AN INVESTIGATION OF THE VORTEX THICKENER AS A POSSIBLE MEANS OF LIQUID-LIQUID SEPARATION

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SEPARATION

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PREFACE

Although a significant amount of research has been done, prior to the present time, both on the vortex thickener, particularly in the field of solid-fluid separation, and the separation of unstable macro-molecular two-liquid systems, no indication of work correlating liquid-liquid separation with the vortex thickener has been found. The object of this investigation, then, is to determine, by means of a laboratory analysis whether the vortex thickener might be used to separate two interspersed immiscible liquids.

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LIST OF SYMBOLS AND ABBREVIATIONS

A_{of}	Area of Overflow Orifice
A_{uf}	Area of Underflow Orifice
A_{in}	Area of Input Orifice
P	Pressure Differential Across Cyclone $(P_1 - P_2)$
P_1	Input Pressure to Cyclone
P_2	Exhaust Pressure
μc	Viscosity of Continuous Phase
μd	Viscosity of Discontinuous Phase
$\Delta \rho$	Difference of Density of Continuous and Discontinuous Phase
sp gr	Specific Gravity
Ti	Interfacial Tension between Phases
T_s	Surface Tension
%B	Index of Brine Concentration in Underflow
%R	Index of Brine Removal from Total Throughput
Qt	Total Flow Rate in Gallons per Minute
Qu	Underflow Flow Rate in Gallons per Minute
Qo	Overflow Flow Rate in Gallons per Minute
r_o	Radius of Cone Wall at Any Axial Position
r	Any Radius Inside the Cone Wall
V_t	Tangential Velocity
V_r	Radial Velocity

V_z	Vertical Velocity
F_c	Centrifugal Force
W_t	Total Net Weight of Underflow Product
W_k	Specific Weight of the Kerosene in Pounds per Gallon
W_b	Specific Weight of the Brine in Pounds per Gallon
V_u	Total Underflow Volume Flowed in One Run
$V_{u'}$	Underflow Volume Taken During the Timed Portion of the Run
R_b	Ratio of Brine to the Total Volume

CHAPTER I

INTRODUCTION

The cyclone separator, or vortex thickener as it is more formally named, has two principal functions. Perhaps the most widespread is that of removing undesirable foreign particles from a fluid, either liquid or gas, in which they are entrained. A classic example of this application, and certainly one of the oldest, is the fly-ash collector operating in conjunction with the coal-fired furnace. Another example is the separation of the abrasive cuttings and sands from rotary drilling muds which would materially reduce bit life and cause excessive abrasion on the associated drilling equipment, if not removed. In a somewhat more limited scope, the cyclone separator has found usage in the removal of liquid droplets entrained in the flow of certain gases.

The other principal function is to remove excess liquids from solid-liquid slurries. This particular use of the cyclone is in evidence in the mining industry in which the cyclone is used to concentrate the minerals present in the slurry received from flotation processes.

It is seen that cyclone applications, at present, may be divided into three general classifications:

1. Solids from Liquid Separation
2. Liquid from Gas Separation
3. Solids from Gas Separation

A fourth possible classification, the subject of this investigation, might possibly be liquid from liquid separation. If such an application is possible, it could be used to good advantage in the different phases of petroleum production and refining. In the oil field the cyclone might possibly be used to remove free and loosely emulsified water from the crude petroleum, as it comes from the wells. In the refinery it might be used in applications demanding the extraction of water from organic compounds.

Another possible use might be that of removing water from different fuels, particularly in the field of jet aviation where the presence of water in the fuel system is disastrous.

It must be realized that a single cyclone might not be capable of obtaining a separation efficiency that would merit its use in any of the above applications. However, it has been found that several cyclones can be used in series, with the overflow of one exhausting into the input of another, to produce the needed efficiency.

Some of the present means of effecting a separation of two immiscible fluids include the centrifuge, the settling tank, and a more recent innovation, the porous membrane filter. The use of the centrifuge seems occasionally to be undesirable because of financial considerations. The settling tank, while effective, is slow and in some cases too bulky. The porous membrane filter, from the initial research that has been done in that field, would seem to be reasonably satisfactory for many particular applications. A thorough treatment of this latter means of separation is given by G. V. Jordan, Jr. (1).

CHAPTER II

PREVIOUS INVESTIGATION

No evidence was found that any work has been published relative to the proposed investigation. There have been published, however, many general papers on cyclone theory, design, and operation. Since there are a number of different cyclones in production, uniformity of test results can not, of course, be expected. The papers do show some correlation on the general theory.

A very rigorous and complete treatment of cyclone theory, with respect to both particle motion and fluid motion, is given by H. E. Criner. (2). The author first discusses the fluid velocity fields in the separator, and then the particle motion. The velocities in a two-dimensional cylindrical vortex are derived taking into account the effect of the 'turbulent viscosity' and radial flow. The values for the axial velocities are then approximated by recognizing the fact that the radial flow at each axial cross section must be constant, and by the use of an approximating hyperbolic axial velocity distribution. The paths of solid particles suspended in the fluid are derived from the fluid velocities and the velocities of the particles with respect to the fluid. The influence of particle volumetric concentration on the particle velocity relative to the fluid is taken into account.

Driessen, (3), gives data and curves on actual cyclone tests conducted in his laboratory, and also a thorough mathematical analysis. The theory of the flow in a cyclone is discussed under the assumption that it can be compared with an ideal sink in a nonviscous fluid. The Navier-Stokes equations, in polar coordinates, are used to obtain a first approximation considering the effect of viscosity on the maximum tangential velocity near the cyclone core. For the velocities of small particles in media under the influence of centrifugal forces, plots are designed which give the solutions for a certain range of particle sizes and velocities that are impossible to calculate by an exact equation.

CHAPTER III

CYCLONE THEORY

Fluid Motion

A cyclone of typical construction is illustrated in Figure 1, with the various orifices labeled. Cyclones are made in several shapes but the conical cyclone, shown with its arrangement of openings, is probably the more common and is the type to be employed in the laboratory tests. The included angle of the cone varies with manufacturers with the more common values ranging from 10 to 60 degrees.

In operation the fluid is pumped in through the input orifice tangentially to the wall of the vessel, thus imparting a normal acceleration. Since the fluid enters at the perimeter of the cone at one vertical level and

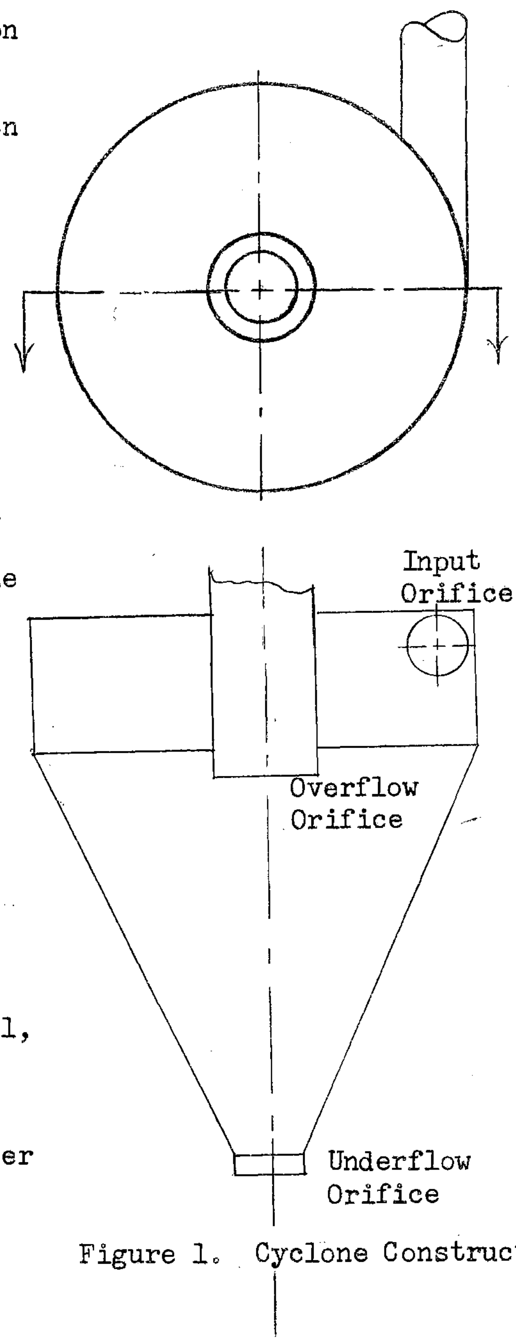

Figure 1. Cyclone Construction

leaves through the center of the cone at two other levels, it is seen that the motion of any one element of fluid may be represented by the resultant of three different velocity vectors. These motions are illustrated in the flow diagram of Figure 2. (2).

First, there is a tangential velocity, V_t, which is determined, at the perimeter of the cone, principally by the geometry of the input orifice and the pressure drop across the cyclone. For a Newtonian fluid the tangential velocity at any point would be inversely proportional to the radius of that element from the center of the cone. Driessen (3) found that for kinematic viscosities in the vicinity of one centipoise irrotational flow may be assumed to be present in a cyclone.

The movement of the fluid along the vertical axis of the cone is denoted by V_z and the velocity of the fluid in toward the center of the cone is given by V_r. The flow pattern illustrated on the left side of the diagram is the flow brought about by the

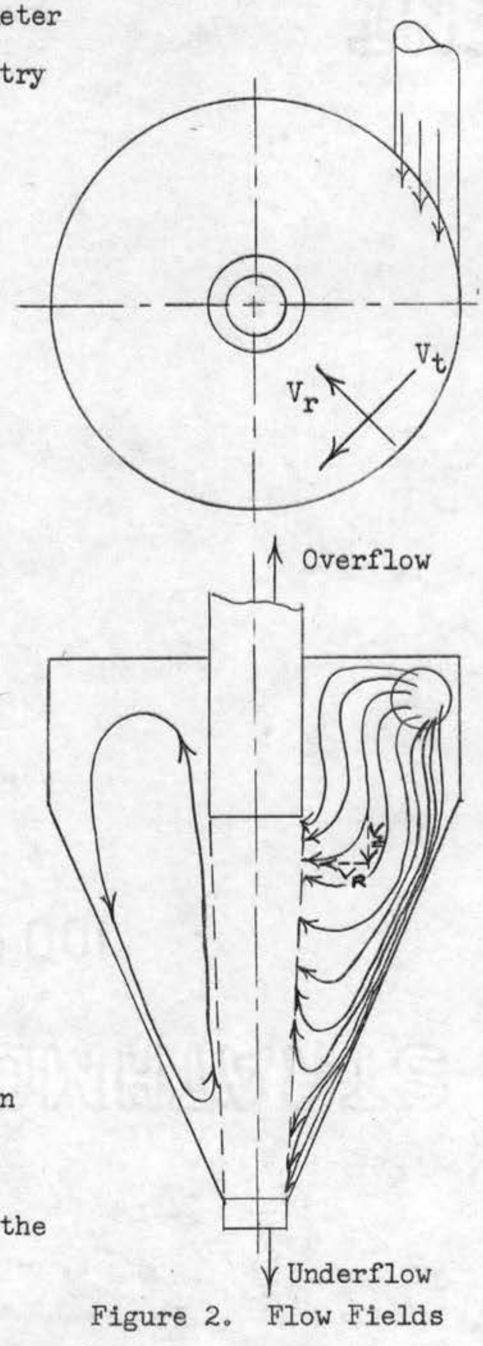

Figure 2. Flow Fields

large energy losses in the tip of the cone where the fluid velocity is very high, adjacent to the boundary of the cone. This flow component tends to keep the kinetic energy level constant over the entire vertical axis at any radius. (2).

The diameter of the air core is determined mainly by the diameter of the overflow orifice. This core always exists if the cyclone is operating properly, although it might not extend to the underflow, and is usually at lower than atmospheric pressure. Because of this, air is continually drawn in through the underflow orifice and exhausted through the overflow, along with the fluid.

Particle Motion

At any location in the cyclone flow field, a foreign particle entrained in the fluid medium will be subjected to two different forces in addition to that of gravity. One of these is the drag force exerted upon the particle by the difference in velocities of the particle and the surrounding fluid. The other is the centrifugal force due to the angular velocity about the center of the cone. In most cases, for small cyclones, the magnitude of the centrifugal force is so much greater than that of gravity, the gravity force is negligible and the cyclone can be operated satisfactorily in any position, even upside-down.

Assuming irrotational flow to be existent in a cyclone, the angular velocity may be expressed:

$$\omega = c\,\frac{1}{r}$$

where c is a constant and r is the distance from the center of the cone. The centrifugal force may then be expressed:

$$F_c = \frac{C_1}{r}$$

in which C_1 is a constant including the mass of the element under consideration and c^2. From this latter equation it is seen that the centrifugal force varies with the reciprocal of the distance from the center. Therefore, at some distance from the center of the cone the centrifugal force will become equal in magnitude to the drag force exerted on the particle by the V_r component of the velocity, opposite to the direction of the velocity, and the motion of the particle will be arrested. The distance from the center of this arrestment of the motion will depend upon the difference of densities of the particle and fluid medium and the size of the particle. The particle will then be moved in a vertical plane, the direction of which is dependent upon the direction of the fluid flow, V_z, at the point where the radial motion is arrested. The motion of the heavier particles will be arrested in the outside downward-moving layer of fluid and thus they will be carried through the underflow. The lighter particles will be arrested nearer the center of the cone, possibly in the upward moving layer of fluid, and the lightest ones may not be arrested until they impinge upon the turbulent core. At any rate, there is no clear-cut boundary on one of whose sides the particles are transported downward, and on the other side, upward. In actual practice, it has been found that particles of many different sizes will exist both in the underflow and overflow. Thus the cyclone is not actually a separator but a thickener or classifier, concentrating the heavier particles in the underflow and the lighter ones in the overflow, with both products containing particles of a transitional size range.

CHAPTER IV

STATEMENT OF PROBLEM

The objective of this investigation is to determine whether the cyclone separator can be used to separate two designated immiscible fluids combined in the form of an unstable emulsion.

Due to the mathematically indeterminate characteristics of portions of the cyclone flow, an analytical attack of the problem is not probable. Therefore, laboratory research will be utilized as the vehicle of investigation. The variables to be used, and also the predictions of the results, will have to be dictated by an analogy of the fluid globule of the disperse phase, to the solid particle of the solid-liquid separation system. The problem, then, will be to obtain a two fluid system as similar to the solid-liquid system as possible, within limits of practicality, so an analogy can be drawn.

CHAPTER V

ANALYSIS OF PROBLEM

It has been stated earlier, in this investigation, that the variables to be utilized in the laboratory tests would be dictated by an analogy of the fluid disperse phase particles to the solid particles in the solid-liquid separation system. In this analysis, then, an attempt will be made to deduce what the optimum two-fluid system might be for good separation in the cyclone. In the event that this optimum system can not be separated in the cyclone, then, of course, it would be useless to try to effect a separation of other two-fluid systems of less suitable characteristics.

It has been proved in numerous investigations that the separation efficiency of a cyclone is determined largely by the difference of densities of the solid particle and the fluid phase. The reason for this is explained in the preceding theory. The first requisite for the two-fluid system then, will be that the two fluids have as great a difference in densities as possible.

Another factor contributing to a high separation efficiency in the solid-liquid cyclone is the utilization of large particles. A large disperse phase globule size should be assured, as the fluid counterpart of the solid particle, with the use of a fluid-fluid system with high interfacial tension and a disperse phase with a high surface tension. Also, since the disperse phase is a fluid with a high surface tension, the globules will have a stronger tendency to coalesce or flocculate. At this point, however, a potentially great deterrent to this analogy becomes apparent. At all points in the cyclone flow field, shear, in varying magnitudes, is present. Also, in a few localized areas of the flow, high turbulence is in evidence. The effect of shear forces on a liquid globule is to fracture the globule into several smaller ones. In fact, this is the very principle upon which emulsifying equipment is designed and operated. One obvious means of circumventing this difficulty is to reduce the magnitude of shear force by reducing the tangential velocities. This is accomplished by a decrease in the pressure differential across the cyclone. Since the object is to obtain optimum conditions for effecting separation of a singular two-fluid system, a second method may be entertained, to offset the effect of the shear forces. This is to use a disperse fluid globule which should have a high resistance to shear, or in more direct terms, a high viscosity. This can be further realized by the reasoning that a fluid of infinite viscosity is a solid.

At this point it might be well to mention that a separation of two fluids would almost certainly be impossible to accomplish if the fluids possess an affinity toward stable emulsification. Also, in this same line, it must be mentioned that in some cases solid impurities might tend to stabilize any emulsion which might be formed.

To meet the requirements of a large density differential, a high interfacial tension, a high surface tension of the disperse phase, and high viscosity of the disperse phase, kerosene, sp gr .79 at 80°F was chosen as the continuous phase, and calcium chloride brine, sp gr 1.26 at 80°F was chosen as the disperse phase.

To comply with the requirement for low velocities, the input pressure will be varied in a range below the rated operating pressure of the commercially built cyclone to be used, for the purpose of determining the optimum pressure, if any exists, for maximum brine concentration in the underflow product. The percentage of brine in the underflow, by volume, will be the principal dependent variable. The other will be the percentage of the total brine, removed in the underflow.

The other independent variable to be used is the area of the underflow orifice. This variable was chosen for the reason that it has, probably, the greatest effect on the qualitative and quantitative characteristics of the underflow product.

CHAPTER VI

PRELIMINARY LABORATORY RESEARCH

A laboratory analysis was made of the two fluids proposed for the tests to determine their relative compatibility. Calcium chloride brine, sp gr 1.26, and kerosene, sp gr .79, were mixed with a high-speed laboratory mixer, in volumes of one to four, respectively. At the termination of a run of 30 minutes, no foaming was evidenced. An analysis made under a microscope with a graduated eyepiece showed a very slight degree of emulsification, the brine globules being approximately 1 micron in diameter and dispersed widely. A 30 minute run in a 6-inch centrifuge at 2200 rpm removed virtually all the entrained brine globules. On a subsequent examination of the kerosene under a magnification of 440, no brine globules were visible.

The mixture was then left in an open beaker for a period of a week. At the end of this time no reaction or change seemed to have taken place since no products were visible at the interface.

In the remaining test, one specimen each of zinc, aluminum, and rubber, since these are to be the materials encountered in the test apparatus, were placed in a beaker of the calcium chloride brine for a period of a week. At the end of this time, no corrosion, or other damage was visible in the specimens.

It can be concluded from these results that the calcium chloride-kerosene system will lend itself to this application satisfactorily with respect to resistance to emulsification, chemical stability and general cleanliness.

CHAPTER VII

PROCEDURE

Two different means of running the experiments were tried before the actual runs were begun. To begin a run, with the first method, the mixer and pump were started while the full output of the pump was shunted back into the mixing tank where it served to aid the mixing process by creating turbulence in the corners of the tank. As soon as a visual check indicated that the brine was evenly dispersed through the kerosene, a condition shown by uniform color of the mixture, the input valve to the cyclone was opened slowly to its full-open position. The input pressure was then set by slowly closing the shunt valve until the intake gage read the predetermined pressure for that run. The timed portion of the run was then begun by starting the time simultaneously with the opening of the underflow flap-valve and the shunting of the overflow to the overflow tank. The duration of the run was governed by an arbitrary constant volume of fluid pumped for each combination of parameters. When this volume was pumped from the storage tank, the time was stopped as the underflow flap-valve was closed and the overflow shunted back to the mixing tank. Then, with the pump still running and thereby holding a vacuum in the cyclone core, the volume and weight of the underflow product was then taken. After this final step, the pump and mixer were stopped, all valves closed, except the underflow valve which was opened to drain the cyclone, and the tanks drained by gravity back into the mixing tank.

During the run three mixture samples were taken from a bleed line on the input line to the cyclone. This arrangement proved unsatisfactory, however, since the acceleration of the fluid around the elbow where the bleed line was connected was thought to have a centrifuging effect upon the mixture and thus moved the brine to the outside where it was picked up by the bleed line, as was evidenced by abnormally low kerosene to brine ratios.

Another bleed line was then installed on the casing of the centrifugal pump, at the exhaust pressure tap. At this location the dispersion proved to be well-mixed and the readings seemed to be of a more consistent nature.

At the termination of several sets of formal runs it was seen that for some reason the data were not too consistent. This necessitated a modification of the test procedure. It was found, upon analysis of the cyclone contents, that while the underflow valve was closed, awaiting the start of the timed run, the brine concentration seemed to build up in the cyclone to a value above the input ratio. Then when the valve was opened, the first few gallons might conceivably be almost pure brine. For this reason the "floating beam" method of collection was inaugurated. The underflow drain tank valve was left open as was the underflow flap-valve, until the proper operating constants were reached. A predetermined tare was then placed on the beam of the scales and the drain valve closed. When the beam of the scale rose, the time was started simultaneously with the shunting of the overflow product to the overflow tank. The remainder of the method was identical to that outlined above. This latter method proved to be slightly more satisfactory, even though no radical change in results was noted.

CHAPTER VIII

DISCUSSION OF APPARATUS

The schematic diagram of the test apparatus is designated by Figure 3 with the actual arrangement of the components illustrated by Figures 4 and 5, photographs of the completed installation. An electric powered mixer, built especially for this project, was utilized to maintain the brine and kerosene in the state of an unstable emulsion inside the storage tank. The design of the mixer had to be undertaken judiciously in order that a high mixing capacity might be obtained without the danger of having air mixed in also. The placement of the mixer was effected so as not to create vortices in the tank, a condition resulting in aeration of the fluid.

A single-stage electrically driven centrifugal pump was used to force the mixture through the cyclone. Input pressure control of the cyclone was brought about by means of a shunt line which returned a portion of the pump output to the storage tank. This latter fact was exploited for the purpose of increasing the turbulence in the storage tank.

Since all runs were made at as constant as possible temperature, a thermometer well in the input line to the cyclone was necessitated. Another was supplied in the overflow line to determine if the cyclone

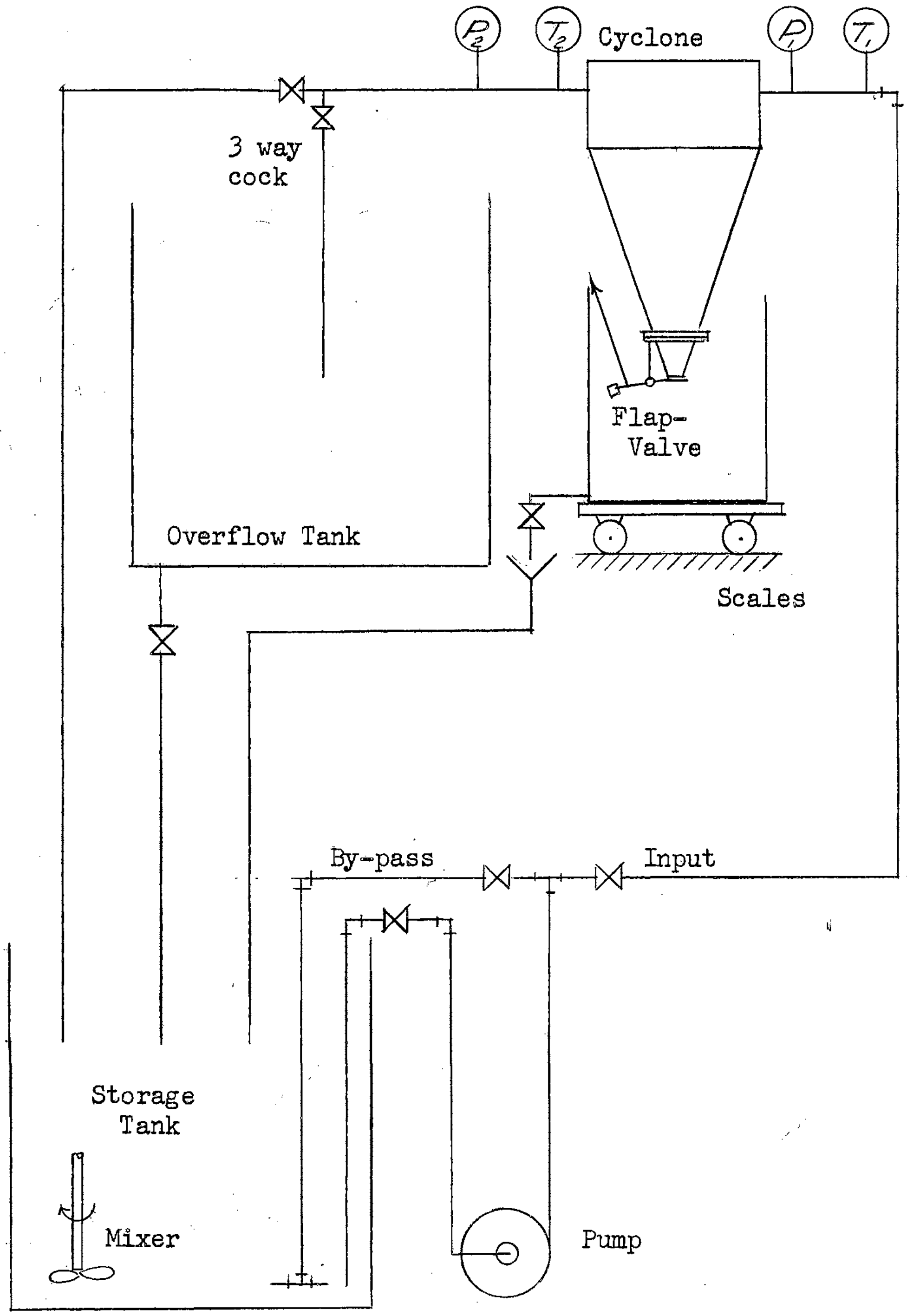

Figure 3. Schematic Diagram of Apparatus

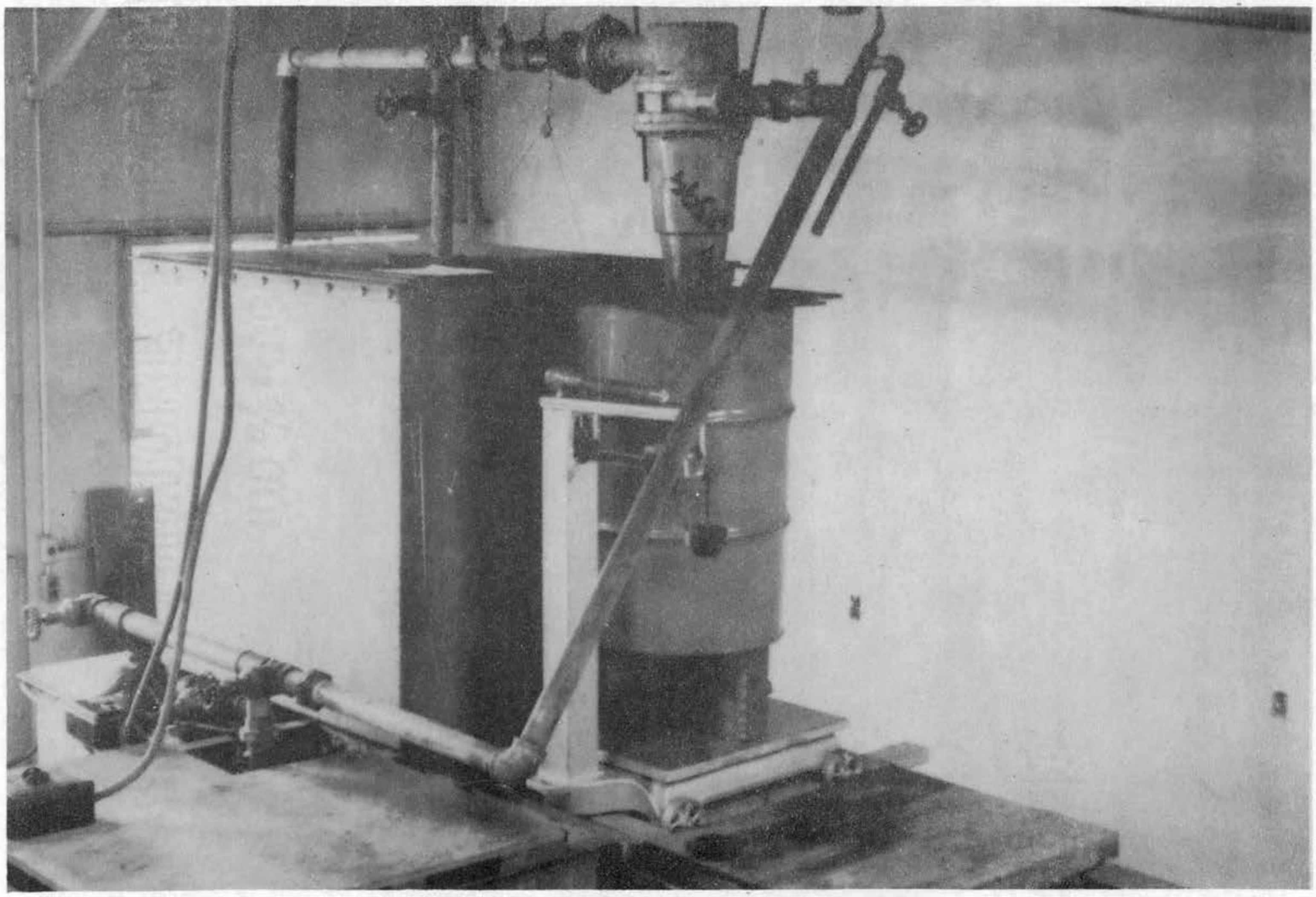

Figure 4. Physical Arrangement of Apparatus.

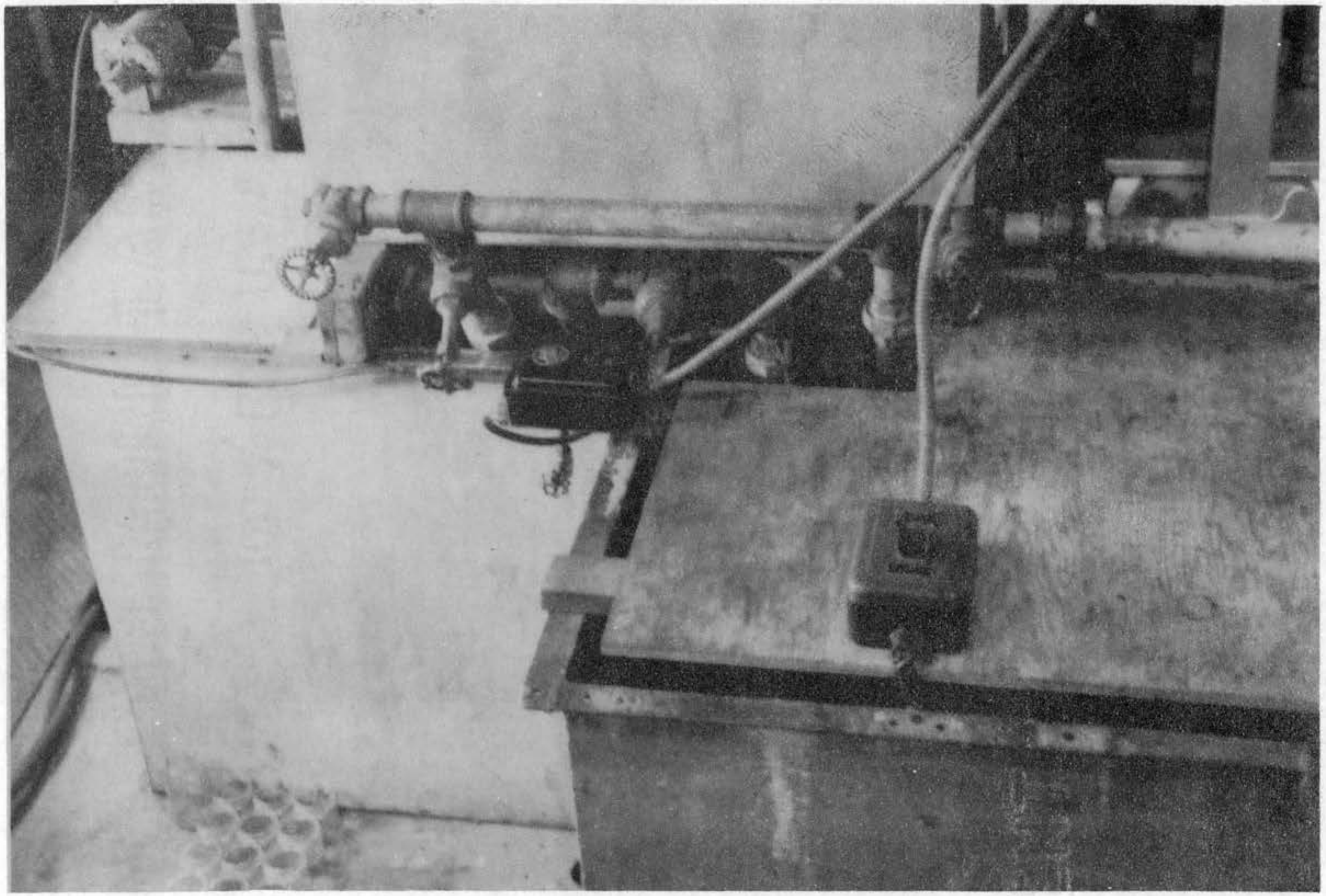

Figure 5. Arrangement of Controls

brings about a significant rise in temperature of the overflow product.

Bourdon pressure gages were located on the input and overflow lines, each being mounted in a 2-inch reducing tee. A gate valve was provided in the overflow tank line to regulate the overflow pressure.

The flow of the overflow product was shifted from its respective collecting tank to the storage tank by means of the 2-way plug valve in the overflow line. The use of this valve enabled the shift to be made rapidly and easily.

The underflow measuring-tank, a 55 gallon drum with an open end, was drained by gravity through a line with a funnel end into the storage tank. The funnel arrangement was necessary because the tank was mounted on scales and therefore any connection directly to the tank would be a deterrent to accuracy in weighing.

The underflow orifice of the cyclone was fitted with a counter-balanced flap-valve which was controlled by a light cord strung through a pulley. The purpose of this valve was to prevent the cyclone cone from draining into the underflow tank at the end of a run, and thereby causing inaccuracy. It would also be used to retain the underflow product, while the cyclone was pressurized, until the run was started.

A 3/8-inch line was connected to the gage tap on the output channel of the pump housing to enable the operator to take a sample of the mixture passing through the pump at any given instant. At this particular point, the mixture proved to be very homogeneous, having just passed through the pump.

CHAPTER IX

OBSERVED AND CALCULATED DATA

The observed data of this investigation are presented in Tables I to V. The calculated data are listed in Table VI with graphical representation in Figures 6 through 15.

Figure 6 is a graph of the input mixture ratio, parts of kerosene to parts of brine ≠ emulsion by volume, with time, plotted for an actual run using a pressure differential of 15 psi.

For Figures 7 through 10 the following variables were plotted against pressure differential:

Index of brine removal, %R.

Index of brine concentration, %B.

Underflow flow rate, Q_u.

Total flow rate, Q_t.

In Figures 11 through 15 the index of brine removal and the index of brine concentration were plotted against underflow orifice area.

Both of the index curves for variable pressure differential and also variable underflow orifice area were plotted with straight, broken lines for the reason that in some of the curves it was impossible to ascertain the exact path between two particular consecutive points.

TABLE I

RATIO CHECK

June, 1957

$\Delta P = 15$ psi 9/16" Orifice

Sample Number	Time in Seconds	ml Kerosene	ml Brine and Emulsion	Ratio Kerosene to Brine and Emulsion
1	0	352	80	4.40
2	10	225	55	4.10
3	20	245	65	3.75
4	30	255	85	3.00
5	40	245	75	3.27
6	50	245	70	3.50
7	60	275	75	3.65
8	70	235	65	3.62
9	80	200	75	3.48
10	90	200	70	3.70
11	100	245	60	4.09
12	110	245	60	4.09
13	120	230	60	3.83
			Average	3.7

TABLE II

OBSERVED DATA

June 11, 1957

Underflow Orifice Diameter 3/8"

Run Number	1	2	3	4	5
Pressure Diff.	5	10	15	20	25
Input Pressure psig	10	15	20	25	30
Exhaust Pressure psig	5	5	5	5	5
Input Temp °F	85	86	88	90	93
Exhaust Temp °F	85	86	88	90	93
Ambient Temp °F	87	89	89	89	89
Time Minute Interval	3.5	3.5	3.0	2.5	2.0
Total Volume Gal.	93	110	111	110	100
Underflow Volume Gal.	20.30	15.20	10.95	8.43	6.75
Net Wt. of Und.	182	139	100	81	66

TABLE III

OBSERVED DATA

June 21, 1957

Underflow Orifice Diameter 1/2"

Run Number	6	7	8	9	10
Pressure Diff.	5	10	15	20	25
Input Pressure psig	10	15	20	25	30
Exhaust Pressure psig	5	5	5	5	5
Input Temp °F	89	90	93	95	96
Exhaust Temp °F	89	90	93	95	96
Ambient Temp °F	87	89	89	89	89
Time Minute Interval	2.50	2.50	2.25	2.00	2.00
Total Volume Gal.	70	87	93	90	105
Underflow Volume Gal.	30.40	23.65	20.70	17.75	17.75
Net Wt. of Und.	266	281	259	170	178

TABLE IV

OBSERVED DATA

June 15, 1957

Underflow Orifice Diameter 9/16"

Run Number	11	12	13	14	15
Pressure Diff.	5	10	15	20	25
Input Pressure psig	10	15	20	25	30
Exhaust Pressure psig	5	5	5	5	5
Input Temp °F	86	86	88	89	91
Exhaust Temp °F	86	86	88	89	91
Ambient Temp °F	83	83	83	83	84
Time Minute Interval	3	2.5	2	2	2
Total Volume Gal.	87	95	90	100	105
Underflow Volume Gal.	29.5	23.6	18.6	16.9	16.1
Net Wt. of Und.	269	224	178	169	156

TABLE V

OBSERVED DATA

June 11, 1957

Underflow Orifice Diameter 5/8"

Run Number	16	17	18	19	20
Pressure Diff.	5	10	15	20	25
Input Pressure psig	10	15	20	25	30
Exhaust Pressure psig	5	5	5	5	5
Input Temp °F	87	87	88	90	91
Exhaust Temp °F	87	87	88	90	91
Ambient Temp °F	84	84	84	84	84
Time Minute Interval	2.0	2.5	2.5	2.25	2.0
Total Volume Gal.	60	87	100	110	110
Undeflow Volume Gal.	35.0	30.3	24.3	26.2	21.9
Net Wt. of Und.	278	270	266	259	216

TABLE VI

CALCULATED DATA

Run Number	Orifice	ΔPsig	Q_t	Q_u	%B	%R
1	3/8"	5	26.7	5.80	61.7	63.2
2	3/8"	10	31.5	4.35	65.8	42.6
3	3/8"	15	36.6	3.65	65.6	30.3
4	3/8"	20	44.0	3.37	77.3	27.5
5	3/8"	25	50.0	3.37	82.0	26.0
6	1/2"	5	28.0	12.15	55.5	110.0
7	1/2"	10	34.8	9.45	68.0	84.0
8	1/2"	15	41.2	9.20	77.8	78.2
9	1/2"	20	45.0	8.88	78.0	69.7
10	1/2"	25	52.5	8.88	88.0	66.6
11	9/16"	5	29.0	9.93	65.0	100.0
12	9/16"	10	38.0	9.43	74.5	84.2
13	9/16"	15	45.0	9.30	77.0	71.5
14	9/16"	20	50.0	8.45	88.0	66.8
15	9/16"	25	52.5	8.05	80.0	55.0
16	5/8"	5	30.0	17.50	35.1	93.8
17	5/8"	10	34.8	12.10	59.9	96.5
18	5/8"	15	40.0	11.30	72.1	87.0
19	5/8"	20	49.0	11.65	85.0	92.0
20	5/8"	25	55.0	10.95	84.5	76.0

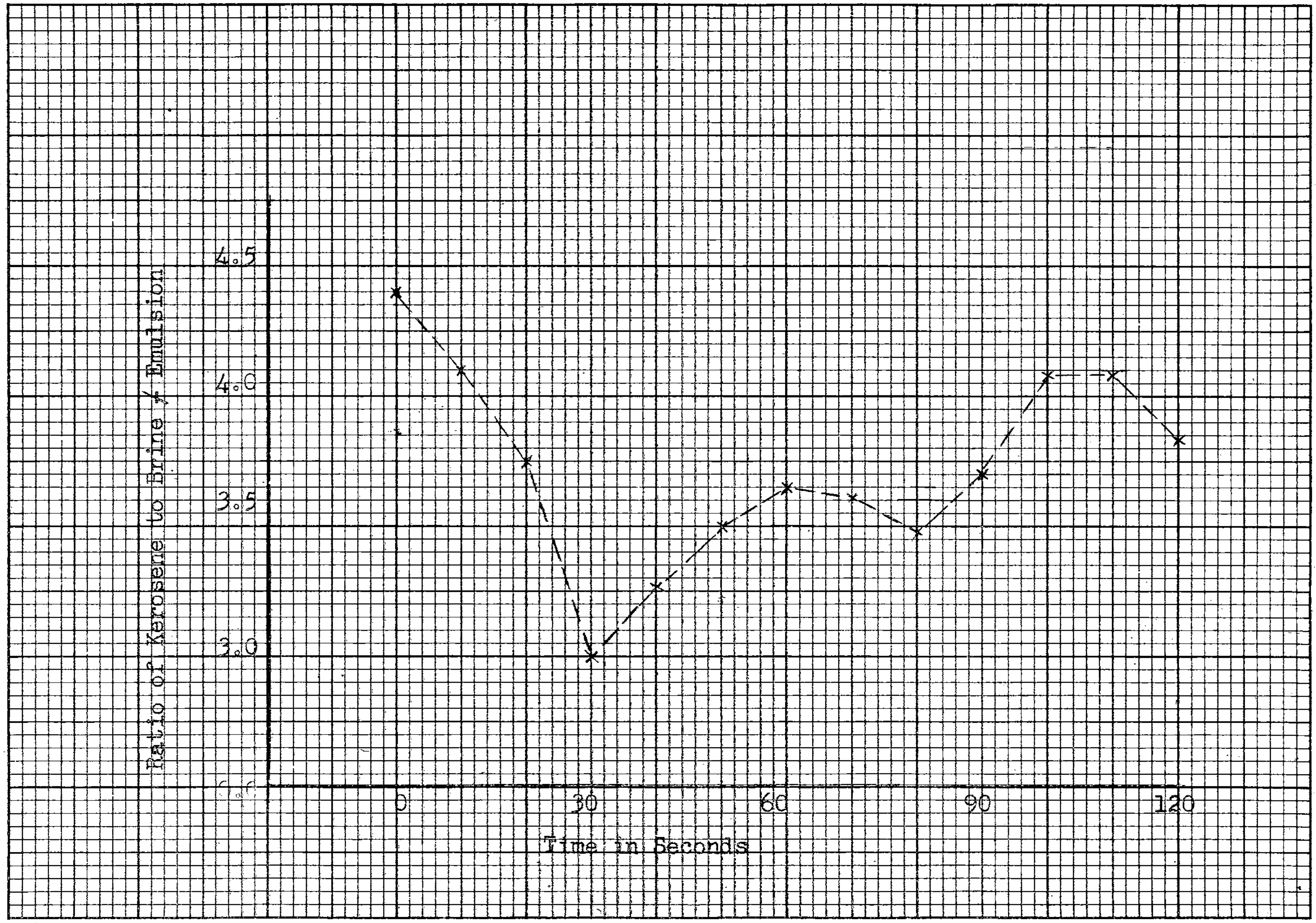

Figure 6. Input Ratio vs. Time

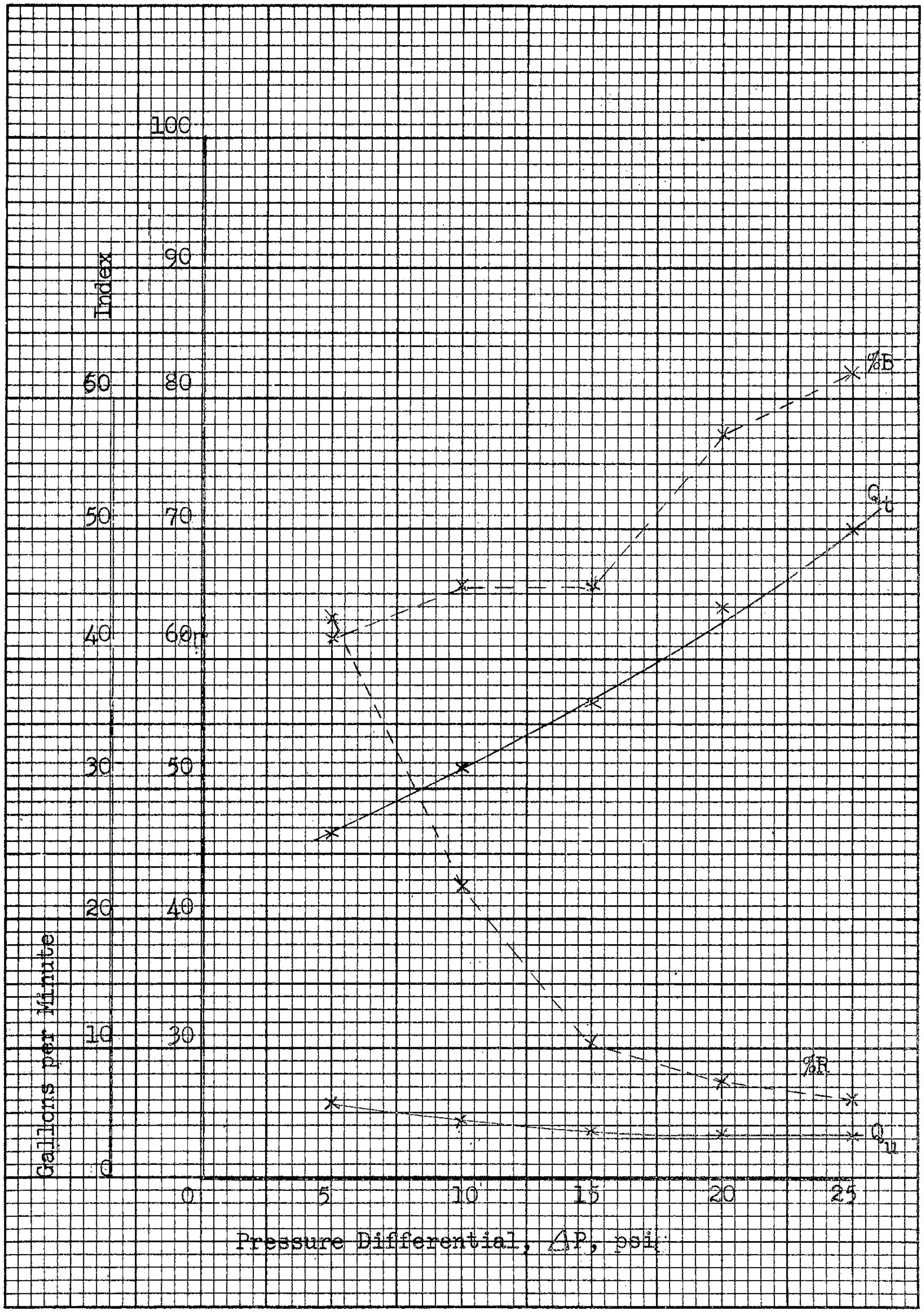

Figure 7. %R, %B, Q_t, Q_u, vs. $\triangle P$, 3/8" Underflow Orifice

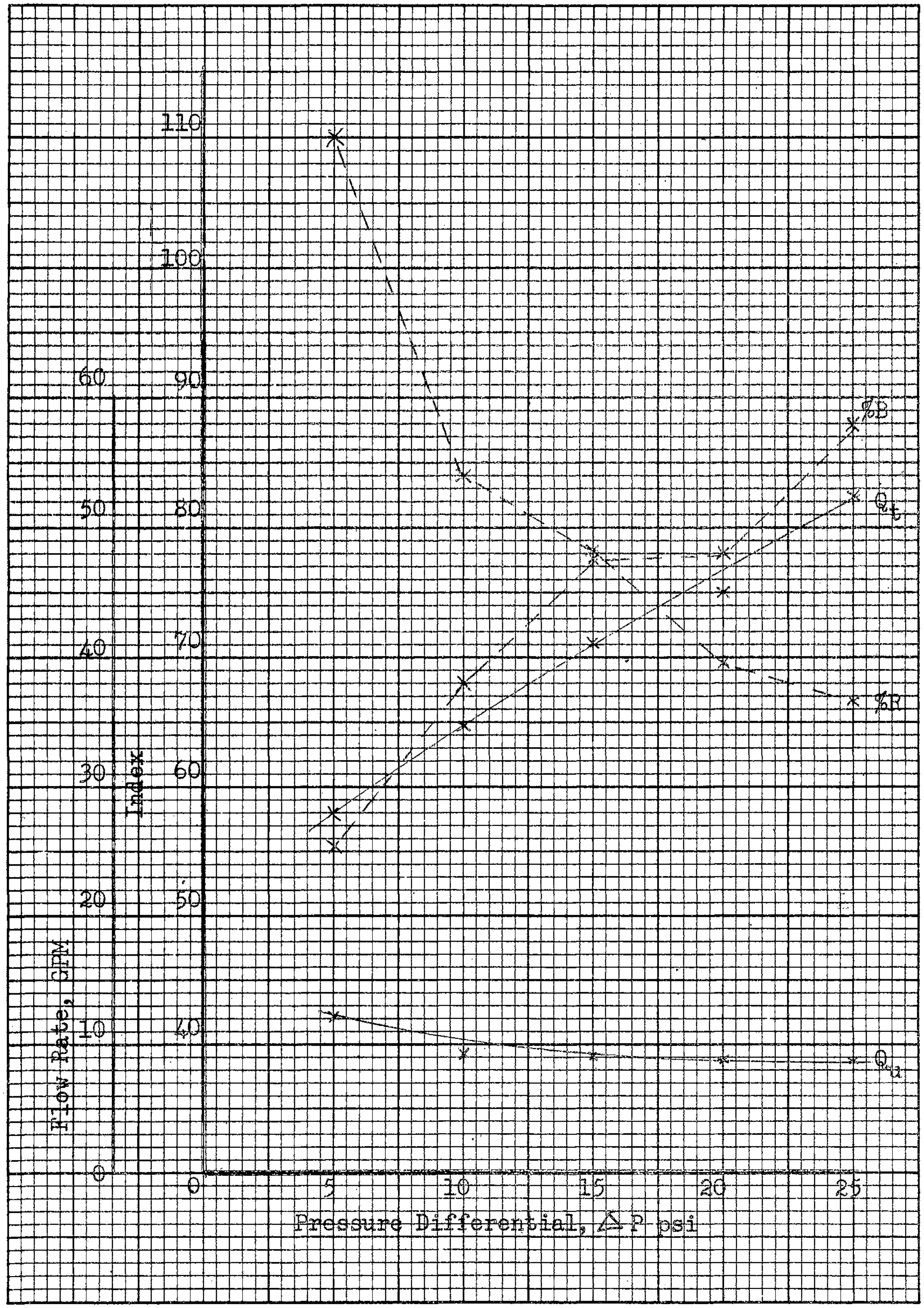

Figure 8. %R, %B, Qt, Qu, vs. △P, 1/2" Underflow Orifice

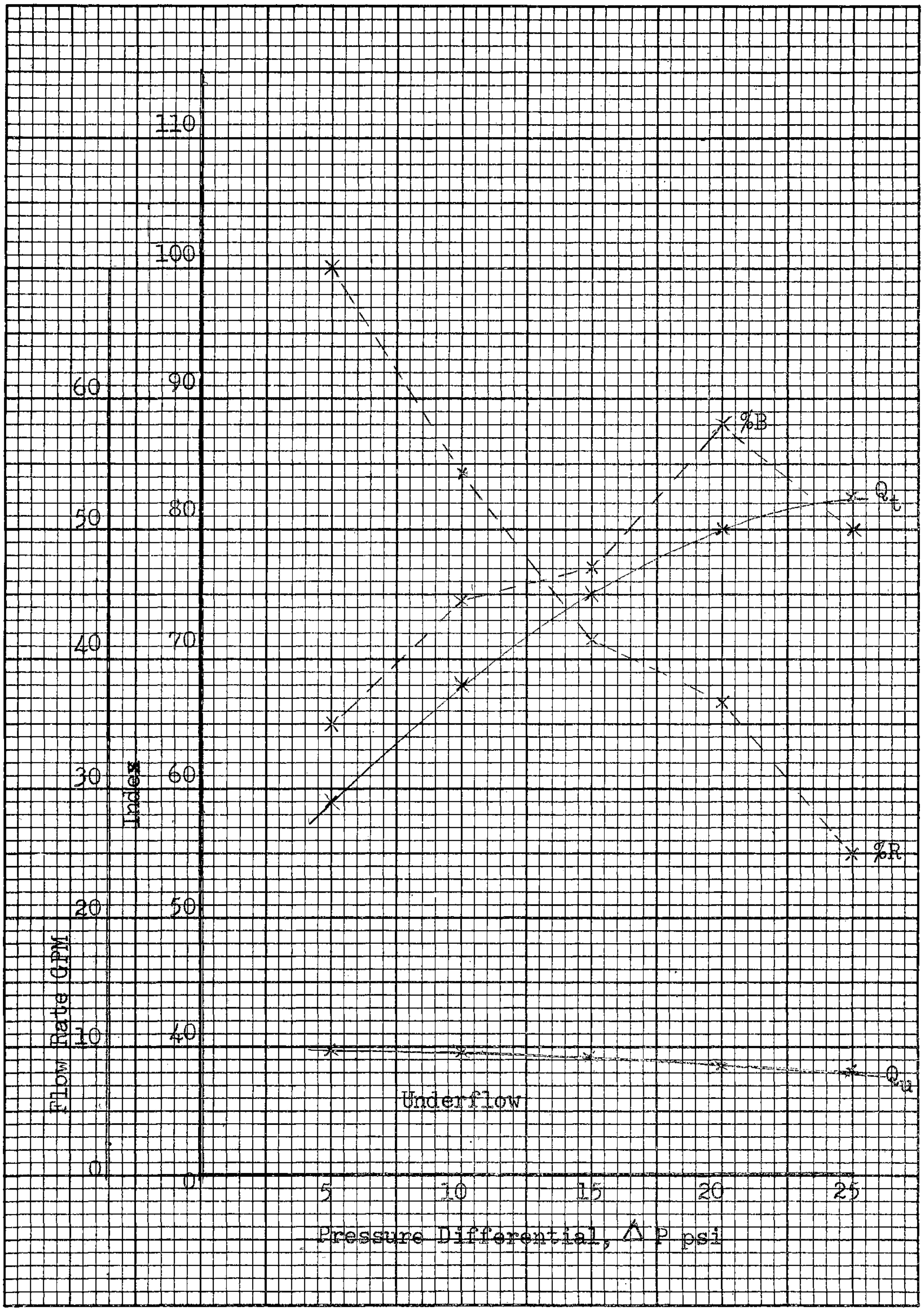

Figure 9. %R, %B, Q , Q , vs. △ P, 9/16" Underflow Orifice

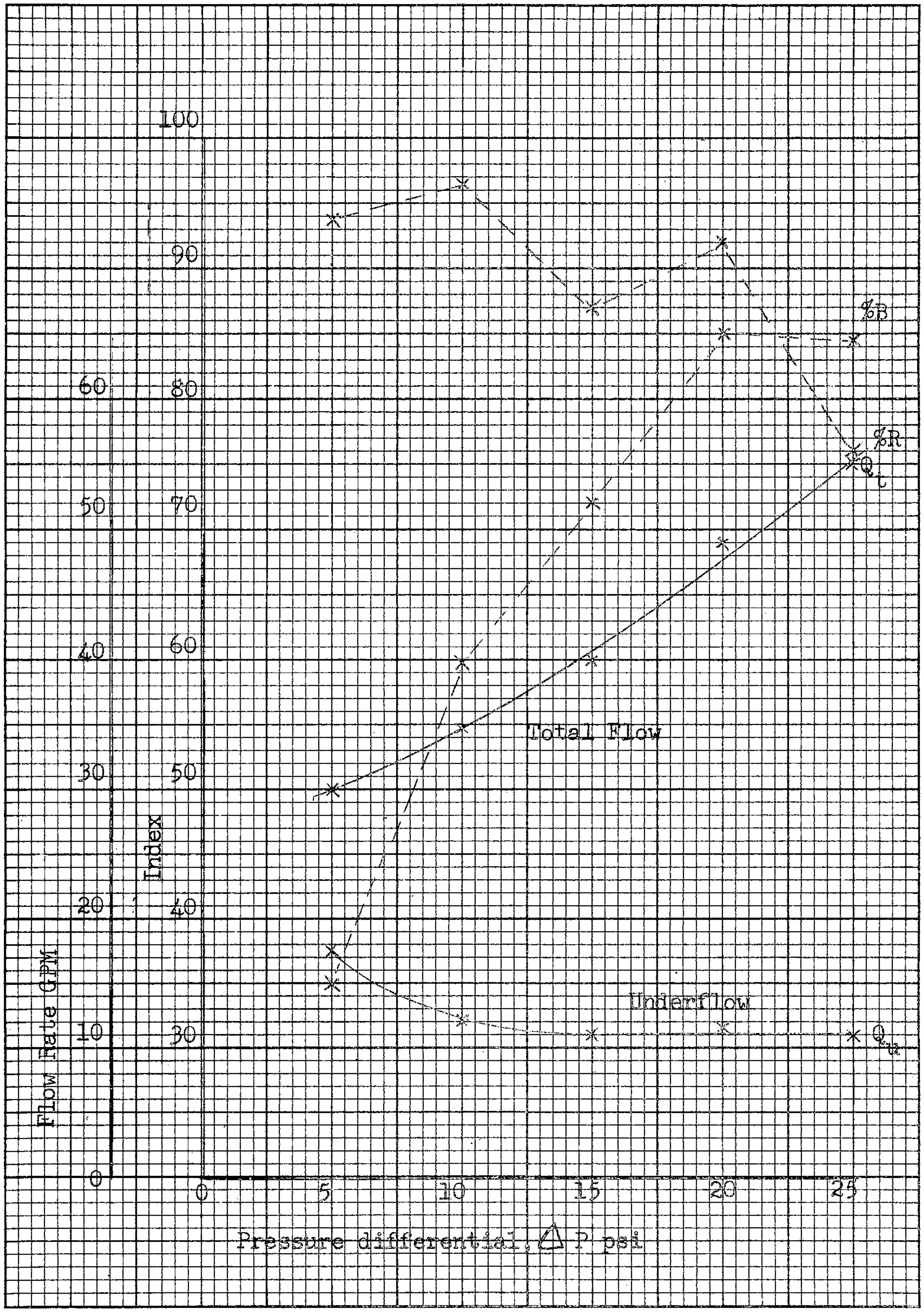

Figure 10. %R, %B, Q_t, Q_u, vs. $\triangle$P, 5/8" Underflow Orifice

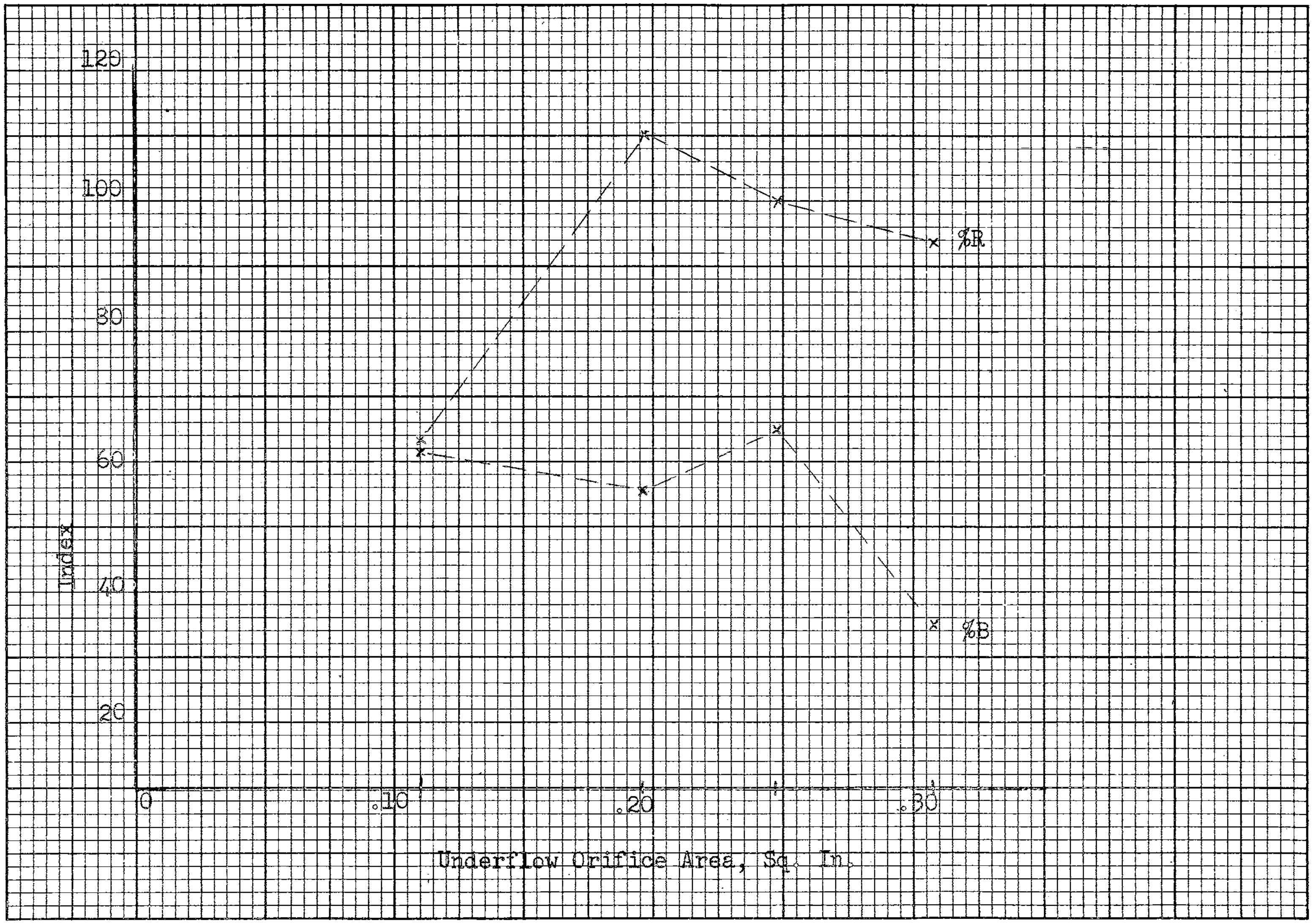

Figure 11. %R, %B vs. Auf, $\triangle P$ = 5 psi

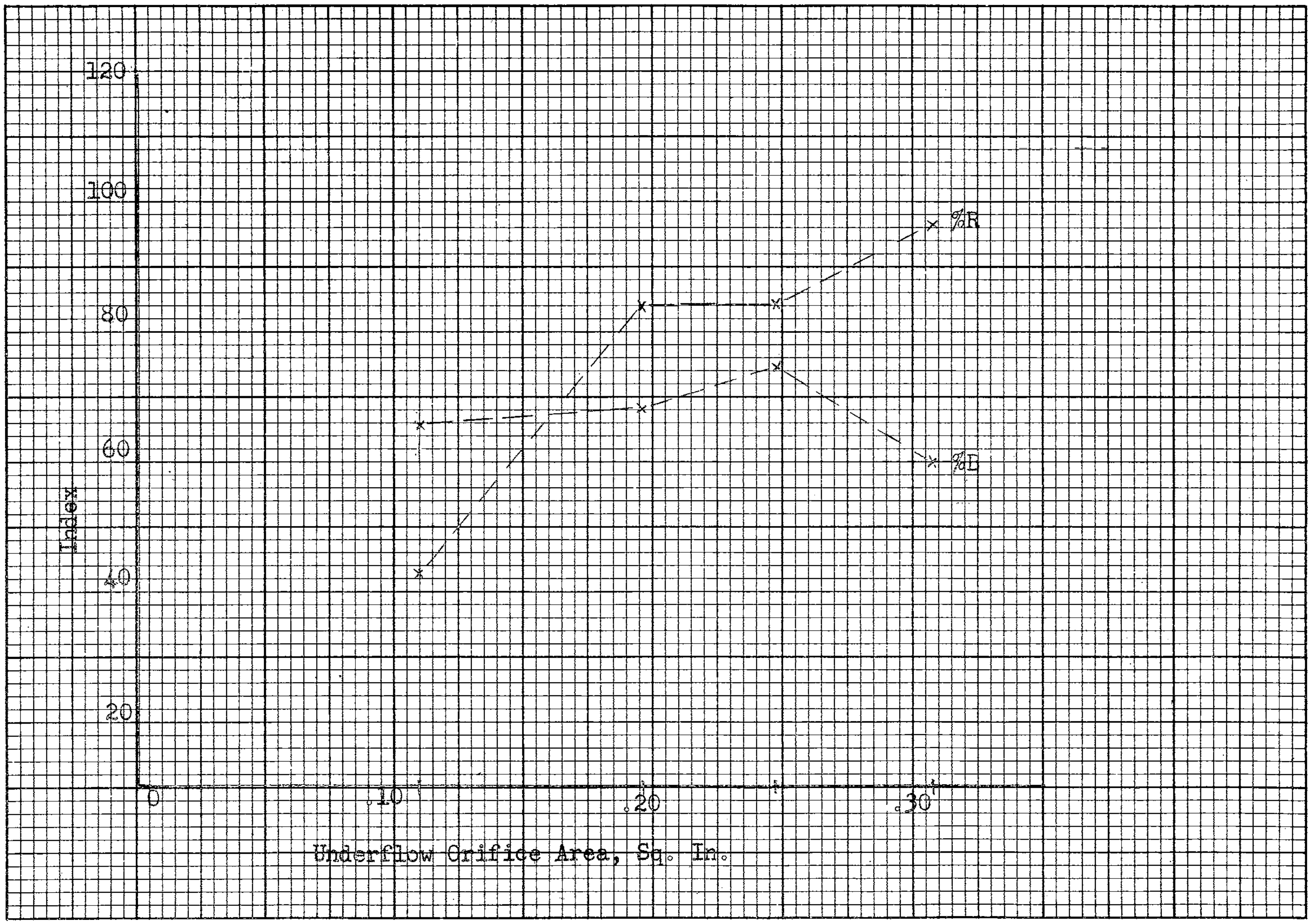

Figure 12. %R, %B vs. Auf, ΔP = 10 psig

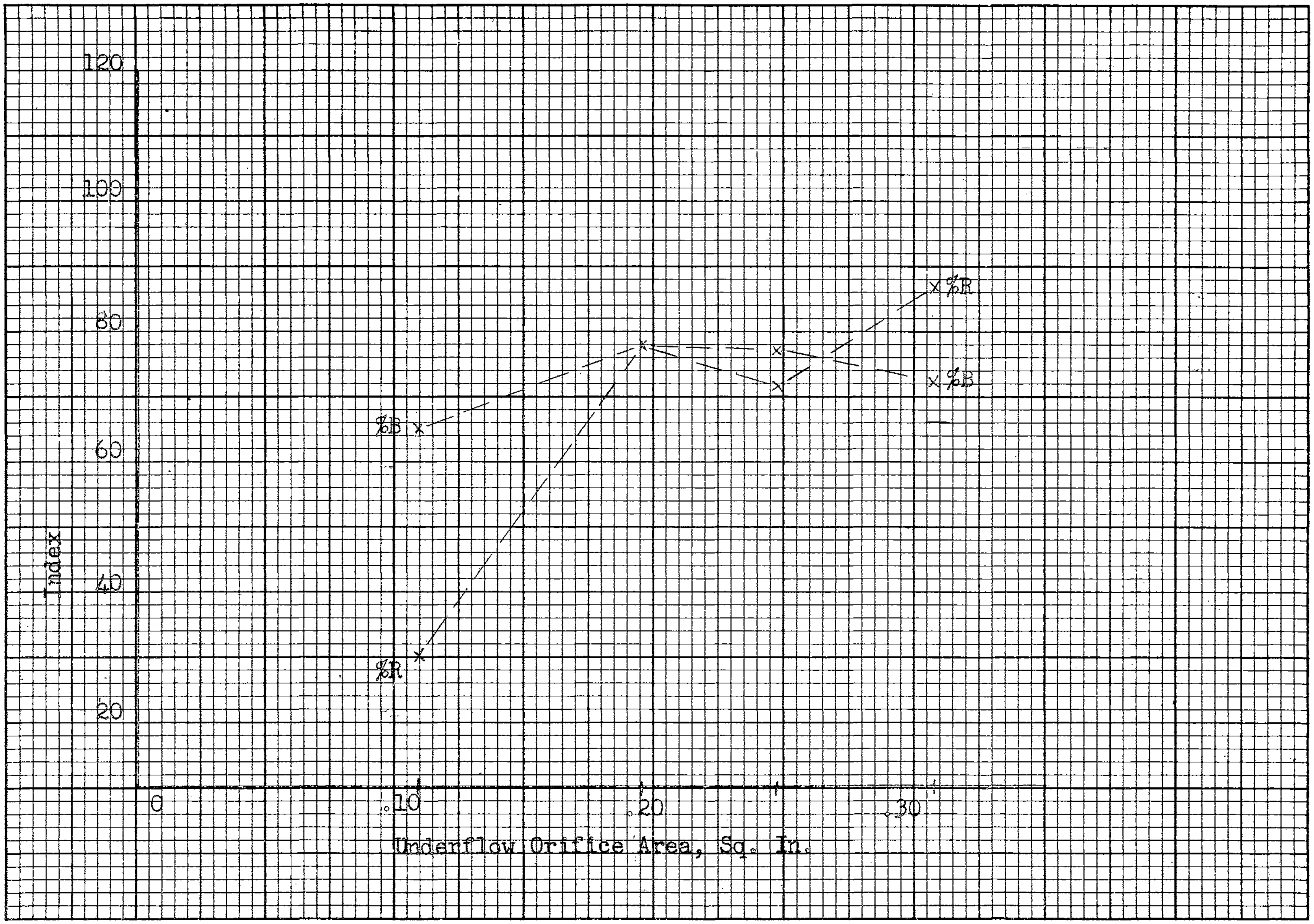

Figure 13. %R, %B vs. Auf, $\triangle P = 15$ psig

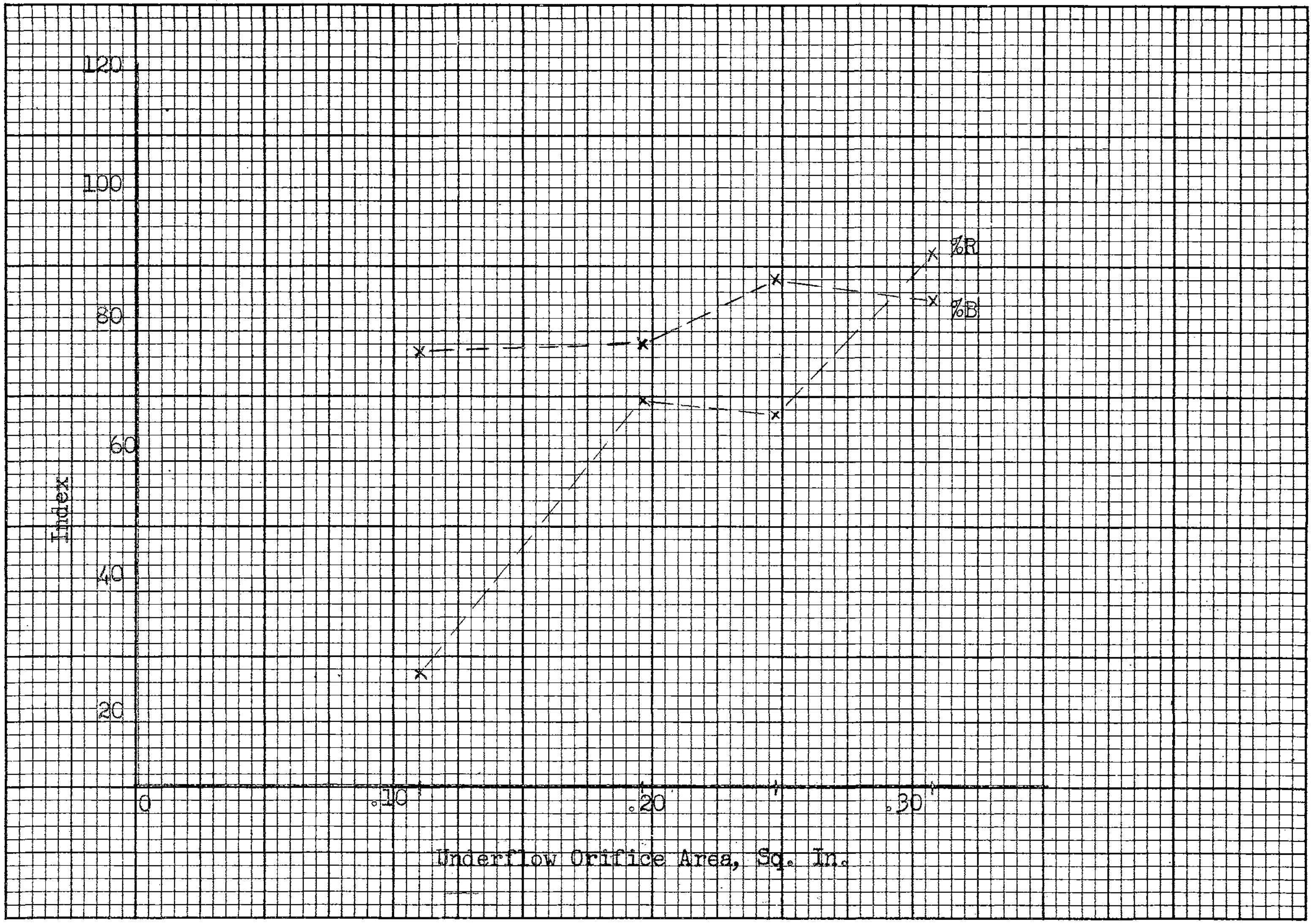

Figure 14. %R, %B vs. Auf, $\triangle P = 20$ psig

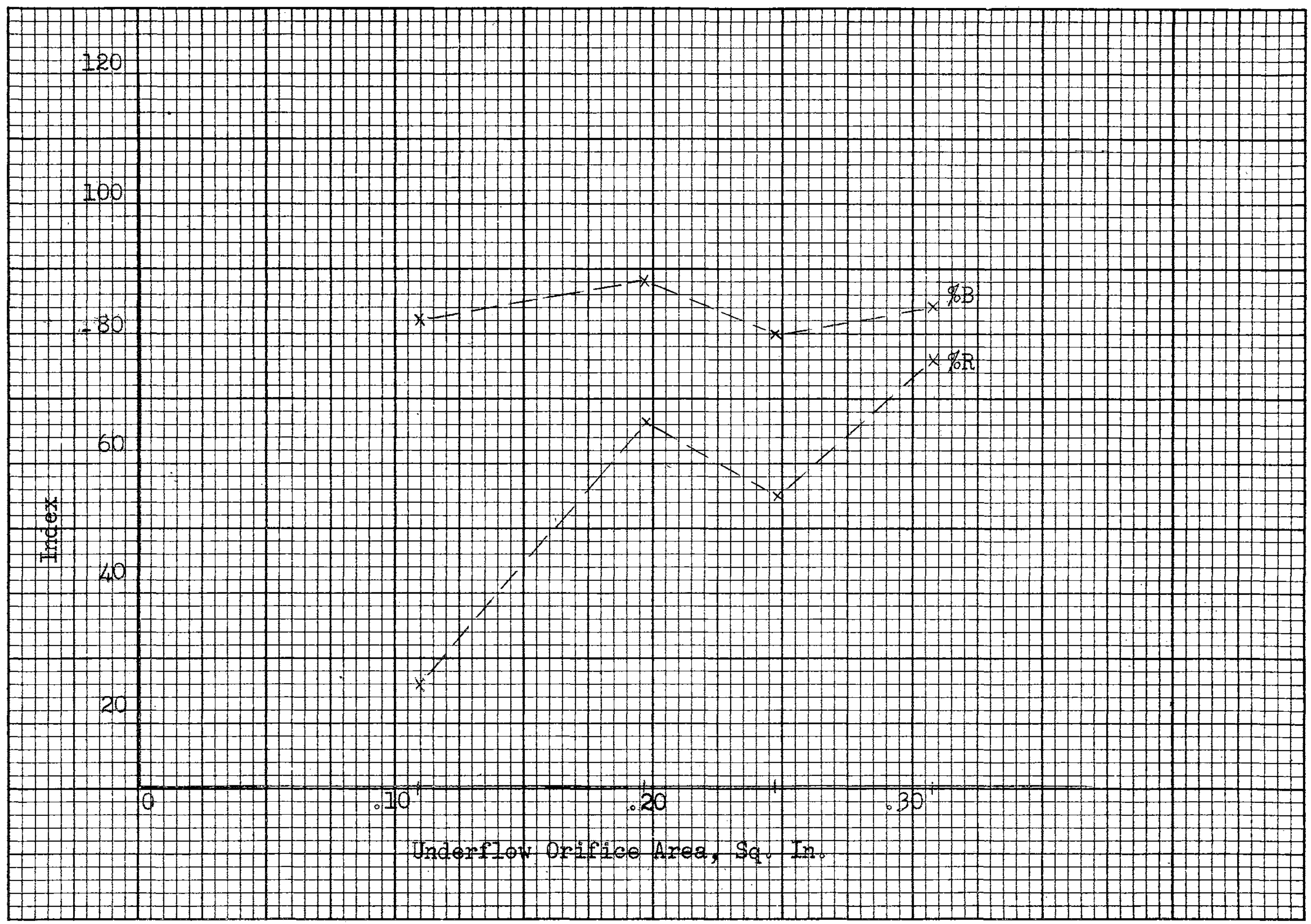

Figure 15. %R, %B vs. Aof, ΔP = 25 psig

CHAPTER X

DISCUSSION OF RESULTS

In the execution of the tests several difficulties were encountered. Possibly the most serious was the problem of maintaining a constant input ratio in the input mixture. An appreciable amount of experimentation with the mixer was necessary before the formal tests were run. At the higher blade speeds of the mixer it was found that excess cavitation occurred causing the exhaust pressure of the centrifugal pump to fluctuate rather seriously. When the blade speed was reduced slightly, the mixing action was not sufficient to maintain a constant mixture. This was solved by the removal of 3 of the 6 original blades, and increasing the blade speed to the original value.

It was also found that the original placement of the intake line was not satisfactory since the ratio of kerosene to brine, in the first few seconds of a run, was abnormally low. This defect was remedied merely by some experimentation to determine a satisfactory level for the end of the pipe. There is also a slight possibility that the initial location of the inlet coincided with a vortex caused by the mixer, thus influencing the ratio.

With the completion of the above mentioned alterations, the formal runs were resumed. The majority of the mixture samples taken from the pump were consistent, within 5%, except for a few samples which were considerably inconsistent. Samples were then taken every 10 seconds for a period of 2 minutes with the input pressure set at 20 psig. The plot of these ratio values is shown in Figure 7. It is seen that the values tend to cycle irregularly. Other tests tended to bear out this cycling effect. One possible explanation for this phenomenon is that the mixer in the tank tended to set the entire contents of the tank into a slow rotational motion with a period possibly corresponding to that of the peaks in the plot. From this information, it was seen that samples taken during a run, and then averaged to obtain a representative ratio, were misleading. For this reason the points of the curve were averaged and this average was used as the value of the ratio for all runs.

After the first few runs were completed an unusual, spongy mass was noted to be floating seemingly upon the interface of the two fluids, in the underflow product, and in some cases extended above the kerosene surface. A microscopic analysis showed this curious substance to be a very concentrated water-in-oil emulsion with very many small particles of different impurities entrained. Several conjectures might be made as to the cause of this emulsion. As was mentioned earlier, the kerosene and brine system was tested for chemical stability and resistance to the forming of stable emulsions. There was, however, one eventuality which was not considered at that time. This was that the piping used in the project had been used previously, and although water had been pumped through it several days prior to the formal runs, it still had a coating of rust particles and other scale on the inside. These impurities might have served to stabilize the emulsion formed by the mixer and pump. Since there was too great a quantity of the emulsion and loose impurities to be neglected, roughly one-third the volume of clear brine in any sample, for calculation purposes it was assumed to be a part of the brine. This assumption was, of course, slightly in error since a water-in-oil emulsion actually contains more oil than water. This error was probably less than the error introduced by trying to deduce the ratio from the quantity and physical appearance of the emulsion. The average value of this ratio, as found in the above outlined test, proved to be 3.7 parts of kerosene, by volume to 1.0 part of brine plus emulsion. This value was consequently used in all of the runs. This value, of course may not be accurate for every run but it is considered representative since it is near the theoretical value obtained if all the components were perfectly mixed. Actually, the only method to ascertain the value of the ratio is either to meter separately the two phases, or analyze, volumetrically and by weight, both the underflow and the overflow products.

The one other difficulty worth mentioning was that after a discrepancy was noted in some of the runs it was found that a set-screw was missing from the slider weight on the beam scales, thus causing the scales to register 5 pounds heavy on full scale deflection. The scales were otherwise sufficiently accurate when checked, up to 300 pounds with calibrated test weights.

Figures 7 through 10 are plots of index of brine concentration in the underflow product, %B, index of brine removed from the total throughput, %R, and underflow and throughput capacities. The index of brine concentration in the underflow, %B, will actually correspond to the percentage of brine, by volume, of the underflow product. The index of brine removed from the total throughput, %R, is an approximation of the percent of brine removed from the fluid pumped through the cyclone. If the exact input ratio was known, and also the exact volume, this index would be equal to the percent of brine removed from the total flow. The indexes, then, are more for comparative and qualitative examination rather than for quantitative examination.

It is seen, in all except the first of the curves, that %B increases, with decreasing slope, with the increasing pressure differential. This decreasing slope would seem to indicate that at some higher pressure a maximum would be reached. This point, of course, would be the optimum operating pressure for that particular set of conditions. The maximum value of %B proved to be 88.0, occurring with the 1/2 inch dia. underflow orifice, at a pressure differential of 25 psig. The corresponding brine removal index, %R, was 66.6. A value of 88.0 was also obtained for the 9/16 inch underflow orifice. This point is thought to be inconsistent since it fell some distance off the respective curve.

The minimum value of %B was 35.1 occurring with the 5/8 inch dia. underflow orifice at a pressure differential of 5 psig. This was to be expected, since at this low pressure and large opening, the underflow rate is abnormally large.

Figures 11 through 15 are plots of %R and %B against underflow orifice area. Most of these curves display similar geometric characteristics. While the %B curves are all reasonably consistent, it appears that some irregularity is present in the %R curves. Either the point for the 1/2 inch dia. orifice or for the 9/16 inch orifice seemed to be discontinuous with the rest of the data, even though these runs were both checked twice. One possible explanation for the discrepance is the fact that the so-called 1/2 inch dia. orifice was not exactly 1/2 inch in diameter. It was actually flattened on two opposite sides due probably to error in the sandcasting process by which it was manufactured. The hole in the 3/8 inch orifice plate was of a similar nature. The other two orifice plates were bored to their respective diameters in the shop, and as a result were much smoother. All of the %B curves seem to peak either on the 1/2 inch or 9/16 inch orifice areas.

There is a result to support the notion of a discrepancy. This is the fact that in Figure 11, the plot for 5 psig pressure differential, the %R point corresponding to the area of the 1/2 inch has an index of 110 and is the highest point encountered in all of the plots. Since the %R index would be the same as the percent brine removed from the total flow, if the input ratio were actually exactly the same as the assumed one and no error were made in measurement, it is seen that there is probably some variation between the actual value and the assumed value of 3.7. Because the %R curves are all similar in shape it might possibly be assumed that since there is some error in the above mentioned curve, the others might also contain proportional error.

The input temperatures were held to an approximate tolerance of $10^{o}F$ to insure their variation did not affect the runs by influencing the specific weights of the fluids or their viscosities. It was noted that the input and exhaust temperatures usually were of the same value. An interesting occurrence was observed in the collection of the underflow product. The layer kerosene on the top of the tank always seemed much warmer to the touch than did the brine and emulsion layer underneath, even though it was impossible to obtain positive verification with the existing instrumentation. The reason probably lies in the fact that the specific heats of the two fluids are very different, causing the kerosene to have a greater temperature rise for a given amount of work put into the system by the mixer and pump.

CHAPTER XI

SUMMARY AND CONCLUSIONS

The purpose of this investigation was to determine whether the vortex thickener might be used to separate two immiscible fluids, one dispersed in the other. The method of attack was a laboratory analysis using variables dictated by an analogy to the solid-liquid cyclone.

In the tests kerosene, sp gr .79, and calcium chloride brine, sp gr 1.26, were mixed by a propeller type mixer, and then pumped through the cyclone by means of a centrifugal pump. The input pressure and the area of the underflow orifice were varied by five increments for the input pressure and four increments for the underflow orifice area.

Difficulty was encountered in obtaining a constant mixture ratio through the cyclone. For this reason, the dependent variables chosen were index of brine concentration in the underflow product and index of brine removal from the total throughput. The former is numerically equal to the percentage brine concentration in the underflow, by volume, while the latter would be the same as the percentage of total brine removed from the throughput, only if the exact mixture ratio could be ascertained.

It was found that the maximum concentration index, 88.0, occurred with the use of the 1/2 inch dia. underflow orifice at a pressure differential of 25 psig with a corresponding index of brine removal of 66.6. The maximum index of brine removal occurred at a pressure differential of 5 psig with the 1/2 inch dia. orifice. This latter quantity is actually not a very important variable since at this maximum index there was a large quantity of the kerosene moving through the underflow.

Although the removal and concentration indexes proved to be definitely related to both the underflow orifice area and the pressure differential, an attempt at developing mathematical relationships, by dimensional analysis, failed because of the sharp breaks in the index curves plotted for varying underflow orifice area. These breaks represented either peak values or inconsistent data. This uncertainty could possibly have been rectified had additional increments of underflow orifice area been taken, thus enabling a more accurate representation of the shape of the curve to be made.

It may therefore be concluded, since the concentration index proved to be definitely related to both independent variables, that the vortex thickener may be used to separate two immiscible liquids combined in an unstable emulsion, if the liquids have properties characteristic of those used in this investigation.

CHAPTER XII

RECOMMENDATIONS FOR FUTURE RESEARCH

If further research on this problem is undertaken, a more suitable method of forming unstable emulsions must be found. One possible method might be that of metering the two fluids from two separate storage tanks and mixing them in a manifold. While this method would be slower and require considerable instrumentation, it would also lead to greater accuracy in controlling the total flow.

Another need is a filter on the suction lines to remove any impurities and stable emulsion which tend to complicate mixture readings. If the two-tank system, outlined above, were used, it might be advisable to use flexible intake lines mounted on floats to insure that the heavier impurities would not be picked up and for the more important reason that the head on the suction side of the pump would be constant thus eliminating the bothersome variation in input pressure encountered in this investigation.

To increase the accuracy of the recorded data the use of greater total flow volume would probably be advantageous, since with a small underflow volume, at high pressure with small orifices, a small measuring error, either volumetric or weight, will make a very significant error in the ratio calculations.

Assuming that a suitable means of maintaining a constant ratio input to the cyclone is available, it might be profitable to continue this investigation, using the same parameters, and increasing the input pressure until the peak separation efficiency, corresponding to maximum %B index, is reached. Also, to get a more accurate representation of the effect of the underflow orifice area on the separation efficiency, a greater range of orifices might be employed.

Another parameter which has a very great effect on the composition and quantity of the underflow product is the exhaust pressure, which was set at 5 psig in the preceding investigation. The varying of the diameter of the overflow orifice would have, probably, much the same effect.

Earlier investigations on the solid-fluid cyclone have shown that the smaller cyclones have increasing separation efficiencies. This, of course can be explained by the increased rotational velocities of the fluid. A possible deterrent in using the smaller cyclone is the fact that its flow fields are more turbulent than those of the larger cone. At any rate, the cyclone diameter must not be dismissed as a possible variable in future tests.

The area and geometry of the input orifice is an important variable since it controls, to a very large extent, both the input velocity and the throughput for any given set of conditions.

No mention has been made of the many possible variables of cyclone construction such as cone angle, nozzle entry angle, interior geometry of the overflow chanber, lengths of the various orifices, and other allied physical considerations. It is entirely conceivable that the optimum cyclone for fluid-fluid separation might have a much different configuration than that of the common solid-fluid cyclone.

The remaining parameters, of course, are in the composition and concentration of the input mixture. It has been found in solid-liquid separation that the concentration of solids in the mixture has a strong influence upon the separation efficiency as did the difference of specific gravities of the two. Both these quantities could be varied using the test apparatus outlined above, and the mixture constituents used in this investigation.

In conclusion, it might be said that the liquid-liquid cyclone is a virtually untouched field. If this field is to be exploited, eventually most all of the above mentioned variables need to be examined.

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APPENDIX A

LIST OF PRINCIPAL EQUIPMENT

1. Cyclone Unit.

   Manufacturer: Heyl and Patterson Company.

   Size: 8 inches, inside diameter.

   Type: Aluminum casting with bonded neoprene liner.

2. Centrifugal Pump.

   Manufacturer: Deming-Mueller.

   Model: 2A - Figure 4012.

   Type: Side suction, belt driven.

   Impeller: 10 inch diameter cast iron, open.

3. Pump Motor.

   Manufacturer: General Electric Company.

   Type: 3 Phase, 220/440 volt 60 cycle ac, inductive.

   Power Rating: $7\frac{1}{2}$ horsepower at 1740 RPM.

4. Tanks.

   Manufacturer: Tokheim.

   Type: Hot galvanized.

   Size: 4 foot cube.

5. Mixer.

   Manufacturer: Mechanical Engineering Laboratory

   Rating: $\frac{1}{2}$ hp at 350 RPM.

APPENDIX B

OPERATIONAL PROCEDURES

1. Close overflow tank drain valve.
2. Open underflow tank drain valve.
3. Open underflow flap-valve.
4. Close input line valve.
5. Close shunt line valve.
6. Turn overflow cock valve to tank.
7. Start mixer motor.
8. Start pump motor.
9. Open shunt valve full.
10. Open input line valve full.
11. Close shunt line valve until desired pressure is obtained.
12. Set tare on beam scales.
13. Close underflow tank drain valve.
14. When beam floats, turn cock to overflow tank, start time.
15. Adjust back pressure by overflow valve.
16. Stop time, turn cock to storage tank, close underflow valve.
17. Make measurements.
18. Stop mixer.
19. Close input line valve.
20. Close shunt line valve.
21. Stop pump motor.
22. Drain tanks.

APPENDIX C

SAMPLE CALCULATIONS

The calculations shown are for Run Number 20, using the 5/8 inch underflow orifice and 25 psi pressure differential.

INDEX OF BRINE CONCENTRATION IN THE UNDERFLOW, %B

$$\%B = \frac{W_t - W_k V_t}{(W_b - W_k)\ V_t}$$

Where:

W_t is the total net weight of the underflow product.

W_k is the specific weight of the kerosene in pounds per gallon.

W_b is the specific weight of the brine in pounds per gallon total underflow volume.

$W_k = 6.58$ lb/gal.

$W_b = 10.50$ lb/gal.

$W_t = 216$ lb.

$V_u = 21.9$ gal.

$$\%B = \frac{216 - (6.56)(21.9)}{(10.50 - 6.58)(21.9)} = 84.5$$

INDEX OF BRINE REMOVED FROM TOTAL THROUGHPUT, %R

$$\%R = \frac{(\%B)(V_u')}{V_t(R_b)}$$

Where:

V_u' is the underflow volume taken during the timed run.

R_b is the ratio of brine to the total volume

V_t is the total throughput volume of the run, in gallons

$$V_u' = V_u - \frac{\text{Fluid tare}}{\text{Density}}$$

$$= 21.9 - \frac{8 \text{ lb}}{216 \text{ lb}/21.9 \text{ gal.}}$$

$$= 21.09 \text{ gallons}$$

$$R_b = \frac{1}{1 + 3.7} = \frac{1}{4.7} = 1 \text{ part brine to } 4.7 \text{ parts total volume.}$$

$$V_t = 110 \text{ gallons}$$

$$\%R = \frac{(.845)(21.09)(4.7)}{110} = 76.0$$

VITA

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