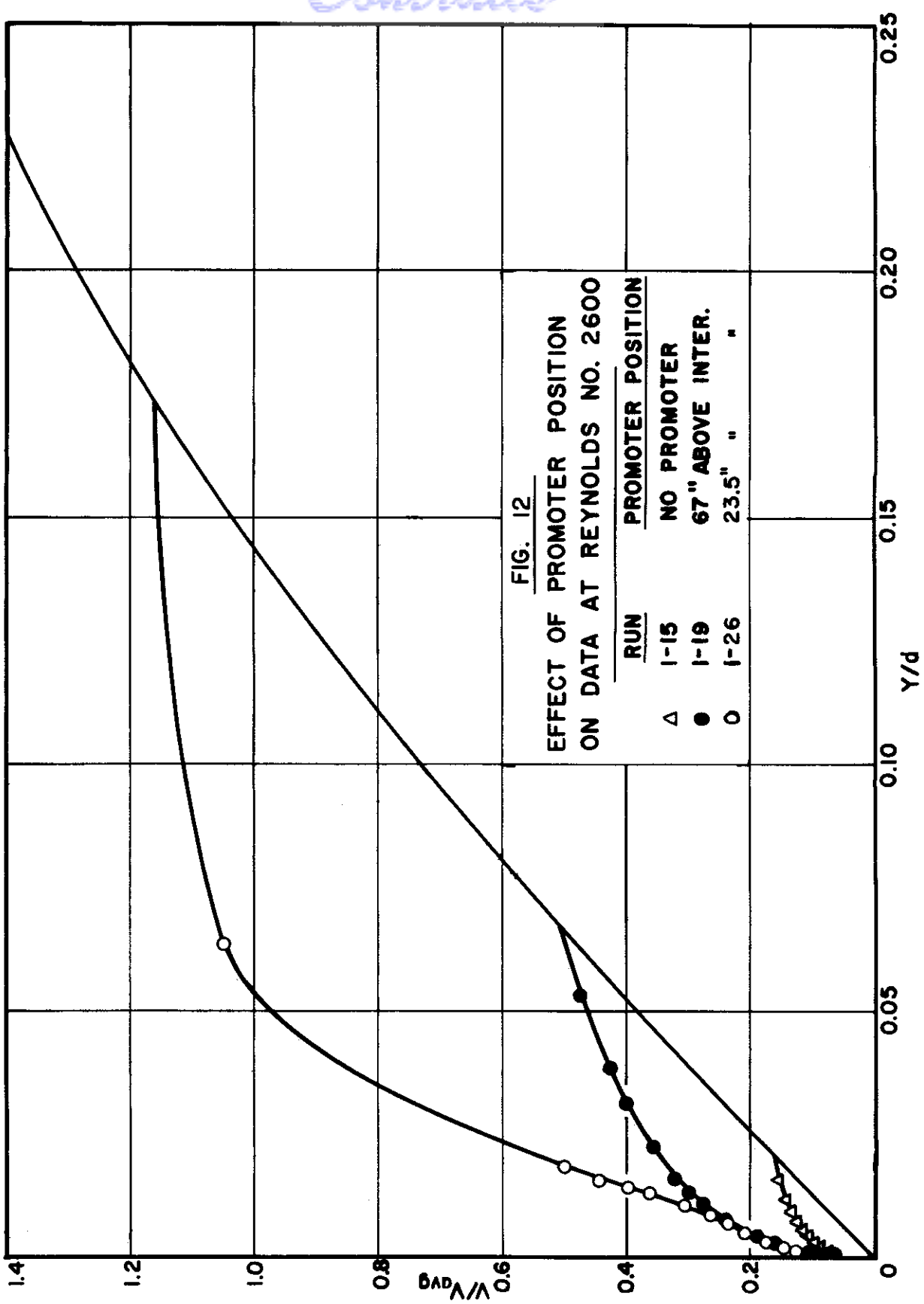


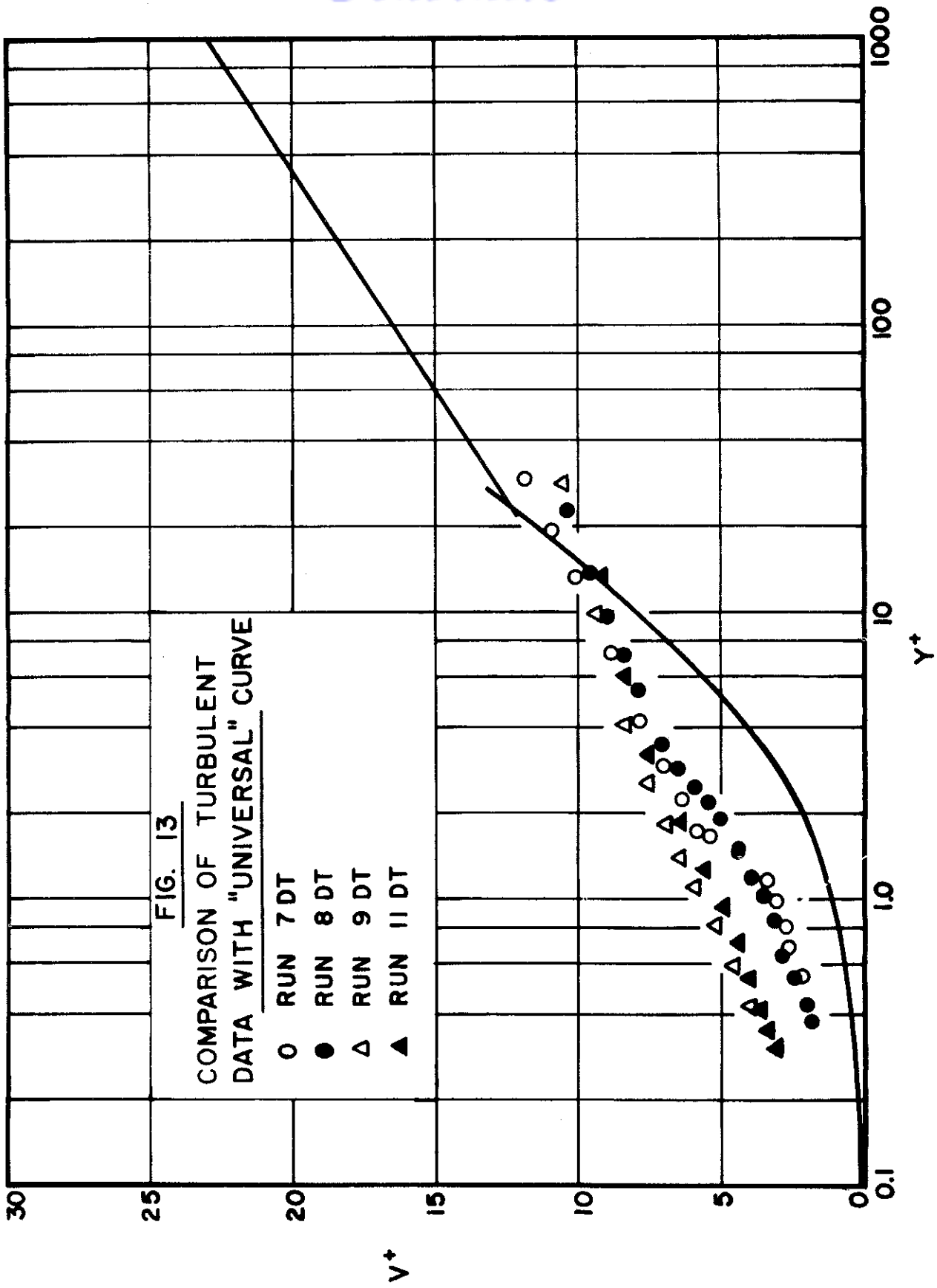
FIG. 10

COMPARISON OF RUNS 6DT & 7DT
STRIP CHART RECORDING
OF TRANSMISSION DATA
REYNOLDS NO. 3550

—— RUN 6DT
----- RUN 7DT







examination of these data shows marked evidence of a break in the neighborhood of $y^+ = 2$. The portion to the right of this break has a slope appreciably less than that of the "universal" curve.

Runs 9DT and 11DT were made at Reynolds numbers of 6956 and 6214 respectively. These data show no clear sign of a "break" although their shape is slightly convex upward. These curves, like those for runs 7DT and 8DT, have a much smaller slope than that of the universal curve. It is difficult to suggest any satisfying explanation of these curves. The immediate reaction is to attribute the shift of data toward the left to an effect of eddy diffusion analogous to that produced by molecular diffusion in laminar flow, but this explanation does not seem adequate. If eddy diffusion is the sole factor, one wonders why the data of $u^+>10$ fall to the right of the curve, i.e., a slower rate of displacement of tracer than predicted. This might be attributed to washdown of dye "scrubbed" off the tube walls about the spectrophotometer location, but on quantitative grounds this appears questionable. The location of the clearly defined break points in both runs 7DT and 8DT is not consistent with a simple eddy diffusion explanation. It may well be that these data simply indicate that for a liquid in a small tube the effects of turbulence extend much closer to the wall than would be indicated by the universal curve. Some resolution of this problem may be reached in later work by observing the effect of location of the spectrophotometer relative to the interface.

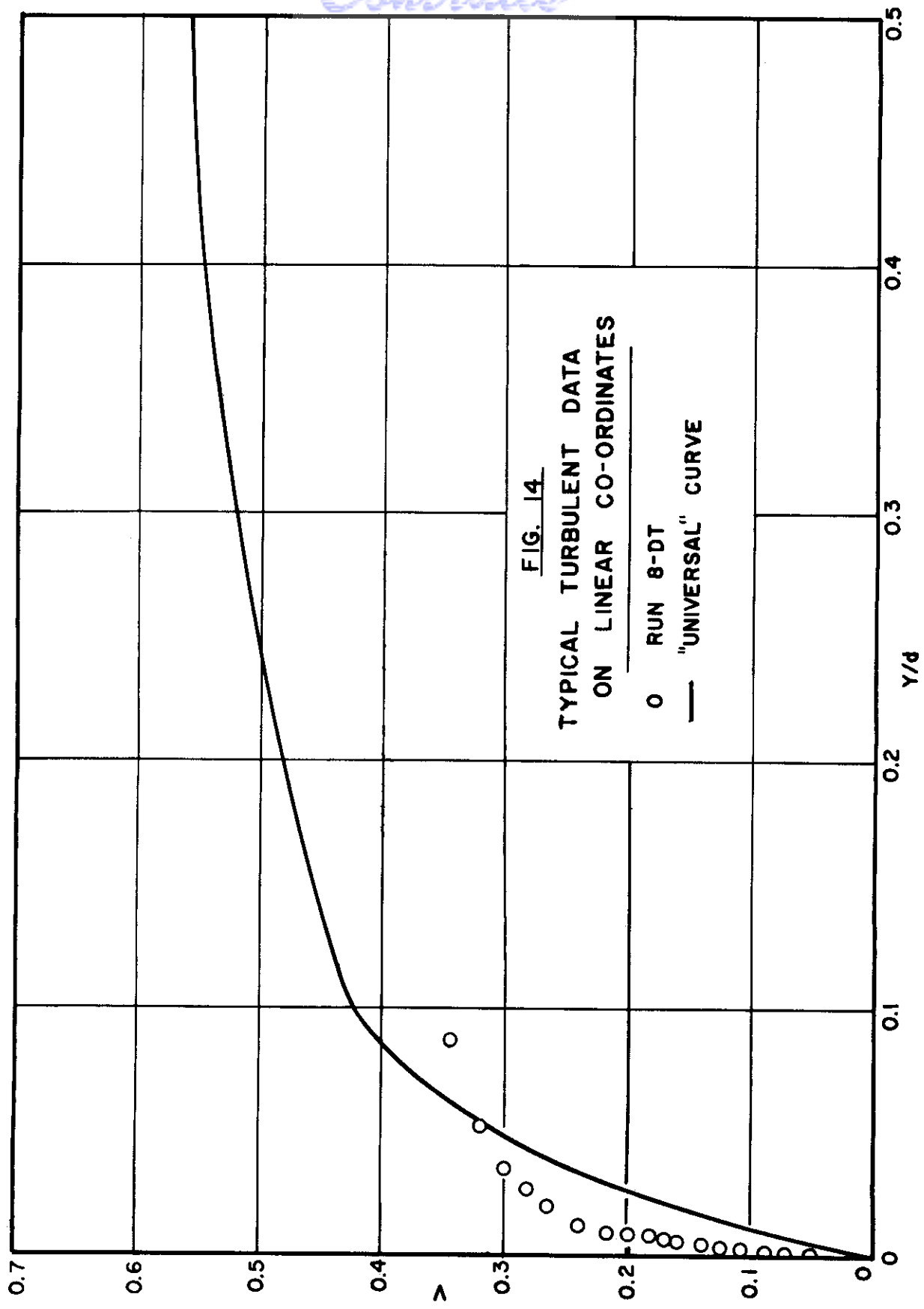
The data of 8DT are shown in linear velocity-position coordinates in Figure 14. The solid curve in this figure corresponds to the universal velocity distribution and the shift of the data may be clearly seen.

Before proceeding with a discussion of this and some other runs, it is appropriate to introduce some photographs which show something of the nature of the conditions near the tube wall in turbulent flow. Figure 15 is a sequence of six photographs showing the displacement of a dye from a one-inch diameter tube at a flow rate of 0.92 fps corresponding to a Reynolds number of 7200. These runs were made in a sliding block column and hence start from a static condition.

In Figure 15A, the fluid in the lower portion of the tube is in laminar flow and turbulence can be seen starting near the top of the picture. Five seconds later the flow is completely turbulent but a filamentation of the tracer can be clearly seen. These filaments come and go, persisting for short periods at various locations. They still exist, however, more than 35 seconds after the initiation of turbulence.

Both from photographic and visual examination it appears that these filaments are formed in the wall-adjacent region. To test this critically several experiments were run in which dye was introduced near the center of the tube after flow was well established. In all cases, the dye introduced in this manner appeared to be distributed rapidly and uniformly throughout the tube without trace of filamentation. The tests showed conclusively that this was a wall effect. Tests with increasing concentrations of dye showed no limit to the observation of this filamentation. The more concentrated the dye the longer the period of time during which filamentation could be clearly observed.

An explanation of this phenomenon is difficult. Had light streaks been seen, these might have been attributed to eddy swirls scraping through a dye layer at the walls. Dark filaments such as shown in the photographs could only be formed by the collecting together of dye from an area of the wall. This behavior may be consistent with the "filament" nature of flow pointed out by Schubauer (21). These filaments give an explanation of the highly irregular light transmission record obtained from thespectrophotometer in turbulent flow (see Figures 9 and 10). Based on the photographic observations, the method of transcription of data from the charts has been to pass a smooth curve through the transmission maxima, i.e., to assume that the irregularities are caused by random filaments of more concentrated dye superposed on a relatively smooth layer. Actually the magnitudes of the fluctuations are such that choosing the minima instead of the maxima would make comparatively small difference. On run 8DT, for example, a plot of the minimal data would be about half way between the plotted data and the solid curve on Figure 14.



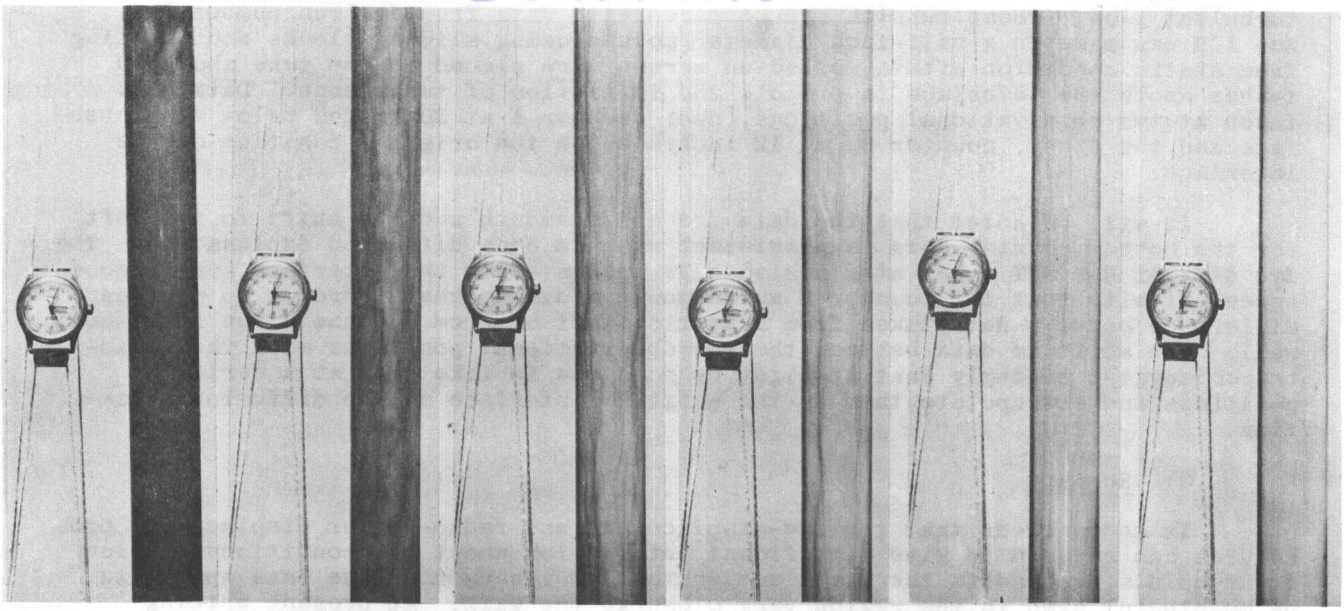


Figure 15

Photograph of "Streamers"

Turbulent displacement of dye in a 1-inch column at a Reynolds number of approximately 7200. Watch is 50 inches below original interface.

Pontamine Blue Dye Mean velocity, 0.92 fps

(a) Turbulence starting near top of picture taken approximately ten seconds after start of flow. Note that the tube is not full of dye but dye layer is smooth indicating laminar flow in lower portion of picture.

(b), (c), (d), (e), (f)

Development and persistence of filament clearly visible even thirty-five seconds after start of turbulence.

Figure 16 shows the results of the single radioactive run, 17R, made in turbulent flow. These results are compared with data from dye run number 9DT. Run 17R was made in a half-inch diameter column using sliding blocks and starting from static condition with a rolled-up screen wire placed in the tube about 20 inches above the interface to promote the initiation of turbulence. Data were taken at two observational positions; one, counter A at 30 inches below the interface and the other, counter B, at 12 inches below the original position of the interface.

It will be noted that the data are quite smooth and the shift to the left for the bottom counter data is consistent with an eddy diffusion explanation. The dye data of Run 9DT taken at a position 39 inches below the interface are in good agreement with that for counter B which would indicate that there is no profound difference between data taken from a static start or from a dynamic run near the wall. The shift in data between the two observational positions with the radio-tracer suggest strongly that it might be possible to take data at a series of positions and extrapolate them to the original interface or "no diffusion" location.

C. Summary

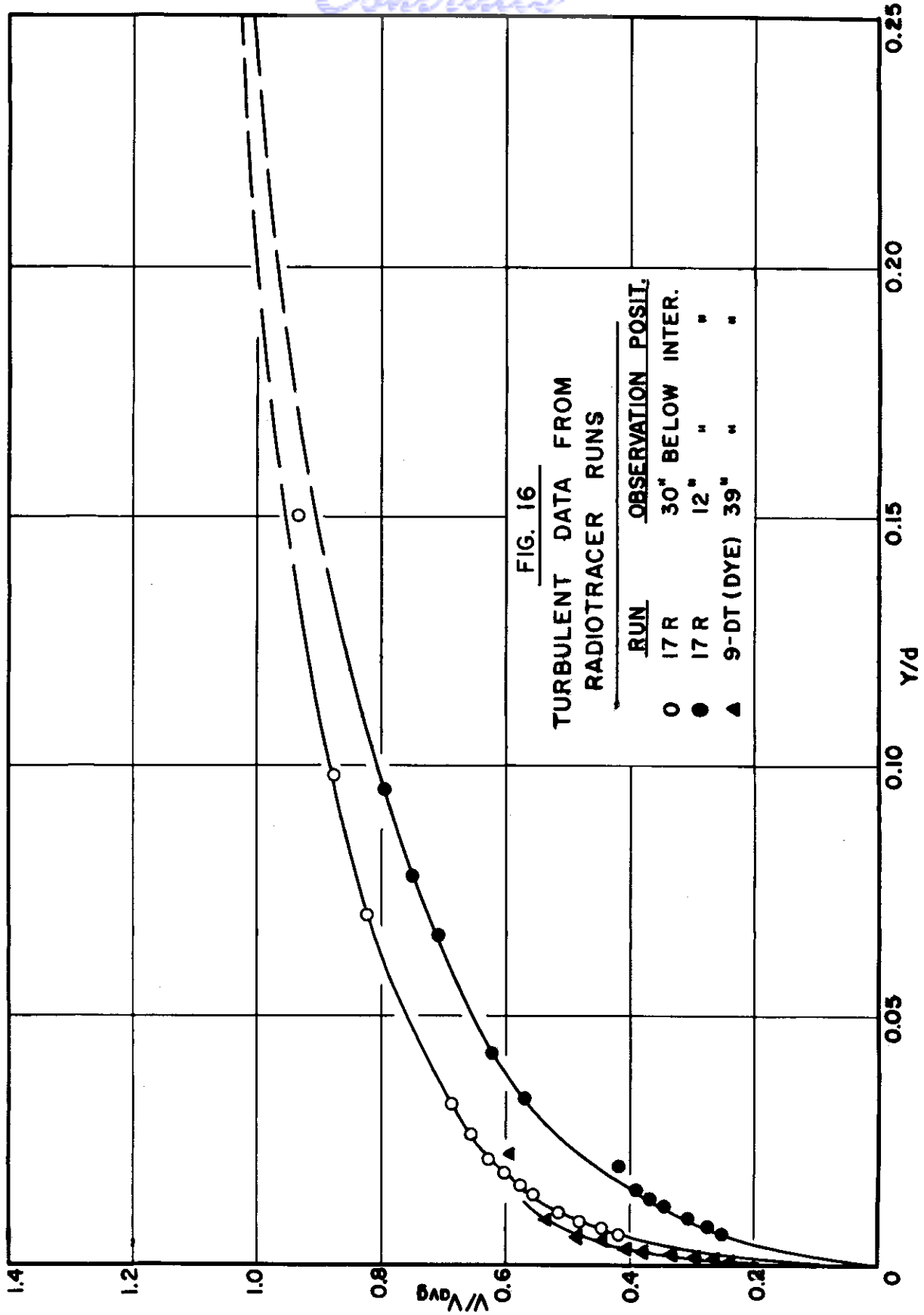
It seems clear that the dye-displacement and radio-tracer displacement procedures can be used to give significant information about the conditions of flow at Reynold's numbers in the turbulent region. Furthermore these data appear to be meaningful even in the region very close to the wall. At present writing there is much doubt about how these data should be interpreted, but photographic evidence indicates that interpretation may be greatly aided by further photographic studies. There seems no doubt from the data that effects of turbulence exist and can be detected in regions extremely close to the tube wall.

II. FLOW WITH MASS TRANSFER

Preliminary experiments were carried out in the original one-half inch flow system in an attempt to determine the influence on the velocity distribution of the effects accompanying mass transfer. Both single phase and two-phase liquid systems were used. The single phase flow studies differed from previous runs in that a large mass concentration difference across the interface was deliberately produced to increase the rate of mass transfer. In both the single phase and the two-phase systems, the physical properties of the fluids undergo an abrupt change at the interface, giving rise to experimental difficulties.

The first procedure employed a two-phase liquid system and a tracer soluble in only one of the two liquids. Mass transfer between the two phases consisted of transfer of a solute soluble in both phases or of a partial solution of one of the solvents in the other. The second procedure utilized a single phase system in which the tracer element itself and its inactive equivalent were subject to transfer from a region of high concentration in the displaced fluid to a region of negligible concentration in the displacing fluid.

In order to carry out experiments by the first procedure one of several non-polar organic solvents was used in conjunction with water or alcohol solutions of a dye and the transfer characteristics of the combination were observed visually. Pontamine Blue is nearly insoluble in most non-polar organic solvents. From the available two-phase systems, an octane-water system was chosen for the first actual flow experiments. In this case the water phase containing dissolved dye was placed in the lower portion of the column with clear white octane above so that during flow the octane displaced the aqueous dye solution. In order to have mass transfer between the water and the octane it had been planned to add methyl alcohol, which is soluble in both octane and water, to one phase of the system during a second run. A comparison of measurements with and without mass transfer would then have been possible. When flow tests were made with the octane-water system, however, "plug" type flow occurred in which an almost perfectly flat interface persisted between the two phases throughout the flow. Only a minute amount of tracer-bearing water remained near the wall after the passage of the interface and this water layer broke into small rivulets, draining down the tube



wall. This behavior was attributed, at least in part, to the appreciable difference in densities of the two fluids, further complicated by preferential wetting effects, viscosity differences, and interfacial tension. The nature of the data obtained was such that further study of this system spectrophotometrically did not seem of value.

An attempt was then made to find two slightly miscible liquids which were matched in density but only one of which would dissolve the dye and/or radiotracer. A system which had approximately these properties was composed of aqueous methyl alcohol, one phase, and kerosene as the other. By adjusting the water content of the aqueous alcohol its density was made to approximate the measured density of No. 1 grade kerosene. In this system Pontamine Blue was readily soluble in the alcohol phase and insoluble in the kerosene. The transmission of 620 A light through both dye-free phases appeared to be satisfactorily matched. A preliminary "non-transfer" run was made using spectrophotometric measurement of the displacement of the dye-alcohol by kerosene. The results of this observation again indicated "plug" flow of the same type as seen with water and octane. Further experiments using two-phase systems containing one or more hydrocarbons was rather abruptly abandoned at this point because of the increasingly deleterious effects of these organic solvents on the plastic interface blocks and lubricants.

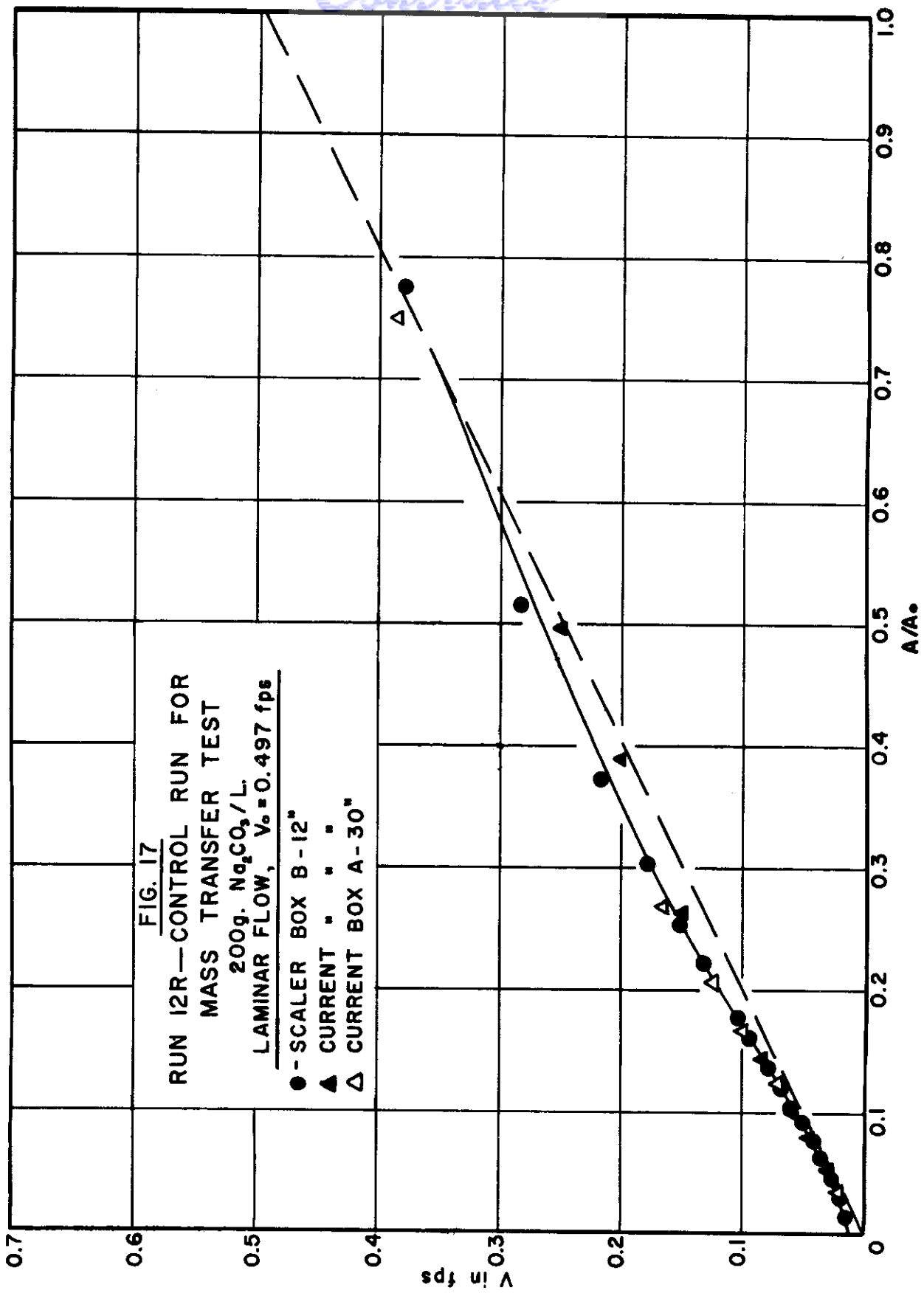
We then proceeded to the testing of single phase systems in which the tracer material itself made up the mass transferring under a concentration gradient. Two runs were made under conditions which provided for a comparison between flow with and flow without mass transfer (except that inherent in molecular diffusion). For one of these, the displaced and displacing fluids were both concentrated aqueous sodium carbonate solutions of identical concentrations. The displaced fluid, as usual, contained a small amount of $Na_2^{24}CO_3$. During the run using these solutions mass transfer was limited to the self-diffusion rate. In the second run the displaced fluid was again concentrated sodium carbonate solution containing radiotracer, but the displacing fluid was pure water.

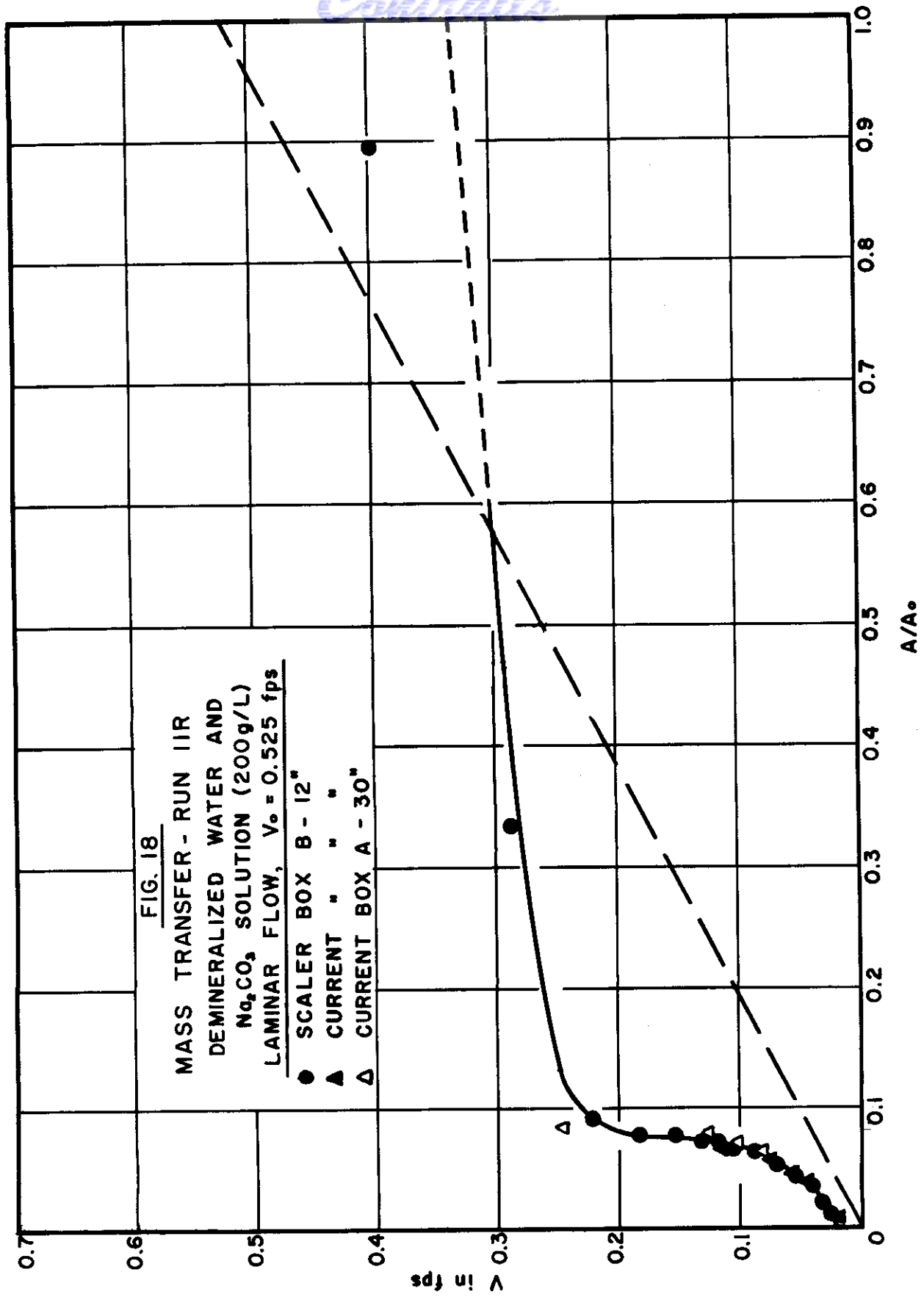
The results of two runs are shown in Figures 17 and 18, where the count rate ratio is plotted as a function of velocity. Figure 17 shows the results of a control run using concentrated (200 g/liter) sodium carbonate solution with no mass transfer except that due to self-diffusion. The flow rate was definitely in the laminar region, but an exact value of the Reynolds number is not known since the viscosity of the solution was not measured. It will be noted that the data for this control run show measurable deviation from the straight line prediction for parabolic velocity distribution. This may have been caused by a slight difference in density of the active and inactive solutions, even though these were made up as closely as possible.

In Figure 18, there are shown the results of a run in which the radioactive solution, i.e., the displaced fluid, contained approximately three grams of sodium carbonate per liter solute and the inactive solution, i.e., the displacing fluid, contained 200 grams per liter. The result is a very definite "plug" type flow with marked deviation from the parabolic pattern. This plug flow probably results more from the density difference than from any effect of mass transfer associated with the high concentration difference between the active and inactive solutions. If the mass transfer had been the controlling factor, one would expect an appreciable difference between the observations made at position B, 12 inches below the interface, and those at position A, 30 inches below the interface.

In summary, it may be said that attempts to observe the effects of mass transfer on fluid flow are unsuccessful because of side effects which mask those from the mass transfer. Mass transfer requires a difference in activity which can be obtained either by a difference in concentrations in a single solvent or by a difference in solvents. Both of these sets of conditions produce plug flow and fail to reveal any effect which may be definitely attributed to mass transfer alone.

An alternative procedure would be to study the possible effects occurring when a soluble solid is dissolved from the tube walls rather than an interchange between portions of the liquid. This is a very important case and it may well have fewer auxiliary complications than the liquid-liquid transfer systems which have been studied.





III. FLOW IN ROUGH TUBES

The tracer displacement technique should be an especially useful tool for supplementing other experimental evidence of the effect of roughness on the velocity patterns in tubes, particularly where the roughnesses are of the order of magnitude of other measuring devices. Measurement of the tracer displacement rate using the radiotracer procedure is inherently more informative than that using a dye procedure as the latter must be carried out in a pipe incorporating a small unroughened section to allow for the unhindered passage of the light beam across the diameter. Nevertheless dye runs were made in a roughened glass tube in order to observe what effects, if any, could be observed in this kind of flow system.

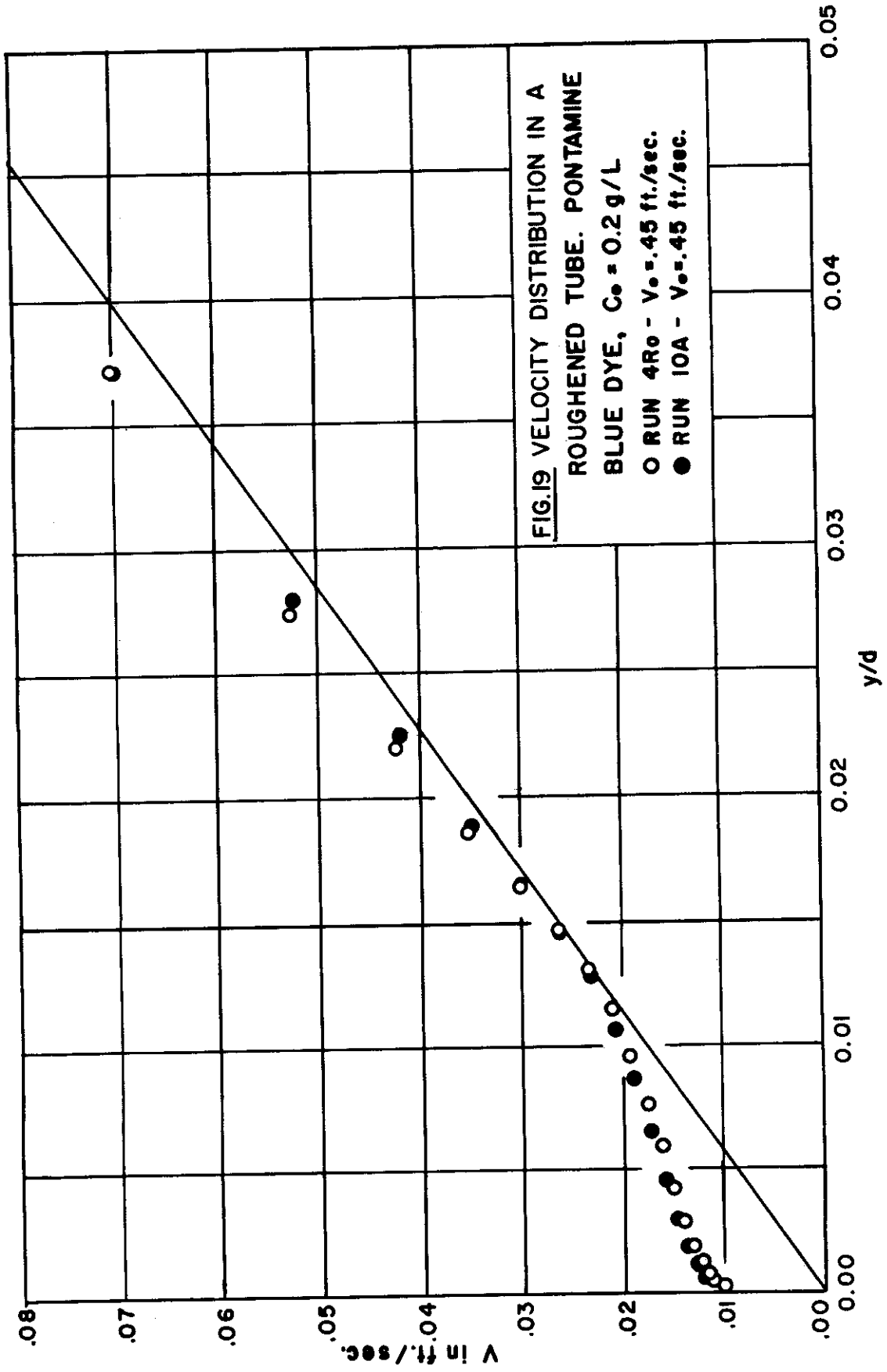
The one-half inch flow column was first modified for roughness measurements by inserting a 2-1/4 foot length of roughened glass tubing below the bottom liquid junction-forming device. This section of tubing was prepared by turning a section of one-half inch diameter gauge glass tubing around a metal mandrel covered with No. 220 carborundum until the glass acquired an even frosted appearance. Near the bottom of the section, a length of about 3/4-inch was left unfrosted to allow for the passage of light to the spectrophotometer photocell. Microscopic examination of a small piece of tubing prepared in this way showed a relatively uniform distribution of the protuberances averaging approximately 0.001 inch in height. The Beckman Model B spectrophotometer was mounted around the column near the bottom of the tube.

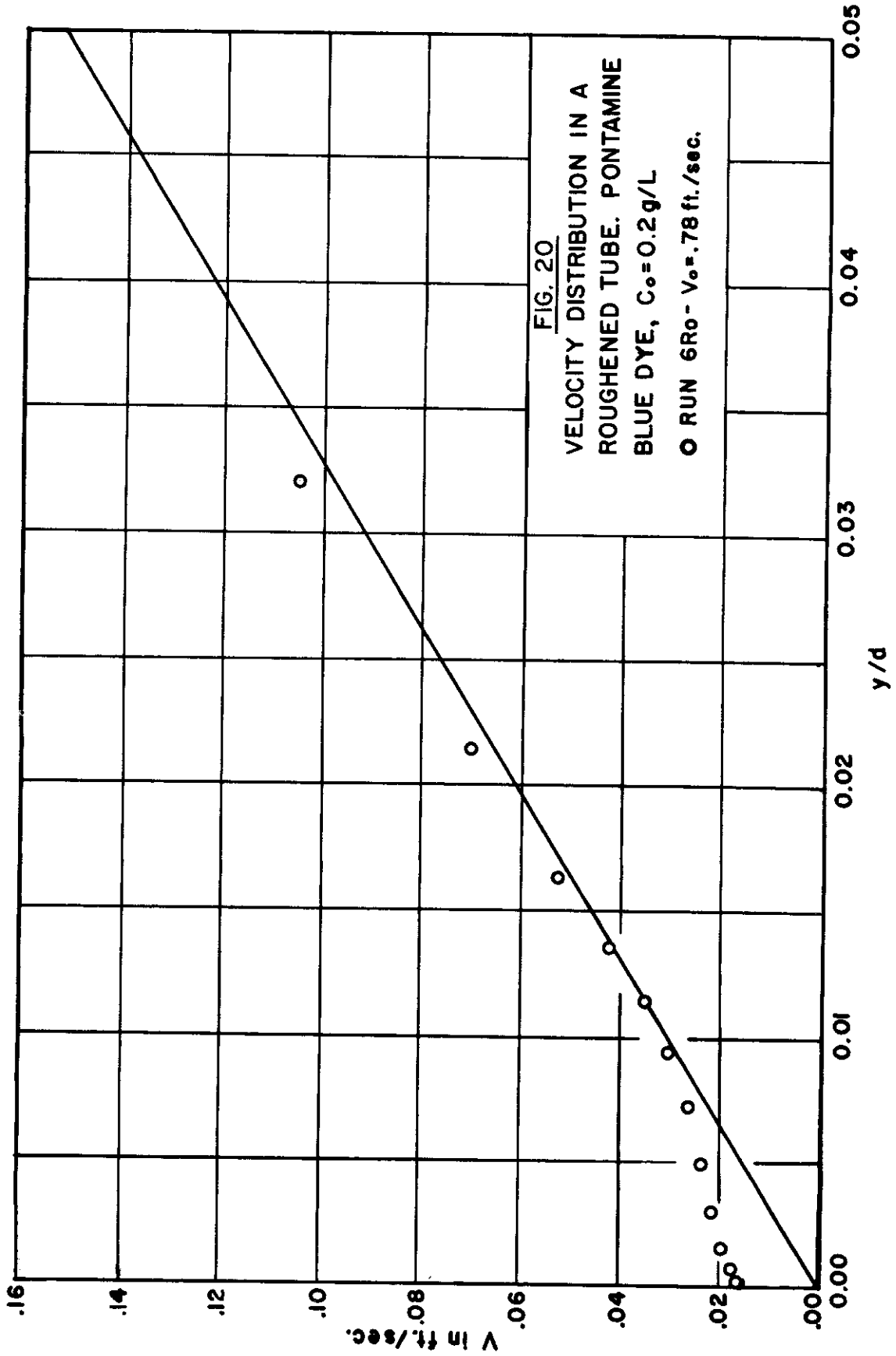
The same procedure used for making distribution measurements in smooth tubes was followed in these runs. Using 0.2 g/liter solutions of Pontamine Blue dye, runs were made at maximum flow rates of 0.45 fps and 0.78 fps, corresponding to Reynolds numbers of 975 and 1689 respectively. The results of these runs expressed in terms of y/D and velocity are given in Figures 19 and 20. For comparison the data from a run made at 0.45 fps maximum velocity in a smooth tube (Run 10A) is also shown in Figure 19. Inspection of these data does not reveal any apparent marked effect of the roughened tube on the velocity pattern observed over the short unroughened observation section when compared to flow though completely smooth tubes. Although this procedure does not lead to velocity measurements applying directly to a rough section, it does demonstrate that any small irregularity in the smooth column we had previously been using is not apt to cause a detectable disturbance in the flow patterns obtained by our technique.

We next turned our attention to the radioactive tracer as an indicator of roughness effects. Subsequent to determining that the radiation transmission through tne walls of an aluminum tube was not appreciably different from that through glass tubes (Figure 21), two radiotracer runs were made in rough aluminum tubes. These were prepared by using a modified one-quarter inch standard pipe thread tap to cut a thread on the inside of a one-half inch i.d. aluminum tube. A cut-away section of this pipe showed the surface to be cut with 18 evenly spaced 0.039-inch grooves per inch. The top edges of the threads appeared to be smooth and flat.

The threaded tube was inserted in the one-half inch flow column in place of the glass observation section used in other runs. The plastic interface devices were used as before. A solution of sodium carbonate (4.0 g/liter), neutralized to a pH of approximately 7 with hydrochloric acid to prevent active attack on the metal tube, was used as the inactive solution. The active solution was similarly neutralized and adjusted to the same concentration. A maximum flow rate of 0.534 fps was measured during the run.

The results of this run are shown in Figure 22 where both current and scaler data are given. The shape of these curves agrees with a picture of flow involving some hold-up of tracer fluid in the grooves along the walls which, at first, causes the apparent cps/cps_o values to be greater than would be found for smooth walls. After some length of time the effect of molecular diffusion then begins to predominate causing the count ratio to decrease below that predicted for smooth walls.





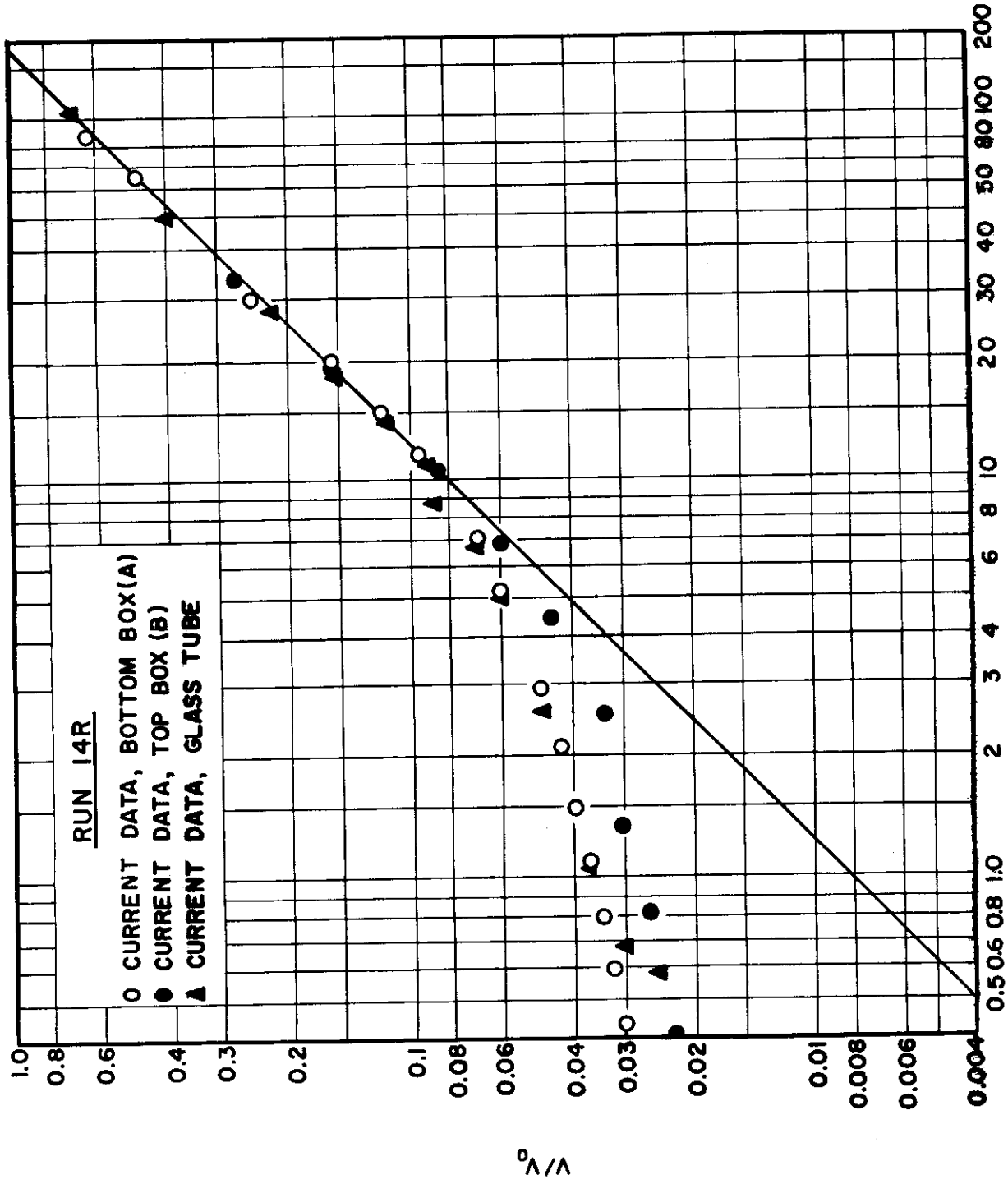


Figure 21. Velocity Distribution in Smooth Aluminum and Glass Tubes

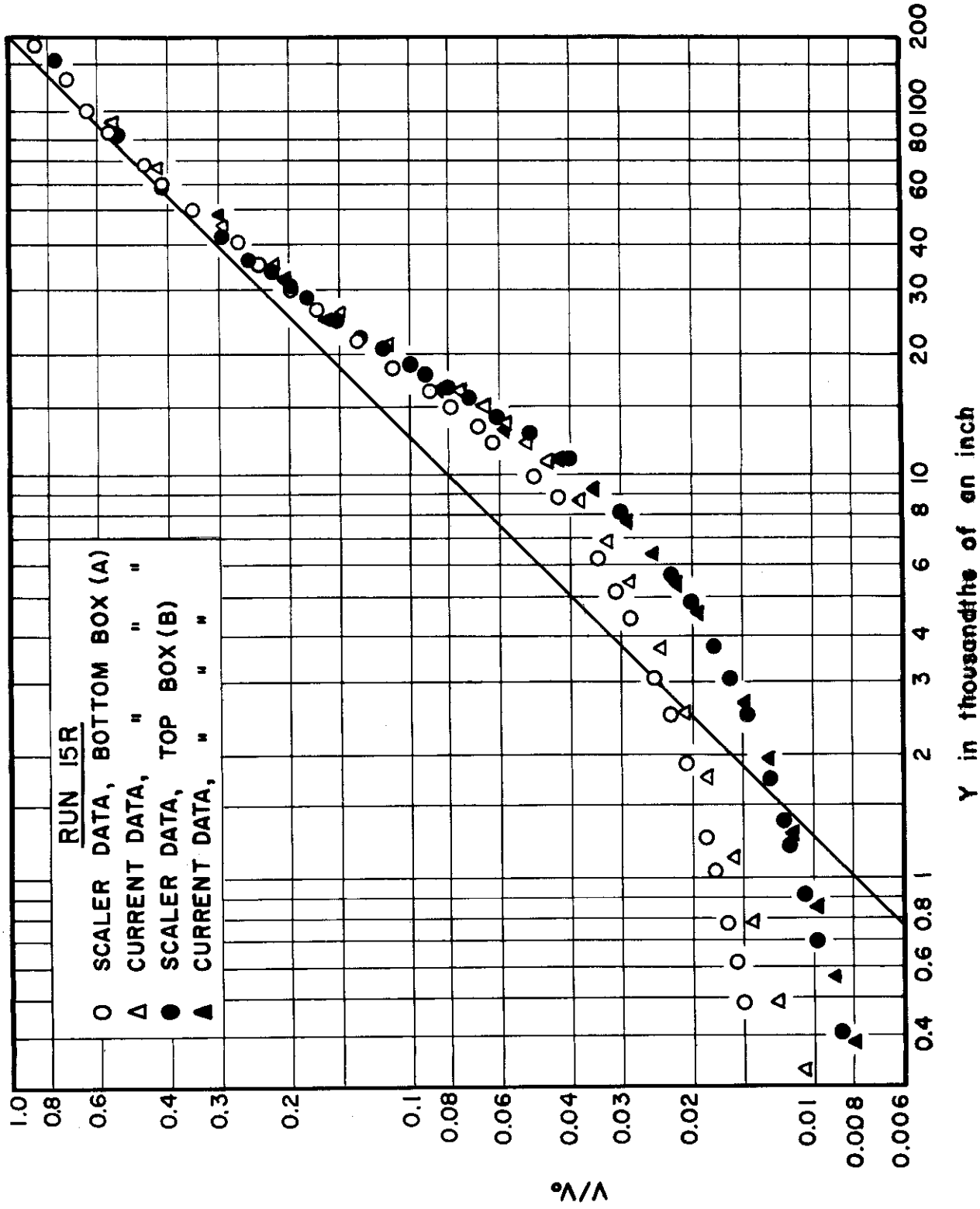


Figure 22. Velocity Distribution in Aqueous Solutions in a Roughened Aluminum Tube

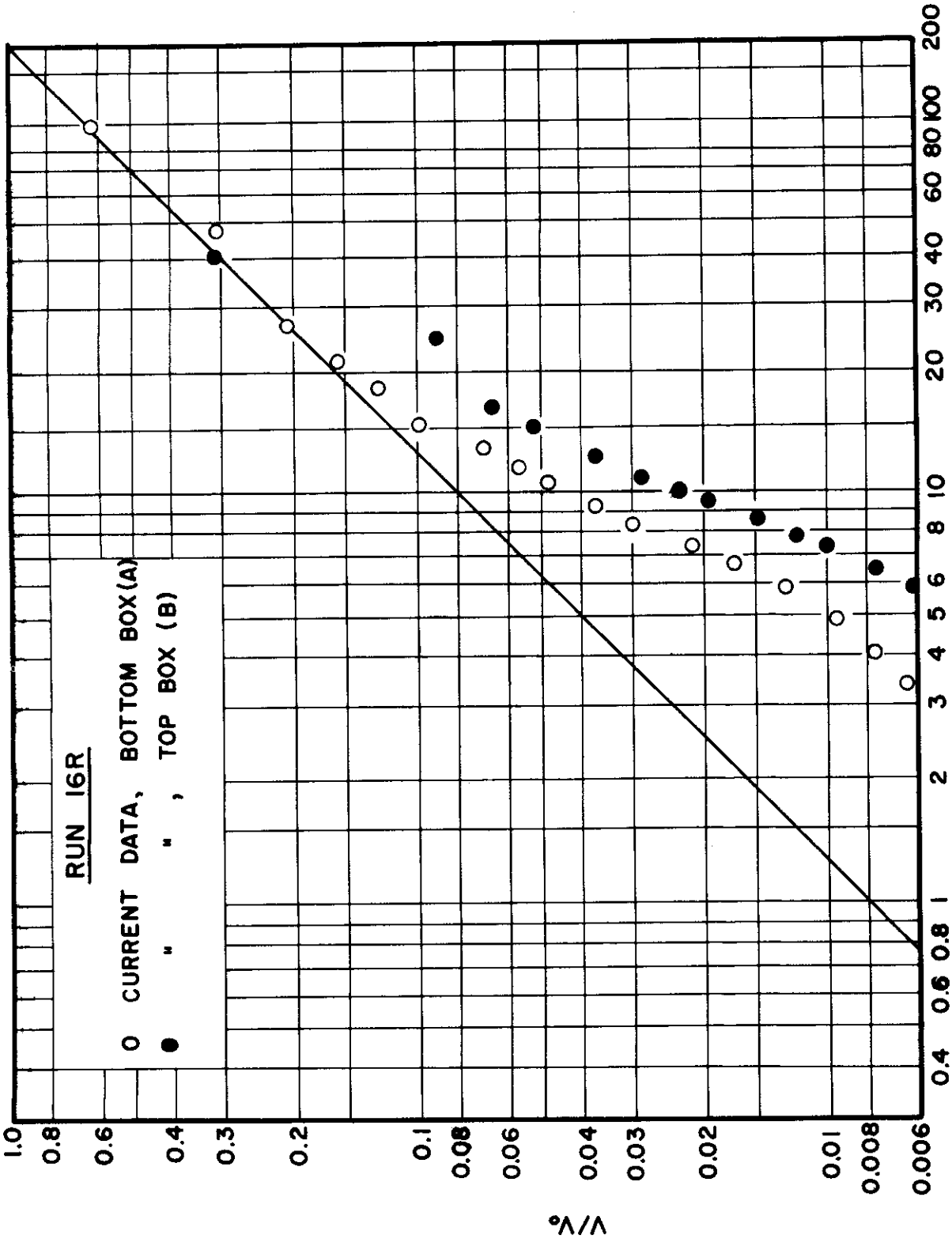


Figure 23. Velocity Distribution in Glycerin Solutions in a Roughened Aluminum Tube

In an attempt to clarify the flow situation existing in the grooved tube, a second radiotracer run was made in the same tube using approximately 80% glycerin-water solution of sodium carbonate. The maximum flow velocity here was 0.804 fps. The effect of viscosity was very evident in this run for there was an appreciable amount of tracer remaining in the tube even 45 minutes after flow was started. Current data for the first five minutes of the run are shown in Figure 23. It is apparent here, as in the previous case, that the count rate ratio demonstrates lengthy hold-up in the grooves. The relative position of the curves for the top and bottom counters seems to be an indication of the influence of the diffusion and roughness on the curve placement and shape as it depends on the distance of the counters from the active-inactive interface.

The results of these runs confirm definitely that in laminar flow the influence of even large roughnesses at the wall does not extend materially into the main flow stream. With viscous materials in particular the behavior is almost the same as that for a smooth tube having a bore equivalent to the minimum diameter of the rough tube. Thus one might anticipate that such roughnesses would decrease the heat transfer rate in laminar flow.

The data also show that the radioactive tracer procedure is definitely applicable to metal tubes and to conditions of roughness that might well make probe techniques invalid. The extension to turbulent flow of these measurements on the effect of roughness should be of value in heat transfer and mass transfer predictions.

IV. VIBRATED FLOW

A fourth flow condition investigated with the tracer displacement technique was that in which the liquid flowing through the column had superposed upon it a vibration of moderate amplitude and frequency. The structure of the flow system precluded experiments in which the column itself was vibrated, but the liquid could be vibrated directly by transmitting pulses to it through a diaphragm actuated by a pneumatic vibrator. A very simple apparatus for imposing these pulses was constructed as shown in the sketch in Figure 24. The pulse rate delivered to the liquid was recorded on a Brush recorder by signals from the electromagnetic detector connected to the vibrator as shown. The frequency was of the order of 1200 to 1500 cpm. No measure of its amplitude was attempted.

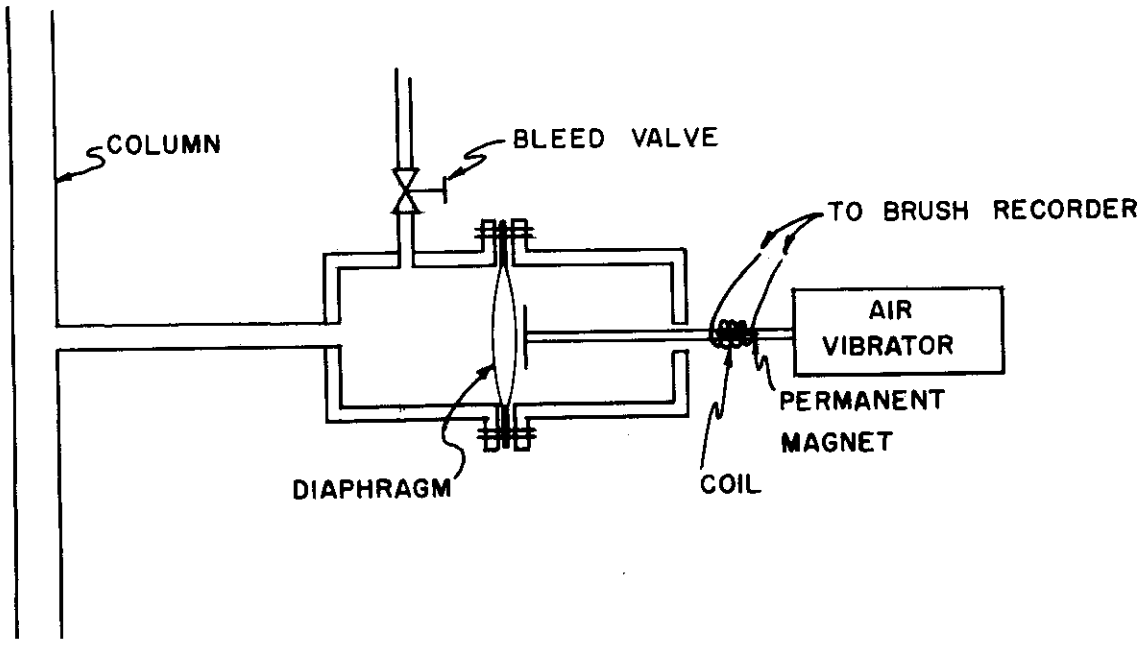


Figure 24. Small sketch of vibrator.

Transmission measurements were made with the Beckman Model B Spectrophotometer mounted 25-1/4 inches below the bottom liquid junction device. The output was recorded on a Brown recording potentiometer as before. Using Pontamine Blue solutions of various concentrations with water as the displacing fluid, a number of runs were made with and without vibration at average flow rates of 0.19 and 0.28 feet per second.

Comparison of the results of all these measurements has indicated that vibration has no important effect on flow under the conditions we imposed on the system. Vibration may be said to produce a slight shifting of the curve of dye concentration (layer thickness) vs. time in a direction indicating a slower "washout" as compared to vibrationless conditions. When plotted as velocity vs. y/D, the order of magnitude of this curve shift is about 2%. The shift was consistent in direction and magnitude though the latter was not much larger than the normal spread of the data points.

Initially it was occasionally found that the motion of the vibrating apparatus was sometimes transmitted through the column supports to the spectrophotometer even though the vibrator was carefully isolated from the tube so a shock mount for the vibrator was used to eliminate this on subsequent runs.

One radiotracer run was made during which the liquid was vibrated as in the dye runs. Unfortunately the results of this run were inconclusive. As it seemed inadvisable to employ any of the usual flow meters with highly radioactive materials, continuous metering of the flow during radiotracer runs was not attempted. Analysis of the data from this run, however, indicated a probable abrupt change in flow rate during the course of the run and subsequent examination of the column showed that leakage near the upper part of the active section may also have been a complicating factor. Even though the magnitude of the vibration was rather small and the pulses were transmitted to the column primarily through the flowing liquid, pulsation soon began to have a very noticeable destructive effect on the column. Glass-plastic connections were loosened and a spiral crack appeared in one piece of the glass tubing. For this reason, further attempts to run with vibration were abandoned.

V. NON-NEWTONIAN FLOW

The characteristic flow profiles of non-Newtonian fluids, i.e., those in which the rate of shear is not directly proportional to the applied shear stress, have not been widely studied. This is particularly true of fluids which exhibit thixotropic, rheopectic, and dilatant properties. As these materials usually consist of thick suspensions, they are difficult to observe visually and the isolation of relative fluid motion during flow is virtually impossible to achieve by conventional methods. In these systems, the radiotracer displacement technique seems especially promising as a tool for more enlightening scrutiny of the microscopic flow behavior in all of the several regimes of flow.

For theoretical treatment the non-Newtonian fluids are classified according to their particular flow variations with respect to applied shear stress (1, 8). In practice, however, classification is made on the basis of the kind of "consistency" curve which the material exhibits. These curves are formed simply by plotting rate of shear as a function of shear stress. Any point along a curve obtained by this plot, expressed as the ratio shear stress/rate of shear, is an index of the material's resistance to flow under a particular stress condition and as such is sometimes called its "apparent viscosity" or consistency. A Newtonian fluid thus observed exhibits a linear relationship passing through the origin and has a constant viscosity.

The non-linear consistency curves are of three usual forms. The first of these is associated with materials termed pseudoplastic and appears as a curve passing through the origin and curving convex to the force axis. The second curve applies to plastic materials and is also convex toward the force axis for small values of the rate of shear after which the curve becomes straight. This curve does not pass through the origin, but requires a finite value of the applied stress before there is any flow. This point is often referred to as the "yield value" of the plastic material.

A third type of curve which is concave to the force axis applies to a class of substances termed "dilatant." These materials, like the pseudoplastics, do not show a yield value.

There are in addition two special classes of substances which invariably exhibit non-Newtonian behavior and are further characterized by a change in their consistency with time. These are the so-called thixotropic and rheopectic fluids. The former class at a constant shear stress undergoes a decrease in apparent viscosity with time to some minimum value and the latter under constant shear stress shows an increase with time to some maximum value. Any measure of the consistency of these fluids will depend on the past history of the fluid. For this reason, it is usual to measure consistency in such a way that, starting from rest, increasing states of agitation are sequentially imparted to the fluid as part of the measurement. When done in this manner, usually by use of a rotational viscometer, consistency curves are obtained which follow one or other of the three non-linear patterns depending on whether the suspension is thixotropic or rheopectic. If the consistency of the agitated material is measured immediately after the disturbance has been applied, a different straight-line curve is obtained which may be extrapolated to give a "yield value" of the shear stress. Thus these time-dependent phenomena exhibit a kind of hysteresis loop formed by the consistency curves made on the material in the two states of agitation.

In order to explore the application of the displacement technique to such systems, a slightly thixotropic, plastic fluid was prepared and observed in laminar flow. This fluid consisted of a bentonite-water suspension composed of approximately 3% solid of $< 0.5\mu$ particle size. Electrolyte was added to the mixture in the form of Na_2CO_3 partially neutralized with hydrochloric acid to prevent attack on the aluminum parts of the flow system by the alkaline carbonate solution. This suspension showed marked thixotropy, particularly after the addition of electrolyte though the solution was not very gelatinous and flowed easily.

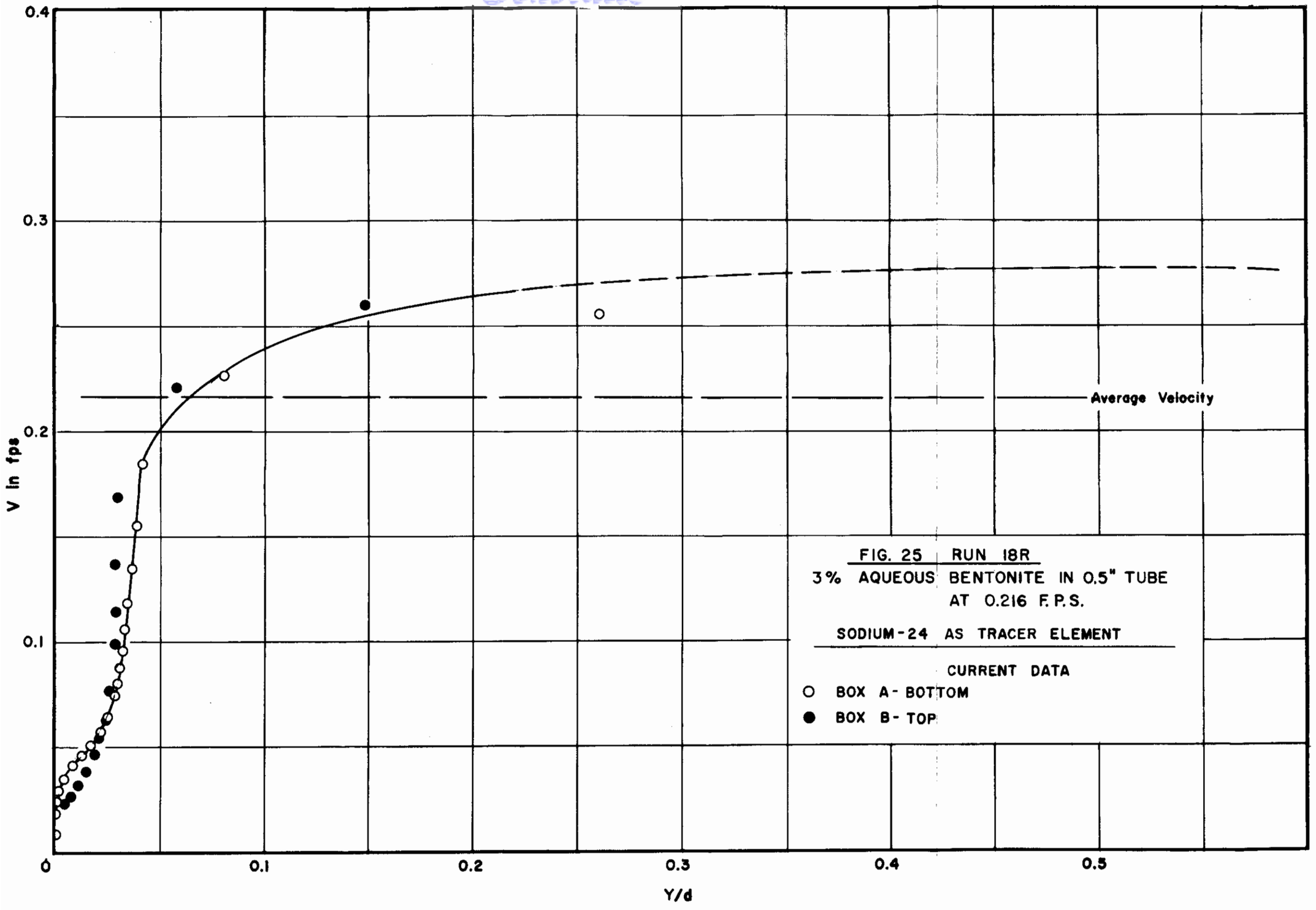
A laminar flow run was made using this bentonite solution as the flow medium. The suspension was passed through a one-half inch flow column from a constant head tank, through an observation section of aluminum tube into a storage tank. The flow run was carried out by a procedure duplicating the original laminar flow procedure where flow was initiated in a static system and controlled by a fixed orifice.

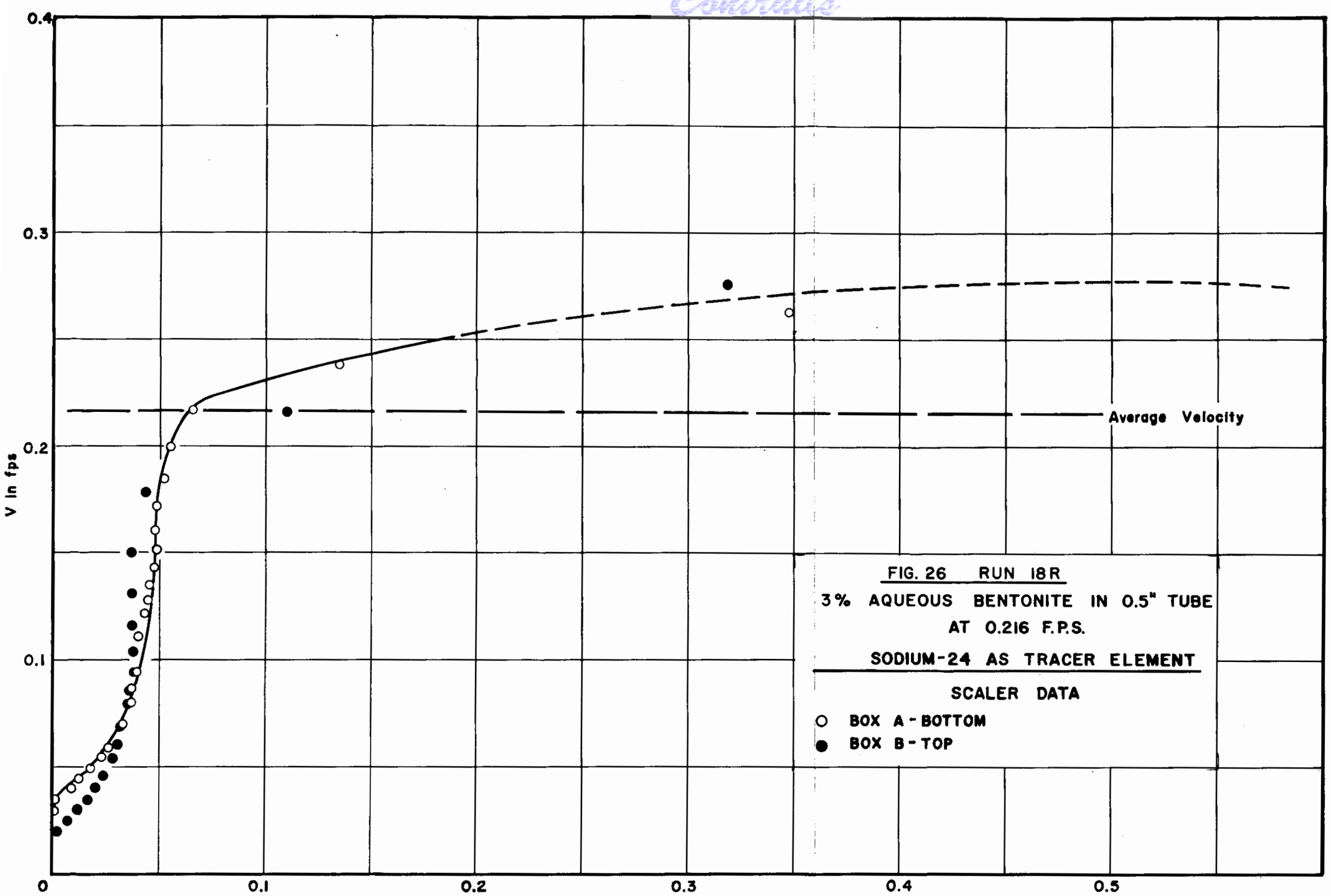
The suspension was carefully made by adding powdered bentonite to water and stirring vigorously. After sufficient swelling of the bentonite grains to give a reasonably uniform mixture, a calculated amount of HCl was added and the solution again stirred. A small amount of this mixture was taken for the preparation of the radioactive solution. The whole volume was allowed to stand for approximately four hours before use. Just before the run, enough sodium carbonate was added to the inactive portion to bring it to the half neutral point. This amount corresponded to the relative amount of $Na_2{}^{24}CO_3$ used with the aliquot from which the radioactive portion was made.

The neutralized inactive material was circulated through the flow system so as to fill the upper and lower sections of column and then permitted to stand in the column for approximately one hour before starting the actual run.

The radioactive solution was prepared by adding the small amount of acidified bentonite taken above to the radioactive sodium carbonate received in a small irradiation can and transferring the mixture to a brass cup where a magnetic stirrer thoroughly mixed the components. The handling and transfer procedures are described in detail in Reference 16. The active suspension was placed in the center section of the flow column and flow was begun eight minutes after filling. Counting data were taken as before for a period of approximately five minutes. The volumetric flow rate, measured just prior to flow, was 0.5 liter per minute, corresponding to an average linear velocity of 0.216 feet per second.

The results of the counting data obtained for this run are shown in Figures 25 and 26. In the first of these the counting records of the two current recorders are shown and in the second the scaler records. The profiles obtained indicate a flow pattern involving a plug type flow in the center of the tube which passes over to a different flow type, probably laminar, near the wall. This is consistent





with the picture of plastic flow of other suspensions such as pigment suspensions, which have been observed microscopically (1). Under the conditions of our measurement the boundary of the plug seems to be in the vicinity of 0.05 inch from the wall. This mixed flow regime might be expected from consideration of the structural characteristics of the system. Simply, it is composed of a liquid medium in which colloidal particles are suspended. When force is applied to such a mixture confined in a small tube, flow begins fairly evenly over the cross section initiating a plug which fills the entire tube. The situation at the wall is traditionally visualized as involving a very thin layer of particle free liquid lying at the wall surface outside of which the particulate material moves in a non-layer fashion.

As flow progresses some of the particles in the outer layer of the plug become detached and move independently in slower layers near the wall. When pressure is increased, more layers shear and laminar flow occurs in this region. In the center of the tube the lateral shearing forces are still less than the force necessary to start flow with the result that the center plug is held intact. The general form of the Run 18R flow curves is consistent with this picture.

There are several aspects of the performance of Run 18R which should be considered in evaluating the results. In the first place the ion exchange properties of the bentonite suspension will influence the precise interpretation of the tracer displacement as there will be an exchange equilibrium set up between the amount of sodium adsorbed on the clay particles and that remaining in the suspending medium. This equilibrium will depend on predominating exchangeable cations in the particular clay, the pH, the state of subdivision, etc. If sodium ion absorption on the particle is relatively complete, any "slippage flow" caused by an appreciable layer of non-particulate, non-active material close to the wall might appear in the curve as a series of points having a positive intercept on the velocity axis. This effect would be difficult to detect in a suspension of very fine particles because these would undoubtedly have periods of wall contact, even in slow laminar flow, that would tend to obscure the picture. The magnitude of the diffusion effect would also be greatly altered.

Where the radioactive atom is present primarily as the Na^{24} ion in the external solution (which is probably the case in 18R), the interpretation of the flow pattern would undergo little or no modification due to the ion exchange properties. A second and more serious effect which should be considered is the effect of the thixotropic properties of the suspension on the appearance of the flow pattern. Materials which exhibit thixotropy apparently undergo the build-up of a three dimensional network structure while they are in a quiescent state, and this structure is disrupted by the application of mechanical disturbance. Fluidity then, as we have said, is strongly dependent on the past history of the material and its value will depend on the rigidity of the original structure, the magnitude of the work done on the system, and the characteristic breakdown-time relationships. Therefore, careful specification of the experimental state of a material must be given in quantitatively estimating the degree to which it exhibits thixotropy. Unfortunately, we were not able to quantitatively determine a "hysteresis" consistency curve for our 3% bentonite suspension with added electrolyte due to the lack of an appropriate consistometer. We were, however, able to ascertain that thixotropy did occur to a slight degree by noting the time-change in apparent viscosity, as indicated by measurements made with a Stormer viscometer under constant viscometer loading. The phenomenon was also noted from visual observation. As well as could be determined, the effect was noticeably operative over a 3 or 4 minute period when agitated with the force of viscometer rotor movement.

The question arises as to the magnitude of the thixotropic effect under the flow conditions in the column. From the results of viscometer measurements, it was noted that an agitated suspension, allowed to stand, "sets up" rather quickly when quiescent. There is, however, some question of an effect at the boundary between the non-active suspension which had been standing in the column for about an hour and the active suspension which had only been in the column for approximately 10 minutes. Since the set-up time is short and the degree of agitation, at the laminar-plug interface, inherent in gravity flow, is great only in a very small segment of the profile, it is doubtful whether the thixotropic effect predominated in the non-Newtonian flow behavior. Except in the narrow shear layers at the very edge of the laminar portion of the profile, it is probable that the flow

profile is one describing uncomplicated plastic flow although, of course, further work will be necessary to fully support this assumption. This might be done by carrying out the technique with successively diverging observation points, i.e., different counter distances. This will give profiles for flow having been subjected to differing degrees of disturbance at the laminar edge. It would also be necessary to control temperature and consistency conditions in order to obtain accurate information.

Toward the end of Run 18R a small obstruction lodged against the orifice plate causing a considerable blockage of the flow. As this event occurred in the last minute of record-taking and was considerably subsequent to reaching background level, it is not felt that any of the effects noted in Figure 24 can be ascribed to this flaw in the experiment.

The results of Run 18R are of importance not so much for the rate data which might be interpolated from them, but for the indication of a general pattern in a flow regime particularly difficult to observe experimentally and the obvious implication that this technique can provide a new and fruitful means of exploring the dynamic behavior of these interesting non-Newtonian fluids. The dynamic behavior should, in turn, increase our knowledge of the various internal liquid "structures" which are evidently inherent in the different systems.

It is suggested that further studies along three lines might make very promising contributions to our understanding of the theoretical and practical aspects of non-Newtonian flow. These are (1) the measurement of velocity patterns and distributions in the non-time-dependent laminar flow of non-Newtonian fluids, e.g., those exhibiting plastic and pseudoplastic flow, and the correlation of these with design parameters; (2) the study of time-dependent non-Newtonian flows, e.g., thixotropic and rheopectic fluids, with emphasis on the development of applicable structural models for this little-studied type of flow, as well as design parameters; and (3) the study of transition and turbulent flow of non-Newtonian fluids.

VI. DISCUSSION AND CONCLUSIONS

1. The use of the tracer displacement technique has been shown to be a valuable tool in the study of turbulent flow, of non-Newtonian flow and of flow in aritifically roughened tubes in addition to simple laminar flow. The results of its use for studies with superposed fluid vibrations and with accentuated mass-transfer have been inconclusive.

2. The outstanding characteristic of the turbulent flow data has been the high degree of reproducibility and marked similarity of general pattern over the Reynolds number range of 2500 to 7000. It has been found that when data are taken on runs made from a static start, the pattern is materially influenced by the location of the upstream disturbance promoting the transition from stream line to turbulent flow. When the distance between the turbulence promoter and the original interface position is reduced, the velocity profile is flattened and begins to approximate closely the generally accepted pattern for turbulent flow.

A dynamic flow column in which velocities were fully established before displacement was started gave excellent results. With this column, it was shown that velocity fluctuations extended into the region very close to the wall with no evidence of a true laminar sub-layer. These observations, as recorded by the spectrophotometer, were substantiated by visual and photographic observation of the displacement process.

Photographs of the displacement of a dye solution in turbulent flow showed that in the wall-adjacent region thread-like filaments of dye appear, persist for a few seconds and then vanish. These are believed to be caused by the action of eddies or vortices.

The turbulent flow data obtained using dye displacement have been shown to be different from those for radiotracer displacement. In the former case the spectrophotometer makes observations at highly localized positions on the circumference of the flow tube, while in the latter the scintillation crystal averages the information around the entire tube circumference. Because the rate of displacement in turbulent flow is not a function of radial position alone (as it is

in laminar flow) the two procedures give supplemental information rather than mere mutual confirmation.

It is concluded that the turbulent flow data obtained by use of the tracer displacement technique does give new information about the wall-adjacent region and that further study using this technique is amply justified.

3. The study of the effects of mass-transfer on velocity profiles was made inconclusive by the inherent complexity of the problem. Two types of runs were attempted in which the mass transfer effects were enhanced by a high concentration difference of dissolved material in the displaced and the displacing fluids. In one set of runs the solvent in both the displaced and the displacing fluids was identical. In the other set of runs the two solvent fluids were immiscible. In both cases, a modified plug-type flow was obtained. It was felt, however, that this may well have been the result of density differences, heat effects, and interfacial tensions rather than of mass transfer alone.

It was recommended that further studies on effects of mass transfer include dissolution of soluble matter from the tube walls as this is an important case and should eliminate some of the difficulties involved in the liquid-liquid transfer.

4. The effects of vibration were observed by superposing a pulse of 1200 to 1500 cycles per minute on the flowing fluid in the column by use of a diaphragm cell and a pneumatic vibrator. Runs were all made in the laminar region using dye tracer and, except for minute fluctuations in the transmission data, there was no visible effect on the parabolic velocity pattern.

5. The effects of roughness on the inside of the flow tube were determined by use of a one-half inch aluminum tube with eighteen 0.039-inch deep internal threads per inch of length. Studies were made both with water and with 80% aqueous glycerine solution using radioactive sodium carbonate as tracer. The results showed clearly that the influence of the roughnesses does not extend more than a few hundredths of an inch, at most, into the stream. With the glycerine solution, the last of the tracer was displaced very slowly and appreciable tracer remained even forty-five minutes after the start of the run. This indicates definitely that there is no marked eddying down into the thread grooves.

Dye runs were made in a one-half inch diameter glass tube "frosted" internally by grinding with carborundum powder. These roughnesses, approximately 0.001 inches in height, had no discernible effect on the laminar flow data.

6. Data on non-Newtonian flow were obtained using a thixotropic aqueous suspension containing 3% bentonite and using radioactive sodium carbonate as the tracer material. The flow rates used were definitely in the laminar region, but the velocity profile obtained was of a plug type with a very steep gradient near the tube wall. There was some evidence of a slip region very close to the wall but the data on physical properties of the bentonite suspension are inadequate to permit quantitative interpretation.

The study of non-Newtonian fluids by use of the radiotracer displacement technique should prove to be very fruitful since these materials are of increasing importance and other techniques for measuring local velocities are almost useless with such suspensions or colloids.

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APPENDIX

A large number of runs have been made, both with dyes and with radioactive tracers, during the course of this project. In this report runs typical of each of the several categories of runs have been described and discussed, but complete analysis of each run made has not been possible.

Complete tabulation of the data from the many runs made is not feasible because of their nature and even photographic reproduction of the original data curve records would not be adequate for further analysis unless full details of each run were also tabulated.

In the belief that other investigators may from time to time desire full data on one or more runs of particular interest in their own work, we have prepared tables listing the runs which have been made, together with the more pertinent facts regarding the conditions used in the run. The original data and tabulations of calculated values obtained from these data are available and may be obtained by writing to the senior author of this report, c/o Department of Chemical Engineering, North Carolina State College, Raleigh, North Carolina.

TABLE I

Turbulent Flow Runs in 1/2" Column,

Pontamine Blue Dye Tracer

Run	Dye concentration grams/liter	Reynolds number
1-T	0.020	7033
2-T	0.200	7033
3-T	0.020	7033
4-T	0.200	7033
5-T	2.000	7033
6-T	0.200	4632

All of the above runs were made starting from non-flow conditions without any turbulence promoter in the tube. Runs 3-T through 6-T appear to be very good.

TABLE II

Turbulent Flow Runs in 1" Static-start Column, Pontamine Blue Dye Tracer, Interface to Spectrophotometer Distance--5.18 ft.

Run	Dye concentration grams/liter	Reynolds number	Initiation of Turbulence	Turbulence break point sec.	Comments
1-1	0.0200	995	Laminar	-	Calibration run
1-2	0.01007	1049	Laminar	-	Recorder calibration
1-3	0.00504	1472	Laminar	-	Recorder calibration
1-4	0.1007	1040	Laminar	-	Recorder calibration
1-5	0.1007	1061	Laminar	-	Recorder calibration
1-6	0.00126	2702	No promoter	-	Recorder calibration
1-7	0.00504	2696	No promoter	140	Few data points obtained from low dye concentration
1-8	0.1007	2696	No promoter	146.9	-
1-9	0.1007	2696	No promoter	147.5	-
1-10	0.00126	3731	No promoter	51.5	Only few points obtained from low dye concentration
1-11	0.00252	3731	No promoter	52.5	same
1-12	0.00504	3731	No promoter	54.0	-
1-13	0.1007	3734	No promoter	52.8	-
1-14	0.1007	7769	No promoter	12.2	-
1-15	0.1007	2688	Promoter 5" from column entrance	125	5" rolled screen wire as promoter
1-16	0.1007	2696	Promoter 2' from column entrance	124	2' rod with stirring loop revolving in column near entrance from head tank
1-17	0.1001	2696	No promoter	≤ 20	Train of air bubbles agitated liquid
1-18	0.1001	2722	No promoter	137.5	-
1-19	0.1001	2714	Promoter 67" above interface	39.0	5" rolled screen wire
1-20	0.1001	2702	Promoter 67" above interface	37.4	-
1-21	0.1001	3734	same	25.3	-
1-22	0.1001	3734	same	23.8	-
1-23	0.1001	3734	Promoter 23 1/2" above interface	<20	-
1-24	0.1001	3734	same	-	First part of flow missing because of mechanical failure
1-25	0.1003	3872	same	17	-
1-26	0.1003	2787	same	25.4	-
1-27	0.1003	2060	same	Laminar	-
1-28	0.02005	2811	same	31.6	Data not fully reliable because of defective recorder
1-29	0.02005	2824	same	22.2	same
1-30	0.02005	2824	same	16.1	same
1-31	0.02005	3905	same	15.9	same
1-32	0.02005	3725	same	14.7	-
1-33	0.02005	3740	same	15.2	-
1-34	0.02005	2824	same	23.9	-
1-35	0.1000	2643	same	~ 14.0	Detector to interface distance changed to 2.59 ft.
1-36	0.1000	2647	same	~ 16.1	same

TABLE III

Turbulent Flow Runs, 1-inch "Dynamic" Column, Pontamine Blue Dye Tracer, Interface to Spectrophotometer Distance--3.25 ft.

Run	Dye concentration grams/liter	Reynolds number	Comments
E	0.055	1894	Laminar flow, bad interface
1-DT	0.0295	3043	-
2-DT	0.0300	3660	-
3-DT	0.0270	-	Flow rate changed on opening valve. Faulty interface.
4-DT	0.0330	3312	-
5-DT	0.0320	-	Faulty valve opening.
6-DT	0.0270	3520	Plastic gaskets replaced rubber-foil gaskets.
7-DT	0.0270	3582	-
8-DT	0.1100	3677	-
9-DT	0.0600	6956	-
10-DT	0.0600	-	Faulty valve opening
11-DT	0.0560	6214	-
12-DT	0.1320	6536	-

TABLE IV

Turbulent Flow Run, Radioactive Tracer; 1/2" column; Interface to Detector Distances 2.5 Ft. and 1 Ft.

Run	17-R
Reynolds number	3811
Column	One-half inch inside diameter, aluminum tube
Active solution	Neutralized sodium carbonate, 0.0039 gm/cc
Inactive solution	Neutralized sodium carbonate, 0.0040 gm/cc
Comments	Turbulence promoter made of a 6-inch length of copper screen inserted 12 inches above upper interface block.

TABLE V

Mass Transfer Runs, Radioactive Tracer; 1/2" column;
Interface to Detector Distance--2.5 Ft. and 1 Ft.

Run	11-R
Active solution	Sodium carbonate solution, 200 gm/liter
Inactive solution	Demineralized water
Average velocity	0.262 ft/sec
Purpose of run	To measure the effect of high concentration gradients on the velocity distribution.

Run	12-R
Active solution	Sodium carbonate solution, 200 gm/liter
Inactive solution	Sodium carbonate solution, 200 gm/liter
Average velocity	0.248 ft/sec
Purpose of run	As a control for run 11-R.

TABLE VI

Fluid Vibration Runs

Run	Dye concentration gm/l	Average velocity ft/sec	Distance spectrophotometer to interface ft	Comments
1-V	0.20	0.234	2.08	Check run--no vibration
2-V	0.20	0.234	2.08	Vibration
3-V	0.20	0.234	2.08	Check run--no vibration
4-V	0.20	0.234	2.08	Vibration
5-V	0.20	0.190	2.08	Check run--no vibration
6-V	0.20	0.190	2.08	Vibration
7-V	0.20	?	2.08	Flow rate uncertain
8-V	0.20	?	2.08	Flow rate uncertain
9-V	0.20	0.190	2.08	Vibration causing spectrophotometer error
10-V through 14-V				Experimenting with flow indicating device. Data unsatisfactory.
1-A	0.02	0.227	2.08	Check run--no vibration
2-A	0.02	0.227	2.08	No vibration
3-A	0.02	0.227	2.08	Vibration at 19 cps
4-A	0.20	0.227	2.08	No vibration
5-A	0.20	0.227	2.08	Vibration at 19.5 cps
6-A	0.02	0.227	2.08	Calibration run. No vibration.
7-A	0.02	0.227	2.08	same
8-A	0.02	0.227	2.08	Vibration
9-A	0.20	0.227	2.08	Calibration run
10-A	0.20	0.227	2.08	same
11-A	0.20	0.227	2.08	Vibration at 27 cps
12-A	0.20	0.227	2.08	Vibration at 21 cps
13-A	0.20	0.227	2.08	Vibration at 20 cps
14-A	0.20	0.227	2.08	Vibrator failed
13-R	Radioactive*	~ 0.1		Data poor because of variation in flow velocity during run.

*This run was made using radioactive Na_2CO_3 as the tracer material instead of dye.

TABLE VII

Rough Tube Runs

Run	Dye concentration gm/l	Average velocity ft/sec	Distance spectrophotometer to interface ft	Comments
1-Ro	0.02	0.229	2.08	1/2 in. I.D. gauge glass tube, roughened inside; 3/4 in. clear section at spectrophotometer.
2-Ro	0.02	0.229	2.08	
3-Ro	0.20	0.229	2.08	
4-Ro	0.20	0.229	2.08	
5-Ro	0.20	0.229	2.08	
6-Ro	0.20	0.390	2.08	
7-Ro	0.20	0.390	2.08	

Run	Radioactive solution	Inactive solution	Average velocity ft/sec	Comments
14-R	Neutralized carbonate 0.0039 gm/cc	Neutralized carbonate 0.0039 gm/cc	0.269	Smooth 1/2 in. I.D. aluminum tube for control on rough tube runs.
15-R	same	same	0.269	1/2 in. I.D. aluminum tube threaded inside with 18 threads per inch, 0.039 in. deep.
16-R	80% glycerine in water 0.0038 gm/cc Na_2CO_3	80% glycerine in water	0.401	Same as 15-R

TABLE VIII

Non-Newtonian Flow

One-half inch column. Interface to detector distances, 2.5 ft. and 1 ft.
Radioactive tracer.

Run	18-R
Column	One-half inch inside diameter, aluminum tube
Active solution	3% bentonite solution, neutralized; 0.004 gm/cc sodium carbonate
Inactive solution	3% bentonite solution, neutralized; 0.004 gm/cc sodium carbonate
Average velocity	0.215 ft/sec