DOCTORAL DISSERTATION SERIES

TITLE THE MIXING OF DISSIMILAR LIQUIDS BY SUCCESSIVE FLOW THROUGH PIPES

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THE MIXING OF DISSIMILAR LIQUIDS BY SUCCESSIVE FLOW THROUGH PIPES

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A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Chemical and Metallurgical Engineering at the University of Michigan

Ann Arbor, Michigan June, 1949

DEDICATION

To My Father and Mother

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STATEMENT OF PROBLEM

To develop a method for instantaneous and continuous analysis of the contaminated portion between two liquids while in successive flow in a pipe.

To extend the range of contamination data for the water-water system to high Reynolds Numbers, within the limits of the equipment, and to systems of different density and viscosity.

ABSTRACT

Experimental data are presented for the mixing which results when two liquids are transported by successive, turbulent flow through a pipe line of one inch diameter and 168 feet in length. The pipe line was constructed of brass tubing, having a roughness of 10 - 20 microinches, r.m.s., and terminating in a short section of glass pipe. Analysis of the contaminated mixture between the two liquids while in flow was accomplished by means of photoelectric colorimetry.

The systems investigated consisted of : (1) liquids having no differences in properties, (2) liquids differing only in density, and (3) liquids differing only in viscosity. The range of Reynolds Numbers covered was from 2,500 to 92,000. Viscosities ranged from 0.6 to 15 centipoise, and densities from 0.88 to 1.47 grams per cubic centimeter. Average velocities of flow varied from 1.2 to 6.2 feet per second.

For any two liquids which are in successive, turbulent flow in a pipe line, and have the same physical properties, the volume of the contaminated portion is a function of Reynolds Number. The volume of contamination may be expressed by the general relation

$$M = A \ (1/Re) \not{} B \ ,$$

where M is the volume of contamination, Re is the Reynolds Number, and A and B are constants.

For dissimilar liquids, the volume of the contaminated portion is not a simple function of Reynolds Number. The quantity of contamination is dependent upon the order of flow when the liquids have different properties. For two liquids having the same density, but different viscosities, contamination will be greater when the more viscous liquid is leading than for the reverse order of flow. For two liquids having the same viscosity, but different densities, the contamination will be greater when the more dense liquid is leading than for the reverse order of flow.

An empirical graphical relationship is presented for estimating the independent effects of density and viscosity on the contamination.

INTRODUCTION

Commercial interest in the problem of pipe line contamination centers primarily in the products pipe lines of the petroleum industry. The present method of operation involves the transportation of several refined products through the same pipe line for considerable distances. In this process, the products flow one behind the other and there is a significant amount of contaminated mixture produced at the interface between the adjacent liquid products.

There have been comparatively few papers published giving experimental data on the general problem of pipe line contamination. Schoder (4) appears to have done the earliest recorded work in the estimation of contamination of liquids moving by successive flow in pipes. He reports limited data on field tests with oil pipe lines, and some data on water in the Cornell hydraulic laboratory. Fowler and Brown (1) made a detailed study of the effect of length of pipe, diameter of pipe, and velocity of flow on contamination in laboratory glass tubing. The system used was fresh water flowing against salt water. The salt water solution was fairly weak (0.8% salt by weight), and there was no significant difference in viscosity or density between the water and salt solution.

Smith and Schulze (2) made extensive studies of contamination in experimental pipe lines of 0.6 inch and 2.0 inches in diameter.

The pipe line was a closed loop of pipe about 5000 feet in length. The variables studied were velocity, viscosity, density, and length of flow. Liquid systems employed were propane, butane, gasolines, kerosenes, and fuel oils. The range of Reynolds Numbers was from 500 to 195,000. Velocities ranged from less than 0.5 ft. per second to slightly more than 7.0 ft. per second. The results of their research are presented as a graph of the contaminated quantity plotted against Reynolds Number on logarithmic paper, as shown in Figure 1. The Reynolds Number is computed from the kinematic viscosity of the 50-50 blend of the two liquids in the line. All of their data may be correlated by this plot. They conclude that the volume of contamination is a function of the Reynolds Number of the 50-50 blend and length of the flow path in the pipe. They did not observe any difference in contaminated volume when the order of flow was reversed, other variables remaining constant. In no case did they make a study of the independent effects of density and viscosity.

Birge (3) reports some data on contamination in commercial lines and offers a chart which predicts contamination with moderate success.

In the liquid systems employed by Smith and Schulze, density and viscosity are not independent, as one may be expressed as a function of the other. It is desirable to investigate the problem by including liquids whose densities and viscosities are independent.

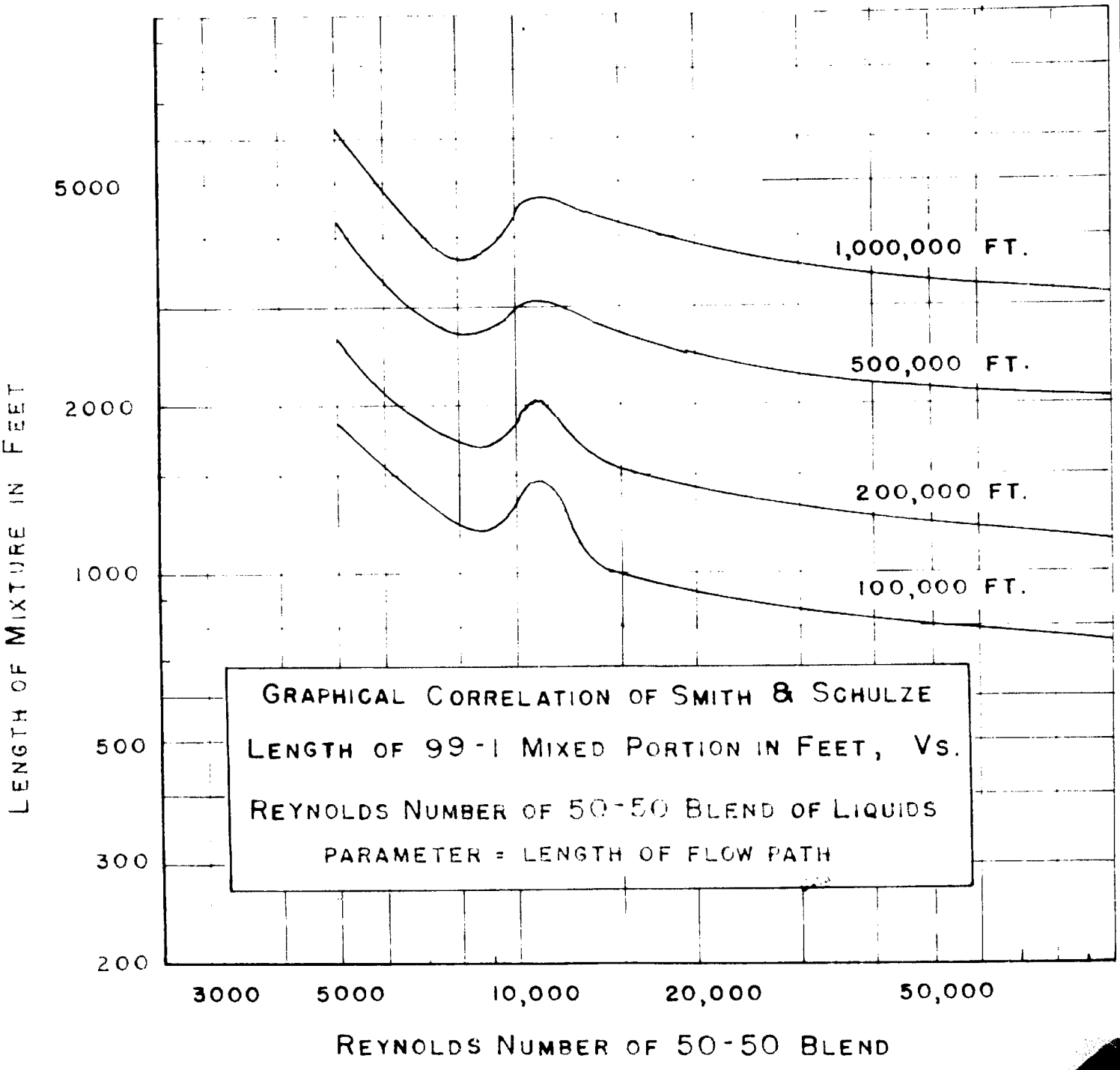

LENGTH OF MIXTURE IN FEET
5000
2000
1000
500
300
200
1,000,000 FT.
500,000 FT.
200,000 FT.
100,000 FT.
GRAPHICAL CORRELATION OF SMITH & SCHULZE
LENGTH OF 99-1 MIXED PORTION IN FEET, VS.
REYNOLDS NUMBER OF 50-50 BLEND OF LIQUIDS
PARAMETER = LENGTH OF FLOW PATH
3000
5000
10,000
20,000
50,000
REYNOLDS NUMBER OF 50-50 BLEND

FIGURE 1

A. Method of Analysis

Perhaps the most important single consideration in planning experiments on contamination in pipe lines is that of analyzing the mixed portion between the two uncontaminated products.

Schoder (4) made frequent measurements of specific gravity of samples withdrawn from a pipe line while oil was flowing in the field tests. For the water tests, he used a water soluble dye injected into the line upstream from two observing stations several feet apart. These stations consisted of jets of liquid forced from the center of the pipe by the velocity head of the liquid in flow. He observed the time interval for persistence of color at each station. Knowing the flow rate, and calculating the increase in time interval for color persistence at the second station, he estimated the contamination which occurred while the water flowed between the stations. Fowler and Brown (1) used a train of beakers moving at constant speed past the discharge end of the pipe line to catch the effluent as the contaminated portion was discharged. Each beaker was analyzed for salt content and the contamination curve (instantaneous composition versus volume discharged) was readily obtained by this technique. Most of the data were taken at velocities less than 3 feet per second, and errors due to spillage were not significant. Smith and Schulze (2) devised a continuous flow densitometer to detect the volume of the contaminated portion. Changes in specific gravity could be measured to 0.001 unit without interrupting the liquid flow through the pipe.

In the present investigation, the use of high velocities (up to

6 feet per second) required a method of analysis which would not necessitate taking samples from the pipe. This meant the development of a method for instantaneous and continuous analysis of the liquids while in flow in the pipe.

Several techniques for accomplishing this readily suggest themselves, namely: conductivity change, refractive index change, density change (densitometer), radioactive tracer elements, and colorimetric analysis.

The conductivity method suffers from at least three disadvantages: (1) necessity for close temperature control, (2) the electrodes would be coated with the leading liquid, with resulting loss in efficiency if this liquid were a non-conductor, and (3) minute traces of moisture very appreciably alter the conductivity of non-aqueous systems.

The refractive index method is primarily suitable for use in those liquid systems where there is considerable difference in refractive index between the liquids. Again close temperature control is required. Modern techniques recently reported (7) after this work was done make this method appear more attractive.

Densitometer changes involve the use of appen and chart system with its attendant inertia. This inertia leads to prohibitive error when the time for analysis is a matter of three or four seconds. Again close temperature control is required.

Radioactive tracer technique appears quite promising, and it appears that a satisfactory method could be devised. The radiation counter would have to be adjusted to account for the radiation of a

particle at some distance on either side of the point selected for analysis when the radiating particles flow through a pipe.

Taking the foregoing factors into consideration, it was decided that perhaps the simplest way to obtain satisfactory instantaneous and continuous analyses of liquid mixtures in flow way by photoelectric colorimetry. This method was developed and proved to be satisfactory, with the qualifications listed in the section entitled "Discussion of Results."

B. Theory of Colorimetric Analysis

The application of colorimetric analysis to pipe line contamination means that one liquid will be tinted with a soluble dye, and the other will be chosen so that its natural color is either complementary to the dyed liquid, or else it is practically colorless and nearly transparent. The principle here is that monochromatic light passing through the transparent conduit at right angles to the axis of the conduit, will either be absorbed or transmitted, depending on the color of the incident light and the liquid in flow through the conduit. This affords a quantitative measure of the amount of each liquid present if the transmitted light is allowed to fall upon a suitable photoelectric cell and its resulting photoelectric current is measured. By photoelectric principles, the photocell current is directly proportional to the amount of light falling on the photocell, which in turn is directly proportional to the amount of dye present in the conduit.

Chemical colorimetry implies the determination of the concentration of a colored solute by measurement of the relative light absorption or transmission of the solution. According to modern theory, the absorption of light is due to vibrating charged particles (electrons) associated with molecules and ions; therefore, it is natural to expect that the character of the absorption will depend, in general, upon the nature of the system with which the electrons are associated.

It is customary to speak of the charged particles and whatever they are associated with as the "absorbers" (5). A "simple"

absorbing solution would be one containing only one kind of absorber. In such a solution, the absorption of light of a given wave length would be proportional to the number of the absorbers in the path of the light beam. This is one way of stating a colorimetric principle known as "Beer's Law." If a monochromatic light beam of intensity I_o (see Figure 2a) strikes a solution of thickness t, having a concentration of absorber of magnitude c, and the emergent intensity is I, then

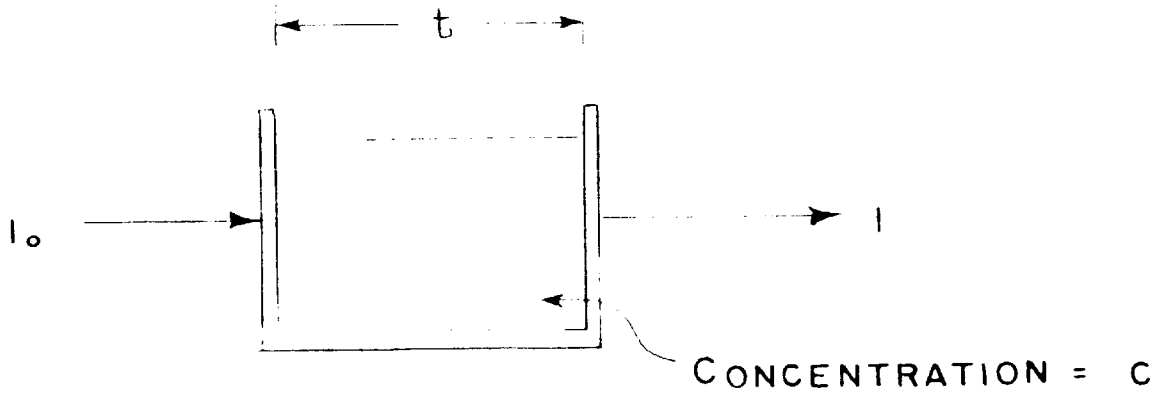
$$I = I_o \ 10^{-kct}$$

or

$$\log_{10} (I/I_o) = -kct = -E,$$

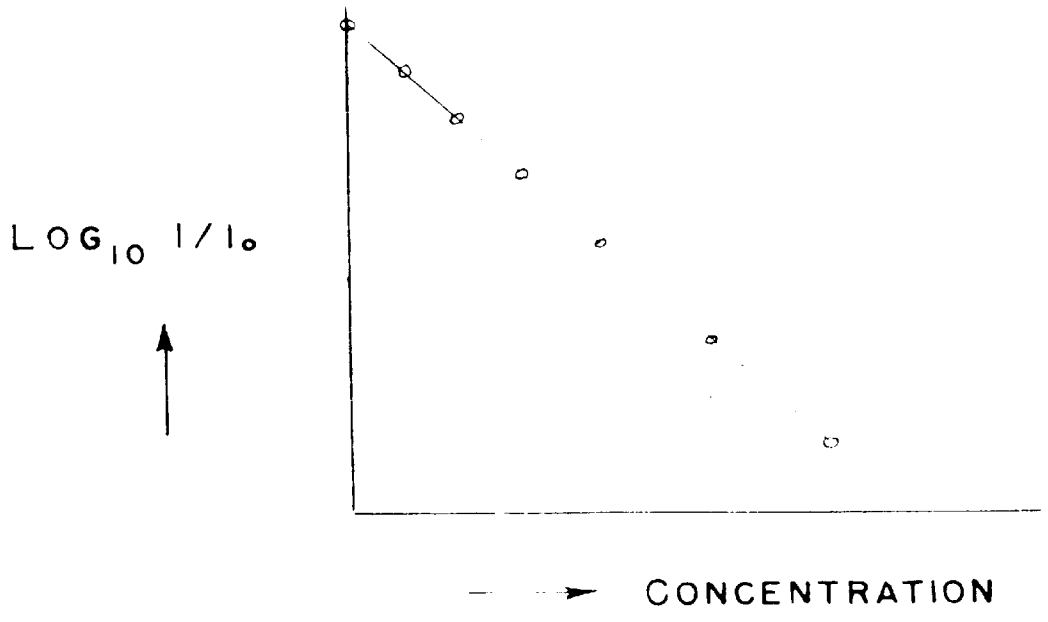
Where E is the "extinction coefficient." The relationship given above is a mathematical expression for the Beer-Lambert Law. For all cases where t is maintained constant (as in a pipe line), the relationship becomes an expression for Beer's Law. In order to test whether a given absorber will follow Beer's Law, it is sufficient to plot experimental values of log (I/I_o) as a function of c (t held constant) and note if the result is a straight line graph (see Figure 2b). Although Beer's Law is strictly valid only whenamonochromatic light band of 30 to 100 millimicrons in width is used. It is customary to refer to the term (I/I_o) as the "transmittance" (8).

If the absorbers are not changed by adding more of the solvent, it is readily seen that the absorption will not change if the product of the concentration and thickness of the solution is kept constant.



$$\text{LOG}_{10}\ I/I_o = -KCt$$

(2A)



(2B)

FIGURE 2 ILLUSTRATION OF BEER'S LAW

In simple absorbing solutions, if the concentration is very great, the absorbers may be so close together that they cease to act independently of each other. In such cases, Beer's Law may not apply. In general, however, Beer's Law holds for simple absorbing solutions, or mixtures thereof.

The analytical method used depends upon the application of Beer's Law to the dyed liquid and its solution with another liquid when mixing results at the interface between them. The preliminary experimental work was designed to select suitable dyes for use in the liquids chosen for this research. The procedure, in brief, was to make a standard dye solution of known dye concentration in one of the two liquids. A measured portion of this standard dye solution was then diluted to a somewhat lower dye concentration by adding a measured amount of the other liquid chosen to flow against the first in the contamination tests. Several such dilutions were made, giving dye solutions of varying dye concentrations in mixtures of the two liquids eventually to be pumped through the line. The values of I/I_o were determined in the laboratory by means of a Fisher Electrophotometer. These values were determined with the same filter that was later used in the illumination system of the pipe line analytical equipment. Plots of Log (I/I_o) (Percent Transmittancy) versus dye concentration were made. In all runs reported in this research, the dye systems used followed Beer's Law. Plots of Log Percent Transmittancy versus dye concentration are presented in the appendix for those dyes actually used.

The practical advantage of working with dye solutions which obey Beer's Law is that the light absorption is directly proportional

to the number of dye particles in the light path and is independent of their distribution.

The proper selection of dye for a given pair of liquids depends on a number of factors. First of all, the dye should be readily soluble in both liquids, Secondly, the spectral transmittance characteristics of the dye should be such that it exhibits maximum absorptivity at the peak wavelength of the light beam used for analysis. Thirdly, it should follow Beer's Law in the liquids used. If Beer's Law is followed, it means that the light absorption is dependent solely upon the number of absorbers in the light beam, regardless of their spatial arrangement.

A basic assumption in the application of colorimetric analysis to this problem is that there is uniform distribution of dye across the conduit at a given time and at a given cross section of the pipe, several diameters removed from the beginning of successive flow. Another way of stating this is to say that it is assumed that the only concentration gradient of dye in the mixture occurs along the axis of the conduit in fully established turbulent flow. The fact that the liquids were always flowing at Reynolds Numbers greater than 2100, and that the point of analysis was 2120 diameters downstream from the point where successive flow was started makes this a reasonable assumption. This point will be discussed later in the section where experimental results are reviewed.

EXPERIMENTAL WORK

A. Apparatus

The two chief classes of apparatus needed are the pipe line for obtaining successive flow and the analytical equipment.

The Pipe Line

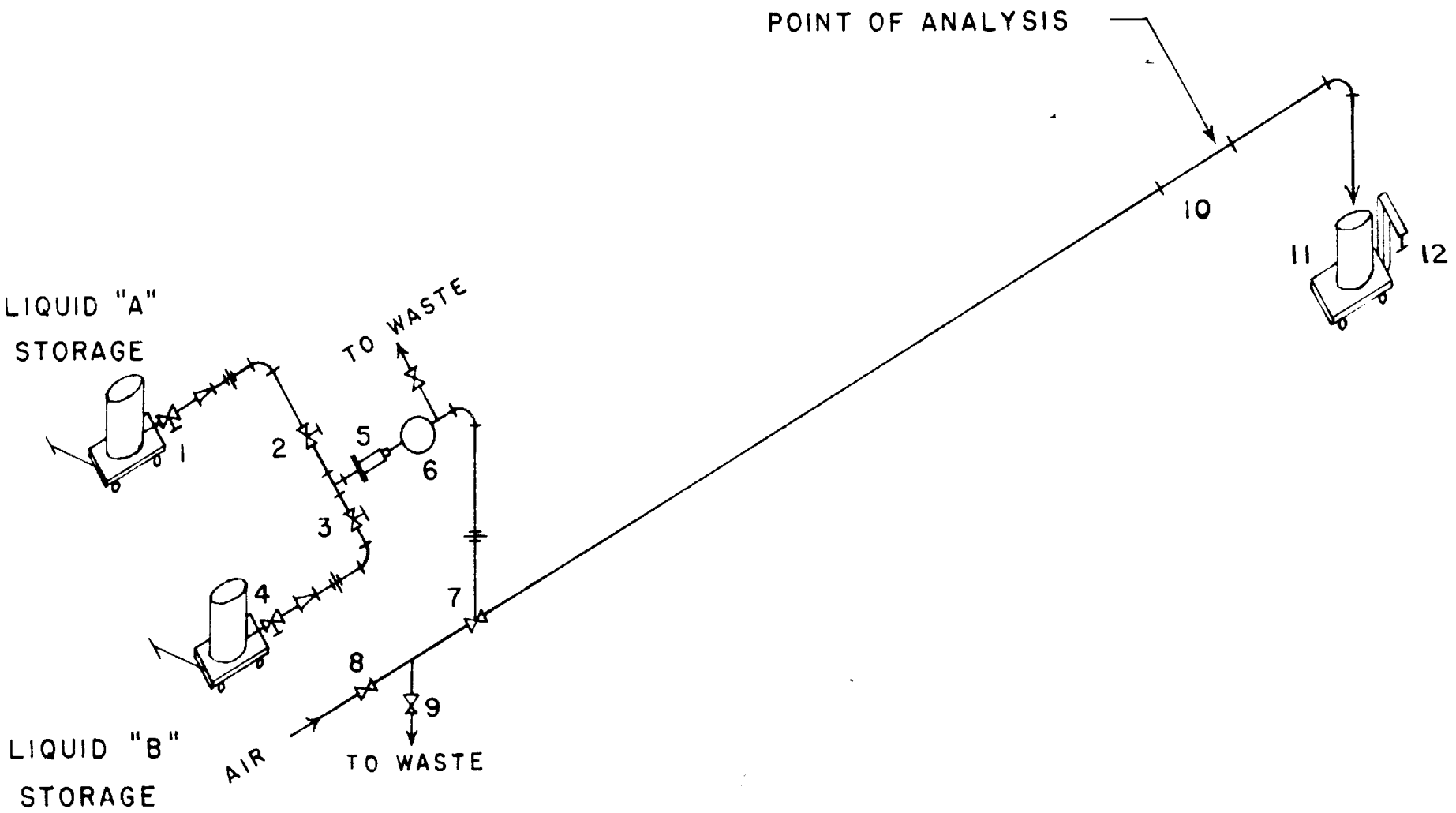
One of the purposes of this research was to investigate the effect of differences in properties of the two streams upon the mixing produced between them in successive flow. This meant that the three major variables to be considered were velocity, viscosity, and density. Other factors that are known to affect the mixing are length, diameter, and roughness of the pipe. These are to be held constant. The roughness of the inner surface of the pipe line was measured with a Profilometer, manufactured by the Physicists Research Company. Explorations were made for a distance of about four inches parallel to the axis of the tubing, and at several locations in the particular pipe section. Circumferential measurements were made at several places also. This was done on two different sections of the pipe line. There seemed to be no fundamental difference in the measurements between the longitudinal and the circumferential explorations. The roughness values observed on the meter of the instrument were predominantly in the range of 10 to 20 microinches (r.m.s.), with very infrequent readings as high as 30 microinches.

It was evident from the work of Fowler and Brown that short lengths of pipe were undesirable. Therefore, one objective was to construct an experimental line as long as possible in the confined space of an engineering laboratory. For this research, a maximum length of 168 feet was found to be practical and was constructed of one inch brass tubing. The individual lengths of tubing were about twelve feet in length (with the exception of the last section), and were joined together by streamline soldered fittings. At the analytical end of the pipe line, a six-foot section of pyrex glass pipe of one inch internal diameter was joined to the brass section by means of a ferrule adapter. The actual internal diameter of the brass tubing and glass pipe were both one inch, within engineering tolerance.

The liquids were introduced into the line by means of a three-way brass valve and auxiliary brass connecting lines, as shown in Figure 3.

The microscopic mechanism of turbulent flow is still obscure. The path of any liquid particle is chaotic and cannot be described precisely. It is necessary to describe the flow in such general terms as velocity distribution, average velocity, and so on. It is known that eddy currents are a prominent feature of turbulent flow, and are completely absent in laminar flow when liquids are flowing in a straight, horizontal conduit.

When fluids are transported through a bend in a pipe, a phenomenon known as "secondary flow" results (6), (9). Secondary flow is observed both when the fluids are in laminar flow and in turbulent flow. In travelling through a bend, the fluid near the outer



LEGEND

1,2,3,4 -- GATE VALVES

5 -- STRAINER

6 -- POSITIVE DISPLACEMENT PUMP

7 -- THREE-WAY VALVE

10 -- PYREX PIPE SECTION

11 -- EFFLUENT TANK

12 -- PLATFORM SCALES

FIGURE 3

ISOMETRIC SKETCH OF PIPE LINE

radius is under higher pressure than that near the inner radius of the bend due to centrifugal force. This means that there is a pressure gradient across the conduit due to flow around the bend. This gives rise to fluid motion from the wall at the outer radius toward the wall at the inner radius of the bend. The net result is a double spiral motion; the direction of rotation of the two spirals being opposite to each other. It should be observed that secondary flow will obtain even though the curvature of the conduit is very slight. Once established, secondary flow persists for several diameters downstream (9).

It is apparent that this secondary flow phenomenon produced by bends in the pipe line will have some effect on the mixing that takes place in successive flow of liquid products. This is particularly true of short lines, such as this laboratory installation required. For this reason, considerable care was used in laying a straight, horizontal line. The line was laid horizontally by use of a mason's level. A straight path was surveyed and the line installed using a guide wire under tension. The pipe line was then constructed so that the path of flow of the two liquids in contact would be straight and horizontal.

The pump used was a positive displacement pump manufactured by Yale and Towne Manufacturing Co. (Model 20 DVM). It was rated at 20 g.p.m. when driven at 1140 r.p.m. It is evident that if the velocities of the liquids were to be controlled, it would be necessary to use a positive displacement pump. The principle of action in such a pump is that the volume discharged is substantially independent of the discharge pressure, over the design limits of the

pump. This pump was equipped with a variable volume control valve built in as an integral part of the pump itself. Discharge rates from 0 to 20 g.p.m. could thus be obtained by changing the control valve setting. The pump was connected for direct drive to a 1 HP explosion-proof motor with a shaft speed of 1160 r.p.m.

A centrifugal pump is not suitable as its discharge rate is dependent upon the discharge pressure. This makes it impossible to control the velocity when the two streams in successive flow have different properties.

By way of summary, the equipment used in this investigation consisted of a 20 gpm positive displacement pump, a three-way valve, and a brass pipe line 168 feet long (the last six feet being pyrex pipe). The internal diameter of the line was one inch, and the analytical point was held constant a few inches from the end of the glass section. The ratio of length to diameter was 2120 and the volume of the line was 6.84 gallons.

The Analytical Equipment

It became necessary to devise equipment to give a permanent record of the variation of instantaneous composition of liquid in the conduit with time. Photoelectric colorimetry was the analytical tool chosen for this purpose.

Photoelectric colorimetry, when applied to problems of chemical analysis in general, involves only the light absorption of a small portion of the solution. This is a batch pperation. The analytical problem was rendered more complex since it involved a continuous analytical operation. It was continuous in the sense that the

solution undergoing analysis by light absorption was undergoing rapid change of composition with time. In the usual batch operation, the light absorption of the solution is measured in a photoelectric colorimeter containing a microammeter to register the current produced in the photocell by the light which passes through the solution without being absorbed. This measurement requires a few seconds, perhaps of the order of 5 to 10 seconds, before the microammeter reading comes to a steady value. In some of the runs in this investigation, the entire mixture to be analyzed passed the analytical point in a matter of 3 or 4 seconds. It is evident that any instrument as sluggish as a microammeter could not be used.

In addition to having a quick-acting metering device to measure the photocell current, it was necessary to have a continuous record of the photocell current as it changed with time.

The analytical speed required ruled out the possibility of using barrier-layer type of photocells. Such cells are simple and efficient, but have an appreciable time lag, which is prohibitive in the application outlined here. A vacuum photocell does not suffer from the disadvantage of an appreciable time lag, and so R.C.A. photocell number 926 was chosen for this investigation. In addition to being a vacuum photocell, its spectral sensitivity range was found to occupy more of the visible spectrum than most vacuum photocells.

The only current measuring instrument that seemed to meet the requirement of speed of response was a cathode ray oscillograph.

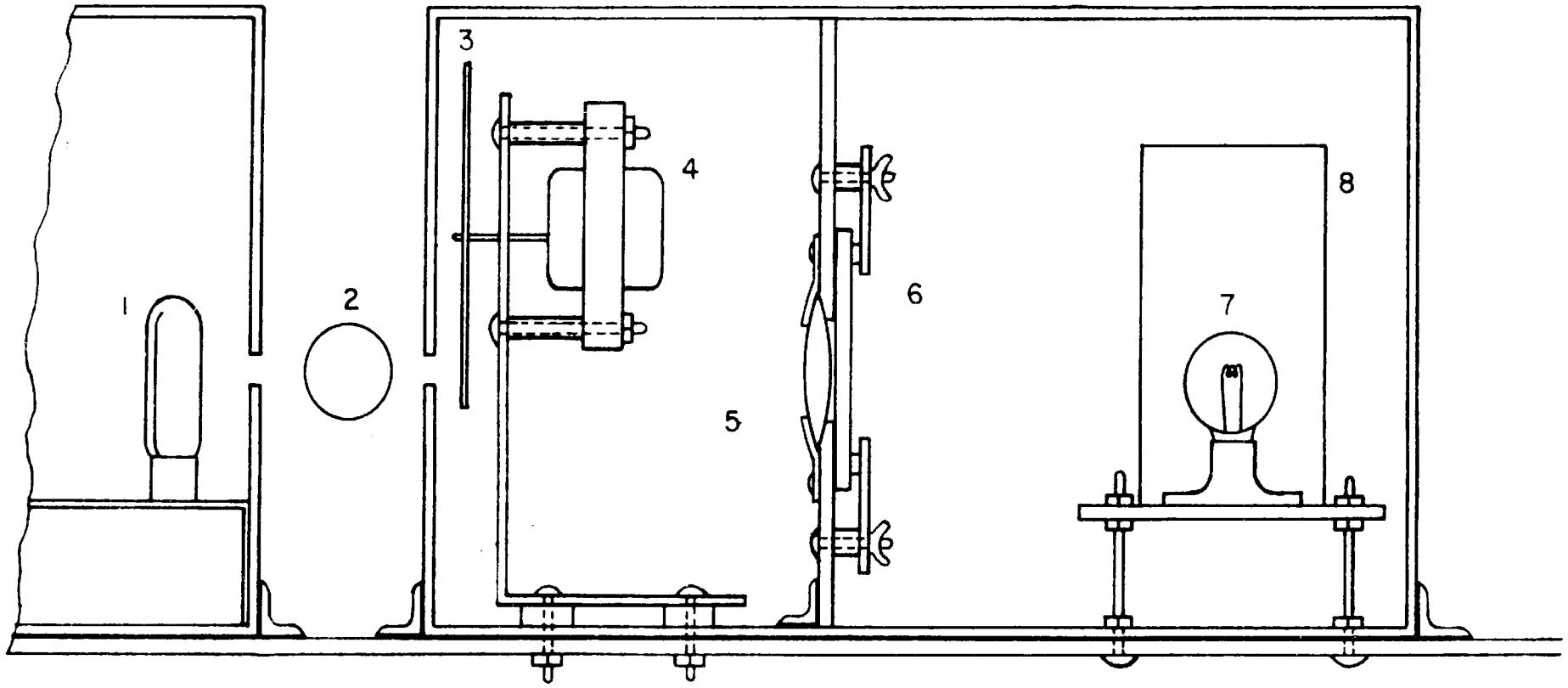
Since its electron beam has negligible inertia, the oscillograph is capable of instantaneous response to changes in photocell current. This instrument could furnish a permanent record of photocurrent variation with time if the trace on the oscillograph screen were photographed. For this investigation, a Du Mont Type 208-B oscillograph was selected with a type 5 L P 11 cathode ray tube. This tube has a sulfide screen which gives a blue trace when hit by the electron beam and is particularly suited for making photographic records.

The light source employed was a 6.5 volt, 2.75 ampere microscope lamp. It was mounted in a rectangular box shield with a small circular opening. The light beam passed through this opening, a colored glass filter, a lens, a "chopper" disc, and finally through the pyrex glass pipe section before striking the photocell. The necessity for installing a light chopper arises from the fact that the oscillograph has A.C. amplifiers built into it. If the light falling on the photocell were uninterrupted, and merely showed variations in intensity, then the photocell would produce only a direct current of varying magnitude. Such direct current could not be amplified by the amplifier section of the oscillograph. For this reason, the chopper disc was used. This was simply a circular plastic disc of about 5 inches diameter, having ten holes drilled in it near the outer edge, and evenly spaced. This disc is driven at nearly constant speed of 60 r.p.s. by a phonograph motor. This produces pulsating direct current of 600 cycles per second which can be amplified by the A.C. amplifiers.

The lens and lamp of the light source system were so arranged that the image of the lamp filament fell at the center of the pyrex pipe section. Suitable slits were placed in the light beam so that the beam that passed through the pipe and into the photocell was about 1/8 inch in diameter. The light beam was put into position in such a way that the beam travelled through the pyrex pipe section on a diameter line of the pipe. This technique eliminated, for practical purposes, the undesirable refraction of light which would result when liquids of different refractive indices were employed. A sketch of the illumination system and auxiliary apparatus is shown in Figure 4.

The R.C.A. 926 vacuum photocell used produces a current of only a few microamperes when illuminated by white light. If narrow band light is used (as it must be), the magnitude of the photocell current is greatly reduced. For this reason it was necessary to design and construct a linear pre-amplifier for use with the oscillograph. The wiring circuit diagram for the pre-amplifier is shown in Figure 5a. The linearily test curve for this pre-amplifier is shown in Figure 6. The pre-amplifier required a plate voltage of 300 volts D.C. To provide this voltage, a regulated D.C. power supply was built and its wiring diagram is shown in Figure 5b. When the input A.C. voltage changes from 95 to 130 volts, the D.C. output of the power supply changes from 298 to 301 volts. Under ordinary conditions, this meant that the power supply gave output voltage of not more than one volt variation.

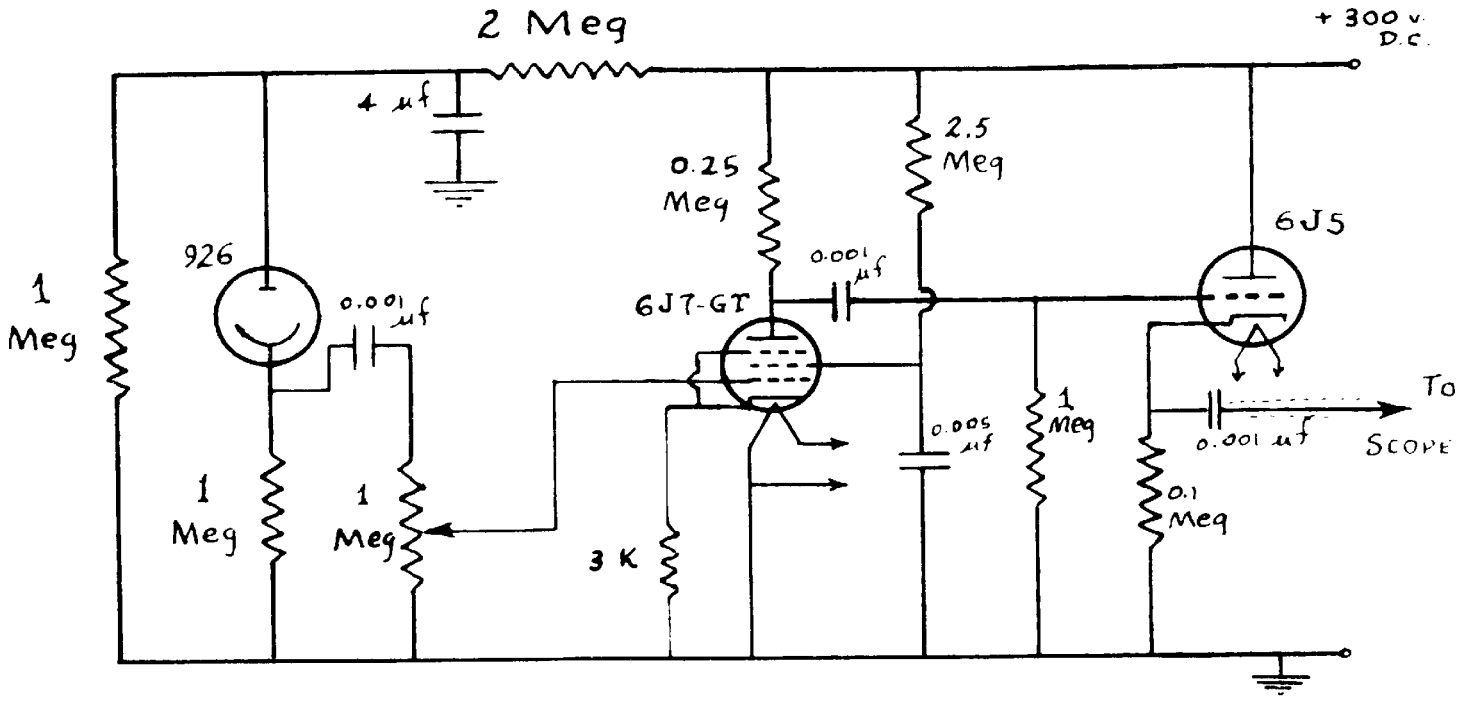
Considerable difficulty was experienced in the early stages of this work when storage batteries were used to supply the lamp. Since



1 -- PHOTOCELL
2 -- PYREX PIPE SECTION
3 -- CHOPPER DISC
4 -- PHONOGRAPH MOTOR
5 -- LENS
6 -- GLASS FILTER
7 -- LAMP
8 -- LAMP SHIELD

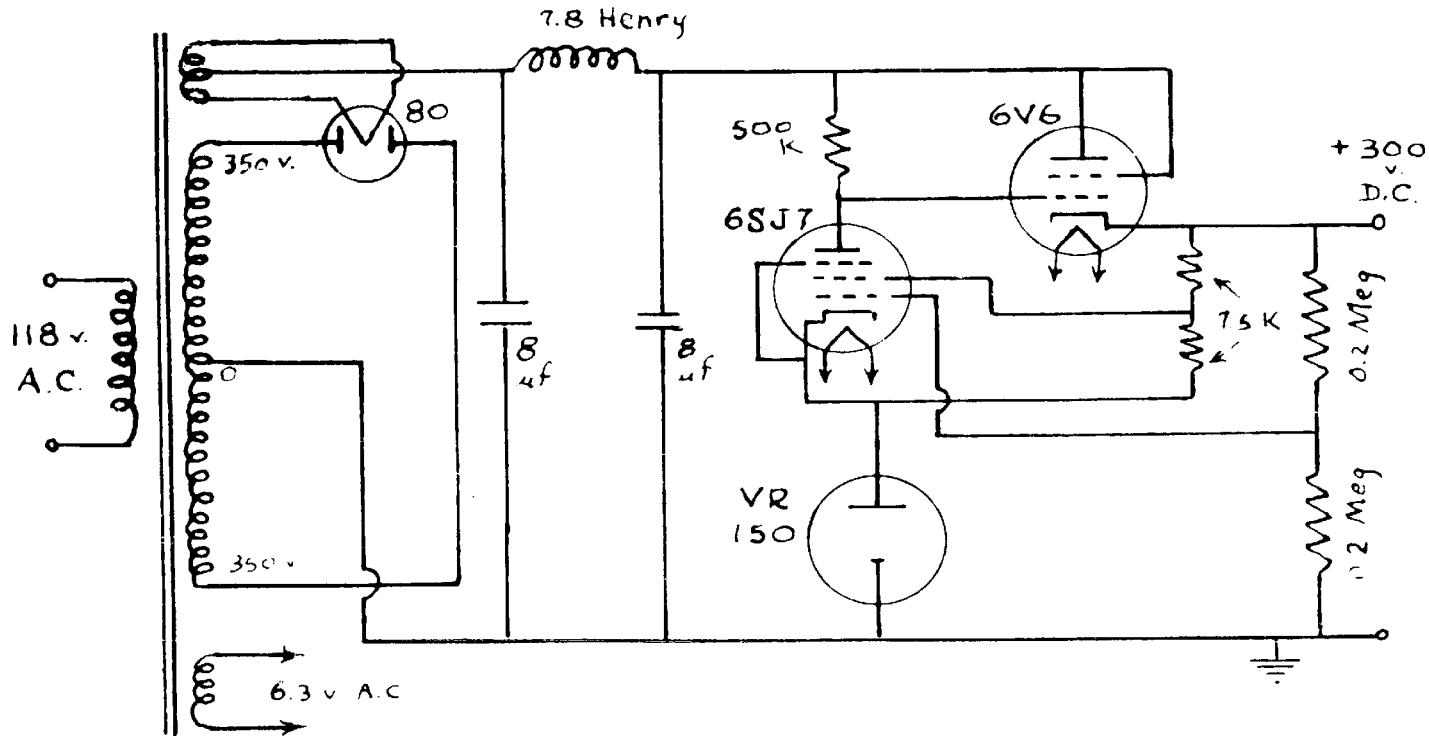
FIGURE 4

SIDE VIEW
OF
ILLUMINATION SYSTEM



PRE-AMPLIFIER CIRCUIT

FIGURE **5A**



300 V. D.C. REGULATED SUPPLY

FIGURE **5B**

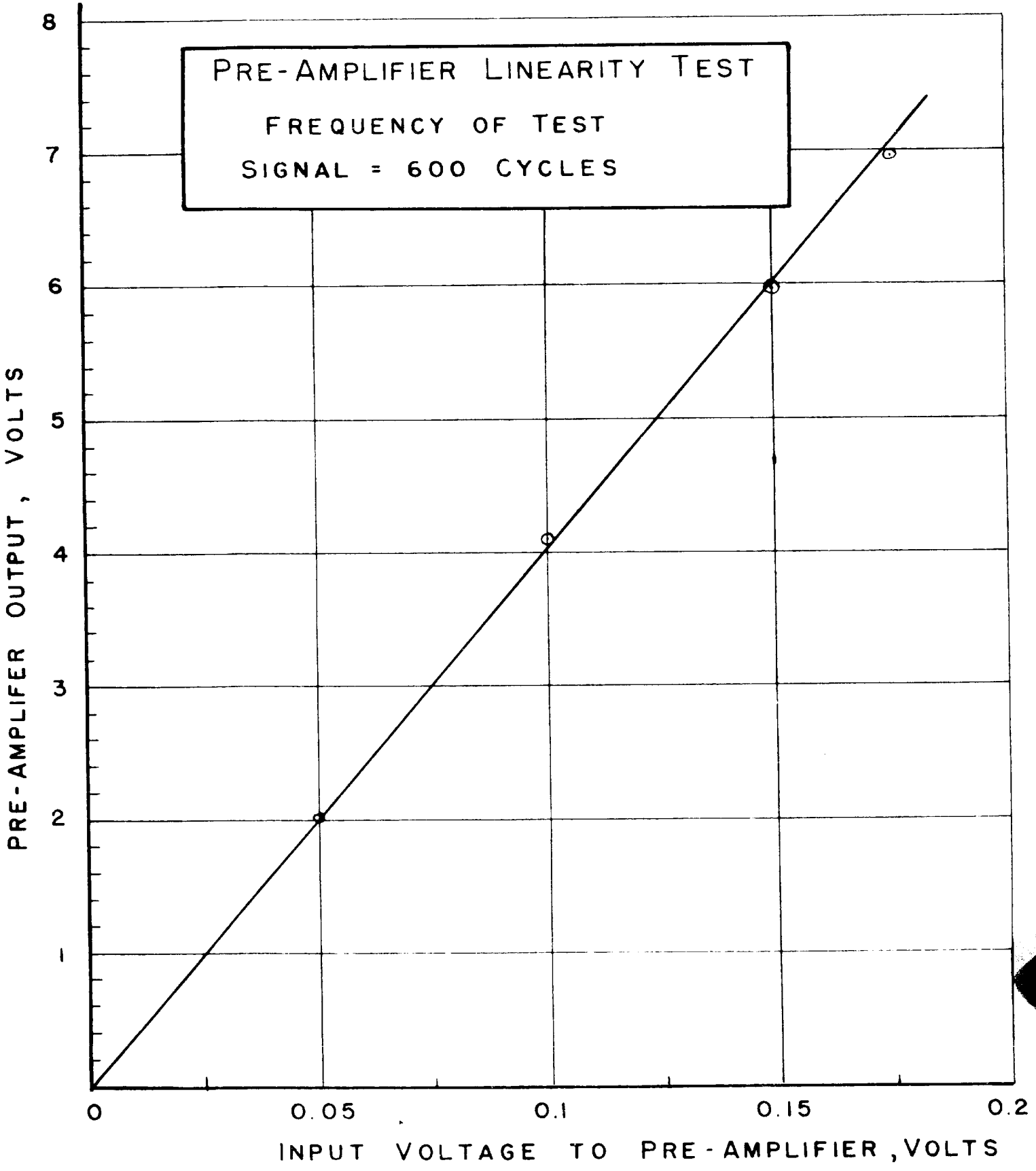

PRE-AMPLIFIER LINEARITY TEST
FREQUENCY OF TEST
SIGNAL = 600 CYCLES
PRE-AMPLIFER OUTPUT, VOLTS
8
7
6
5
4
3
2
1
0
0.05
0.1
0.15
0.2
INPUT VOLTAGE TO PRE-AMPLIFIER, VOLTS

FIGURE 6

the current drain was fairly high, the batteries discharged fairly rapidly and over the course of an hour or two there was a noticeable change in the photocell current as recorded on the oscillograph. A one percent decrease in lamp voltage means about four percent decrease in light intensity. Thus, if the battery voltage dropped from 6.00 volts to 5.96 volts, the photocurrent would drop from, say 10 microamperes to 9.6 microamperes. This was serious and had to be eliminated. Trickle charging of the batteries proved unsatisfactory, primarily due to the 60 cycle pick-up (stray voltage ripple) from the d.c. generator.

A Sorensen constant voltage power supply, known as a "Nobatron," operating on the 115 volt A.C. line supply, delivered between 5 and 10 amperes at 6.00 volts D.C. with no observable variation in voltage. The voltage regulation was guaranteed by the manufacturer to be plus or minus one half of one percent. This instrument also supplied the filaments for the vacuum tubes in the pre-amplifier and its 300 volt regulated supply.

The 115 volt A.C. supply line in the engineering laboratory showed a voltage variation ranging from 112 to 126 volts on a recording voltmeter during a 56 hour test. This seemed to be the source of some variation in the amplitude of a steady signal as applied to the oscillograph from a signal generator. For this reason, a Sola constant voltage transformer was used to supply the A.C. input to the oscillograph.

A rotating drum camera was used to obtain a photographic record of the variation of composition of the mixture in the pipe with time. The essential components used were a light-tight box, a synchronous

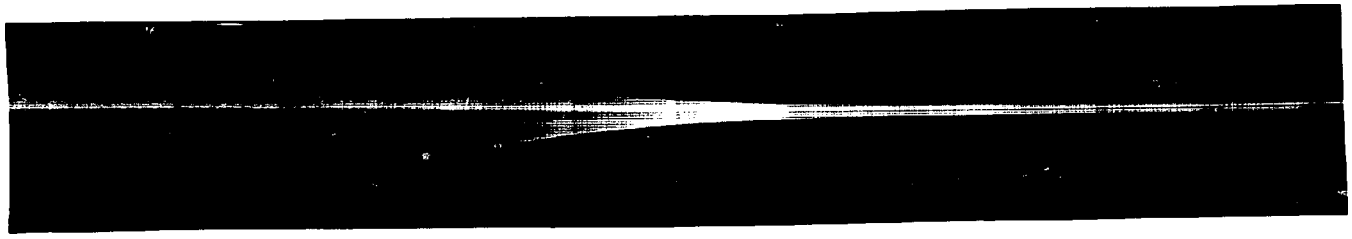
motor, a circular wooden drum, a relay, a switch, and a lens and shutter. The length and width of the box were about 14 inches and the thickness about 6 inches. The motor, manufactured by the Leich Electric Company, had a shaft speed of 2 r.p.m. The actual time for one revolution was found to be 29.8 seconds with the wooden drum in place. The wooden drum was 19.39 inches in circumference and contained a brass bushing that had been pressed into the wooden drum at the center. The drum was mounted on the shaft of the motor and held in place by a set-screw in the bushing. The drum weighed only 300 grams. A grooved path was cut in the surface of the drum to accomodate the 35 mm. film strip used. The lens had a 50 mm. focal length and lens opening of f/3.5. The 115 volt A.C. supply was wired to the motor in parallel with the relay. When the switch was closed, the motor would start and the relay would close simultaneously. The motion of the relay was imparted to the shutter by means of a lever system so that the camera lens always opened in synchronism with the operation of the motor and the film drum.

Both Eastman Super XX film and Ansco Ultra speed Panchromatic film were used with equally satisfactory results when the intensity setting on the "scope" beam was between 55 and 65 units. The distance from the camera to the screen of the scope was approximately 16 inches.

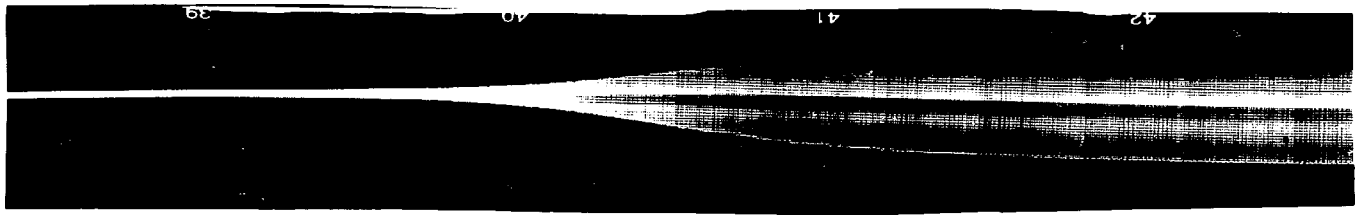
In setting up the camera in relation to the scope, the following points should be noted. The major axes of the camera and the scope should coincide. Care should be taken to see that the center line of the lens is in the same line with the center line of the electron beam trace on the scope screen. In such an arrangement, the time

axis is measured along the length of the film, while the signal axis is across the film. In order to take advantage of the greater gain available in the Y-axis amplifiers of the oscillograph, the scope screen was rotated through an angle of 90 degrees and left in this position in all runs. By keeping the X-axis amplifier gain set at zero, the signal changes appeared as changes in the length of a horizontal line trace on the scope screen. The direction of motion of the film formed an angle of 90 degrees with the plane in which the signal trace was located.

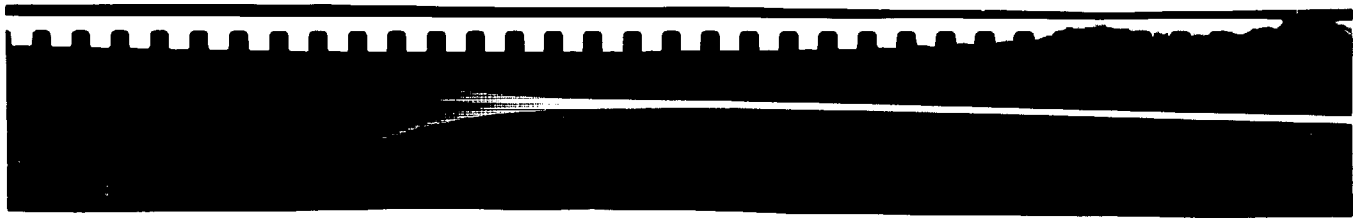
A typical group of oscillograms taken with this equipment are shown in Figure 7. A sketch of the analytical equipment as assembled for experimental work is shown in Figure 8.



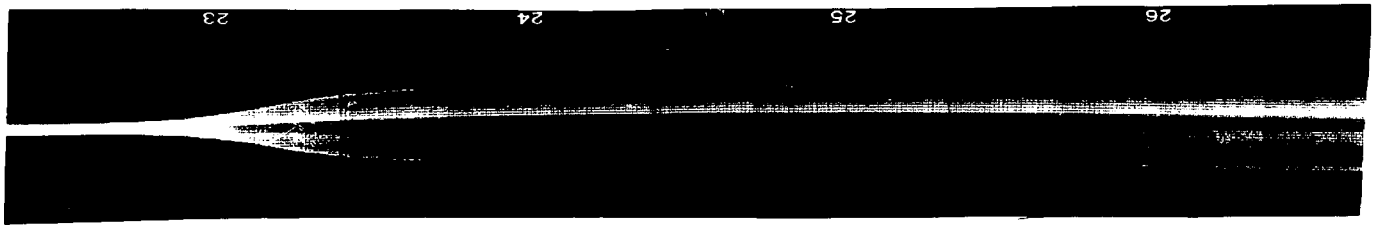
A. RUN 37. WATER - DYED WATER, AVG. VEL.= 2.64 FT/S.
REYNOLDS NUMBER = 20,500



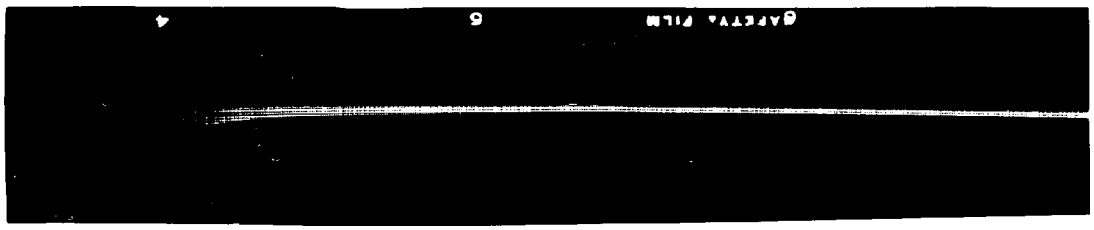
B. RUN 102. 44 WT % T.E.GLYCOL LEADING DIST. WATER
V = 2.97 FT/SEC.



C. RUN 101. 44 % T.E. GLYCOL FOLLOWING DIST. WATER
V = 2.97 FT/SEC.



D. RUN 146. 6.15 WT % SALT SOLUTION LEADING WATER
V = 5.02 FT/SEC., DYE IN SALT SOLUTION



E. RUN 182. 6.15 % SALT SOLUTION LEADING WATER
V = 5.02 FT/SEC., DYE IN WATER

FIGURE 7. TYPICAL OSCILLOGRAMS OF EXPERIMENTAL RUNS.

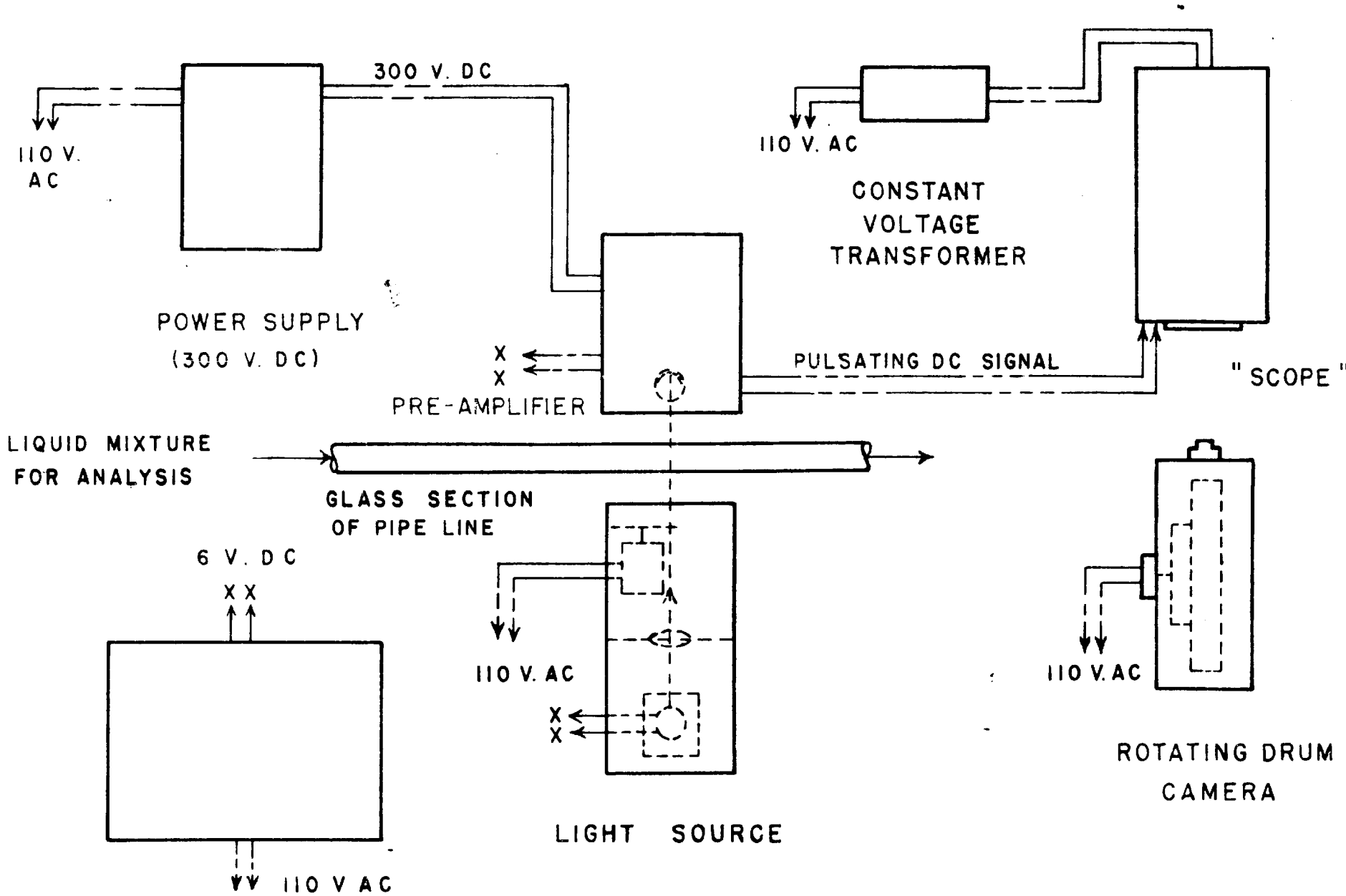


FIGURE 8

PLAN VIEW
OF
ANALYTICAL EQUIPMENT

B. Procedure

The experimental method can probably be explained best by describing a typical run. About 50 gallons of each liquid were poured into 55 gallon drums. These drums were fitted with a nipple welded near the bottom of the tank and sealed off with a gate valve. Both drums were connected to the manifold by means of a short length of neoprene hose. The manifold and pump are about four feet higher in elevation than the three-way valve. The description that follows refers to Figure 3.

Two operators are required to make a run. The line is first filled with liquid "A". In this operation, valves 1 and 2 are open, while valves 3 and 4 are closed. The three-way valve 7 is set in such a way as to allow the liquid to discharge at the distant end into a suitable vessel. After all air bubbles are out of the line, the pump is stopped, and valves 1 and 2 are closed. One operator, stationed at the discharge end, puts a stopper in the outlet of the pipe to prevent gravity flow of liquid from the pipe. The other operator then turns the three-way valve so as to permit liquid to be pumped from the liquid "B" storage tank and out through valve 9 to waste. Valves 3 and 4 are opened in this operation, the pump is started, and liquid "B" is pumped through the connecting lines and out to waste behind liquid "A". Since one of these liquids contains dye, the operator is able to observe when the line is purged completely. After sufficient purging has been done, the three-way valve is quickly turned to permit flow of liquid "B" into the main line. In this way, liquid "B" travels down the line in successive flow behind liquid "A".

The pump operator uses a stopwatch to clock the time from the instant the valve is turned (inaugurating the run of two liquids in successive flow) until the time the camera lens should be opened to record the analysis. Previous to the analysis, the scope had been adjusted to give a maximum deflection of about 3.5 inches (when liquid "A" was clear). The quantity of dye placed in the second stream is of such a magnitude as to reduce the amplitude of the signal trace to about 0.5 inch when the pure dye stream passes the analytical point. The camera opening time is computed from the average flow velocity, allowing a few seconds for the early arrival of the contaminated mixture at the point of analysis. During the time that liquid "A" is flowing past the point of analysis, the trace on the scope shows a constant deflection of about 3.5 inches (when liquid "A" is clear). The camera is opened sufficiently in advance of the arrival of the contaminated mixture to record the constant deflection of the pure leading liquid for at least three to five seconds.

The pumping operator closes a remote control switch at the proper instant which opens the camera shutter and simultaneously starts the revolving drum motor. After ample time has elapsed to sweep the line free of the mixture, the camera shutter is closed, the pump is stopped, and valves 3 and 4 are closed. The operator at the discharge end puts a stopper in the line to prevent loss of liquid by gravity flow from the line. The film is removed from the camera and the camera reloaded.

The next run is carried out at the same average velocity, only this time liquid "A" is the following liquid. In the run just outlined

above, liquid "B" was the following liquid. The operating technique is the same in all other respects.

A new run would then be made at a different flow rate. Thus, all of the data taken were in pairs of runs in which liquids "A" and "B" were both alternately used for the leading liquid at the same average velocity.

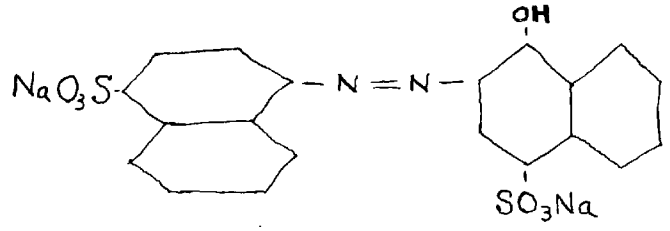
The flow rate was determined by calibrating the pump for different liquids. The calibration technique consisted in weighing the effluent over a measured time interval. The total weight of liquid collected was usually between 100 and 200 pounds, readings being estimated to the nearest 0.25 pound. The time was measured by a calibrated electric chronometer, and readings estimated to the nearest 0.1 second. A graph of the pump calibration for different liquids is given in the appendix.

C. Materials Used

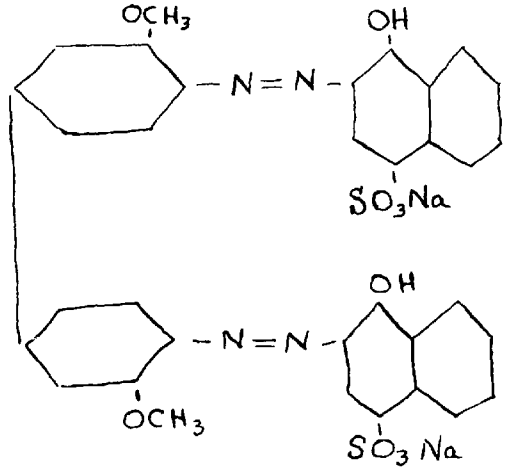
For the system water-dyed water, distilled water was used in all runs except numbers 148 to 153, where tap water was used. The dye used for distilled water was Pontamine Blue AX, Conc., manufactured by the E. I. Du Pont De Nemours & Co. The dye used for tap water was Pontachrome Blue R, Conc., also manufactured by Du Pont.

The chemical composition of the dyes is given in the structural formulae below:

Pontachrome Blue R (Color Index No. 179)



Pontachrome Blue AX (Color Index No. 502)



It was found that Pontamine Blue AX was unsatisfactory for use with tap water due to the pronounced effect of the higher pH (about 8.5) on the color intensity of the dye. Also the spectral transmission characteristics change with pH when the pH is much above 7. No difficulties of this sort were encountered when distilled water was used.

Pontachrome Blue R dye was equally satisfactory in tap water or in distilled water. There is only a slight change in the spectral transmission due to pH change.

Pontamine Blue AX dye is precipitated from its water solution when more than 2% by weight of sodium chloride is added. Therefore all runs on the system water -aqueous sodium chloride were made with Pontachrome Blue R dye which is unaffected by the presence of the sodium chloride. The precipitate formed in the case of Pontamine Blue AX rather slowly, and complete precipitation did not result until 8 or 10 hours after mixing.

The spectral characteristics of the dyes are shown in Figure 9.

Triethylene glycol (TEG) was used in preparing liquids of high viscosity. It is readily miscible with water in all proportions. The viscosity of its water solutions increases greatly with concentration with little change in surface tension between 30% and 70% TEG. It was not known whether surface tension was an important variable or not, and so it was advisable to eliminate it as a variable as much as possible. The TEG was of commercial grade, supplied by the Dow Chemical Company. Its properties are shown graphically in the appendix. In all cases the water solutions of TEG were made using distilled water. The water stream flowing succesively with the TEG stream was also distilled water.

The sodium chloride used was technical grade as used in water softening treatments, and manufactured by the Michigan Salt Company.

The benzol used was a crude benzol, containing some toluene. At 20 degrees centigrade, its specific gravity was 0.8785 and its viscosity

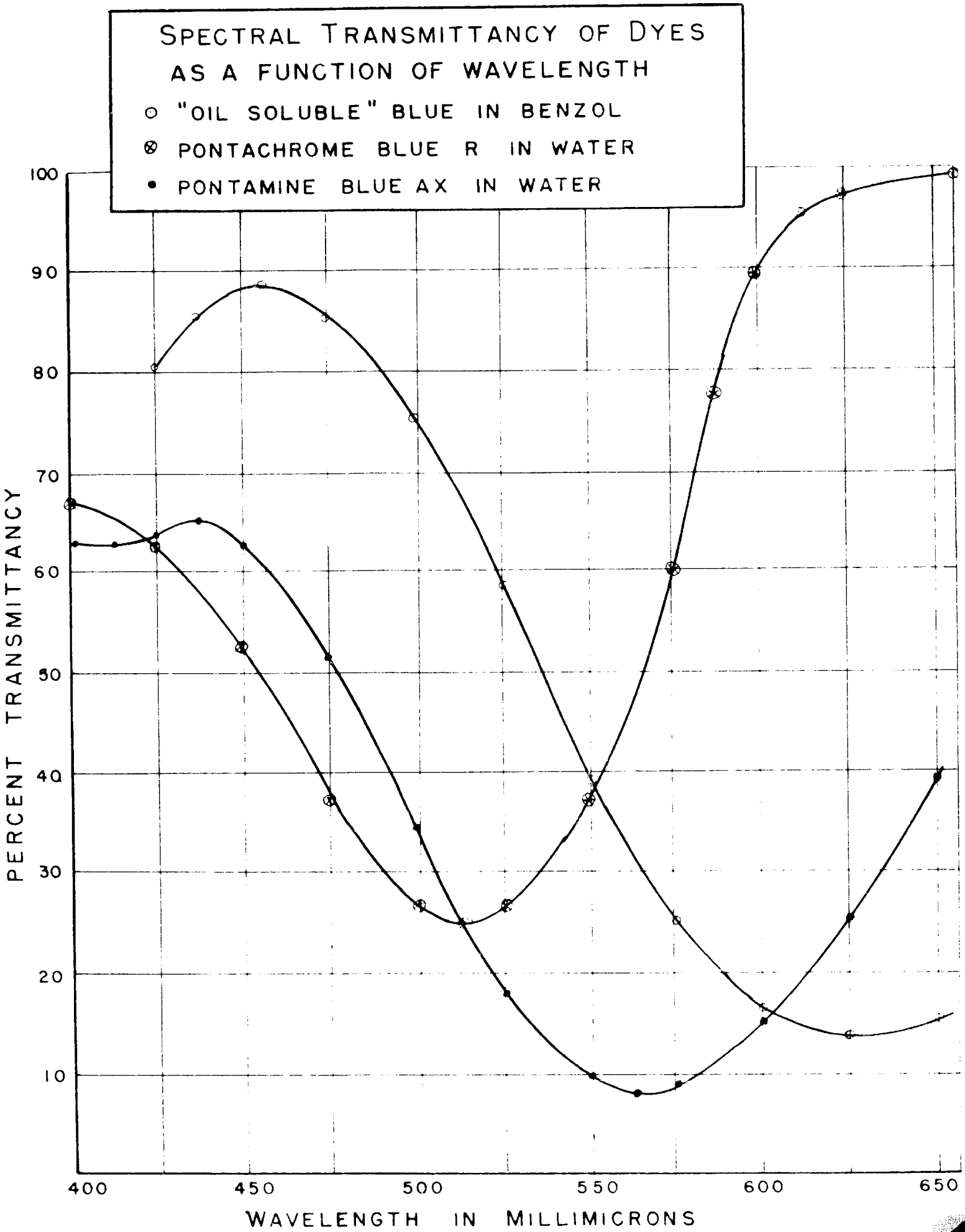

SPECTRAL TRANSMITTANCY OF DYES
AS A FUNCTION OF WAVELENGTH
○ "OIL SOLUBLE" BLUE IN BENZOL
⊗ PONTACHROME BLUE R IN WATER
• PONTAMINE BLUE AX IN WATER
PERCENT TRANSMITTANCY
100
90
80
70
60
50
40
30
20
10
400
450
500
550
600
650
WAVELENGTH IN MILLIMICRONS

FIGURE 9

was 0.640 centipoise. An oil soluble dye of unknown composition and source was used in the system benzol-dyed benzol.

The toluene used was technical grade, having a viscosity of 0.560 centipoise and a density of 0.8625 at 25 degrees centigrade.

The glass filters used were numbers 525-B and 580-B, both manufactured by the Photovolt Corporation. The 525 filter transmits a light band of approximately 100 millimicrons in width, and has a peak transmission at about 530 millimicrons. The 580 filter transmits a light band of approximately 75 millimicrons in width, and has a peak at about 585 millimicrons.

D. Experimental Errors

Experimental errors would be most likely to arise from the following sources:

(1) Flow rate measurements

(2) Temperature measurements

(3) Determination of viscosity and density

(4) Measurements of the "Y - X" readings on the oscillograms.

Flow Rate Measurements

Flow rates were determined by weighing the effluent from the pipe line over a measured time interval. The weighings were made on a platform scale, the readings being estimated to the nearest 0.25 pound. The time was measured by a calibrated electric chronometer to the nearest 0.1 second. Usually about 100 pounds of effluent were collected during the flow rate determination. Time intervals varied from about 40 seconds to about 300 seconds. Temperatures were measured with a calibrated thermometer to the nearest 0.2 degree centigrade. Properties of the liquids were calculated from the temperature, which in turn were used to compute the flow rate. From this it appears that the probable error in measuring the flow rate would be less than one percent. However, since all of the flow rate measurements were plotted on one graph, referred to as the "Pump Calibration" (see Appendix), the agreement of these data would be a better test of the flow rate errors. The data are scattered slightly from a straight line plot of discharge rate in gallons per minute versus pump control-valve setting. The major deviations occur at 5.0 and 8.5 gallons per minute, and amount to 0.2

and 0.3 gallon per minute, respectively. The percentage error in each case is about 4%.

Temperature Measurements

All liquid temperatures were measured by a calibrated thermometer to about 0.2 degree centigrade. Temperatures were read to the nearest 0.5 degree centigrade for the benzol system due to the cooling effect of its higher rate of evaporation. Errors in density and viscosity introduced by this error in temperature are not very great, but the Reynolds Number would be affected by this error. An error of 0.5 degree centigrade in measuring the benzol temperature would change the viscosity by about 0.005 centipoise at room temperature. This would change the Reynolds by about 100 units. Usually this would introduce less than one percent error. The density of benzol would be in error by only 0.0005 gram per cubic centimeter for an error of 0.5 degree centigrade.

Viscosity and Density Measurements

Viscosities were measured by means of calibrated, modified Ostwald viscometers in temperature baths regulated to plus or minus 0.05 degree centigrade. Densities were measured by means of specific gravity hydrometers calibrated by the Bureau of Standards. Viscosities were measured to 0.001 centipoise and densities to 0.0005 gram per cubic centimeter.

Measurements on the Oscillograms

The oscillograms were recorded on 35 mm. film, examples of which are shown in Figure 7. In effect, these oscillograms consist of a plot of the instantaneous compositions in the conduit (at the point of

analysis) versus time in seconds. Actually, the film record is a plot of the "Y" axis deflection of the oscillograph trace versus distance along the film, measured in frame numbers. The frame numbers are stamped on the film by the manufacturer for reference purposes.

Since the oscillograms were very small, it was necessary to enlarge or magnify them to facilitate reading the data contained thereon. This was done by means of an Argus microfilm reader, having a magnification of about 12 times. When the oscillogram was viewed on the microfilm reader screen, the "Y" deflection appeared to be 1.72 times larger than it did on the oscillograph screen. Thus, when the "Y" deflection was actually 3.5 inches on the oscillograph, it appeared to be slightly more than 6.0 inches on the viewing screen of the reader. "Y" deflection values were read at frequent intervals along the time axis by marking guide lines on the glass viewing plate of the reader. These guide lines corresponded to intervals of about 1/20 of a frame. A frame was approximately 1.5 inches long, when measured along the film, or about 18 inches long when viewed in the reader.

Values of "Y" deflection were measured by means of a steel ruler graduated in 0.01 inch markings. Readings of signal amplitude were made to the nearest 0.01 inch on a quantity varying from about 0.5 inch to about 3.5 inches. This introduces a maximum error of about 2 percent.

Considering all of these four sources of error together, it would seem that the overall maximum error would be about 10 percent, and the probable error about 6 percent.

E. Experimental Results

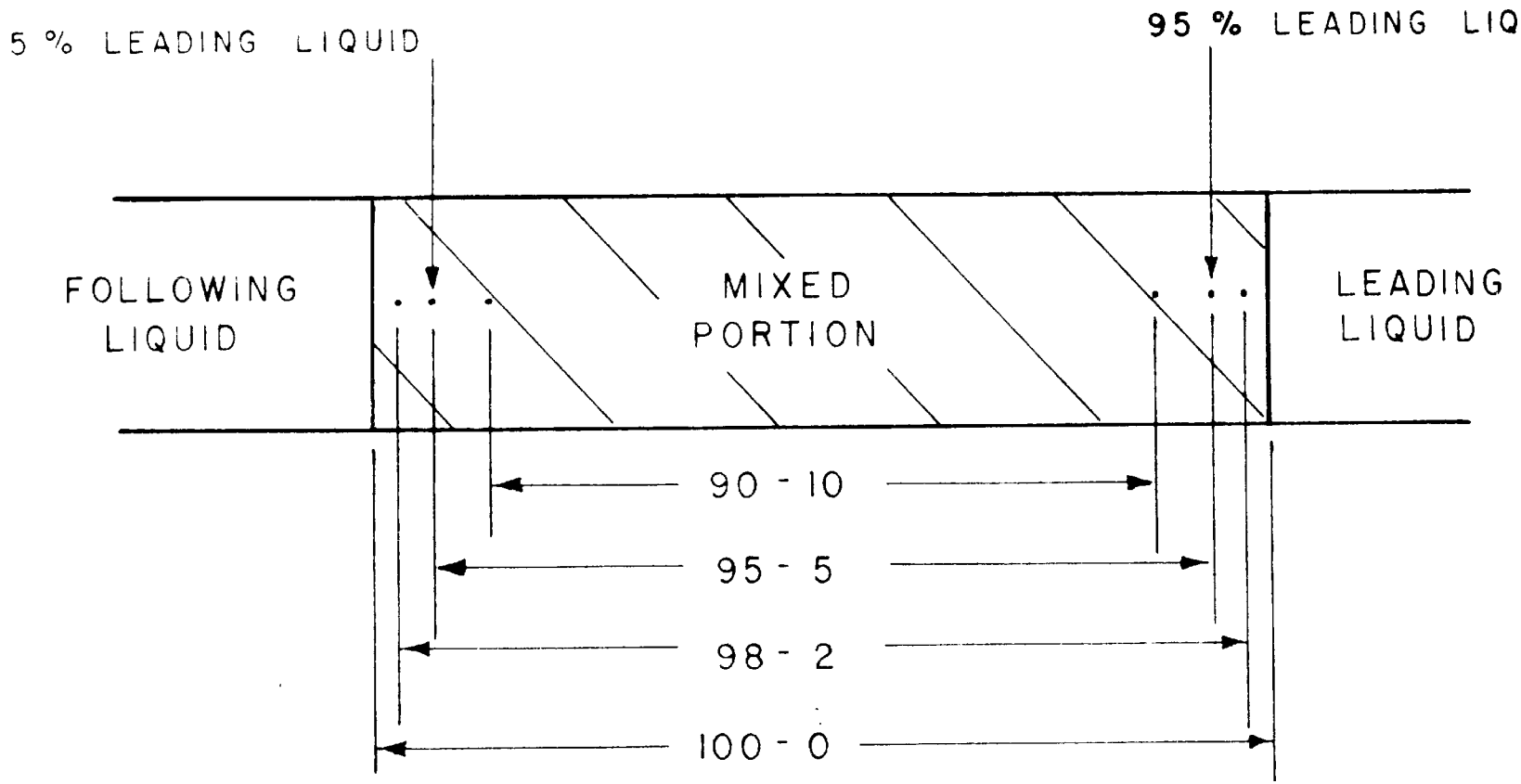
The original experimental data of contamination consist of the oscillograms for each run. The readings of these oscillograms are tabulated in Tables I, II, and III.

The oscillograms afford data as to the relative position of the "theoretical interface" and the "mixed portion."

The position of this "theoretical interface" is the position of a hypothetical particle of liquid which started at the original interface between the liquids, and moved along the pipe at the average velocity of the two streams. Experimentally, the three-way valve determines the original interface separating the two streams. Both streams have the same average velocity due to the action of the positive displacement pump.

The "mixed portion" is that quantity of liquid in the pipe which contains some mixture of the two liquids in successive flow. The "90-10 mixed portion" is that volume of mixture measured as it flows past the analytical point and bounded by the compositions indicated. Stated differently, the "90-10 mixed portion" is that quantity of liquid flowing past the analytical point during the time interval in which the composition of the mixture changed from 90 percent of leading liquid to 10 percent of leading liquid. Figure 10 is a pictorial description of the definition of mixed portion.

Measurements on the oscillograms were made to determine the relative position of the theoretical interface and the 100-0 mixed portion. Results of these measurements are reported in Tables IV, V, and VI, and lead to the following conclusions:



DEFINITON OF "MIXED PORTION"

FIGURE 10

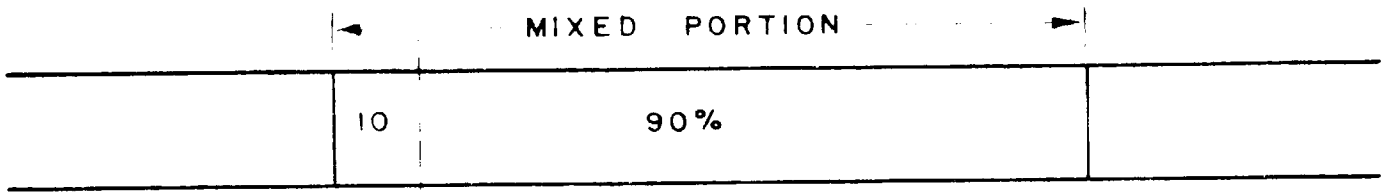
(1) When there are no differences in properties between the two liquids in successive flow, about 90 to 100% of the 100–0 mixed portion lies in advance of the theoretical interface. This is also the case when the low-viscosity liquid leads in all runs with liquids having a difference in viscosity. The same is true when the low-density liquid leads in all runs with liquids having a difference in density.

(2) When the two liquids have a difference in viscosity, and the high-viscosity liquid is the leading liquid, about 30 to 100% (average 68%) of the 100–0 mixed portion lies in advance of the theoretical interface.

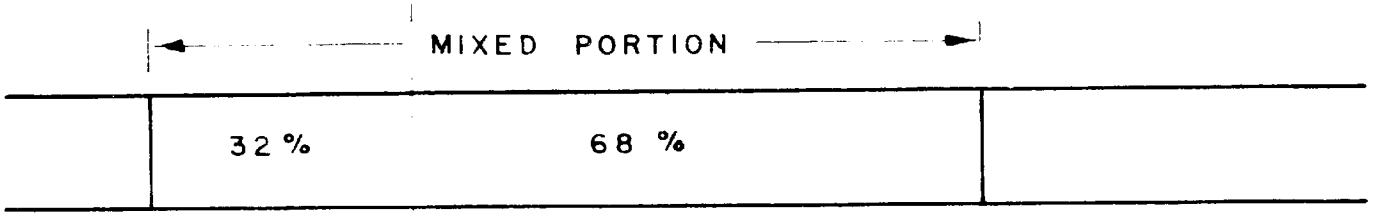
(3) When the two liquids have a difference in density, and the high-density liquid is the leading liquid, about 30 to 100% (average 58%) of the 100–0 mixed portion lies in advance of the theoretical interface.

These observations are summarized in Figure 11.

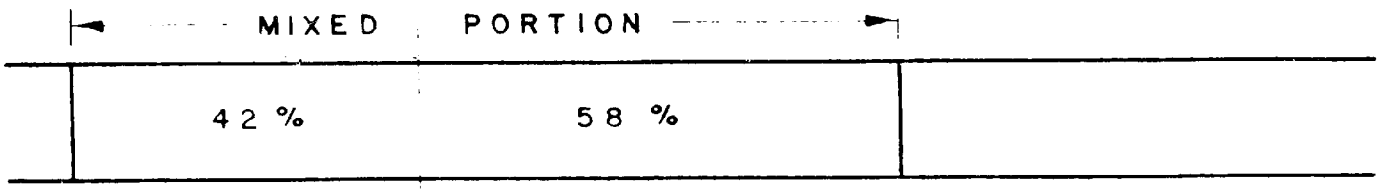
These data are quite inaccurate since we are dealing with the 100–0 mixed portion, which is very difficult to measure. They are included primarily to show the trend for the relative position of the mixed portion and the theoretical interface in the different cases of successive flow.



CASE I. NO DIFFERENCES IN PROPERTIES, OR LOW DENSITY OR LOW VISCOSITY LIQUID IS LEADING



CASE II. DIFFERENCE IN VISCOSITY, HIGH-VISCOSITY LIQUID LEADING



CASE III. DIFFERENCE IN DENSITY, HIGH-DENSITY LIQUID LEADING

THEORETICAL INTERFACE POSITION

FIGURE 11

POSITION OF MIXED PORTION RELATIVE TO THE POSITION OF THE THEORETICAL INTERFACE

POSITION OF THE 100 - 0 MIXED PORTION RELATIVE

TO THE THEORETICAL INTERFACE

TABLE IV

NO DIFFERENCES IN PROPERTIES

A. System : Water - Dyed Water

Run Number	Reynolds Number	Percentage of 100-0 Mixed Portion Lying in Advance of the Theoretical Interface	
		From Individual Runs	Computed from Figure 13
53	9650	100	100
152	9930	75	63
148	12,890	69	64
45	14,100	100	89
52	16,700	91	91
39	31,500	100	100
57	36,100	100	100
47	46,500	100	100
		92 average	88

Overall average is 90 %

TABLE IV (Cont'd.)

B. System : Benzol - Dyed Benzol

Run Number	Reynolds Number	Percentage of 100-0 Mixed Portion Lying in Advance of the Theoretical Interface
154	35,600	100
155	35,600	100
159	65,100	62
	average	87

C. System : T E G - Dyed T E G *

Run Number	Reynolds Number	Percentage of 100-0 Mixed Portion Lying in Advance of the Theoretical Interface
135	21,700	77
136	22,500	100
137	19,800	87
	average	88

* T E G means "Triethylene Glycol" (25 wt. %).

POSITION OF THE 100 - C MIXED PORTION RELATIVE TO THE THEORETICAL INTERFACE

TABLE V

DIFFERENCES IN VISCOSITY

A. High-Viscosity Liquid Leading

Run Number	Reynolds Numbers		Percentage of 100-C Mixed Portion Lying in Advance of the Theoretical Interface
	Leading	Following	
74	3,990	38,700	46
76	3,990	38,700	59
78	4,100	40,100	77
84	4,780	36,800	37
86	4,900	38,300	100
88	6,600	40,600	100
90	5,900	36,600	30
92	4,890	30,700	64
98	9,560	35,200	100
104	3,260	42,300	60
106	3,260	42,300	62
108	2,600	33,800	40
110	2,600	33,800	53
122	30,000	44,100	77
124	27,800	40,400	75
125	25,800	37,200	66
169	7,450	19,600	99
193	7,850	23,600	76
197	11,920	35,900	75
		average	68

TABLE V (Cont'd.)

B. Low-Viscosity Liquid Leading

Run Number	Reynolds Numbers		Percentage of 100-C Mixed Portion Lying in Advance of the Theoretical Interface
	Leading	Following	
75	39,100	3,990	100
79	32,800	4,400	76
85	38,300	4,900	100
89	36,600	5,900	79
91	30,300	4,890	100
97	35,200	9,560	100
99	26,100	7,080	100
101	22,100	6,010	100
105	42,300	3,260	100
107	33,800	2,600	100
119	48,200	33,100	100
121	44,500	30,000	100
123	40,400	27,800	100
168	19,600	7,450	100
192	23,600	7,850	51
196	35,900	11,920	70
		average	92

POSITION OF THE 100 - 0 MIXED PORTION RELATIVE TO THE THEORETICAL INTERFACE

TABLE VI

DIFFERENCES IN DENSITY

A. High-Density Liquid Leading

Run Number	Reynolds Numbers		Percentage of the 100-0 Mixed Portion Lying in Advance of the Theoretical Interface
	Leading	Following	
70	23,300	19,600	63
112	41,100	38,100	47
114	36,200	33,600	49
116	31,000	28,600	54
118	18,200	16,600	50
128	32,900	28,600	42
132	28,000	23,600	27
140	44,300	43,300	31
142	41,900	40,300	30
144	39,600	38,100	29
146	36,500	35,100	29
178	42,200	40,400	100
180	39,800	38,200	100
182	36,700	35,200	100
200	22,400	19,600	59
202	28,100	24,500	60
204	31,300	27,100	50
		average	58

TABLE VI (Cont'd.)

B. Low-Density Liquid Leading

Run Number	Reynolds Numbers		Percentage of the 100-0 Mixed Portion Lying in Advance of the Theoretical Interface
	Leading	Following	
69	24,100	28,700	100
73	24,900	29,600	93
113	33,600	36,200	86
115	28,600	31,000	84
117	16,600	18,200	100
127	28,600	32,900	47
129	26,900	31,000	100
131	23,600	28,000	100
139	43,300	44,300	78
141	40,300	41,900	100
143	38,100	39,600	74
145	35,100	36,500	79
179	40,400	42,200	95
183	35,200	36,700	100
201	19,600	22,400	100
203	24,500	28,100	100
		average	90

CALCULATED RESULTS AND CONCLUSIONS

The calculated data are presented in tabular form (Tables VII, VIII, and IX), and in graphical form in Figures 12, 13, 14, and 15.

Table VII - A lists the contamination data for 27 runs on the water - dyed water system. Contamination is expressed both in percentage of total pipe volume and in gallons for the four mixed portions indicated. Tables VII - B and VII - C report the same class of data for the benzol - dyed benzol system and for the T E G - dyed T E G system. (T E G refers to "triethylene glycol" solution of 25 wt. percent).

Table VIII gives the data on contamination between liquids of different viscosity. The densities are not quite the same, but differ from each other by only a few percent.

Table IX lists contamination data for liquids having a difference in density. In all runs reported in this table, the viscosities of the two streams in successive flow were the same. This was accomplished by cooling the liquid of lower density so that its viscosity was the same value as that of the higher density stream.

Figure 12 is a plot of mixed portion versus reciprocal Reynolds Number for the runs listed in Table VII - A for the water - dyed water system. The data are represented reasonably well by a straight line drawn through the experimental data points for each mixed portion. The straight lines for these four mixed portions converge to a point at a value of reciprocal Reynolds Number equal to -0.00045, as indicated on the graph of Figure 13.

TABLE VII

CONTAMINATION DATA FOR LIQUIDS WITH NO DIFFERENCES IN PROPERTIES

A. SYSTEM : WATER - DYED WATER

Run No.	Average Velocity, ft/sec	Reynolds Number	Mixed Portion, % of Pipe Volume (pipe vol. - 6.84 gallons)				Gallons of Contamination			
			100-0	98-2	95-5	90-10	100-0	98-2	95-5	90-10
153*	1.20	7,420	19.52	13.12	10.38	7.75	1.340	0.896	0.709	0.530
53	1.24	9,650	10.52	8.71	6.96	5.36	0.720	0.595	0.476	0.366
151	1.62	9,890	11.41	8.85	7.13	5.40	0.780	0.605	0.487	0.369
152*	1.62	9,930	11.90	8.72	7.17	5.57	0.813	0.596	0.490	0.381
149	1.80	10,920	17.14	11.68	8.05	5.74	1.172	0.730	0.550	0.392
150*	1.80	10,990	18.11	10.58	7.78	5.80	1.239	0.722	0.532	0.397
148*	2.13	12,890	11.18	9.06	7.25	5.59	0.763	0.620	0.495	0.382
45	1.82	14,100	9.64	8.12	6.74	5.12	0.658	0.555	0.460	0.350
55*	1.96	15,200	13.90	9.07	6.98	5.32	0.950	0.6200	0.477	0.364
36*	2.04	15,800	10.64	9.15	6.41	4.90	0.728	0.625	0.438	0.335
52*	2.15	16,700	10.82	8.22	6.53	5.00	0.740	0.562	0.446	0.342

*dyed liquid leading

TABLE VII (Continued)

Run No.	Average Velocity, ft/sec	Reynolds Number	Mixed Portion, % of Pipe Volume (pipe vol. - 6.84 gallons)				Gallons of Contamination			
			100-0	98-2	95-5	90-10	100-0	98-2	95-5	90-10
44*	2.62	19,700	9.05	7.68	6.37	4.70	0.619	0.525	0.425	0.321
37	2.64	20,500	10.11	7.15	6.07	4.71	0.692	0.488	0.415	0.322
51	2.76	21,400	8.64	7.17	5.86	4.54	0.590	0.490	0.401	0.310
50*	3.56	27,600	8.55	6.71	5.43	4.18	0.584	0.459	0.371	0.286
31	3.62	27,600	7.66	6.29	5.30	4.15	0.524	0.430	0.362	0.283
38	3.60	28,000	9.66	6.88	5.52	4.28	0.661	0.470	0.377	0.293
18	4.10	29,500	7.84	6.36	5.25	4.16	0.535	0.435	0.359	0.284
39	4.07	31,500	7.72	5.98	5.05	4.06	0.527	0.408	0.345	0.278
49	4.27	33,000	7.39	5.76	5.08	3.96	0.505	0.394	0.347	0.270
57	4.65	36,100	6.80	5.98	4.92	3.84	0.465	0.408	0.336	0.262
48	5.02	38,900	7.61	6.15	4.90	3.92	0.520	0.420	0.335	0.268
19	5.10	39,300	7.61	5.80	4.80	3.86	0.520	0.396	0.328	0.264
41	5.55	42,800	7.86	6.27	4.74	3.86	0.537	0.428	0.324	0.264
20	5.84	44,900	7.13	5.97	4.81	3.78	0.487	0.408	0.329	0.258



TABLE VII (Continued)

Run No.	Average Velocity, ft/sec	Reynolds Number	Mixed Portion, % of Pipe Volume (pipe vol. - 6.84 gallons)				Gallons of Contamination			
			100-0	98-2	95-5	90-10	100-0	98-2	95-5	90-10
47	6.00	46,500	6.78	5.68	4.68	3.80	0.463	0.388	0.320	0.260
29	6.37	47,700	8.25	6.10	4.81	3.82	0.564	0.416	0.329	0.261
			B. SYSTEM : BENZOL - DYED BENZOL							
154	3.32	35,600	10.9	6.10	4.95	3.92	0.744	0.417	0.338	0.268
155	3.32	35,600	8.92	6.80	5.18	4.14	0.610	0.464	0.354	0.283
156	4.92	52,700	7.45	5.62	4.66	3.66	0.510	0.384	0.318	0.250
159	6.07	65,100	10.40	6.80	4.76	3.66	0.714	0.464	0.325	0.250
			C. SYSTEM : T.E.G. - DYED T.E.G.*							
135	5.54	21,700	14.5	8.55	5.88	4.66	0.990	0.585	0.401	0.318
136	5.54	22,500	9.84	7.64	5.64	4.22	0.673	0.522	0.385	0.288
137	5.14	19,800	14.0	9.63	6.63	4.90	0.956	0.658	0.453	0.335

*"T.E.G." means "Triethylene Glycol" (25 wt.%).



TABLE VIII

CONTAMINATION DATA FOR LIQUIDS OF DIFFERENT VISCOSITY

Run No.	Leading Liquid	Average Velocity, ft/sec	Viscosities Cpe. A	Viscosities Cpe. B	Densities gm/cc A	Densities gm/cc B	Reynolds Numbers A	Reynolds Numbers B	Gallons of Contamination 100-0	98-2	95-5	90-10
74	A*	5.35	11.4	1.07	1.10	1.00	3990	38,670	0.66	0.49	0.42	0.32
75	B	5.35	11.4	1.06	1.10	1.00	3990	39,150	0.66	0.35	0.22	0.15
76	A*	5.35	11.4	1.06	1.10	1.00	3990	39,150	1.17	0.80	0.60	0.42
77	B	5.49	11.4	1.06	1.10	1.00	4100	40,100	0.80	0.41	0.26	0.14
78	A*	5.49	11.4	1.06	1.10	1.00	4100	40,100	1.21	0.88	0.62	0.45
79	A	4.96	1.17	9.5	1.00	1.096	32800	4,400	0.68	0.52	0.40	0.27
80	B*	4.96	1.16	9.5	1.00	1.096	33200	4,400	1.04	0.77	0.58	0.42
81	A	5.21	1.16	9.5	1.00	1.096	34900	4,650	0.56	0.37	0.30	0.22
82	B*	5.21	1.16	9.5	1.00	1.096	34900	4,650	1.03	0.78	0.58	0.40
83	A	5.35	1.16	9.5	1.00	1.096	36800	4,780	0.76	0.46	0.32	0.20
84	B*	5.35	1.13	9.5	1.00	1.096	36800	4,780	0.86	0.70	0.57	0.42
85	A	5.49	1.11	9.5	1.00	1.096	38300	4,900	0.58	0.38	0.30	0.22

*indicates liquid contained dye

TABLE VIII (Continued)

Run No.	Leading Liquid	Average Velocity, ft/sec	Viscosities centipoise A	Viscosities centipoise B	Densities gm/cc A	Densities gm/cc B	Reynolds Numbers A	Reynolds Numbers B	Gallons of Contamination 100-0	98-2	95-5	90-10
86	B*	5.49	1.11	9.5	1.00	1.096	38,300	4,900	0.82	0.58	0.47	0.35
87	A	5.49	1.04	7.1	1.0	1.09	40,600	6,600	0.76	0.50	0.39	0.27
88	B*	5.49	1.04	7.1	1.0	1.09	40,600	6,600	0.72	0.53	0.43	0.32
89	A	4.95	1.04	7.1	1.0	1.09	36,600	5,900	0.97	0.62	0.42	0.27
90	B*	4.95	1.04	7.1	1.0	1.09	36,600	5,900	0.74	0.60	0.46	0.37
91	A	4.09	1.04	7.1	1.0	1.09	30,500	4,890	0.42	0.34	0.28	0.21
92	B*	4.09	1.04	7.1	1.0	1.09	30,500	4,890	0.84	0.63	0.50	0.37
93	A	3.43	1.04	7.1	1.0	1.09	25,700	4,060	0.40	0.34	0.27	0.21
94	B*	3.43	1.04	7.1	1.0	1.09	25,700	4,060	0.77	0.60	0.48	0.37
97	A	4.74	1.04	4.1	1.00	1.07	35,200	9,560	0.69	0.36	0.25	0.19
98	B*	4.74	1.04	4.1	1.00	1.07	35,200	9,560	0.80	0.54	0.41	0.34
99	A	3.51	1.04	4.1	1.00	1.07	26,100	7,080	0.58	0.36	0.29	0.22
100	B*	3.51	1.04	4.1	1.00	1.07	26,100	7,080	0.73	0.52	0.42	0.32
101	A	2.97	1.04	4.1	1.00	1.07	22,100	6,015	0.66	0.34	0.26	0.20

TABLE VIII (Continued)

Run No.	Leading Liquid	Average Velocity, ft/sec	Viscosities centipoise A	Viscosities centipoise B	Densities gm/cc A	Densities gm/cc B	Reynolds Numbers A	Reynolds Numbers B	Gallons of Contamination 100-0	98-2	95-5	90-10
102	B*	2.97	1.04	4.1	1.00	1.07	22,100	6,015	1.02	0.64	0.49	0.32
103	A	5.94	1.09	15.6	1.00	1.106	42,300	3,260	0.73	0.38	0.20	0.16
104	B*	5.94	1.09	15.6	1.00	1.106	42,300	3,260	0.68	0.50	0.40	0.31
105	A	5.94	1.09	15.6	1.00	1.106	42,300	3,260	0.38	0.27	0.22	0.17
106	B*	5.94	1.09	15.6	1.00	1.106	42,300	3,260	1.09	0.65	0.46	0.32
107	A	4.75	1.09	15.6	1.00	1.106	42,300	2,605	0.36	0.25	0.18	0.14
108	B*	4.75	1.09	15.6	1.00	1.106	33,800	2,605	0.65	0.53	0.44	0.34
109	A	4.75	1.09	15.6	1.00	1.106	33,800	2,605	0.39	0.28	0.21	0.16
110	B*	4.75	1.09	15.6	1.00	1.106	33,800	2,605	0.86	0.71	0.56	0.37
119	A	6.02	0.97	1.43	1.00	1.00	48,200	33,100	0.68	0.46	0.34	0.25
120	B*	6.02	0.97	1.43	1.00	1.00	48,500	32,606	0.70	0.47	0.37	0.28
121	A	5.61	0.97	1.43	1.00	1.00	44,500	30,000	0.66	0.46	0.35	0.26
122	B*	5.61	0.97	1.43	1.00	1.00	44,100	30,000	0.67	0.48	0.37	0.28
123	A	5.13	0.97	1.43	1.00	1.00	40,400	27,800	0.69	0.45	0.35	0.27

TABLE VIII (Continued)

Run No.	Leading Liquid	Average Velocity, ft/sec	Viscosities centipoise A	Viscosities centipoise B	Densities gm/cc A	Densities gm/cc B	Reynolds Numbers A	Reynolds Numbers B	Gallons of Contamination 100-0	98-2	95-5	90-10
124	B*	5.13	0.97	1.43	1.00	1.00	40,400	27,800	0.71	0.50	0.39	0.30
125	B*	4.68	0.97	1.43	1.00	1.00	37,200	25,800	0.75	0.53	0.40	0.29
168	A	2.62	1.06	2.75	1.025	1.028	19,600	7,450	0.82	0.57	0.39	0.27
169	B*	2.62	1.06	2.75	1.025	1.028	19,600	7,450	0.96	0.66	0.56	0.41
170	A	3.54	1.06	2.75	1.025	1.028	26,500	10,500	0.99	0.52	0.38	0.26
192	B*	2.96	3.10	0.97	1.06	1.00	7,850	23,600	0.89	0.56	0.40	0.25
193	A	2.96	3.10	0.97	1.06	1.00	7,850	23,600	1.23	0.88	0.67	0.46
196	B*	4.50	3.10	0.97	1.06	1.00	11,900	35,900	0.81	0.53	0.37	0.23
197	A	4.50	3.10	0.97	1.06	1.00	11,900	35,900	1.35	0.89	0.65	0.45

TABLE IX

CONTAMINATION DATA FOR LIQUIDS OF DIFFERENT DENSITY

Run No.	Leading Liquid	Average Velocity, ft/sec	Viscosities centipoise		Densities gm/cc		Reynolds Numbers		Gallons of Contamination			
			A	B	A	B	A	B	100-0	98-2	95-5	90-10
67	A	5.03	1.328	1.215	1.00	1.079	29,200	32,200	0.83	0.67	0.54	0.36
69	A	4.45	1.432	1.215	1.00	1.079	24,100	28,600	0.56	0.39	0.31	0.25
70	B*	3.62	1.432	1.215	1.00	1.079	19,600	23,300	0.90	0.74	0.59	0.40
71	A	2.61	1.432	1.215	1.00	1.079	14,100	16,800	0.56	0.47	0.39	0.31
72	B*	3.97	1.432	1.215	1.00	1.079	21,500	25,600	0.91	0.66	0.51	0.35
73	A	4.60	1.432	1.215	1.00	1.079	24,900	29,600	0.59	0.42	0.35	0.27
111	A	6.00	1.219	1.215	1.00	1.079	38,000	41,000	0.51	0.41	0.33	0.26
112	B*	6.00	1.219	1.215	1.00	1.079	38,000	41,000	1.62	0.94	0.62	0.42
113	A	5.29	1.219	1.215	1.00	1.079	33,600	36,200	0.80	0.56	0.42	0.30
114	B*	5.29	1.219	1.215	1.00	1.079	33,600	36,200	1.25	0.81	0.61	0.41
115	A	4.54	1.219	1.215	1.00	1.079	28,600	31,000	0.83	0.62	0.47	0.30
116	B*	4.54	1.219	1.215	1.00	1.079	28,600	31,000	1.34	0.90	0.62	0.43

*indicates liquid contained dye

TABLE IX (Continued)

Run No.	Leading Liquid	Average Velocity, ft/sec	Viscosities centipoise A	Viscosities centipoise B	Densities gm/cc A	Densities gm/cc B	Reynolds Numbers A	Reynolds Numbers B	Gallons of Contamination 100-0	98-2	95-5	90-10
117	A	2.66	1.219	1.215	1.00	1.079	16,600	18,200	0.70	0.50	0.40	0.31
118	B*	2.66	1.219	1.215	1.00	1.079	16,600	18,200	1.26	0.94	0.68	0.46
126	B*	6.02	1.65	1.64	1.00	1.159	28,200	32,900	2.08	1.44	1.02	0.63
127	A	6.02	1.63	1.64	1.00	1.159	28,600	32,900	1.05	0.84	0.61	0.33
128	B*	6.02	1.63	1.64	1.00	1.159	28,600	32,900	2.23	1.28	0.83	0.52
129	A	5.67	1.63	1.64	1.00	1.159	26,900	31,000	0.59	0.40	0.32	0.24
130	B*	5.67	1.68	1.64	1.00	1.159	26,100	31,000	1.61	1.19	0.82	0.59
131	A	5.12	1.68	1.64	1.00	1.159	23,600	28,000	0.56	0.37	0.30	0.23
132	B*	5.12	1.68	1.64	1.00	1.159	23,600	28,000	2.67	1.53	0.98	0.58
139	A	6.10	1.103	1.105	1.00	1.041	43,300	44,400	0.94	0.73	0.51	0.30
140	B*	6.10	1.103	1.105	1.00	1.041	43,300	44,400	2.20	1.22	0.81	0.44
141	A	5.76	1.103	1.105	1.00	1.041	40,300	41,900	0.68	0.44	0.33	0.27
142	B*	5.76	1.103	1.105	1.00	1.041	40,300	41,900	1.86	1.10	0.66	0.41
143	A	5.45	1.103	1.105	1.00	1.041	38,100	39,600	0.92	0.66	0.50	0.31

TABLE IX (Continued)

Run No.	Leading Liquid	Average Velocity, ft/sec	Viscosities centipoise A	Viscosities centipoise B	Densities gm/cc A	Densities gm/cc B	Reynolds Numbers A	Reynolds Numbers B	Gallons of Contamination 100-0	98-2	95-5	90-10
144	B*	5.45	1.103	1.105	1.00	1.041	38,100	39,600	2.18	1.00	0.56	0.40
145	A	5.02	1.103	1.105	1.00	1.041	35,100	36,500	0.86	0.57	0.42	0.30
146	B*	5.02	1.103	1.105	1.00	1.041	35,100	36,500	1.98	1.07	0.62	0.41
160	A	2.06	0.582	0.580	0.866	1.470	23,600	40,200	0.62	0.50	0.42	0.34
161	B*	2.06	0.582	0.580	0.866	1.470	23,600	40,200	0.76	0.64	0.55	0.42
162	A	3.70	0.582	0.580	0.866	1.470	42,500	72,400	0.70	0.58	0.48	0.37
163	B*	3.70	0.582	0.580	0.866	1.470	42,500	72,400	0.68	0.54	0.44	0.35
165	A	2.60	0.595	0.570	0.872	1.340	31,600	50,700	0.65	0.48	0.40	0.33
167	B*	5.14	0.585	0.578	0.890	1.340	60,400	92,000	0.94	0.59	0.45	0.34
176	A	5.76	1.103	1.100	1.041	1.00	42,200	40,400	0.56	0.44	0.35	0.28
179	B*	5.76	1.103	1.100	1.041	1.00	42,200	40,400	0.69	0.44	0.34	0.26
180	A	5.45	1.103	1.100	1.041	1.00	39,800	38,200	0.68	0.46	0.37	0.28
181	B*	5.45	1.103	1.100	1.041	1.00	39,800	38,200	0.65	0.46	0.35	0.27
182	A	5.02	1.103	1.100	1.041	1.00	39,700	35,200	0.56	0.42	0.35	0.27
183	B*	5.02	1.103	1.100	1.041	1.00	39,700	35,200	0.67	0.45	0.35	0.27

TABLE IX (Continued)

Run No.	Leading Liquid	Average Velocity, ft/sec	Viscosities centipoise A	Viscosities centipoise B	Densities gm/cc A	Densities gm/cc B	Reynolds Numbers A	Reynolds Numbers B	Gallons of Contamination 100-0	98-2	95-5	90-10
200	A	4.09	1.63	1.62	1.159	1.00	22,400	19,600	0.89	0.66	0.53	0.42
201	B*	4.09	1.63	1.62	1.159	1.00	22,400	19,600	0.69	0.54	0.47	0.39
202	A	5.12	1.63	1.62	1.159	1.00	28,100	24,500	0.81	0.64	0.50	0.42
203	B*	5.12	1.63	1.62	1.159	1.00	28,100	24,500	0.66	0.50	0.45	0.38
204	A	5.67	1.63	1.62	1.159	1.00	31,100	27,100	0.88	0.67	0.51	0.40
205	B*	5.67	1.63	1.62	1.159	1.00	31,100	27,100	0.70	0.52	0.46	0.39

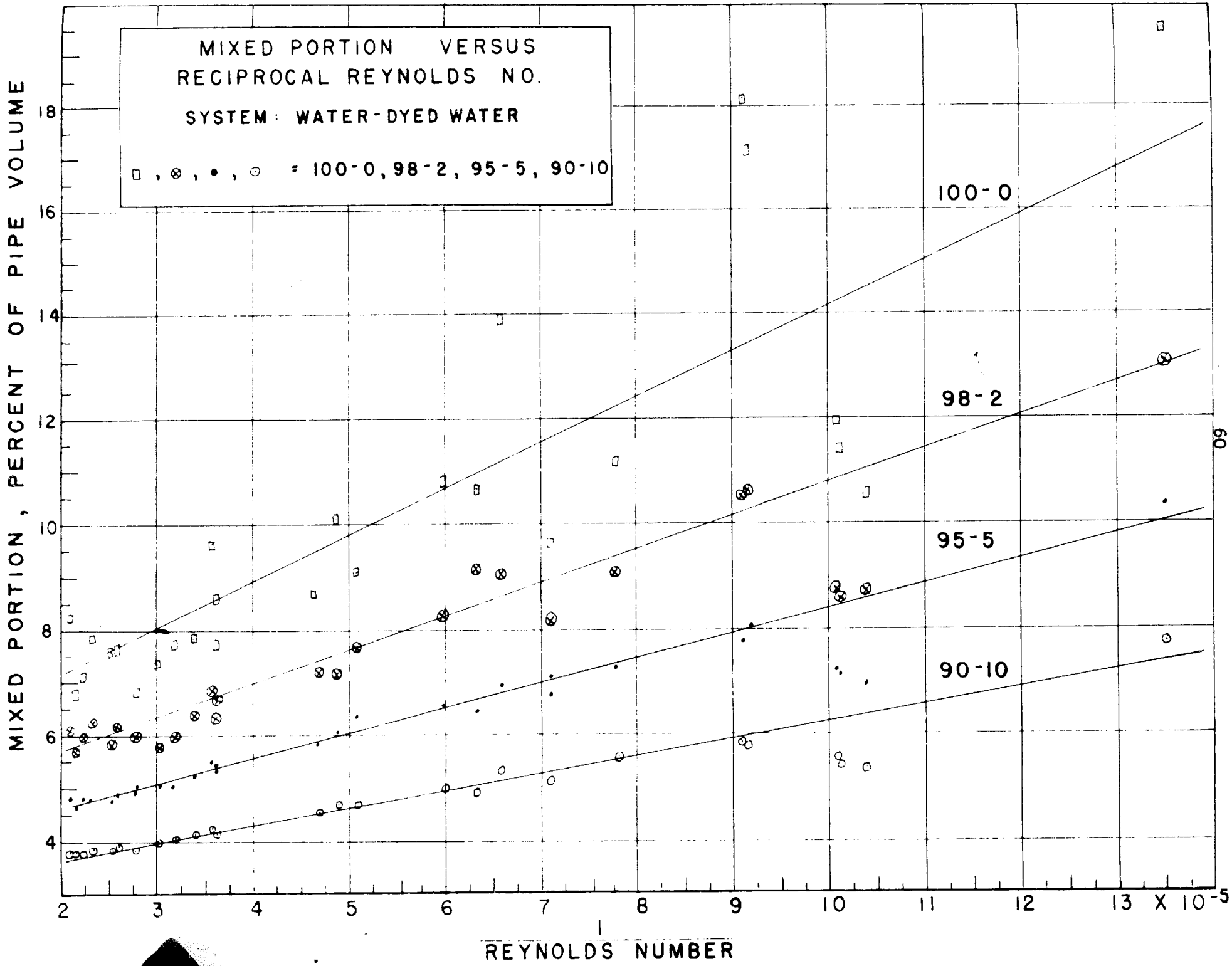

MIXED PORTION VERSUS
RECIPROCAL REYNOLDS NO.
SYSTEM: WATER-DYED WATER
□ , ⊗ , • , ○ = 100-0, 98-2, 95-5, 90-10
100-0
98-2
95-5
90-10
MIXED PORTION, PERCENT OF PIPE VOLUME
4
6
8
10
12
14
16
18
2
3
4
5
6
7
8
9
10
11
12
13 X 10⁻⁵
1
REYNOLDS NUMBER

FIGURE 12

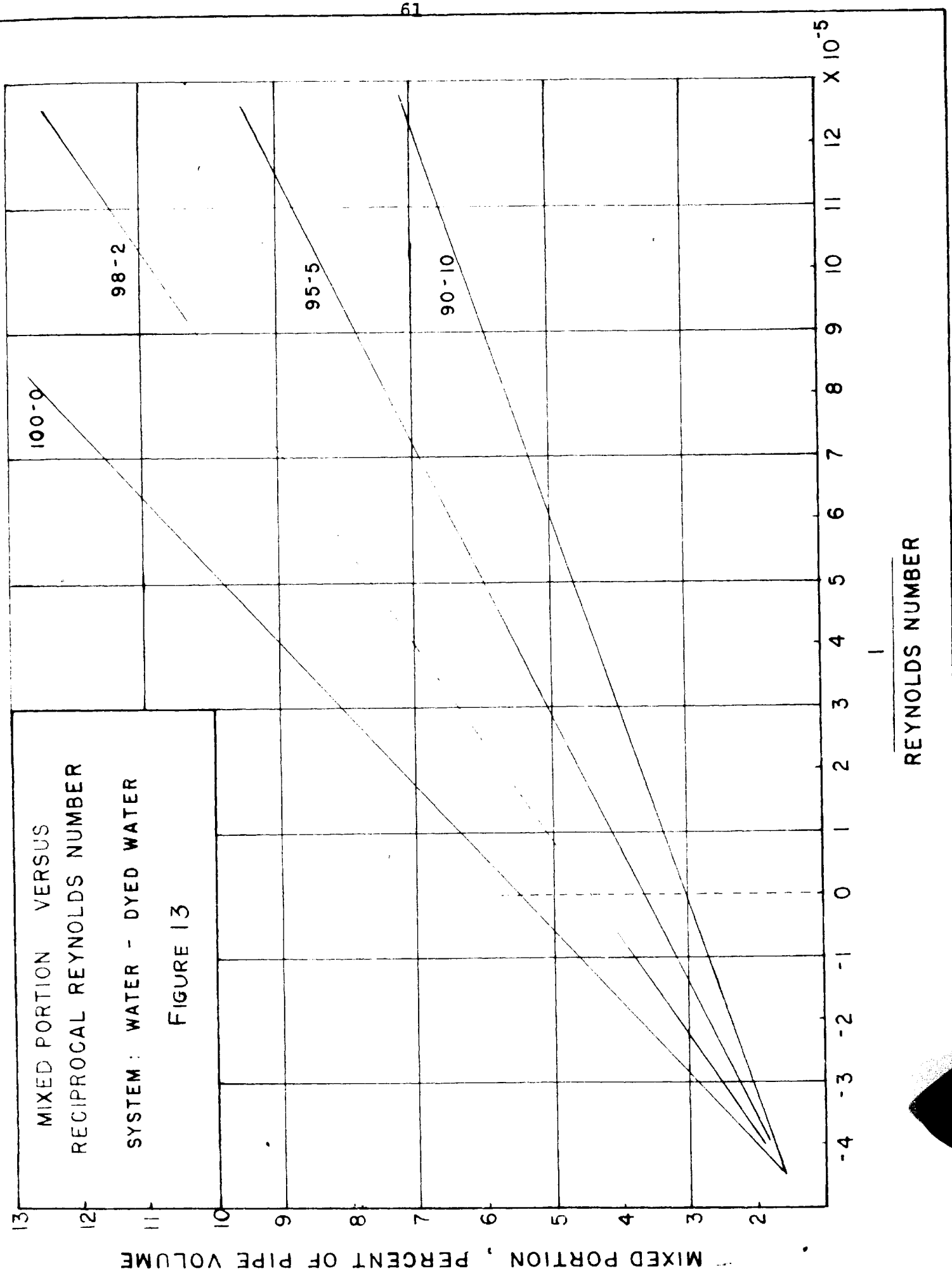

MIXED PORTION VERSUS
RECIPROCAL REYNOLDS NUMBER
SYSTEM: WATER - DYED WATER
100-0
98-2
95-5
90-10
MIXED PORTION, PERCENT OF PIPE VOLUME
1 / REYNOLDS NUMBER
X 10^-5

FIGURE 13

From the slopes and intercepts of these lines it is possible to derive the following equations for contamination:

For the 100–0 Mixed Portion

$$M = 86{,}800 \ (1/Re) + 5.45 \qquad (1)$$

For the 98– 2 Mixed Portion

$$M = 63{,}500 \ (1/Re) + 4.45 \qquad (2)$$

For the 95–5 Mixed Portion

$$M = 46{,}400 \ (1/Re) + 3.65 \qquad (3)$$

For the 90–10 Mixed Portion

$$M = 32{,}500 \ (1/Re) + 3.01 \qquad (4)$$

In these equations, "M" is the symbol of "Mixed Portion", and its units are percent of pipe volume. "Re" is the symbol used for "Reynolds Number". The values of M in percent of pipe volume are readily converted to units of volume (gallons) for the runs in this work by multiplying by 0.0684.

Figure 14 is a plot of the volume of the mixed portions versus Reynolds Number. The solid line curves are plotted from values computed from the equations (1) through (4). The experimental data points are plotted for all runs in which there were no differences in properties between the two liquids in successive flow. The four horizontal dashed lines are drawn on the plot to show the limits that each curve approaches asymptotically.

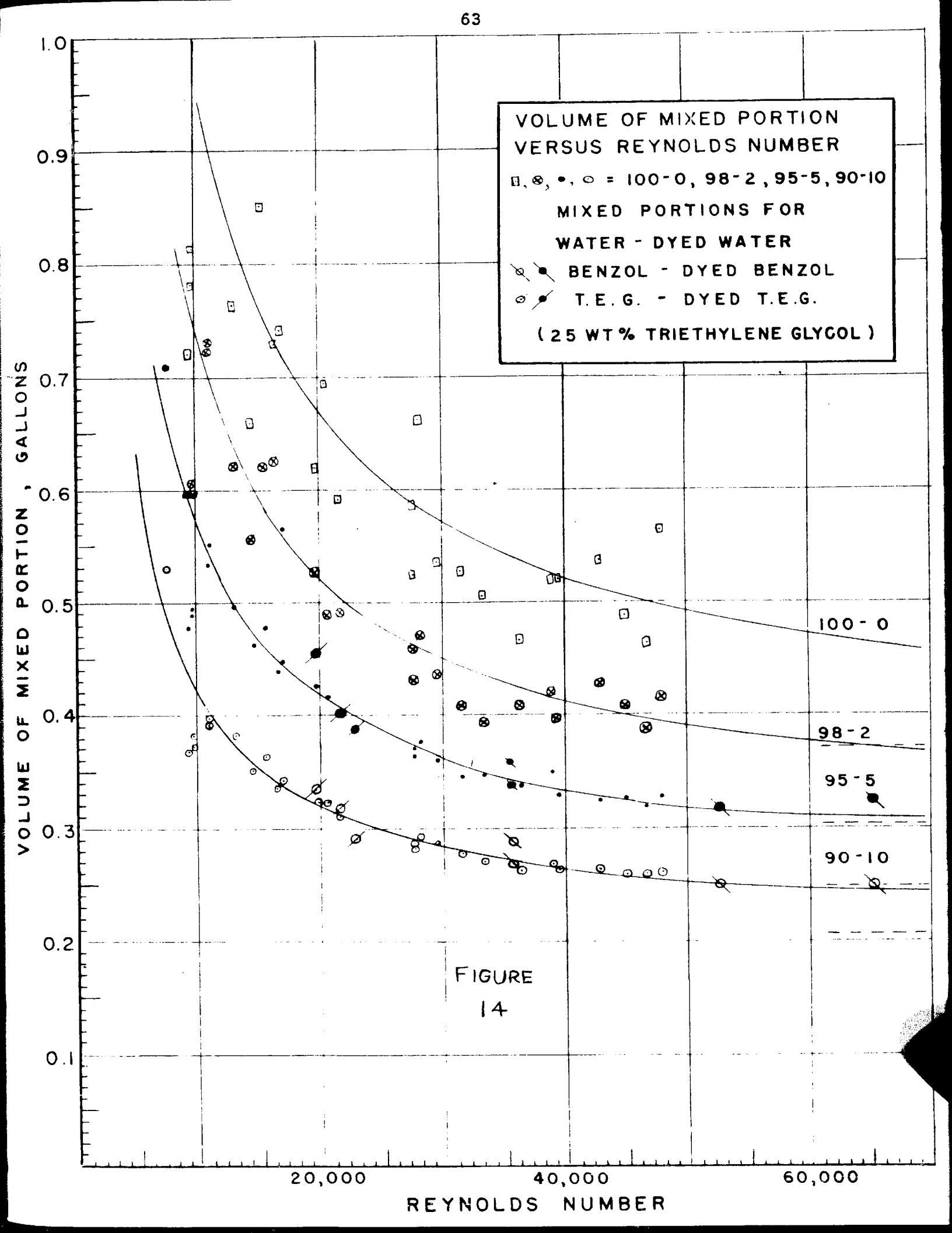

VOLUME OF MIXED PORTION VERSUS REYNOLDS NUMBER
□, ⊗, •, ○ = 100-0, 98-2, 95-5, 90-10 MIXED PORTIONS FOR WATER - DYED WATER
BENZOL - DYED BENZOL
T.E.G. - DYED T.E.G.
(25 WT% TRIETHYLENE GLYCOL)
100-0
98-2
95-5
90-10
VOLUME OF MIXED PORTION, GALLONS
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
20,000
40,000
60,000
REYNOLDS NUMBER

FIGURE 14

Figure 15 presents a graphical method for estimating the independent effect of density and viscosity on the contamination to be expected for any two dissimilar liquids in successive flow. This graph was prepared from the data on Tables VII, VIII, and IX, and is based on the Reynolds Number of the low-density or low-viscosity liquid. When this Reynolds Number is computed, the contamination for the case of identical liquids at this Reynolds Number is then determined from Figure 14. This value is multiplied by the contamination Change Factor, F, determined from Figure 15 for a given case of successive flow of two dissimilar liquids. The values plotted in Figure 15 are for the 90-10 mixed portion.

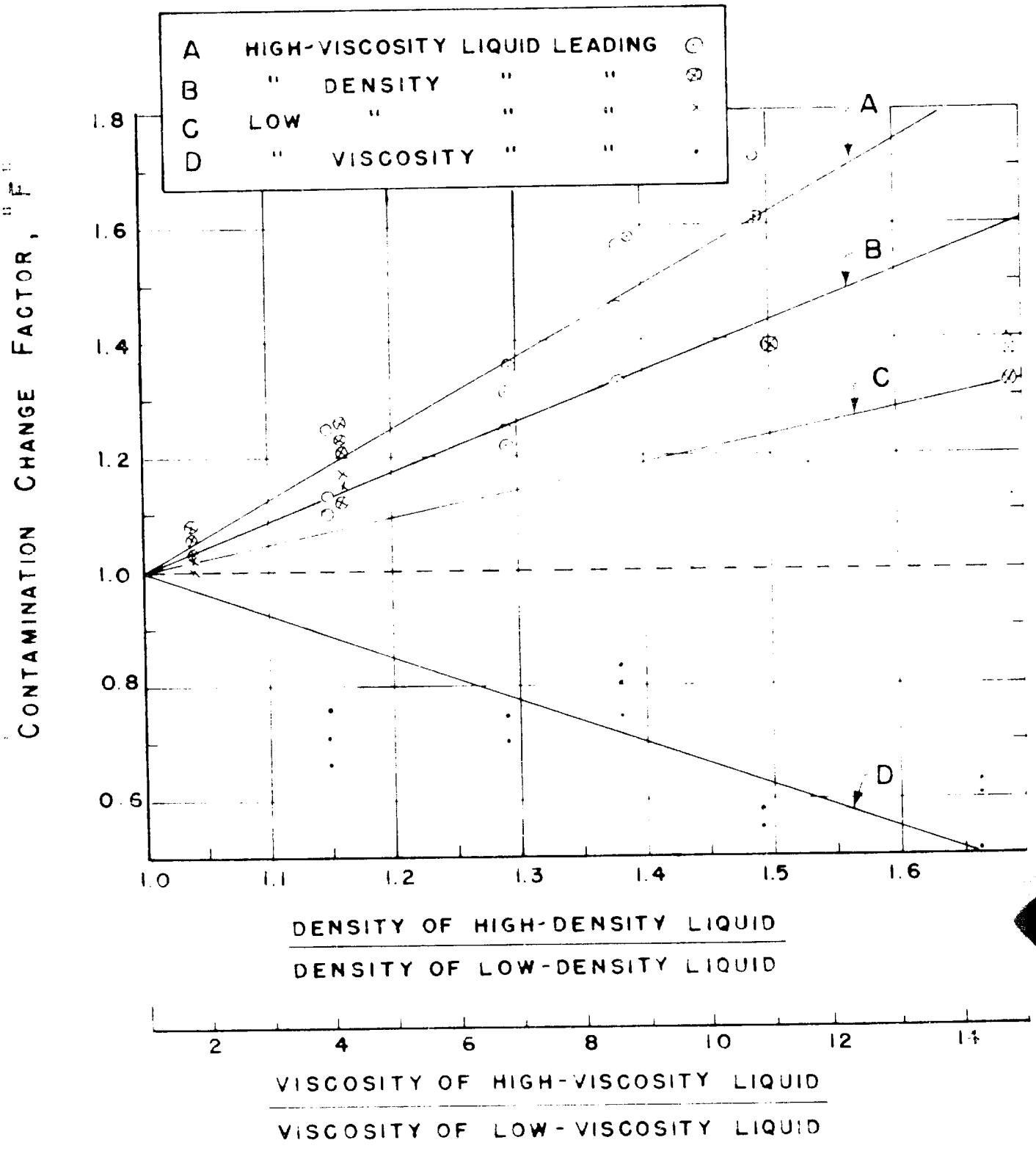
Sample Calculations

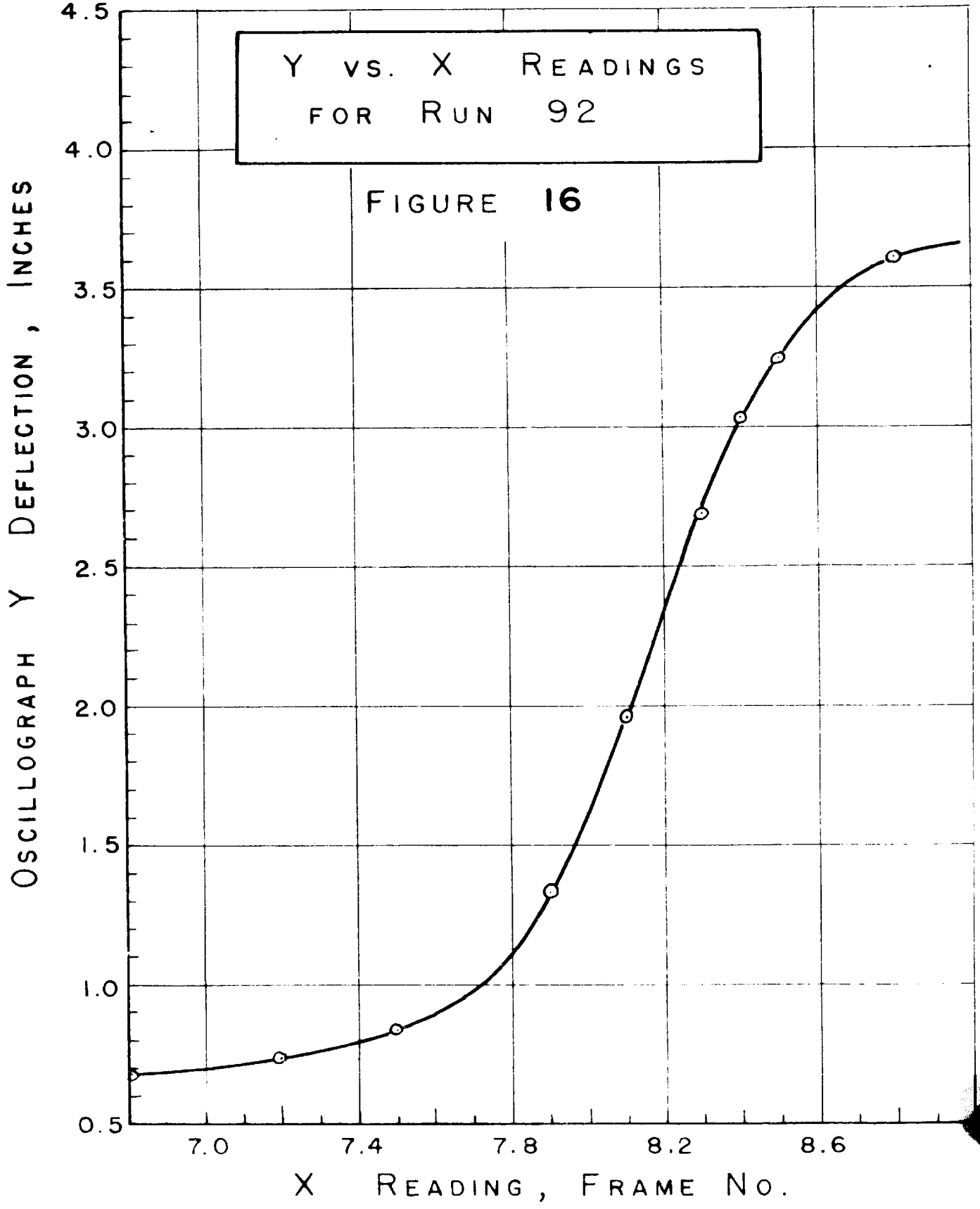
From the original experimental data contained in Tables I, II, and III, plots of Y versus X were made for each run on sheets of graph paper about 16 by 20 inches in size. A sample plot of Y versus X is shown in Figure 16. From these plots, the upper and lower limits of the Y readings are determined. From the sample shown, it may be seen that the maximum reading for the Y deflection was 3.66 inches and the minimum deflection was 0.678 inch. The minimum reading corresponds to the dyed liquid (58 wt. % triethylene glycol in this case), and the maximum reading corresponds to clear distilled water.

Since the dye used for analysis obeyed Beer's Law in all cases, a plot of Log Percent Transmittancy versus Dye Concentration results in a straight line. (Refer to the Spectral Transmittancy Curves in the Appendix). From the Spectral Transmittancy curve for Pontamine Blue AX, shown in the Appendix, it can be seen that the Y deflection on

Approximate Independent Effect of Viscosity and Density on Contamination

Figure 15




Y VS. X READINGS
FOR RUN 92
FIGURE 16
OSCILLOGRAPH Y DEFLECTION, INCHES
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
7.0
7.4
7.8
8.2
8.6
X READING, FRAME NO.

the oscillograph is directly proportional to the Log Percent Transmittancy. Hence, a sheet of semi-log graph paper, about 16 by 20 inches in size, was used to plot a straight line between the maximum and minimum values of Y deflection. A sample of this plot for Run 92 is shown in Figure 17.

The concentration of dye in a mixture corresponding to 5% of leading liquid and 95% of following liquid is easily computed by means of a material balance. For Run 92, this value was found to be 1.0 milligram per liter. The total dye concentration in one of the pure liquids forming the mixture was 20 milligrams per liter. Likewise, the dye concentration in 95% leading liquid and 5% following liquid was found to be 19.0 milligrams per liter. The corresponding Y values are seen to be 3.37 and 0.738 inches. This means that the 95–5 mixed portion could be identified as that volume of mixture passing the analytical point in the time interval during which the Y deflection on the oscillograph changed continuously from 3.37 inches to 0.738 inch.

This information makes it possible to determine the volume of the 95–5 mixed portion. From Figure 16, the value of X corresponding to 3.37 on the Y axis is seen to be 8.56. Similarly, the value of X corresponding to a Y value of 0.738 to 7.25. The change in X is 1.31 (8.56 - 7.25). This means that the distance measured along the film corresponding to the volume of the 95–5 mixed portion is 1.31 frame. The length of one frame on the film used for Run 92 was 1.492 inch. The total length corresponding to the volume of the 95–5 mixed portion. is the product of 1.492 and 1.31 which is 1.96 inch. This value, divided by the velocity with which the film is moving, gives the number

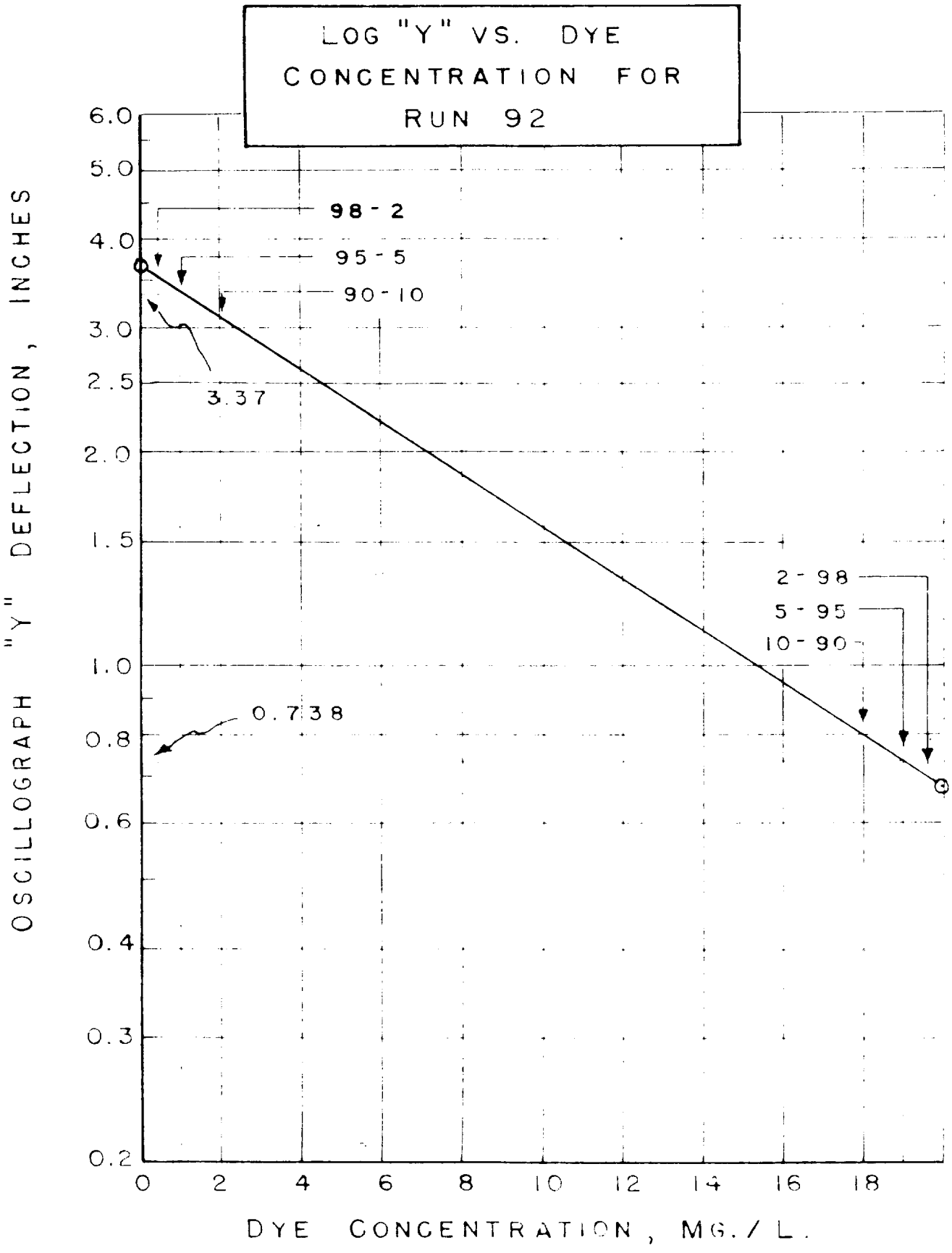

LOG "Y" VS. DYE CONCENTRATION FOR RUN 92
OSCILLOGRAPH "Y" DEFLECTION, INCHES
6.0
5.0
4.0
3.0
2.5
2.0
1.5
1.0
0.8
0.6
0.4
0.3
0.2
98 - 2
95 - 5
90 - 10
3.37
2 - 98
5 - 95
10 - 90
0.738
0
2
4
6
8
10
12
14
16
18
DYE CONCENTRATION, MG./L.

FIGURE 17

of seconds required for the analysis of the 95-5 mixed portion. The film velocity was 0.65 inch per second. Therefore, the time required for the 95-5 mixed portion to pass the analytical point was 1.96 divided by 0.65, or 3.02 seconds. This time, multiplied by the flow rate in gallons per second (0.166 for Run 92), gives the volume of the 95-5 mixed portion. This volume was 0.50 gallon in this example.

When the same type of film and camera drum are used, it is possible to calculate the gallons of contamination by the formula:

$$\text{Volume} = C \times \Delta X \times \text{Flow Rate (gal/sec.)}.$$

"C" in the example given here is a constant, obtained by dividing 1.492 by 0.65. This value is 2.296 for the Eastman Film. Values of this constant "C" are given below for the runs wherein different types of film were used.

Run Numbers	C
18, 19, and 20	2.222
29-79, 83-86	2.258
80-82, 87-205	2.296

It is possible to calculate the volumes of the 90-10, 98-2, and 100-0 mixed portions by this same procedure.

The mixed portion, expressed as a percentage of the total pipe volume, is calculated by dividing the volume of the mixed portion in gallons by the total pipe volume (6.84 gallons).

Conclusions

Instantaneous and continuous analysis of the contaminated portion between two liquids in successive, turbulent flow in a pipe can be accomplished successfully by means of photoelectric colorimetry when the two liquids have the same properties. Application of this method

to liquids of different density has the following disadvantages: (a) the results are dependent upon which liquid is used as the initial solvent for the dye, and (b) the results are dependent upon the orientation of the analytical light beam with respect to the pipe line. This is true for those cases where density currents retard intimate and homogeneous mixing of dyed liquid with clear liquid.

The volume of the contaminated portion between any two liquids having the same properties is a function of Reynolds Number for a pipe of fixed diameter and length. The equation for this relationship has the general form

$$M = A\ (1/Re) + B,$$

Where M is the volume of contamination, Re is the Reynolds Number, and A and B are constants.

For dissimilar liquids in successive, turbulent flow, the volume of the contaminated portion depends upon the order of flow. In this case the contamination will be greater when the leading liquid is either more dense or more viscous, than would occur in the reverse order of flow.

Most of the 100-0 mixed portion lies in advance of the theoretical interface; especially when there are no differences in properties between the liquids. There is a smaller proportion in advance of the theoretical interface when the high-viscosity liquid is leading, and a still smaller proportion when the high-density liquid is leading, other factors being equal.

The volume of contamination for dissimilar liquids in successive, turbulent flow is not a simple function of Reynolds Number, average Reynolds Number, or of the Reynolds Number of an equal volume blend

of the two liquids. Exact quantitative relations between all the variables involved in mixing by successive, turbulent flow must remain obscure until more complete knowledge is available on the mechanics of turbulent motion involved in this type of flow.

An empirical relationship which will serve as an approximate guide for predicting contamination in the general case of any two dissimilar liquids is given in Figure 15.

DISCUSSION OF RESULTS

A. Liquids With The Same Properties

Comparison with the data of Fowler and Brown

The results on the water-dyed water system are in reasonable agreement with the results of Fowler and Brown, as indicated by Figure 18. In nearly all cases, their data indicate a larger quantity of a specified mixed portion than would obtain at the same Reynolds Number by observations made in this investigation. Unfortunately, all of the data reported by Fowler and Brown, for a pipe having the same length to diameter ratio as used in this investigation, lie in the Reynolds Number range of 2000 to 6000. This range is bordered by the critical Reynolds Number which separates laminar from turbulent flow. This means that some of their data were taken in the range which is generally considered to be the "transition range" between laminar and turbulent flow, in which the flow conditions are difficult to reproduce. This probably accounts for the differences noted in the two investigations.

Fowler and Brown (1) also present a graph by which they extrapolate their data to predict contamination at higher Reynolds Numbers. Figure 19 is a plot of their extrapolations for the 98-2 and the 95-5 mixed portions with those obtained in this investigation. Their extrapolated values for the 98-2 mixed portion are 30 to 40% higher, and for the 95-5 mixed portion are about 25% higher than those reported here.

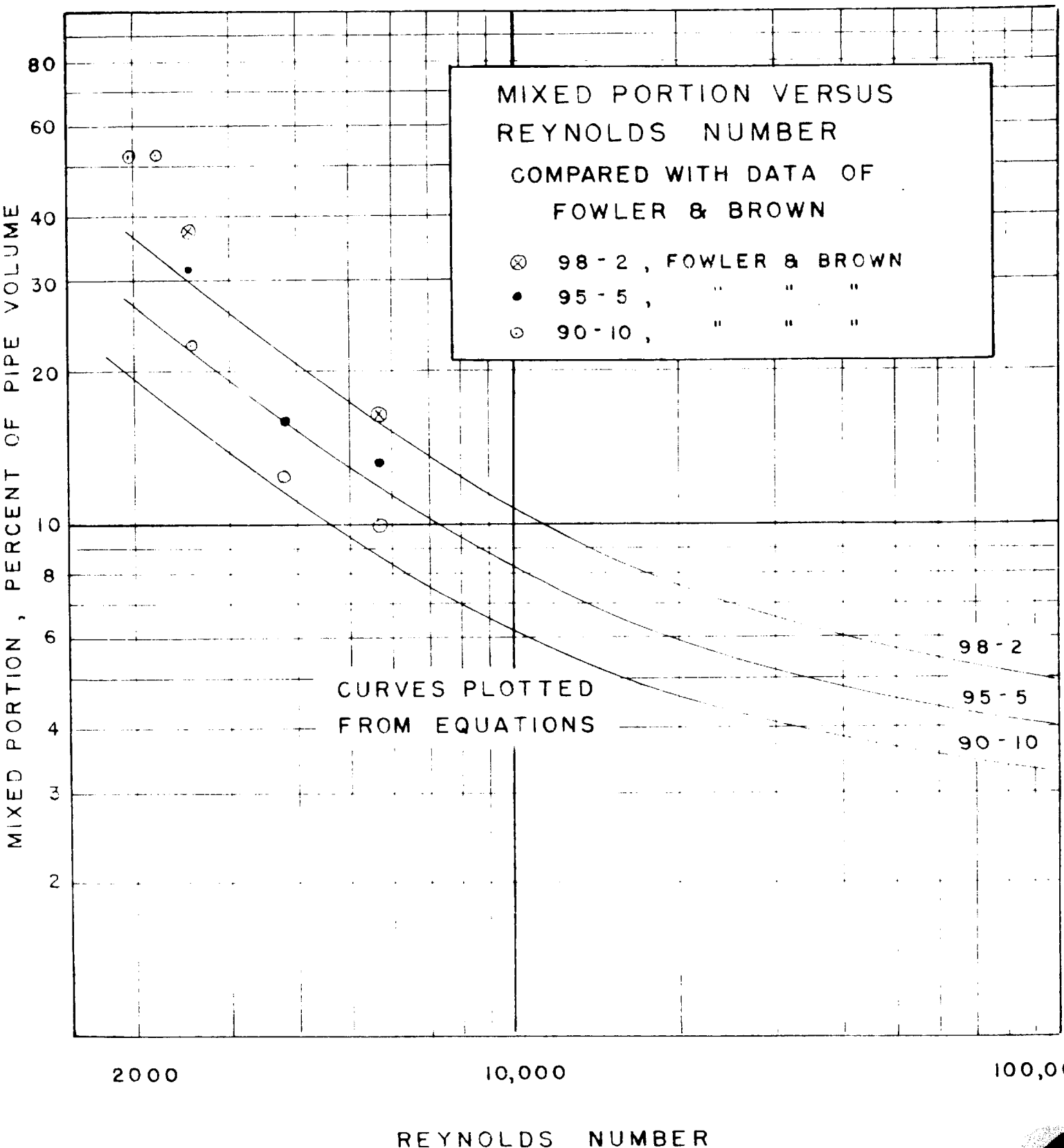

MIXED PORTION VERSUS
REYNOLDS NUMBER
COMPARED WITH DATA OF
FOWLER & BROWN
⊗ 98 - 2 , FOWLER & BROWN
• 95 - 5 , " " "
⊙ 90 - 10 , " " "
MIXED PORTION , PERCENT OF PIPE VOLUME
80
60
40
30
20
10
8
6
4
3
2
CURVES PLOTTED
FROM EQUATIONS
98 - 2
95 - 5
90 - 10
2000
10,000
100,000
REYNOLDS NUMBER

FIGURE 18

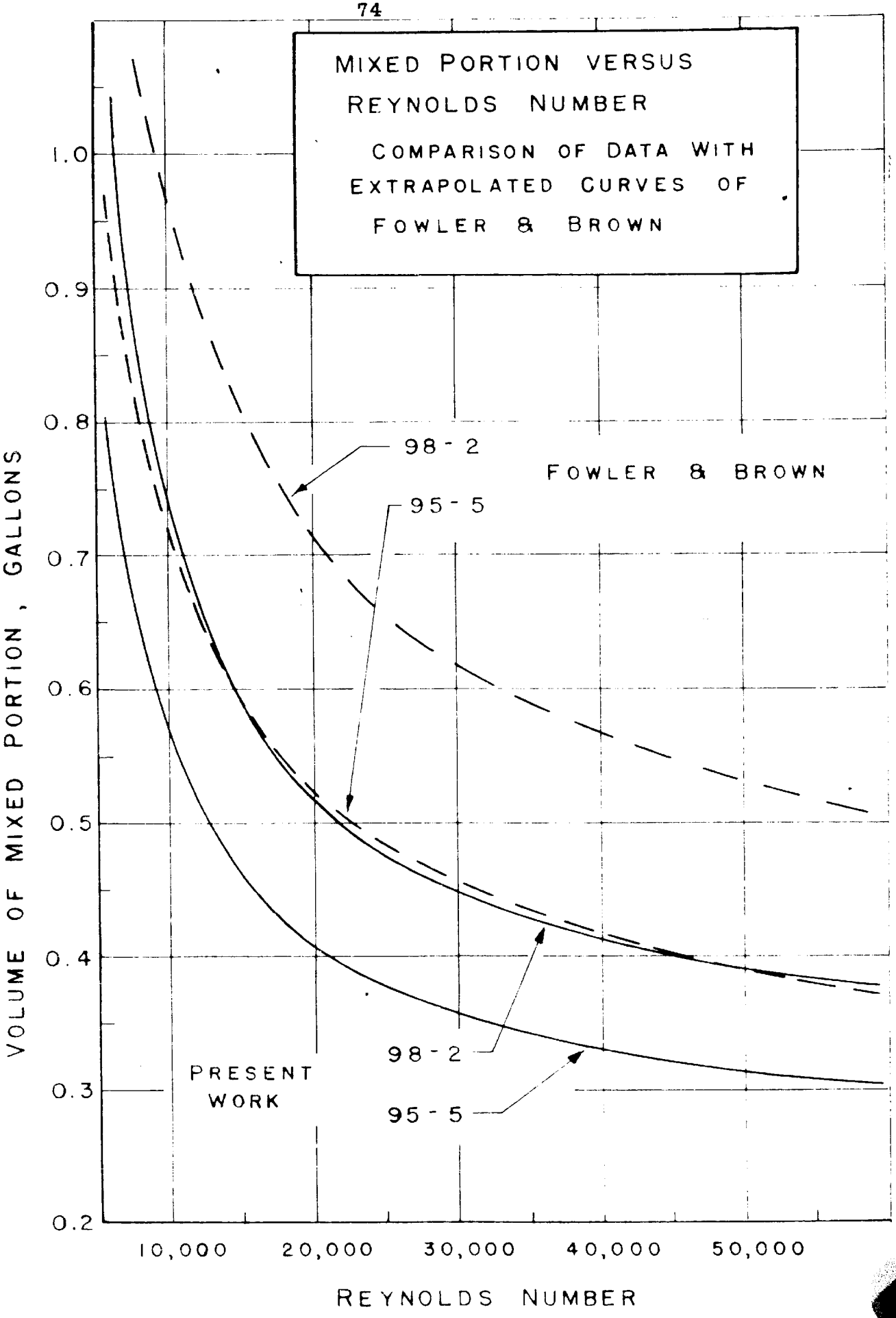

MIXED PORTION VERSUS
REYNOLDS NUMBER
COMPARISON OF DATA WITH
EXTRAPOLATED CURVES OF
FOWLER & BROWN
98 - 2
FOWLER & BROWN
95 - 5
PRESENT
WORK
98 - 2
95 - 5
VOLUME OF MIXED PORTION, GALLONS
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
10,000
20,000
30,000
40,000
50,000
REYNOLDS NUMBER

FIGURE 19

Comparison with the data of Smith and Schulze

The data of Smith and Schulze apply to lines of different lengths, as well as to liquids with different properties. Some of their data are for liquids of identical properties, at different lengths of flow. Thus it is possible to make a comparison with their data for a length of pipe corresponding to the 168 feet used in this investigation. Smith and Schulze present a plot of the amount of contamination as a function of length of flow, with a parameter of Reynolds Number. Values were read from this plot which corresponded to a length of flow equal to 168 feet. These values refer to the 99-1 mixed portion. Corresponding values for the 99-1 mixed portion were estimated from Figure 12 so that the comparison would be as reliable as possible. At Reynolds Numbers of 20,000, 30,000, and 50,000, the values of Smith and Schulze ranged from 27% to 44% higher than those reported in this thesis. This comparison has been made between their general correlation, shown in Figure 1, and liquids having the same properties, as reported here.

It is interesting to note that their experimental results are from 70% to 100% higher than the values which they report for commercial lines operating on petroleum products having the same properties. From this it appears that the equations given in this thesis are definitely more useful in predicting contamination on commercial lines in those cases where the liquids in flow have the same properties.

Also Smith and Schulze found no evidence that order of flow was important. That is contrary to the findings reported here.

Precision of Results

The data for the 90-10 mixed portion in the water-dyed water system

show good precision. In the range of Reynolds Numbers between 10,000 and 60,000, the maximum deviation is about 4%. The average deviation in this range seems to be about 2%. This precision is reasonably to be expected in view of the overall maximum error of 10% and probable error of 6% arising from errors of measurement. The deviation is progressively greater for the 95-5, 98-2, and 100-0 mixed portions. This is due to the difficulty in determining the exact point at which the Y deflection began to change. The shape of the Y-X curve (Figure 16) serves to demonstrate this fact. For this reason the 90-10 mixed portion is, in some respects, the best criterion of the contamination produced when flow variables are altered than any of the other mixed portions reported.

The contamination equations (1) through (4) appear to be general for any case of successive, turbulent flow of two liquids having the same physical properties. In one case (the triethylene glycol solutions), the liquid system investigated was for two liquids whose density and viscosity were higher than for water. In another case (benzol), the liquid system investigated was for two liquids whose density and viscosity were lower than for water.

Mechanism of Mixing

The mechanics of turbulent flow are not completely known at present. Thus it is not possible to arrive at a complete and rigorous understanding of the mechanics involved in the mixing of two liquids by successive flow in the turbulent range. Fowler (10) concluded that the controlling factor in contamination is the velocity distribution curve for liquids flowing in cylindrical pipes. He assumed that the

mechanism of mixing, although unknown, might be approximated by a cycle of two successive motions. One he described as a "forward" motion, and the other as an "instantaneous mixing across the pipe diameter". In the forward motion, which required a very short time interval the following liquid bored into the central portion of the leading liquid. No mixing was considered to take place during this forward motion. This was followed, immediately, by the instantaneous mixing across the pipe diameter. The distance that the following liquid bored into the leading liquid would be smaller, the higher the ratio of average to maximum velocity. This ratio increases with increasing Reynolds Numbers. Fowler relied on this fact to account for the decrease in contamination at higher Reynolds Numbers.

Another important factor involved in the mechanism of mixing by successive flow is the laminar film, which probably plays an equally important role. The thickness of the laminar film may be estimated (11) by the formula

$$d = 32.8 \; D \; / \; Re \; (f)^{\frac{1}{2}} , \qquad (5)$$

where d is the approximate thickness of the laminar film in inches, D is the pipe diameter in inches, Re is the Reynolds Number, and f is the friction factor (Stanton diagram). The relationship between friction factor and Reynolds Number may be estimated by the formula

$$(f)^{\frac{1}{2}} = (0.316)^{\frac{1}{2}} \; / \; (Re)^{0.125} \qquad (6)$$

for the turbulent range. These equations may be combined to give the formula

$$d = 58.3 \; D \; (Re)^{-0.875} \qquad (7)$$

From equation (7), the laminar film thickness becomes smaller as the Reynolds Number becomes larger.

The liquid particles of the laminar film are, by definition, in laminar flow. The velocity across this film varies uniformly from zero to some finite value. The average velocity of the liquid in the laminar film is considerably lower than the average velocity of that portion of the liquid in turbulent flow. This means that the leading stream leaves a thin film of liquid on the wall of the pipe which lags behind the leading end of the mixed portion, and subsequently mixes with the mixed portion itself. For a one inch pipe diameter, the thickness of this laminar film varies from about 0.050 inch (when the Reynolds Number is 3000) to about 0.004 inch (when the Reynolds Number is 60,000). From these considerations it is seen that increased Reynolds Number results in lower contamination due to its effect on both factors assumed to be of major importance in mixing of liquids by successive flow through pipes.

The foregoing discussion gives the foundation for an explanation of the limiting volume that each mixed portion approaches asymptotically at high values of Reynolds Number (see Figure 14). As the Reynolds Number approaches infinity, the thickness of the laminar film approaches zero, and the ratio of average to maximum velocity approaches unity. If it were possible to introduce a second liquid behind a given liquid in a closed conduit while both were flowing under such conditions that their Reynolds Numbers had values of infinity, then there would be no contamination. This assumes that the mechanism outlined above is adequate to account for all contamination. In practice, there is a finite time required to inaugurate successive flow of liquids and to establish a fixed Reynolds Number.

Even if infinite Reynolds Numbers could be realized, the finite time required to attain such conditions would result in a finite value of contamination. Thus the limiting value of contamination would be something greater than zero due to practical considerations, although the limit would be zero mathematically.

Position of the Mixed Portion Relative to the Position of the Theoretical Interface

The data of Table IV indicate that about 90% of the 100-0 mixed portion lies in advance of the theoretical interface when both liquids in successive flow have the same properties. This phenomenon would be expected to obtain in view of the following considerations. Both streams flowing successively have the same velocity distribution curve and average velocities. A high percentage of the liquid particles are moving with velocities greater than the average velocity. A few of the particles move with velocities very much lower than the average velocity. For this reason mixing occurs to a greater extent in those portions of the pipe ahead of the theoretical interface.

As a practical example, consider the experimental data of Run 36. In this run, the Reynolds Number was 15,800 and the average velocity was 2.04 feet per second, for both streams. At the analytical point, 168 feet downstream, it was observed that the 100-0 mixed portion was 18 feet in length. If a particle of liquid, starting at the original interface, moved with the average velocity, it would arrive at the analytical point in 168/2.04 or 82.5 seconds later. Another particle, leaving the same original interface at the same instant, but moving with the maximum velocity, would travel 1.225 times as far in 82.5

seconds. (The maximum velocity is 1.225 times as high as the average velocity at this Reynolds Number). Therefore this faster-moving particle, if undisturbed by other forces, would have moved a distance of 206 feet, which is 38 feet farther. Actually, the fastest-moving particles proceeded only (168 + 0.9 x 18) or 184 feet downstream in 82.5 seconds, which is 16 feet in advance of the theoretical interface.

The forces producing turbulence act in such a way as to disturb the flow of a liquid particle and prevent it from flowing in a straight line parallel to the pipe axis. These forces are responsible for the reduction in distance which the fastest-moving particles are able to attain in this run.

B. Liquids With Difference of Viscosity

The preceeding discussion has been confined to liquid systems having the same properties. When dealing with liquid systems in which the two streams in successive flow have different properties, it is apparent that the mechanism of mixing will be more complicated.

Examination of the data for systems where the liquids have different properties reveals at least one very apparent fact, namely: the volume of contamination depends upon the order of flow. This means that the volume of a specified mixed portion depends upon which liquid was the leading liquid. For those runs in which there was a difference in viscosity, the contamination was found to be greater when the leading liquid possessed high viscosity than for the reverse order of flow. Examination of Figure 10 also indicates that only about 68% of the 100-0 mixed portion lies in advance of the theoretical interface in this case. On the other hand, when the low-viscosity liquid was leading, about 90% of the 100-0 mixed portion lies in advance of the theoretical interface.

A plausible explanation for these facts probably lies in the following considerations.

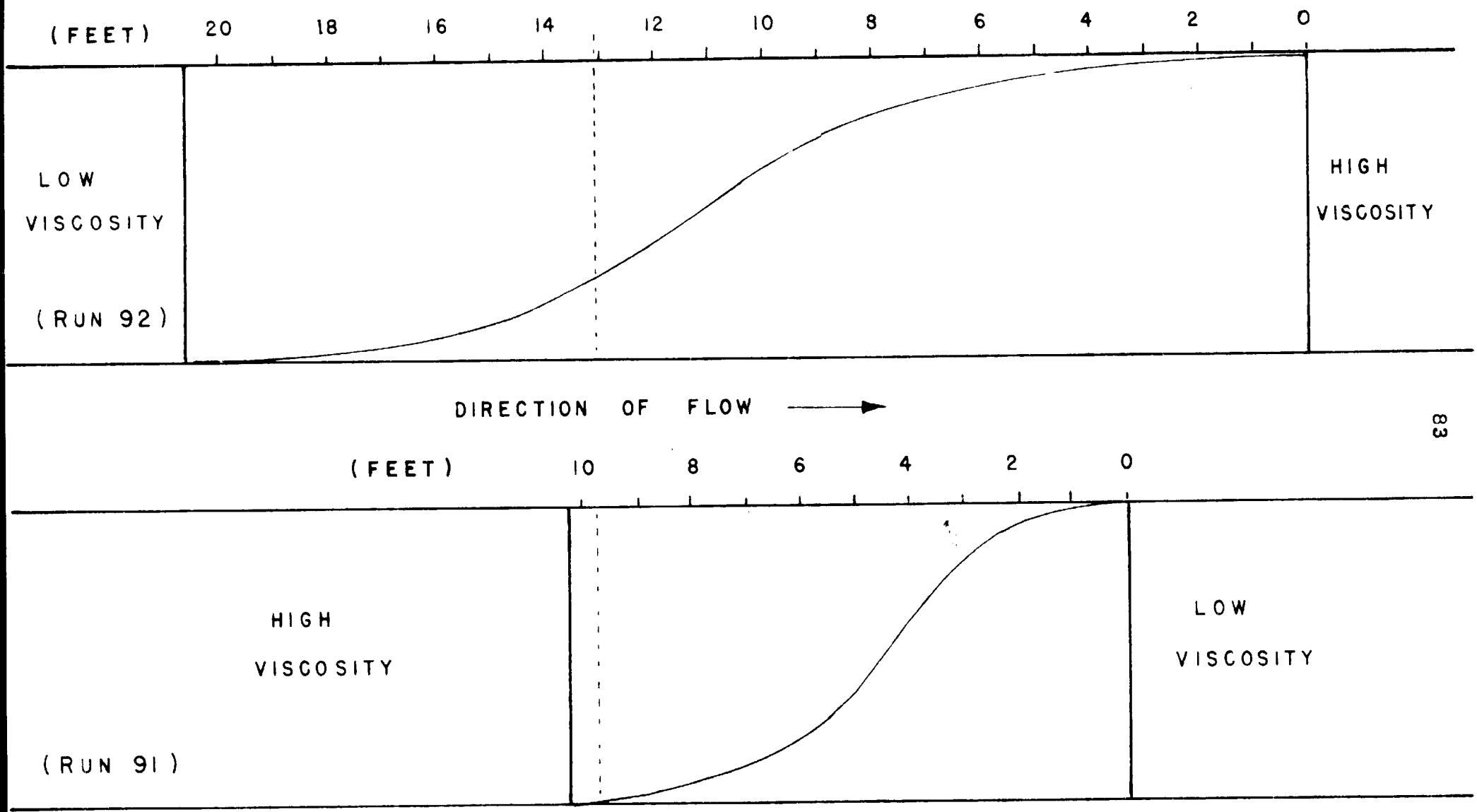
When the higher viscosity liquid is leading, the average velocity of both streams being the same, the laminar film of the leading stream is considerably thicker than that of the following stream. The average velocity of liquid in the film is much lower than the average velocity of the turbulent portion of the two streams. This causes the liquid in the laminar film to lag behind the "front" of the mixing interface. This film is ultimately dissolved in the material following

the mixing interface. From this it follows that the volume of the mixed portion will be greater than it otherwise would be if both liquids had the same thickness of laminar film, other factors equal.

Figure 20 is a pictorial representation of the conditions that were obtained in Runs 91 and 92. The higher viscosity liquid was leading in Run 92. Run 91 was made at the same flow rate, but with the lower viscosity liquid as the leading liquid. In this particular pair of runs, the volume of the 100-0 mixed portion was twice as great when the higher viscosity liquid was the leading stream than for the reverse order of flow.

In Figure 20 the volumes of the 100-0 mixed portions are represented by the length of pipe, in feet, which they occupied at the point of analysis. In both runs the average velocity was 4.09 feet per second, and thus the theoretical interfaces would coincide. The triethylene glycol stream had a Reynolds Number of 4890, and the water stream had a Reynolds Number of 30,500. The laminar film thickness for the triethylene glycol stream was 0.035 inch, and for the water stream it was 0.007 inch. The instantaneous compositions (percent of leading liquid versus length of contamination) are plotted along the entire length of the mixed portion.

It can be seen from Figure 20 that the beginning of the mixed portion is farther downstream when the high viscosity liquid is leading. The chief factor involved in producing increased contamination is the thicker laminar film. It dissolves in the advancing "front" of the mixed portion which, as pointed out previously, appears predominantly in advance of the theoretical interface. This steady supply of film on the wall continually feeds the mixed portion at its "front" with



COMPARISON OF 100-0 MIXED PORTIONS FOR RUNS 91 & 92

FIGURE 20

additional pure leading liquid. The effect of this is to build up a larger quantity of contaminated volume between the two pure liquids ahead of the theoretical interface.

When the leading liquid has a lower viscosity than the following liquid, it is observed that the volume of a specified mixed portion is always lower than when the order of flow is reversed. In this case, the laminar film of the leading liquid is considerably thinner than that of the following liquid. This means that there will be less contamination due to the film than would result in the reverse order of flow. Contamination still occurs, however, and can probably be accounted for by the velocity gradient across the conduit, which is still present. It was observed, however, that when a high-viscosity liquid follows a low-viscosity liquid, that less contamination results than if both liquids had the same properties as the low-viscosity liquid, other factors equal. This indicates that some inhibiting factor is at work which is absent when both streams have the same properties.

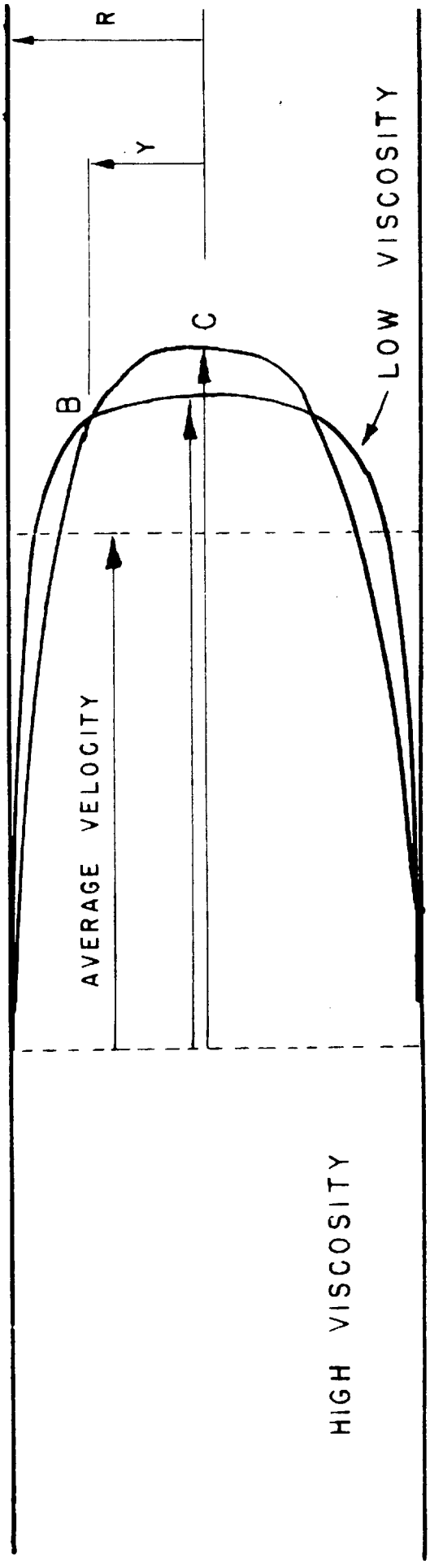
The source of this inhibiting action may be the inequalities of the velocity distribution curves for the two liquids. In the case of Runs 91 and 92, the values of maximum velocity were appreciably different. For the water system, the maximum velocity was 1.25 times larger than the average velocity. For the triethylene glycol solution stream, the maximum velocity was 1.35 times as large as the average velocity. Since the average velocity was the same for both streams, the maximum velocity of the glycol stream was 1.08 times greater than that for the water stream. This condition obtained at the center of the pipe. At some position between the center of the pipe and the pipe wall, both streams would have the same velocity; and between that

point and the pipe wall, a reversal in the relative velocities of the two streams would obtain.

Figure 21 is a sketch of the approximate shape (not experimentally determined) of the velocity distribution curves for the two liquids. At any point in the pipe a distance from the center greater than y and less than r, the velocity is higher for the water stream than for the glycol stream. The reverse is true for any point less than a distance y from the center.

At the time when successive flow is inaugurated, a new situation is produced which is absent in the case of liquids having identical properties. This new situation is a tendency to form additional eddy currents which arise due to the inequalities of velocity. For example, at the center of the pipe, a particle of the more viscous stream seeks to move along the pipe axis with greater velocity than a particle of the lower viscosity stream. This tends to establish a surface of discontinuity, which breaks down into a series of eddies. Thus, additional eddy currents would be formed and additional mixture would be produced in shorter time than would be produced if the liquids had the same properties. This mixture acts as a buffer to decrease the amount of contamination produced for a given pipe length and a given flow rate.

The condition of inequality of velocities is greater at the start of flow than at any later time. This gives rise to an initial driving force to produce mixing, but this driving force gradually diminishes as the mixed portion builds up in the pipe between the two uncontaminated liquids. The point here is that it seems reasonable to believe that this "contamination inhibiting" buffer is built up earlier in flow and continues to operate for a longer time, thereby decreasing



VELOCITY DISTRIBUTION CURVES

RUN 91

FIGURE 21

the overall volume of contamination.

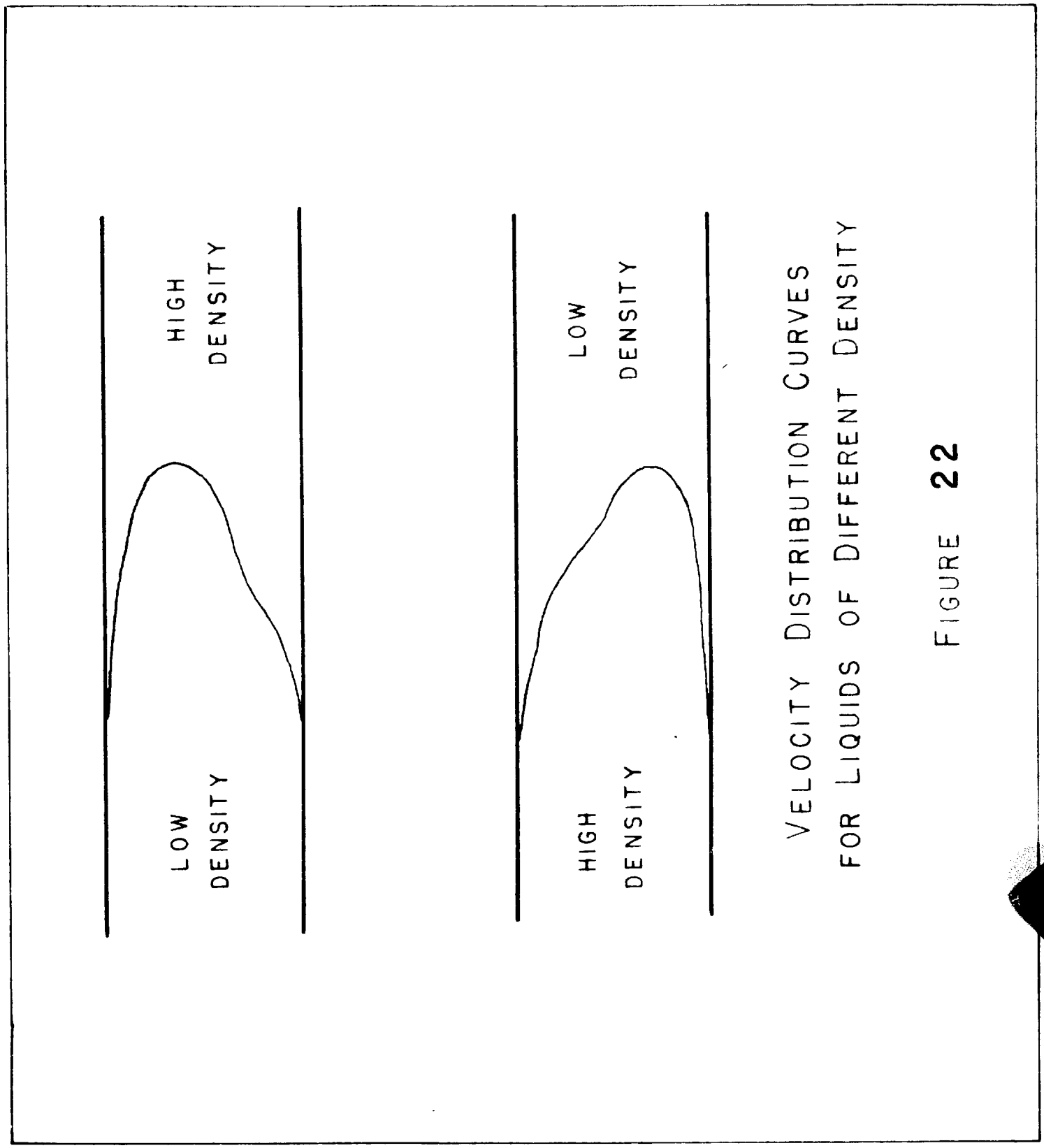
This same "contamination inhibiting" tendency exists in the reverse order of flow (where high-viscosity liquid is leading). It seems likely, however, that it is masked by the effect of the laminar film which persists throughout the entire mixing section of the pipe line. The above discussion is purely hypothetical in nature, and is offered merely as a possible mechanism for explaining the experimental data.

C. Liquids With Differences of Density

When two liquids of equal viscosity, but having different density, are in successive flow in a pipe, the gravitational effects become significant. It is evident that the liquid of higher density has more tendency to flow along the bottom portion of the pipe than does the lighter liquid. This tendency produces distortion in the velocity distribution curve in a manner similar to those sketched in Figure 22.

The experimental data indicate that the volume of contamination is larger when the high-density liquid is leading. If the distortions of the velocity distribution curves were unequal in the two cases, then it is possible that it might be unequal in such a manner as to allow greater mixing in the case of the high-density liquid leading. This assumes that the mixing interface between the two liquids is qualitatively related in some way to the distorted velocity gradient. It is recognized, of course, that any such relationship becomes less and less distinct as flow progresses due to disturbances produced by eddy currents.

When the problem is considered from the standpoint of kinematic viscosity, a conclusion may be reached which contradicts the experimental facts. If the contamination is greater when the high-viscosity liquid is leading, then it should also be greater when the low-density liquid is leading. This conclusion results from considering the kinematic viscosity instead of either viscosity or density alone. Such considerations make it appear that effects related to the density stratification tend to override the other effects which are at work in the mechanics of mixing.



VELOCITY DISTRIBUTION CURVES
FOR LIQUIDS OF DIFFERENT DENSITY

FIGURE **22**

Any distortion in the velocity distribution curve would likely tend to introduce error in the analysis of the mixture by the method used in this investigation. This will be discussed more completely in the next section.

D. Limitations Of Photoelectric Colorimetry In Analysis Of Contamination Between Dissimilar Liquids

Distortions of the Velocity Distribution Curve

The successful application of photoelectric colorimetry to the analysis of contamination between two liquids in successive flow depends on the assumption of uniform mixing across a pipe diameter. This seems to be a valid assumption when the two liquids are in successive, turbulent flow and possess the same physical properties. However, the data on the salt water - distilled water system indicate that this assumption may not be completely justifiable for systems having a difference in density.

The distortion of the velocity distribution curve due to gravitational effects on liquids of different density raises the question as to analytical errors when the light beam used for analysis passes through only a small section of the pipe. In this investigation, a light beam of 1/8 inch diameter was passed through the glass pipe at right angles to the axis of the pipe. Also it passed through on a diameter, in the horizontal plane. If the denser liquid tends to flow along the bottom of the pipe — even though the flow is turbulent — there might be an error introduced in analyzing only a small portion at the middle of the pipe. To avoid this error it might be necessary to pass the light beam through the conduit in a vertical plane, rather than in a horizontal plane. Analysis at several different angles, all of which are normal to the pipe axis, might eliminate the errors which appear likely to result when only one position is chosen for analysis.

If the two liquids have differences in viscosity, but no difference in density, it seems unlikely that serious error would be introduced.

Dependence of Results upon the Selection of a Solvent for the Dye

The data for the salt solution-distilled water runs show that it makes considerable difference which of these two streams contains the dye before pumping them in successive flow. When the dye was placed in the salt stream, the contaminated volumes were much larger than when the dye was placed in the water stream -- the more dense liquid being the leading stream. Differences in results were not quite so marked (see Figure 24) in these two cases when the low-density liquid was leading. These differences were quite unexpected since the small amount of dye used was readily dissolved in the salt solution before mixing with distilled water in the pipe line. The quantity of dye used in all runs was never greater than 4 grams per 50 gallons of liquid.

The reason for this unusual behavior is not clear, though it may possibly be due to: (1) any difference in solubilities of the dye in the two liquids, (2) different eddy diffusivities of the dye from salt water to distilled water, as compared with the reverse direction of diffusion. Considerable investigation would be required into this problem before any conclusion could be drawn.

This difficulty would probably not arise when non-ionized liquids are used, or when liquids do not contain another solute in addition to the dye. The triethylene glycol solutions used did not indicate any such difference in results. In runs 192, 193, 196, and 197, the dye was dissolved initially in the water stream. Results from these

VOLUME OF 90-10 MIXED PORTION VERSUS REYNOLDS NUMBER OF LOW-VISCOSITY LIQUID

□ , △ , ▽ , ○ -- HIGH-VISCOSITY LIQUID LEADING FOR 15, 11, 7, 4 CPE'.

■ , ▲ , ▼ , ● -- LOW-VISCOSITY LIQUID LEADING FOR 15, 11, 7, 4 CPE'.

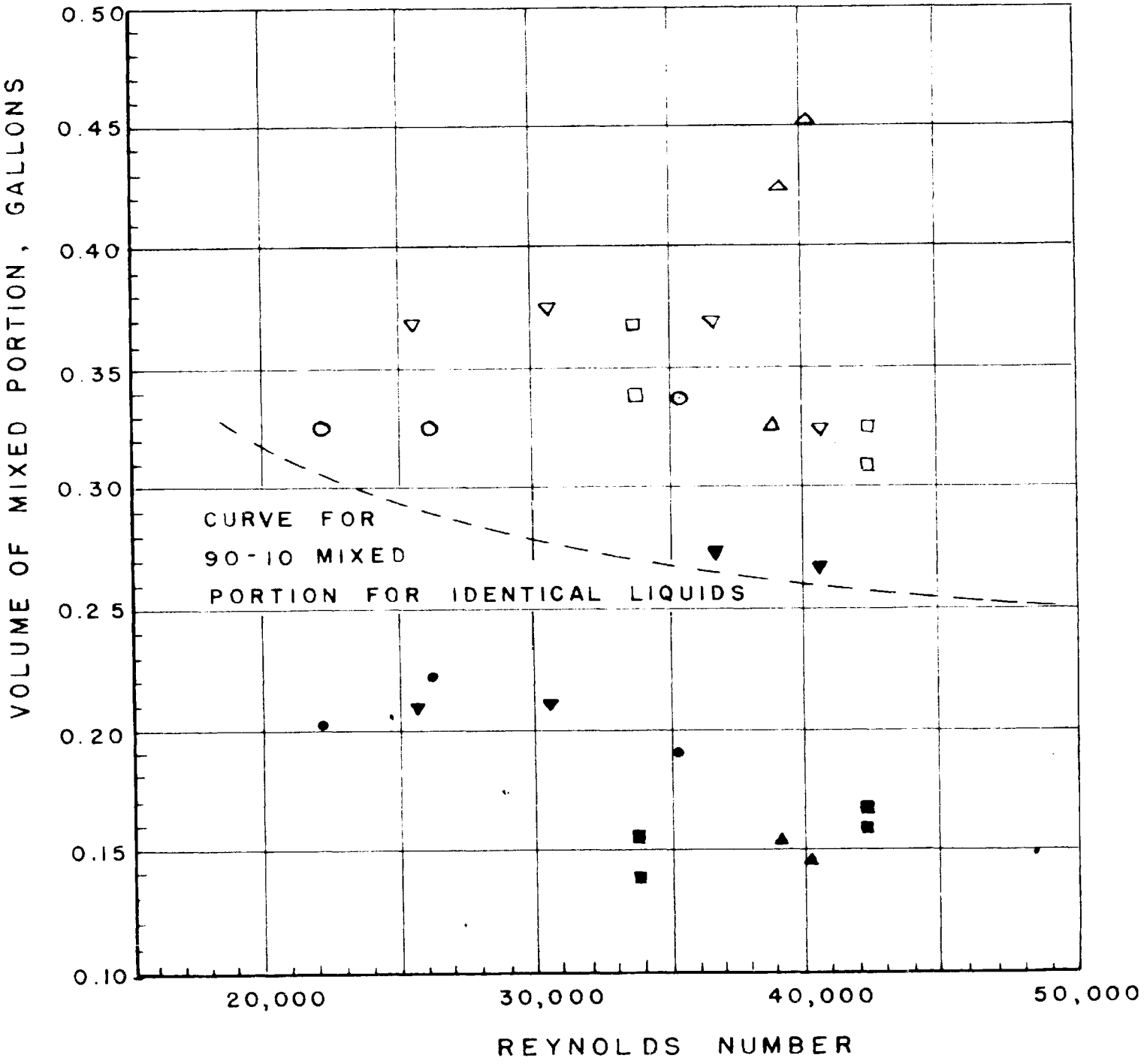


FIGURE 23

VOLUME OF 90-10 MIXED PORTION VERSUS REYNOLDS NUMBER OF LOW-DENSITY LIQUIDS

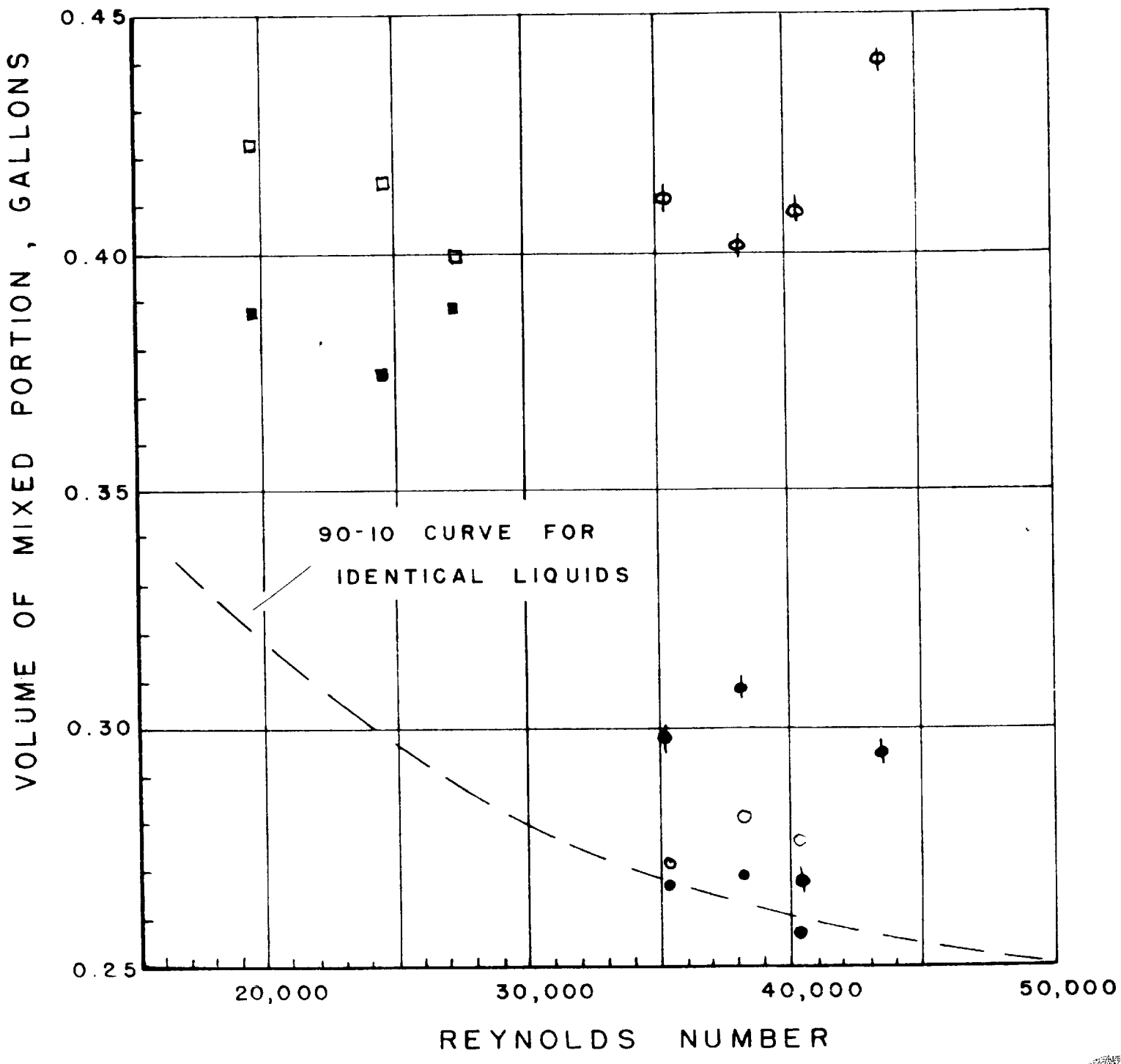


FIGURE 24

runs are in reasonable agreement with the other runs on this system in which the dye was placed in the triethylene glycol stream.

In the case of the runs on salt solution and water, the question naturally arises as to which set of results are more reliable. Since the volumes of contamination are very large when the dye is dissolved initially in the salt water, these appear more unreliable. It seems unlikely that only 4% increase in density would produce a change in contamination of 50% over that where the densities of the two streams were equal. This, however, is what must be inferred from the data of runs 139 and 146. Because of this apparently excessive mixing, the results are considered less reliable than for the runs where the dye was placed in the distilled water. For this reason, the runs where the dye was placed in the distilled water stream are used to indicate the magnitude of mixing between two liquids of different density. The qualitative effect of density on the contamination remains unaffected. In all cases, more contamination was observed when the high-density liquid was the leading liquid.

E. Estimation Of Contamination In The General Case For Dissimilar Liquids

The products transported in commercial pipe lines usually differ from each other in both density and viscosity. Because of this, it is of interest to have information which makes it possible to predict contamination in this general case. The data of this investigation indicate that the amount of contamination is not a simple function of Reynolds Number. The suggestion of Fowler (10) that the arithmetic average Reynolds Number be used to estimate contamination between dissimilar liquids is inadequate. This is true because the value of Reynolds Number for a given flow rate and pipe size depends directly on density and inversely on viscosity; or the kinematic viscosity, in other words. Thus it would appear that if the contamination is greater when the high-viscosity liquid is leading, it should also be greater when the low-density liquid is leading if the kinematic viscosity is the controlling factor. The experimental fact, is, however, that contamination is less when the low-density liquid is leading. Thus the effect due to kinematic viscosity differences does not explain the experimental observations. The arithmetic average Reynolds Number of Fowler, or the Reynolds Number of the 50-50 blend, as employed by Smith and Schulze (2), will not correlate the data reported.

An empirical guide for estimating contamination in the general case is all that can be offered based upon the data reported in this thesis. The following procedure is recommended:

(1) Compute the Reynolds Number of the liquid having the

lower-viscosity of the two dissimilar liquids in successive flow. Also compute the Reynolds Number of the liquid with the lower density. In most cases, the liquid with the lower viscosity also has a lower density (especially in hydrocarbon systems).

(2) The volume of contamination for successive flow of a similar liquid or liquids at the Reynolds Number or Numbers computed in step (1) is found by referring to Figure 14.

(3) The final, corrected volume (i.e., the volume of contamination for the two dissimilar liquids under consideration) is obtained by applying corrections to the volume obtained in step (2) by means of Figure 15.

The numerical value of the contamination estimated by the above procedure will refer to a line 168 feet in length. Adequate allowance for length can be made by data supplied by Fowler and Brown (1), and by Smith and Schulze (2).

If contamination is to be kept at a minimum, then it is obviously better to allow the lower viscosity liquid to be the leading liquid. This is not always possible in commercial practice, and it is usually necessary to estimate contamination for both cases.

A P P E N D I X

EXPERIMENTAL DATA TAKEN FROM OSCILLOGRAMS

TABLE I -- NO DIFFERENCES IN PROPERTIES

X - Frame Number position on the film

Y - "Y" deflection of the signal corresponding to location X, inches.

A. SYSTEM : Water - Dyed Water

Run No.		X , Y Values									
153	X :	8.50	7.00	6.00	5.00	4.00	2.00	1.00	0.00	-2.0	-3.4
	Y :	3.36	3.33	3.24	3.17	3.08	2.38	1.80	1.17	0.59	0.435
53	X :	3.00	3.10	3.50	4.00	5.00	6.00	6.50	7.00	8.00	9.30
	Y :	3.59	3.56	3.50	3.32	2.24	1.08	0.80	0.63	0.49	0.42
151	X :	42.3	43.0	43.5	44.0	44.3	44.5	45.0	45.4	46.0	47.5
	Y :	3.51	3.42	3.20	2.68	2.20	1.91	1.24	0.89	0.66	0.485
152	X :	33.2	32.5	31.9	31.4	30.6	30.0	29.6	29.1	28.5	27.8
	Y :	2.90	2.83	2.72	2.47	1.82	1.27	0.91	0.64	0.48	0.436
149	X :	23.3	24.0	24.8	25.1	25.5	25.9	26.3	27.0	28.0	30.3
	Y :	3.48	3.40	2.52	1.98	1.30	0.91	0.68	0.54	0.47	0.435
150	X :	16.4	14.5	13.5	12.7	11.8	11.1	10.7	10.5	9.50	9.00
	Y :	3.20	3.14	3.06	2.82	2.18	1.33	0.95	0.79	0.46	0.425
148	X :	37.3	37.7	38.2	28.8	39.4	39.8	40.1	40.4	40.8	41.2
	Y :	3.09	3.00	2.84	2.31	1.47	0.92	0.69	0.55	0.45	0.43

TABLE I (Continued)

Run No.										
45	X :	29.2	29.5	30.1	30.4	30.7	31.0	31.5	31.9	32.4	33.15
	Y :	3.71	3.56	2.94	2.33	1.71	1.24	0.78	0.62	0.53	0.465
55	X :	21.1	20.2	19.0	18.0	17.5	17.0	16.7	16.5	16.2	15.65
	Y :	3.40	3.36	3.16	2.44	1.75	1.04	0.76	0.61	0.51	0.40
36	X :	33.2	32.5	32.0	31.5	31.0	30.5	30.3	30.1	30.0	29.4
	Y :	3.56	3.40	3.24	2.91	2.22	1.44	1.07	0.84	0.76	0.51
52	X :	20.1	19.5	19.0	18.5	18.0	17.5	17.2	17.0	16.8	16.4
	Y :	3.35	3.22	3.06	2.68	1.97	1.09	0.77	0.58	0.49	0.40
44	X :	7.50	7.25	6.85	6.65	6.40	6.15	5.90	5.45	5.02	4.85
	Y :	0.45	0.50	0.75	0.98	1.44	2.07	2.60	3.33	3.61	3.68
37	X :	16.0	16.5	17.0	17.3	17.5	17.7	17.9	18.0	18.2	18.9
	Y :	3.69	3.56	2.58	1.67	1.23	0.91	0.71	0.65	0.565	0.465
51	X :	2.00	2.20	2.50	2.70	3.05	3.25	3.50	3.70	3.90	4.33
	Y :	3.71	3.60	3.16	2.58	1.44	0.99	0.70	0.58	0.51	0.436
50	X :	28.7	28.4	28.3	28.0	27.8	27.6	27.4	27.2	27.1	27.0
	Y :	3.56	3.38	3.33	2.76	2.06	1.31	0.83	0.55	0.50	0.436
31	X :	20.6	20.4	20.3	20.1	20.0	19.9	19.7	19.5	19.3	19.0
	Y :	3.71	3.62	3.55	3.06	2.62	2.16	1.34	0.85	0.62	0.47
38	X :	3.10	2.80	2.60	2.50	2.10	2.00	1.90	1.70	1.5	1.10
	Y :	3.31	3.22	3.16	3.0	2.07	1.74	1.38	0.85	0.57	0.42

TABLE I (Continued)

Run No.										
18	X : 21.6	21.4	21.2	21.1	20.9	20.7	20.6	20.4	20.2	20.0
	Y : 3.6	3.50	3.09	2.73	1.84	1.22	0.84	0.60	0.49	0.45
39	X : 26.7	26.9	27.0	27.2	27.4	27.5	27.6	27.8	28.0	28.1
	Y : 3.68	3.49	3.33	2.52	1.70	1.08	0.82	0.56	0.48	0.44
49	X : 0.10	0.20	0.30	0.50	0.60	0.70	0.80	1.00	1.15	1.38
	Y : 3.76	3.70	3.53	2.94	2.40	1.76	1.13	0.74	0.58	0.455
57	X : 8.0	7.95	7.80	7.65	7.55	7.45	7.30	7.15	7.0	6.91
	Y : 3.54	3.46	3.10	2.30	1.70	1.19	0.74	0.54	0.47	0.436
48	X : 21.0	21.2	21.4	21.5	21.7	21.8	21.9	22.0	22.1	22.2
	Y : 3.64	3.51	3.08	2.58	1.46	0.96	0.73	0.55	0.47	0.436
19	X : 5.55	5.80	5.90	6.0	6.20	6.30	6.40	6.50	6.60	6.67
	Y : 3.38	3.18	2.98	2.58	1.52	1.02	0.73	0.58	0.47	0.43
41	X : 2.04	2.10	2.20	2.35	2.50	2.60	2.70	2.85	3.00	3.10
	Y : 3.71	3.60	3.42	2.62	1.57	1.05	0.73	0.55	0.47	0.445
20	X : 36.3	36.2	36.1	36.0	35.9	35.8	35.7	35.6	35.5	35.4
	Y : 3.49	3.32	2.98	2.24	1.47	0.98	0.71	0.58	0.50	0.47
47	X : 34.1	34.0	33.9	33.8	33.7	33.6	33.5	33.4	33.3	33.2
	Y : 3.48	3.38	3.10	2.52	1.76	1.06	0.71	0.50	0.46	0.418
29	X : 6.9	7.10	7.20	7.30	7.40	7.50	7.60	7.70	7.80	7.82
	Y : 3.64	3.46	3.22	2.67	1.56	1.28	0.76	0.57	0.47	0.436

TABLE I (Continued)

B. SYSTEM : Benzol - Dyed Benzol

Run No.										
154	X :	4.40	5.05	5.30	5.50	5.65	5.75	5.90	6.05	6.30	6.80
	Y :	3.48	3.38	3.01	2.24	1.64	1.24	0.76	0.51	0.33	0.265
155	X :	37.8	37.5	37.4	37.1	36.9	36.7	36.6	36.4	36.2	35.8
	Y :	3.25	3.16	3.08	2.60	1.89	1.16	0.89	0.52	0.34	0.235
156	X :	17.1	17.3	17.4	17.5	17.6	17.7	17.8	17.9	18.0	18.2
	Y :	3.84	3.70	3.42	2.80	2.03	1.24	0.74	0.47	0.36	0.255
159	X :	28.4	28.1	28.0	27.8	27.7	27.6	27.5	27.4	27.3	27.2
	Y :	3.20	3.10	3.02	2.40	1.76	1.10	0.66	0.38	0.29	0.237

C. SYSTEM : TEG - Dyed TEG

135	X :	40.8	40.0	39.9	39.7	39.5	39.4	39.3	39.2	39.1	38.9
	Y :	3.84	3.67	3.54	2.90	1.87	1.29	0.89	0.65	0.54	0.46
136	X :	44.5	44.6	44.7	44.8	44.9	45.0	45.1	45.2	45.5	45.8
	Y :	3.42	3.35	2.96	2.40	1.76	1.16	0.76	0.58	0.44	0.40
137	X :	27.5	27.3	27.0	26.8	26.6	26.4	26.3	26.1	25.8	25.5
	Y :	3.52	3.46	3.22	2.82	1.98	1.09	0.80	0.52	0.44	0.41

EXPERIMENTAL DATA TAKEN FROM OSCILLOGRAMS

TABLE II -- DIFFERENCE IN VISCOSITY

X - Frame Number position on the film

Y - "Y" deflection of the signal corresponding to location X, inches.

Run No.	X , Y Values									
74	X :	29.15	29.0	28.9	28.8	28.7	28.5	28.3	28.2	28.1	27.8
	Y :	1.25	1.22	1.16	1.06	0.92	0.64	0.53	0.47	0.44	0.42
75	X :	13.7	1.39	14.0	14.2	14.3	14.4	14.5	14.6	14.8	15.0
	Y :	3.80	3.67	3.27	1.64	1.39	1.31	1.29	1.28	1.27	1.25
76	X :	16.7	16.4	16.1	16.0	15.8	15.6	15.3	14.9	14.5	14.3
	Y :	3.84	3.80	3.66	3.56	2.98	2.12	1.51	1.30	1.27	1.22
77	X :	2.75	2.50	2.40	2.30	2.20	2.10	2.00	1.75	1.5	1.15
	Y :	3.50	3.40	3.19	2.60	1.64	1.23	1.18	1.12	1.10	1.09
78	X :	29.6	29.3	29.1	28.9	28.8	28.5	28.3	28.0	27.6	27.2
	Y :	3.55	3.47	3.27	2.48	1.96	1.33	1.27	1.19	1.12	1.09
79	X :	0.5	0.8	0.9	0.95	1.00	1.10	1.20	1.30	1.50	2.00
	Y :	3.88	3.60	3.00	2.52	2.06	1.24	0.80	0.66	0.54	0.45
80	X :	5.75	5.50	5.30	5.10	4.80	4.60	4.50	4.30	4.00	3.50
	Y :	3.30	3.24	3.05	2.66	1.49	0.91	0.73	0.58	0.49	0.436

TABLE II (Continued)

Run No.										
81	X : 34.1	34.3	34.4	34.5	34.6	34.7	34.8	34.9	35.1	35.3
	Y : 3.69	3.67	3.58	3.15	2.31	1.35	0.84	0.68	0.55	0.49
82	X : 23.4	23.1	22.8	22.6	22.5	22.4	22.2	22.0	21.6	21.3
	Y : 3.53	3.40	3.21	2.80	2.44	1.96	1.13	0.74	0.52	0.48
83	X : 14.0	14.3	14.4	14.5	14.6	14.7	14.8	14.9	15.3	15.6
	Y : 3.58	3.49	3.27	2.58	1.66	0.91	0.66	0.56	0.48	0.456
84	X : 2.50	2.40	2.30	2.10	1.80	1.60	1.50	1.30	1.00	0.75
	Y : 3.50	3.44	3.33	2.92	1.77	1.00	0.83	0.62	0.52	0.475
85	X : 26.3	26.5	26.6	26.7	26.8	26.9	27.0	27.1	27.2	27.5
	Y : 3.71	3.55	3.01	2.02	1.13	0.72	0.58	0.55	0.51	0.47
86	X : 15.5	15.3	15.1	15.0	14.8	14.7	14.6	14.4	14.2	13.9
	Y : 3.61	3.53	3.18	2.87	1.73	1.27	0.91	0.63	0.52	0.48
87	X : 16.3	16.1	16.0	15.9	15.8	15.7	15.6	15.5	15.2	14.8
	Y : 3.77	3.67	3.46	2.75	1.76	1.11	0.76	0.68	0.57	0.51
88	X : 5.10	5.30	5.50	5.60	5.70	5.90	6.00	6.30	6.40	6.5
	Y : 3.51	3.41	2.82	2.28	1.70	0.98	0.82	0.641	0.62	0.61
89	X : 42.1	41.8	41.6	41.5	41.4	41.3	41.2	41.0	40.7	40.0
	Y : 3.65	3.60	3.34	2.75	1.93	1.20	0.9	0.69	0.61	0.548
90	X : 30.6	30.8	31.0	31.1	31.3	31.6	31.7	31.9	32.0	32.2
	Y : 3.5	3.38	3.04	2.73	1.84	1.01	0.88	0.76	0.73	0.67

TABLE II (Continued)

Run No.										
91	X :	19.2	19.3	19.4	19.5	19.6	19.7	19.8	19.9	20.1	20.2
	Y :	3.52	3.31	2.98	2.31	1.65	1.23	0.96	0.82	0.71	0.66
92	X :	9.00	8.80	8.50	8.40	8.30	8.10	7.90	7.50	7.20	6.8
	Y :	3.66	3.61	3.25	3.04	2.69	1.96	1.33	0.84	0.74	0.678
93	X :	33.2	33.3	33.4	33.5	33.7	33.9	34.0	34.1	34.3	34.5
	Y :	3.55	3.50	3.34	3.00	1.84	1.13	0.91	0.84	0.73	0.678
94	X :	29.2	28.9	28.7	28.4	28.2	28.0	27.7	27.4	27.1	26.8
	Y :	3.70	3.61	3.50	3.02	2.46	1.84	1.23	0.90	0.76	0.71
97	X :	16.4	16.9	17.0	17.1	17.2	17.3	17.4	17.6	17.7	18.0
	Y :	3.75	3.70	3.54	3.09	2.51	2.01	1.66	1.47	1.45	1.42
98	X :	6.34	6.10	6.00	5.80	5.60	5.40	5.30	5.20	5.05	4.54
	Y :	3.45	3.42	3.30	3.02	2.25	1.29	0.86	0.58	0.40	0.232
99	X :	33.7	34.1	34.4	34.5	34.6	34.8	34.9	35.0	35.2	35.5
	Y :	3.78	3.74	3.27	2.78	2.15	0.96	0.69	0.53	0.41	0.33
100	X :	23.4	23.1	22.6	22.4	22.2	21.9	21.8	21.7	21.4	21.2
	Y :	3.71	3.67	3.14	2.55	1.76	0.82	0.63	0.53	0.36	0.31
101	X :	7.00	7.80	8.20	8.40	8.55	8.70	8.80	8.95	9.10	9.4
	Y :	3.75	3.72	3.49	2.82	1.91	1.19	0.89	0.60	0.47	0.38
102	X :	42.3	41.9	41.4	40.9	40.6	40.3	40.1	39.9	39.7	38.6
	Y :	3.51	3.44	3.35	2.83	2.20	1.32	0.86	0.58	0.44	0.295

TABLE II (Continued)

Run No.										
103	X :	34.5	34.4	34.3	34.2	34.1	34.0	33.9	33.8	33.4	33.2
	Y :	3.75	3.68	3.36	2.22	1.04	0.56	0.41	0.40	0.38	0.37
104	X :	28.0	28.1	28.3	28.4	28.5	28.6	28.7	28.8	29.0	29.2
	Y :	3.56	3.49	2.90	2.24	1.42	0.97	0.68	0.54	0.46	0.40
105	X :	12.1	12.2	12.3	12.4	—	12.5	12.6	--	12.7	12.8
	Y :	3.56	3.52	3.42	2.76	--	1.53	0.68	--	0.48	0.40
106	X :	19.1	18.8	18.6	18.4	18.3	18.2	18.1	18.0	17.5	17.1
	Y :	3.50	3.44	3.18	2.20	1.49	0.96	0.68	0.53	0.40	0.385
107	X :	0.13	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.70	0.95
	Y :	3.475	3.11	2.78	2.31	1.67	1.09	0.80	0.61	0.44	0.40
108	X :	8.42	8.30	8.10	7.95	7.80	7.65	7.55	7.40	7.20	6.95
	Y :	3.48	3.43	3.13	2.62	1.77	1.15	0.85	0.62	0.49	0.40
109	X :	29.7	29.6	29.5	29.4	29.3	29.2	29.1	29.0	28.9	28.8
	Y :	3.56	3.47	3.09	2.31	1.20	0.61	0.50	0.43	0.41	0.40
110	X :	38.7	38.5	38.3	38.1	38.0	37.9	37.8	37.7	37.4	36.7
	Y :	1.82	1.76	1.60	1.22	0.98	0.75	0.56	0.44	0.28	0.218
119	X :	38.5	38.7	38.8	38.9	39.0	39.1	39.2	39.3	39.4	39.8
	Y :	3.78	3.71	3.53	3.10	2.18	1.33	0.84	0.58	0.49	0.42
120	X :	44.9	44.7	44.5	44.4	44.3	44.2	44.1	44.0	43.9	43.7
	Y :	3.58	3.50	3.18	2.75	2.18	1.53	1.01	0.66	0.53	0.436

TABLE II (Continued)

Run No.										
121	X :	25.7	25.8	26.0	26.1	26.2	26.3	26.4	26.5	26.6	27.0
	Y :	3.72	3.66	3.18	2.45	1.62	1.04	0.71	0.56	0.50	0.44
122	X :	32.0	31.9	31.7	31.5	31.4	31.3	31.1	31.0	30.9	30.8
	Y :	3.38	3.33	3.15	2.34	1.74	1.18	0.60	0.50	0.46	0.436
123	X :	12.5	12.7	12.8	12.9	13.0	13.2	13.3	13.4	13.6	13.9
	Y :	3.84	3.71	3.50	2.95	2.28	1.02	0.74	0.62	0.50	0.475
124	X :	19.7	19.4	19.2	19.0	18.9	18.8	18.7	18.6	18.5	18.2
	Y :	2.49	2.40	2.23	1.72	1.37	1.02	0.74	0.55	0.43	0.343
125	X :	46.0	45.6	45.4	45.2	45.0	44.9	44.7	44.6	44.4	44.2
	Y :	2.72	2.62	2.52	2.24	1.69	1.31	0.75	0.58	0.43	0.40
168	X :	26.2	26.6	27.2	27.6	28.0	28.4	28.6	29.0	29.2	29.6
	Y :	3.66	3.60	3.45	3.26	2.58	1.14	0.76	0.42	0.38	0.337
169	X :	18.0	17.4	16.8	16.2	15.9	15.4	15.2	14.8	14.5	14.1
	Y :	3.50	3.42	3.29	2.90	2.51	1.39	1.02	0.56	0.39	0.328
170	X :	43.5	44.0	44.8	45.2	45.4	45.7	45.8	46.0	46.2	46.5
	Y :	3.89	3.83	3.60	3.22	2.57	1.00	0.71	0.42	0.33	0.291
192	X :	25.4	24.8	24.4	24.1	23.6	23.4	23.1	22.9	22.7	22.1
	Y :	3.46	3.34	3.17	2.90	2.05	1.02	0.71	0.65	0.62	0.60
193	X :	8.67	8.38	8.12	7.86	7.36	6.80	6.15	5.69	5.18	4.20
	Y :	3.65	3.53	3.35	3.06	2.16	1.07	0.75	0.69	0.65	0.63

TABLE II (Continued)

Run No.										
196	X :	6.70	7.00	7.16	7.32	7.47	7.56	7.87	8.04	8.27	8.63
	Y :	3.40	3.28	3.12	2.86	2.04	1.04	0.73	0.67	0.64	0.62
197	X :	16.0	16.8	17.1	17.4	17.8	18.2	18.5	18.7	18.9	19.2
	Y :	3.61	3.49	3.31	3.02	2.13	1.05	0.74	0.68	0.64	0.62

EXPERIMENTAL DATA TAKEN FROM OSCILLOGRAMS

TABLE III -- DIFFERENCE IN DENSITY

X - Frame Number position on the film

Y - "Y" deflection of the signal corresponding to location X, inches.

Run No.	X , Y Values									
67	X :	1.50	1.70	1.80	1.90	2.10	2.20	2.30	2.60	3.0 3.3
	Y :	3.64	3.45	3.11	2.63	1.40	0.94	0.74	0.49	0.41 0.37
69	X :	13.7	13.9	14.1	14.2	14.4	14.6	14.7	14.8	14.9 15.0
	Y :	3.78	3.71	3.44	3.01	1.84	1.02	0.80	0.72	0.62 0.58
70	X :	3.40	3.10	2.70	2.00	1.60	1.40	1.25	1.15	0.95 0.70
	Y :	3.34	3.27	3.10	2.76	2.09	1.58	1.24	1.09	0.89 0.81
71	X :	28.3	28.4	28.6	28.9	29.3	29.6	29.8	30.0	30.2 30.6
	Y :	3.64	3.57	3.27	2.80	1.73	1.17	0.95	0.82	0.73 0.656
72	X :	16.7	16.3	15.9	15.4	15.0	14.8	14.6	14.5	14.4 14.2
	Y :	3.36	3.30	3.11	2.83	2.07	1.46	1.02	0.93	0.88 0.83
73	X :	0.90	1.10	1.30	1.40	1.55	1.70	1.80	1.95	2.15 2.30
	Y :	3.60	3.54	3.11	2.73	1.91	1.26	0;96	0.71	0.60 0.565
111	X :	8.40	8.50	8.65	8.75	8.85	8.95	9.0	9.05	9.2 9.32
	Y :	3.66	3.61	3.06	2.28	1.44	0.87	0.66	0.54	0.36 0.318

TABLE III (Continued)

Run No.										
112	X :	16.6	16.0	15.0	14.7	14.5	14.3	14.2	14.1	13.9	13.7
	Y :	3.44	3.32	3.06	2.62	2.16	1.13	0.75	0.56	0.40	0.364
113	X :	25.2	25.0	24.9	24.8	24.7	24.6	24.4	24.3	24.0	23.6
	Y :	3.72	3.58	3.28	2.76	2.02	1.34	0.65	0.51	0.40	0.364
114	X :	17.4	17.7	18.2	18.6	18.9	19.1	19.3	19.4	19.6	19.9
	Y :	3.53	3.50	3.36	3.00	2.60	1.89	1.02	0.78	0.58	0.513
115	X :	12.6	12.4	12.2	11.9	11.8	11.7	11.6	11.5	11.0	10.6
	Y :	3.44	3.34	2.98	1.44	1.00	0.74	0.60	0.49	0.40	0.364
116	X :	4.15	4.5	5.25	6.2	6.5	6.75	6.85	6.95	7.15	7.32
	Y :	3.62	3.58	3.44	2.73	2.02	1.11	0.84	0.68	0.51	0.455
117	X :	43.2	42.8	42.4	42.1	41.7	41.5	41.3	41.0	40.7	40.3
	Y :	3.62	3.55	3.13	2.34	1.16	0.84	0.63	0.51	0.46	0.418
118	X :	24.2	25.0	26.0	27.5	27.9	28.4	28.6	28.8	29.0	29.3
	Y :	2.73	2.66	2.58	2.14	1.87	1.12	0.84	0.66	0.56	0.50
126	X :	33.8	32.9	32.1	31.7	31.4	30.9	30.7	30.6	30.3	30.0
	Y :	2.87	2.78	2.61	2.51	2.32	1.75	1.06	0.80	0.58	0.505
127	X :	36.6	36.8	36.9	37.0	37.1	37.2	37.3	37.4	38.0	38.5
	Y :	3.73	3.63	3.35	2.73	2.02	1.33	1.04	0.92	0.81	0.735
128	X :	20.5	19.9	19.4	18.5	18.1	17.7	17.6	17.5	17.2	16.5
	Y :	4.3	4.24	4.08	3.71	3.20	1.33	1.11	0.92	0.78	0.76

TABLE III (Continued)

Run No.										
129	X :	23.3	23.5	23.7	23.8	23.9	24.0	24.1	24.2	24.3	24.5
	Y :	3.71	3.67	3.22	2.70	1.93	1.33	1.06	0.91	0.84	0.80
130	X :	6.55	6.00	5.25	4.75	4.35	4.10	3.85	3.70	3.65	3.50
	Y :	3.44	3.38	3.16	2.93	2.51	2.11	1.31	0.94	0.87	0.82
131	X :	10.7	10.8	10.9	11.0	11.1	11.2	11.3	11.5	11.6	11.9
	Y :	3.85	3.82	3.67	3.33	2.70	2.02	1.46	1.02	0.96	0.875
132	X :	41.5	41.0	39.0	38.0	37.3	36.7	36.5	36.4	36.2	35.9
	Y :	3.65	3.61	3.50	3.28	2.88	1.98	1.21	0.94	0.74	0.673
139	X :	22.2	22.0	21.9	21.8	21.7	21.6	21.5	21.4	20.9	20.5
	Y :	3.64	3.54	3.28	2.54	1.66	0.86	0.57	0.42	0.33	0.282
140	X :	13.0	13.5	14.5	15.6	15.9	16.2	16.3	16.4	16.6	16.9
	Y :	3.50	3.46	3.33	3.00	2.63	1.64	1.13	1.74	0.44	0.365
141	X :	43.2	43.3	43.5	43.6	43.7	43.8	43.9	44.0	44.1	44.4
	Y :	3.45	3.40	3.05	2.40	1.66	0.98	0.64	0.46	0.38	0.344
142	X :	8.10	7.50	6.75	5.80	5.30	5.10	5.00	4.90	4.75	4.58
	Y :	3.49	3.45	3.32	3.08	2.38	1.60	1.02	0.72	0.50	0.40
143	X :	30.2	30.4	30.5	30.6	30.8	30.9	31.0	31.1	31.5	32.0
	Y :	3.55	3.45	3.30	2.88	1.51	0.96	0.64	0.49	0.38	0.33
144	X :	39.9	38.5	37.2	36.8	36.3	36.2	36.1	36.0	35.9	35.6
	Y :	3.50	3.44	3.18	2.78	1.16	0.76	0.54	0.42	0.36	0.328

TABLE III (Continued)

Run No.										
145	X : 17.2	17.3	17.5	17.7	17.8	17.9	18.0	18.2	18.5	19.0
	Y : 3.45	3.40	3.24	2.38	1.75	1.14	0.74	0.46	0.37	0.328
146	X : 26.9	26.0	25.0	24.0	23.5	23.3	23.1	23.0	22.8	22.7
	Y : 3.36	3.30	3.18	2.96	2.40	1.86	1.07	0.76	0.51	0.473
178	X : 29.7	29.8	29.9	30.0	30.1	30.2	30.3	30.4	30.5	30.7
	Y : 3.22	3.18	2.98	2.33	1.69	1.15	0.80	0.62	0.54	0.45
179	X : 36.8	36.5	36.3	36.2	36.1	36.0	35.9	35.8	35.7	35.5
	Y : 2.93	2.88	2.72	2.51	2.08	1.51	1.04	0.70	0.53	0.436
180	X : 16.3	16.5	16.6	16.7	16.9	17.0	17.1	17.2	17.4	17.7
	Y : 3.31	3.26	3.19	2.88	1.54	1.09	0.78	0.63	0.52	0.465
181	X : 23.5	23.3	23.1	22.9	22.8	22.7	22.6	22.5	22.4	22.2
	Y : 2.95	2.90	2.78	2.34	1.88	1.38	0.95	0.69	0.56	0.455
182	X : 3.52	3.65	3.75	3.90	4.05	4.15	4.25	4.35	4.50	4.72
	Y : 2.96	2.91	2.80	2.17	1.34	0.96	0.72	0.60	0.51	0.455
183	X : 10.7	10.5	10.3	10.1	10.0	9.8	9.7	9.6	9.45	9.20
	Y : 2.84	2.80	2.70	2.31	1.91	1.02	0.74	0.56	0.45	0.42
200	X : 15.1	14.9	14.8	14.6	14.2	14.0	13.8	13.6	13.3	12.8
	Y : 3.48	3.35	3.13	2.48	1.17	0.89	0.71	0.60	0.52	0.478
201	X : 41.8	41.6	41.4	41.2	40.8	40.7	40.6	40.4	40.2	40.0
	Y : 3.35	3.30	3.13	2.75	1.35	1.11	0.91	0.63	0.50	0.43

TABLE III (Continued)

Run No.										
202	X :	28.7	28.9	29.0	29.1	29.5	29.6	29.8	30.0	30.2	30.4
	Y :	3.33	3.24	3.00	2.61	1.07	0.89	0.68	0.57	0.51	0.49
203	X :	16.5	16.3	16.2	16.1	16.0	15.8	15.7	15.5	15.4	15.2
	Y :	2.96	2.88	2.75	2.49	2.12	1.32	1.04	0.62	0.52	0.39
204	X :	47.0	47.2	47.3	47.4	47.6	47.8	48.0	48.1	48.3	48.7
	Y :	3.34	3.28	3.15	2.78	1.78	1.13	0.78	0.69	0.57	0.51
205	X :	34.3	34.1	33.9	33.8	33.5	33.4	33.3	33.2	33.1	33.0
	Y :	2.98	2.91	2.67	2.38	1.14	0.87	0.67	0.53	0.44	0.385

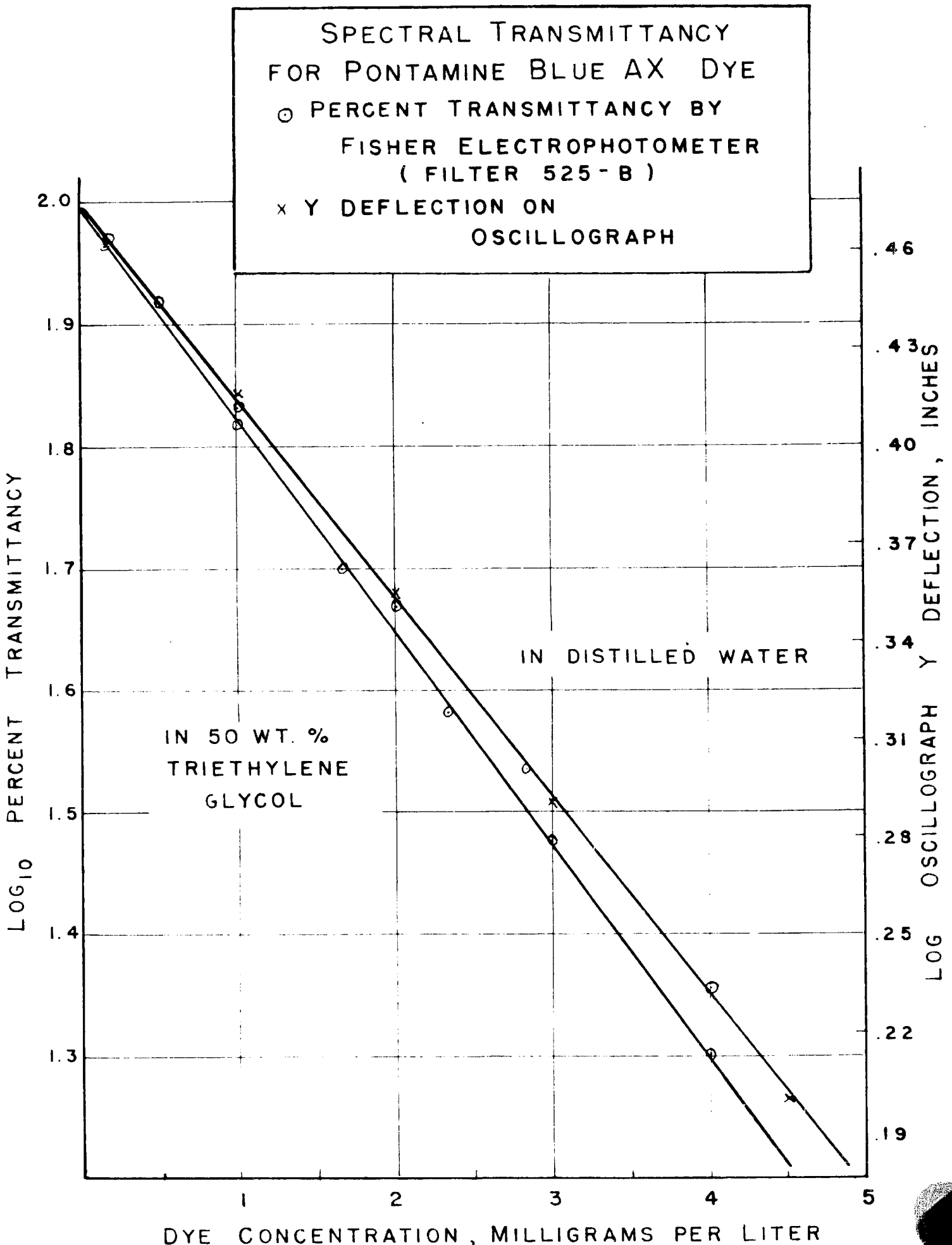

SPECTRAL TRANSMITTANCY
FOR PONTAMINE BLUE AX DYE
⊙ PERCENT TRANSMITTANCY BY
FISHER ELECTROPHOTOMETER
(FILTER 525-B)
× Y DEFLECTION ON
OSCILLOGRAPH
IN DISTILLED WATER
IN 50 WT. %
TRIETHYLENE
GLYCOL
LOG10 PERCENT TRANSMITTANCY
LOG OSCILLOGRAPH Y DEFLECTION, INCHES
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
.46
.43
.40
.37
.34
.31
.28
.25
.22
.19
1
2
3
4
5
DYE CONCENTRATION, MILLIGRAMS PER LITER

FIGURE 25

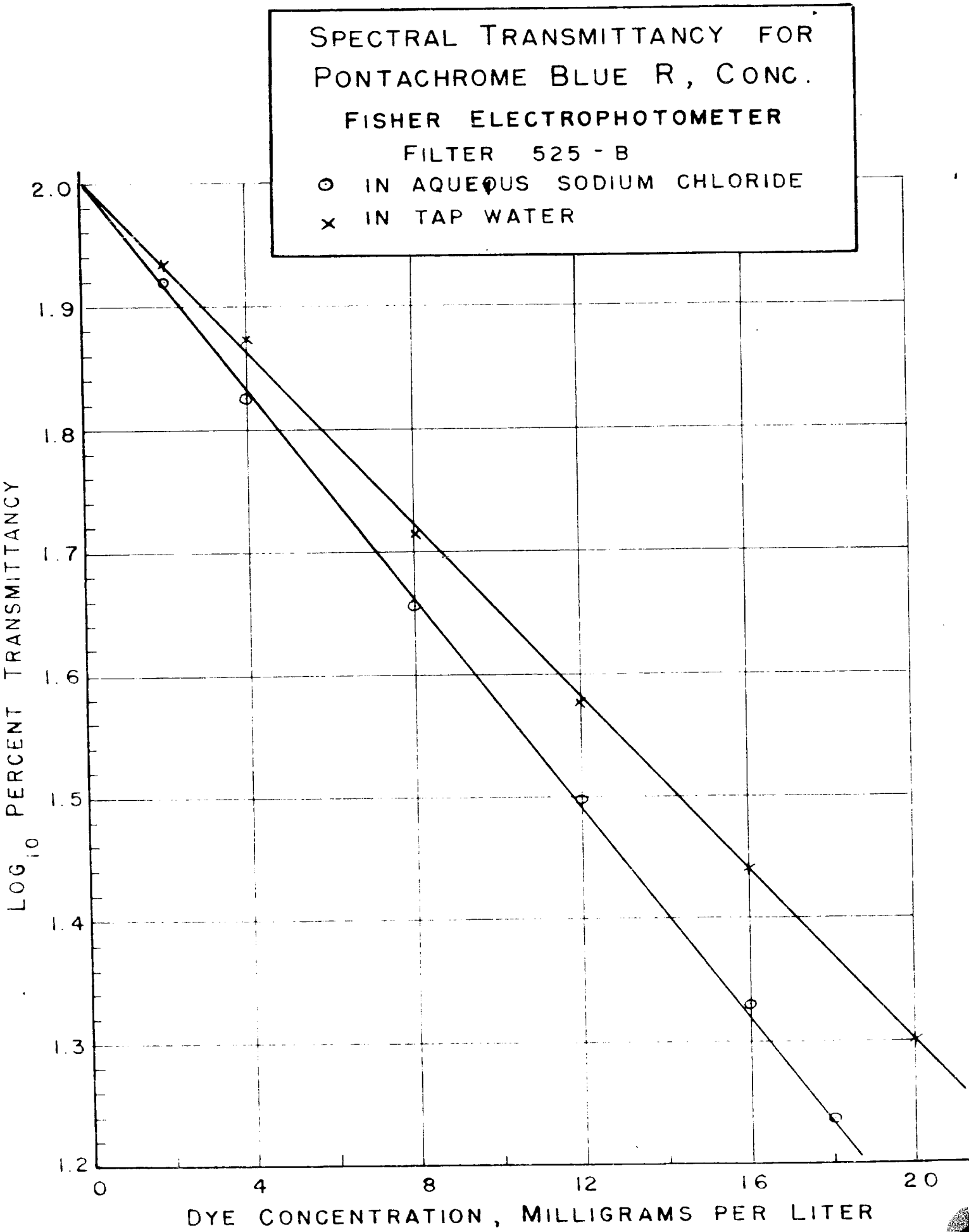

SPECTRAL TRANSMITTANCY FOR
PONTACHROME BLUE R, CONC.
FISHER ELECTROPHOTOMETER
FILTER 525 - B
IN AQUEOUS SODIUM CHLORIDE
IN TAP WATER
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
LOG10 PERCENT TRANSMITTANCY
0
4
8
12
16
20
DYE CONCENTRATION, MILLIGRAMS PER LITER

FIGURE 26

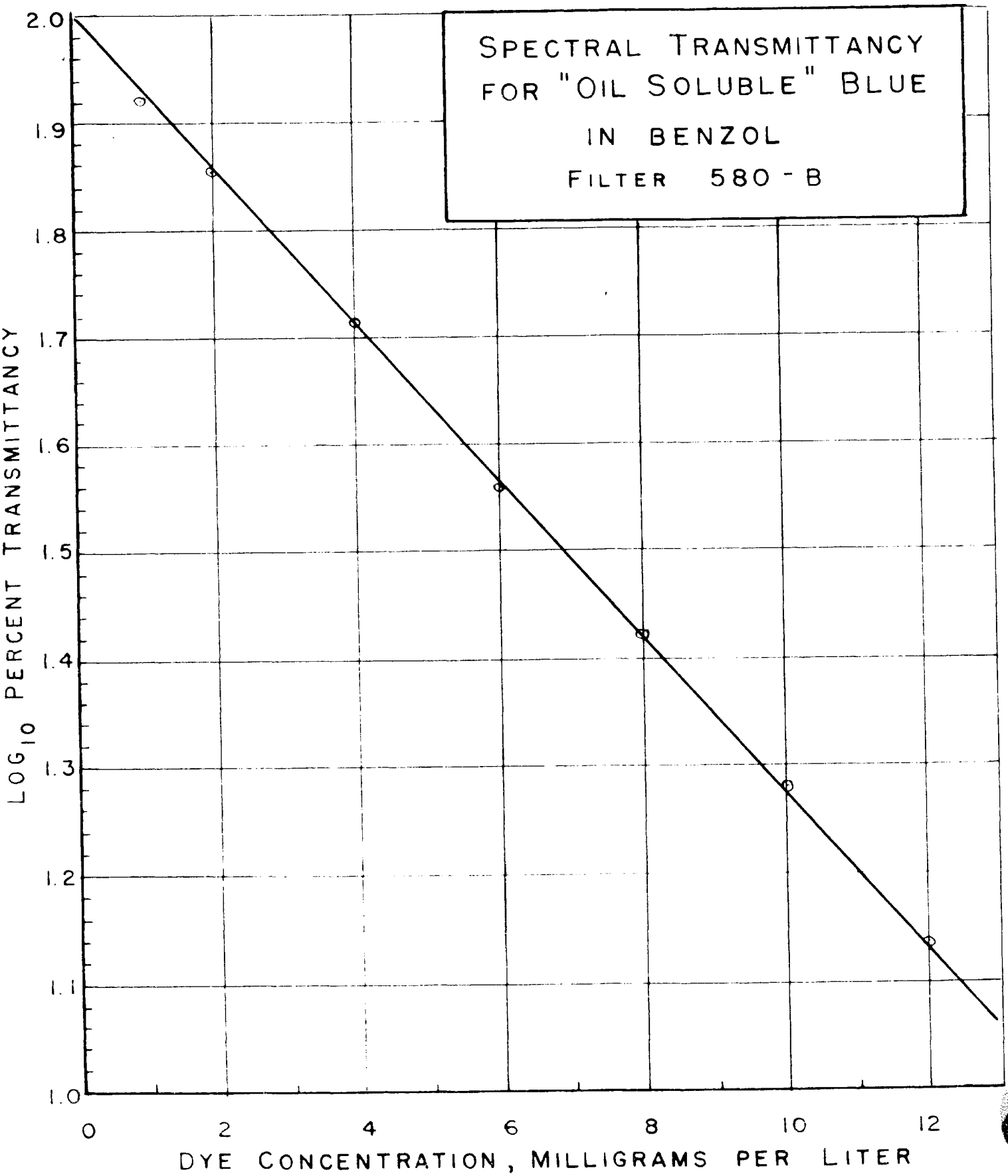

SPECTRAL TRANSMITTANCY
FOR "OIL SOLUBLE" BLUE
IN BENZOL
FILTER 580 - B
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
LOG10 PERCENT TRANSMITTANCY
0
2
4
6
8
10
12
DYE CONCENTRATION, MILLIGRAMS PER LITER

FIGURE 27

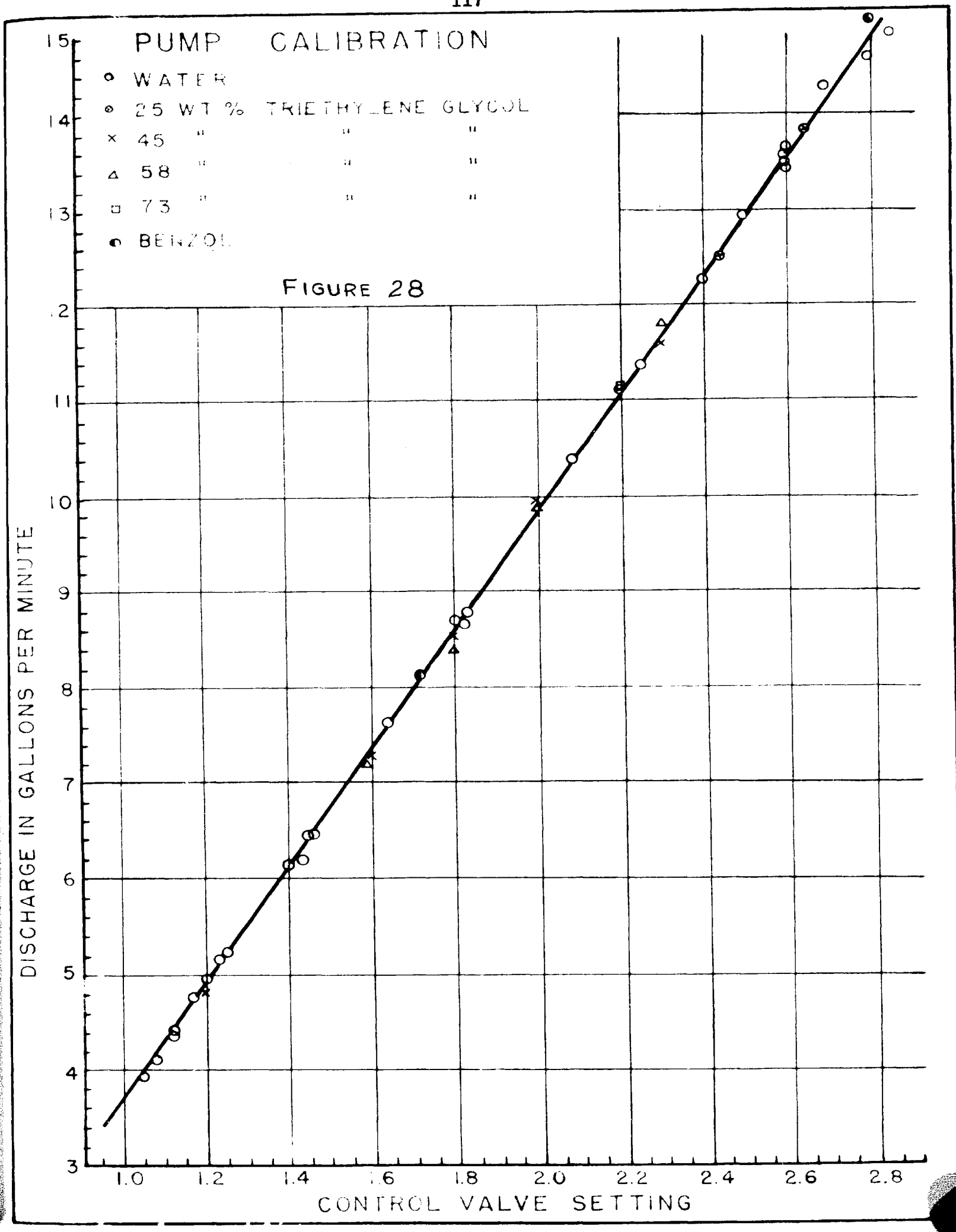

PUMP CALIBRATION
WATER
25 WT % TRIETHYLENE GLYCOL
45 " " "
58 " " "
73 " " "
BENZOL
DISCHARGE IN GALLONS PER MINUTE
CONTROL VALVE SETTING
15
14
13
12
11
10
9
8
7
6
5
4
3
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8

FIGURE 28

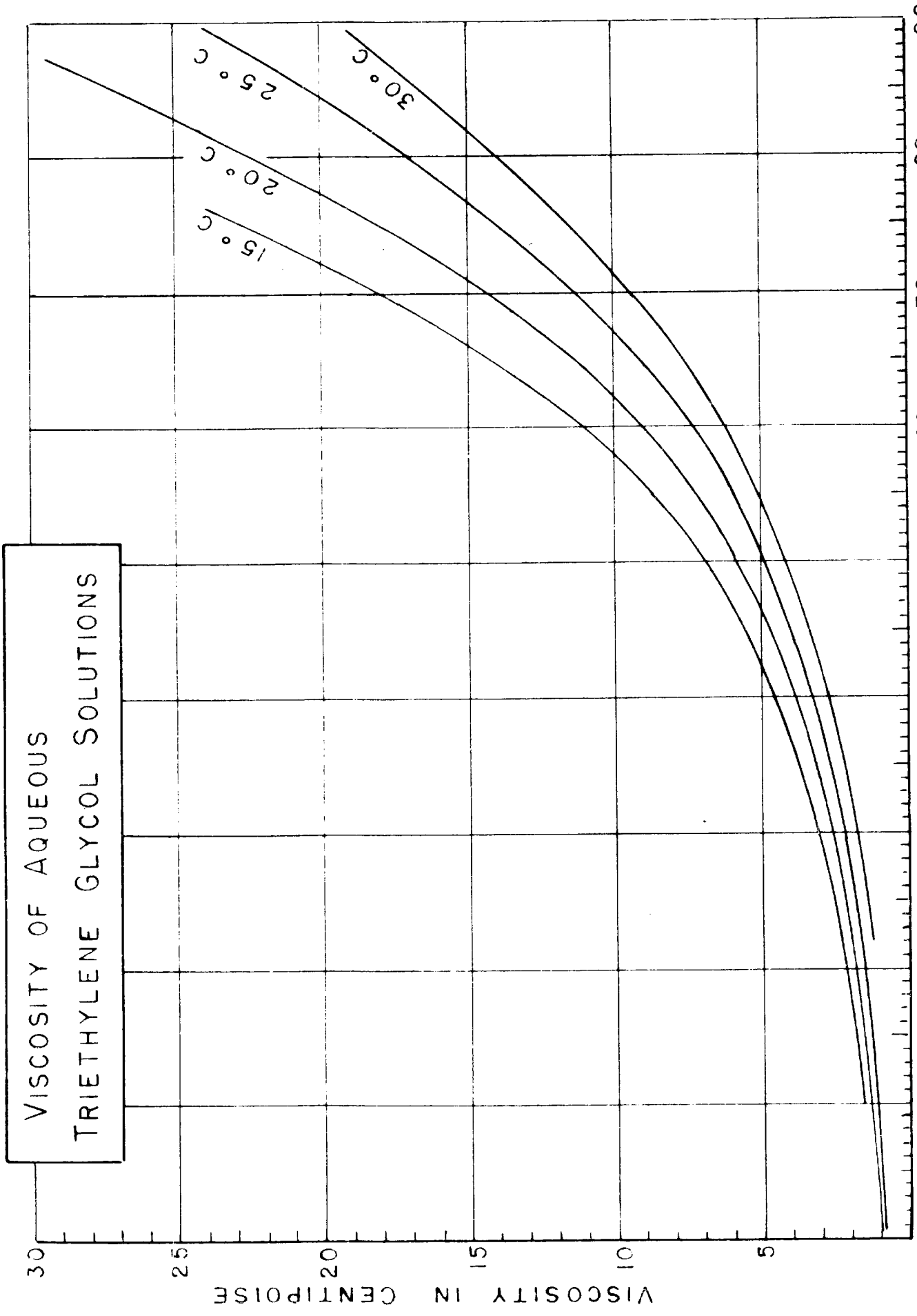

VISCOSITY OF AQUEOUS
TRIETHYLENE GLYCOL SOLUTIONS
15° C
20° C
25° C
30° C
VISCOSITY IN CENTIPOISE
0
5
10
15
20
25
30
10
20
30
40
50
60
70
80
90
WEIGHT % TRIETHYLENE GLYCOL

FIGURE 29

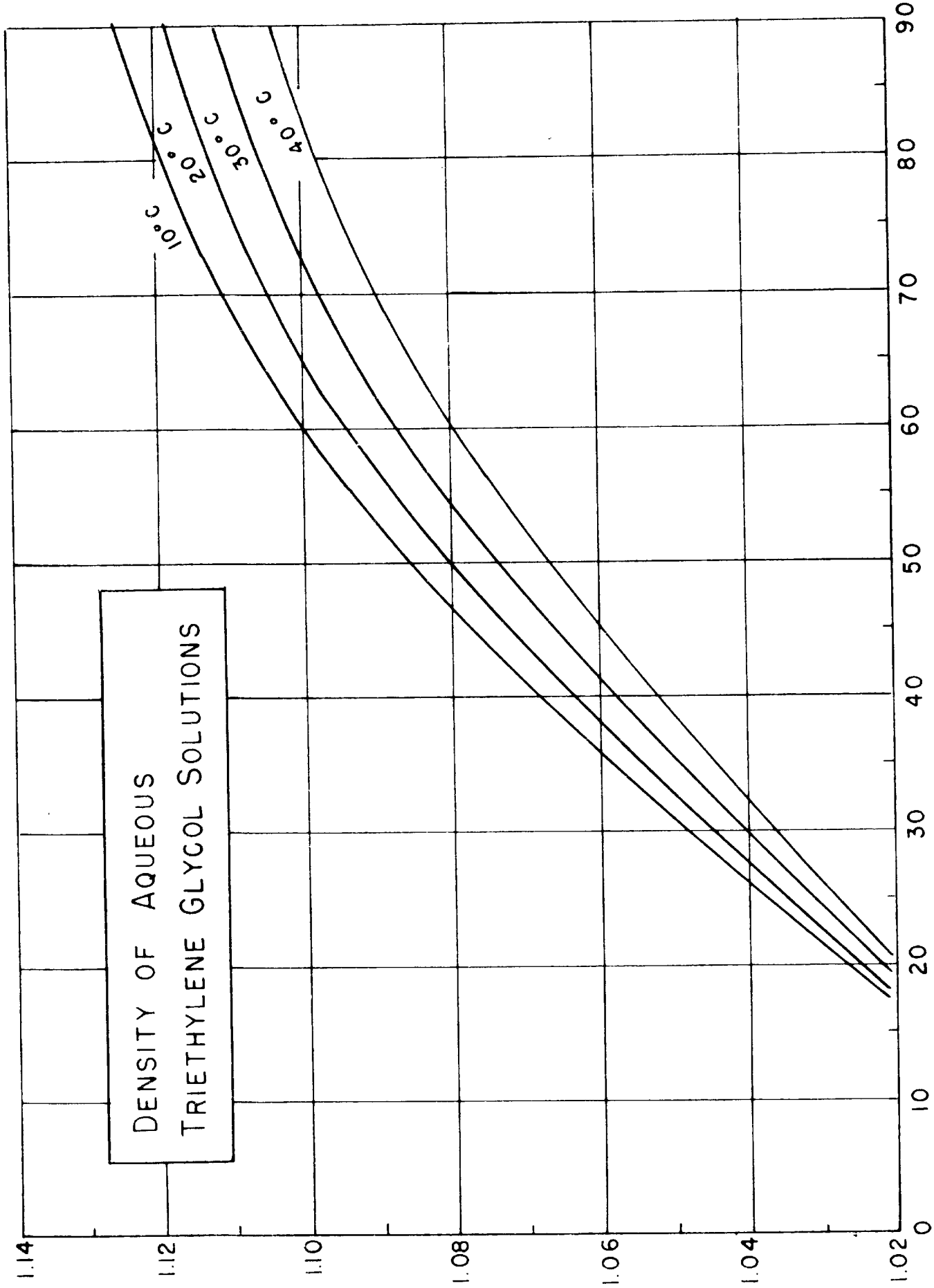
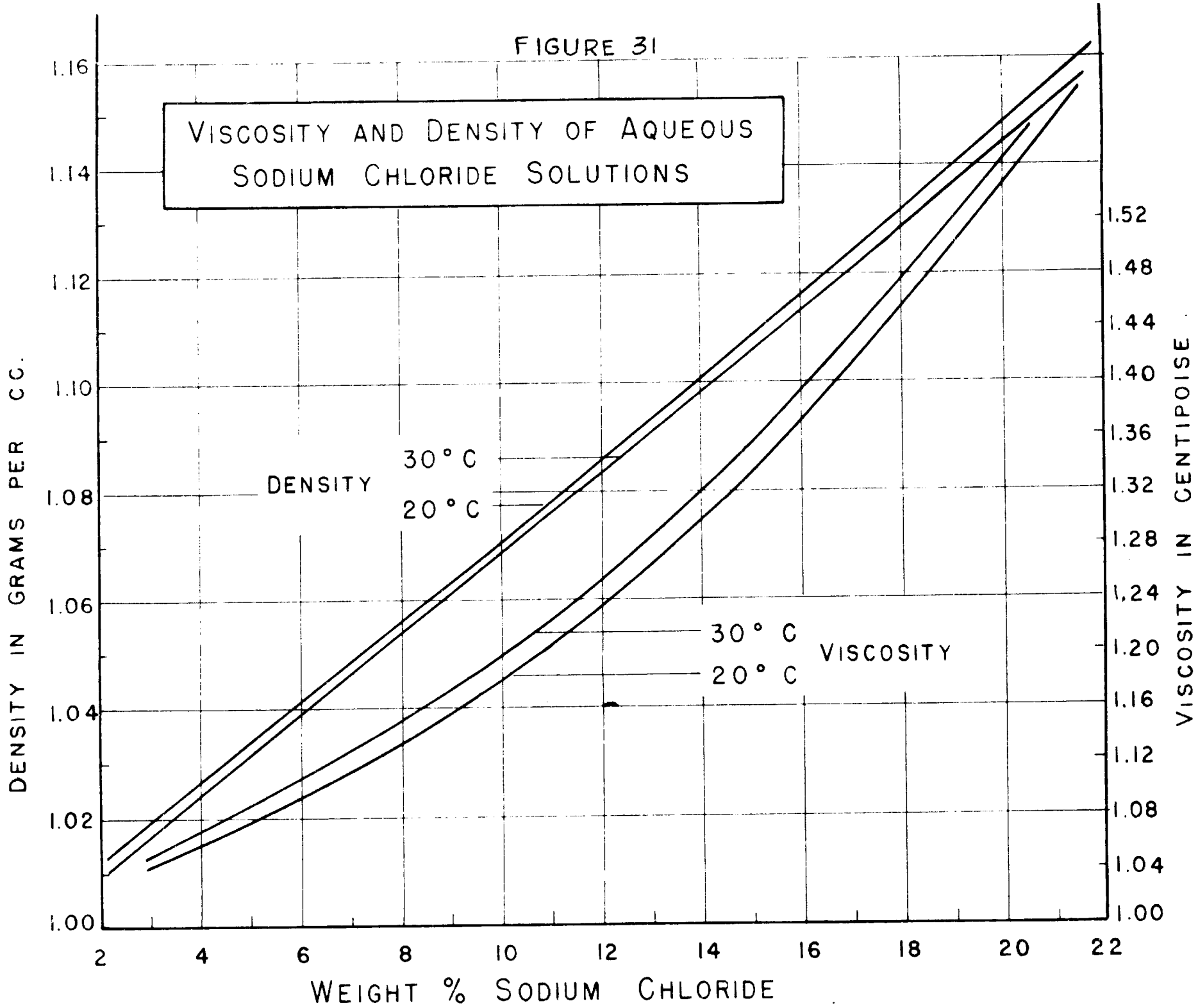

DENSITY OF AQUEOUS
TRIETHYLENE GLYCOL SOLUTIONS
10° C
20° C
30° C
40° C
DENSITY, GRAMS PER C.C.
1.14
1.12
1.10
1.08
1.06
1.04
1.02
0
10
20
30
40
50
60
70
80
90
WEIGHT % TRIETHYLENE GLYCOL

FIGURE 30

FIGURE 31


VISCOSITY AND DENSITY OF AQUEOUS SODIUM CHLORIDE SOLUTIONS
DENSITY
30° C
20° C
VISCOSITY
30° C
20° C
DENSITY IN GRAMS PER CC.
VISCOSITY IN CENTIPOISE
1.16
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
1.52
1.48
1.44
1.40
1.36
1.32
1.28
1.24
1.20
1.16
1.12
1.08
1.04
1.00
2
4
6
8
10
12
14
16
18
20
22
WEIGHT % SODIUM CHLORIDE

NOMENCLATURE

A, B, C	=	constants
d	=	thickness of laminar film, inches
D	=	inside diameter of pipe line, inches
M	=	mixed portion, percent of pipe volume
Re	=	Reynolds Number
X	=	frame number of the oscillogram
Y	=	oscillograph signal deflection, inches
f	=	friction factor, Stanton Diagram

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