EXPERIMENTAL STUDIES OF OIL FLOW THROUGH SANDS

Thesis by

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The percentage recovery of petroleum from underground formations is rather varied. Opinions advanced by various experts range from 10 to 90%. Melcher estimated that approximately 25% is recovered in the Bradford field in Pennsylvania. The estimates for the Texas and Louisana fields run as high as 50%. It can be seen by the above percentages that the recovery of the petroleum present in the formation is by no means complete. A great deal of work has been done to devise methods of increasing the yield.

The Petroleum Experimental Station of the U. S. Bureau of Mines is working on this problem. In an article in the American Institute of Mining and Metallurgical Engineering of October, 1928, R. V. A. Mills, J. Chalmers, and J. S. Desmond gave a short review of the questions which this station is attempting to answer on the basis of their experimental work. They are as follows:

(1) What are the causes of excessive amounts of thick oil where repressuring with compressed air and how can this thick oil be predicted?

(2) Why is the oxygen often converted to carbon dioxide in repressuring? By the oxidation of the oil? How can the formation of low B. T. U. casinghead gas loaded with nitrogen be prevented?

(3) What percentage of the oil can be recovered by ordinary methods when the gas originally dissolved in the oil is the propulsive agent?

(4) What percentage can be recovered by repressuring?

(5) What are the relative propulsion efficiencies of compressed air and natural gas?

(6) Why should the repressuring be done early in the production rather than later?

The flow tubes used in these investigations varied from 3 inches in diameter and 3 feet long to 12 inches in diameter and 26 feet long. The pressures used were from one pound to 800 pounds per square inch. The oil used was Bartlesville crude of 33° A.P.I. and Saybolt viscosity of 60 seconds at 70 F and 47 seconds at 100° F. No results were given in the article.

F. G. Tickell in the American Institute of Mining and Metallurgical Engineering of October, 1928, says that resistance to flow of oil in sand is proportional to its viscosity. In oil the viscosity is inversely proportional to the pressure since dissolved gas reduces the viscosity. Therefore the flow may be taken as proportional to the square of the pressure. Gas bubbles cause increased resistance due to deformation of the bubbles as they pass through the openings in the sand. This resistance is called the Jamin effect. All influences that restrain movements of liquids have the same effect as increasing the viscosity.

L. C. Uren, Professor of Petroleum Engineering at the University of California, in an article in the National Petroleum News of February 9th, 1927, discourses at length concerning resistance to flow of oil through reservoir sands.

He even offers equations by which to calculate the amount of flow. He gives a formula worked out by El Difrawí from the results of King and Slichter who worked on the flow of underground water.

$$q = (0.383 \times 10^{-6}) \times \frac{p \times d^2 \times s \times o^{3.3}}{u \times 1}$$

where q is discharge in gallons.

p is effective pressure in feet of water.

d is effective diameter of sand grains in mm.

s is cross section of sand column.

u is absolute viscosity of oil in poises.

l is length of sand column in feet.

o is porosity of sand in percentage.

Total flow must be found by integration. R. S. McIntyre derived the following equation by using the above, stating, however, that it is not complete. He gave no indication of what additional factors or terms are needed.

$$p = \frac{c \times q \times v}{t \times d^2 \times o^{3.3}} \times \mathrm{Log}_{10} \frac{L}{R} \ldots\ldots.$$

where p is pressure loss in feet of water.

q is quantity of oil in barrels per day.

v is absolute viscosity in poises.

t is thickness of sand in feet.

d is effective diameter of sand in mm.

e is percentage porosity.

L is radius of drainage in feet.

R is radius of well through productive sand in feet.

e is a constant.

Uren then sums up that the flow varies

(a) Directly as pressure.

(b) Directly as the thickness of productive sand.

(c) Directly as the square of the measured diameter of the sand grains.

(d) Directly as the 3.3 power of the percentage porosity.

(e) Inversely as the viscosity.

(f) Inversely as the log of the ratio of radius of drainage to the radius of the well.

These equations, however, do not take into account the Jamin effect. They are worked out on the flow of water. With a change in viscosity u, they should work for oil which is not saturated with gas.

As far as the writer knows there is nothing in the literature concerning definite data on flow measurements of oil and gas through sands. The questions which such measurements should answer are the following:

1. Does the decrease in viscosity due to dissolving gas in oil increase the flow or does the Jamin effect which enters when gas bubbles are present more than counter balance this decrease?

2. What would be the effect of back pressure on the flow?

3. Does the gas which comes out of the oil when the pressure is reduced in a sand formation rise and flow in separate

channels from the oil or continue mixed with the oil?

4. How does the pressure gradient vary with the distance from the well?

5. What effect does the porosity of the sand have upon resistance due to the Jamin effect?

In order to be able to get data with which to obtain some light on these questions a flow tube was constructed with glass sides so that the passage of the gas and oil through the sand could be observed. Means of reading pressures at various points were also incorporated.

Description of Apparatus.

The complete set-up of apparatus exclusive of the carbon dioxide cylinder is shown in the photograph. It consists of three main parts: the mixing and storage chamber (I), the flow tube (II), and the separating and weighing chamber (III). These units were built by Kobe Inc., manufacturers of slotted casings and other oil well supplies.

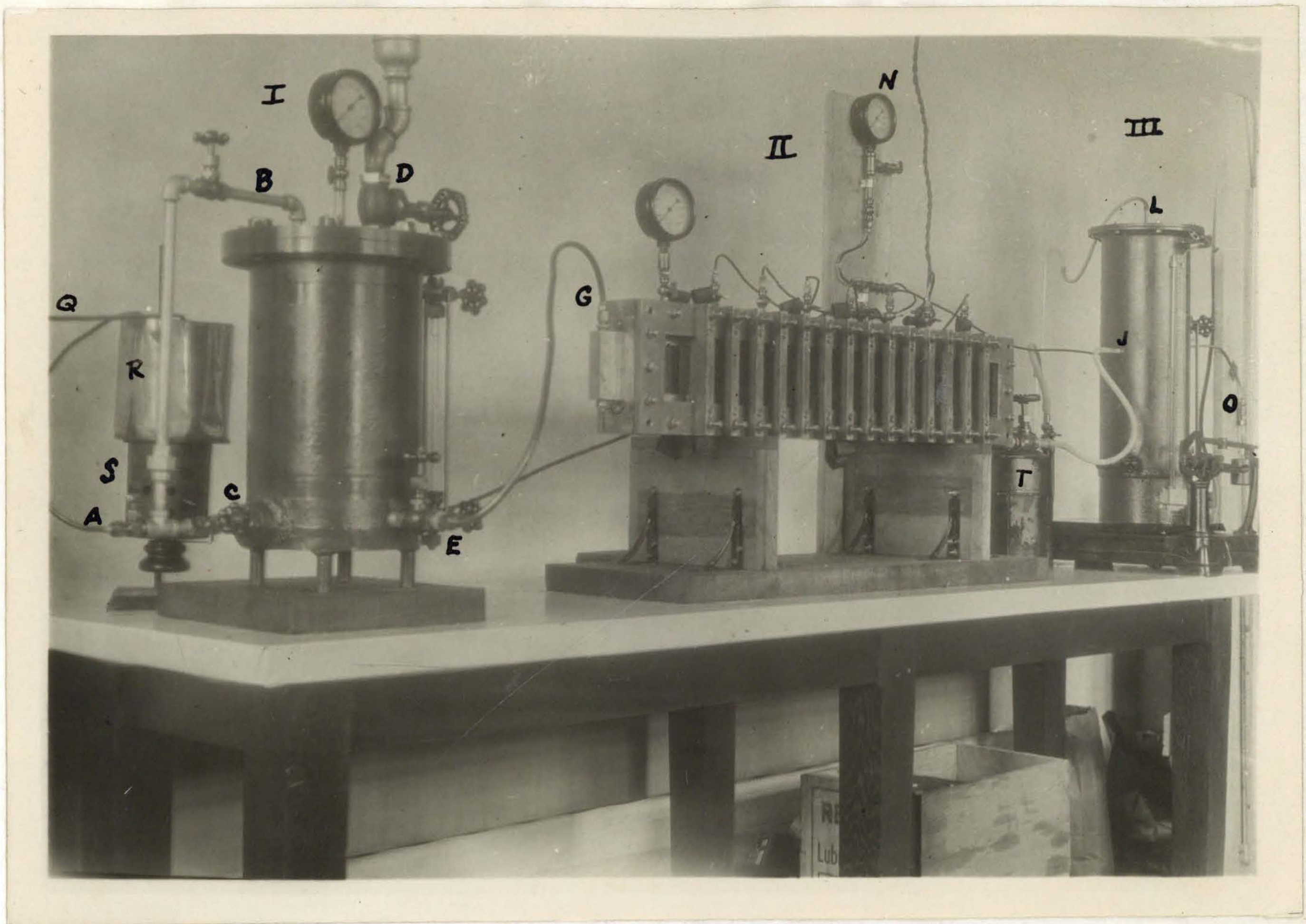
The mixing and storage chamber is 7 inches inside diameter, 14 inches inside height, and has a capacity of about 3 gallons. It is built of one half inch stock and has a flanged cover to facilitate cleaning. D is the oil inlet. A is the gas inlet which is divided so that the gas may be let in over the oil through B or bubbled through the oil through C. The exit to the flow tube is through E.

The flow tube is constructed of steel with glass sides for observation purposes. The glass is very slightly under one inch in thickness and is supported by beams every 2-1/4 inches.

In tests, it was found to withstand a pressure of 250 pounds per square inch without breaking. The length of the sand chamber is 27 inches. Its height is 4 inches and thickness 1/2 inch plus the thickness of gaskets which would average about 1/16 inch, making the total distance between glass plates about 9/16 inch. There is a chamber 3-1/2 inch in length at each end of the sand chamber. The slots are replaceable. Eight pressure tubes are inserted at P_1, P_2, P_3, etc. to obtain differential pressure readings. The oil enters at G from the mixing chamber and leaves at H going from there to the separating and weighing chamber. A gauge is put on P_1 while P_2, P_3, etc. are connected by copper tubing and valves to either gauge N, or a manometer O, reading up to 20 pounds per square inch.

The separating chamber is made of 1/4 inch stock and has a 7 inch inside diameter and is 19 inches high. In the upper half are three screens of 8 mesh to break down the foam. The gas-oil mixture enters at J. The oil may be removed at K while the gas goes through L to a trap and then to an American Meter Co. dry gas meter reading to .001 cubic feet. The separating and weighing chamber is on a 50 pound platform scale so that weights may be taken initially and finally. M is a water manometer to read the pressure within the chamber.

It was found that the vaporization of the carbon dioxide upon expansion caused a cooling of the oil in the mixing chamber so the lead, Q, from the cylinder was sent through a water bath R before going to the mixing chamber. The water was



A. Main gas line.

B. Gas entrance to top of mixing chamber.

C. Gas entrance to bottom of mixing chamber.

D. Oil inlet.

E. Oil outlet from mixing chamber to flow tube.

G. Inlet to flow tube.

H. Outlet from flow tube.

J. Inlet to separating chamber.

L. Gas exit from separating chamber to trap and meter.

N. Gauge.

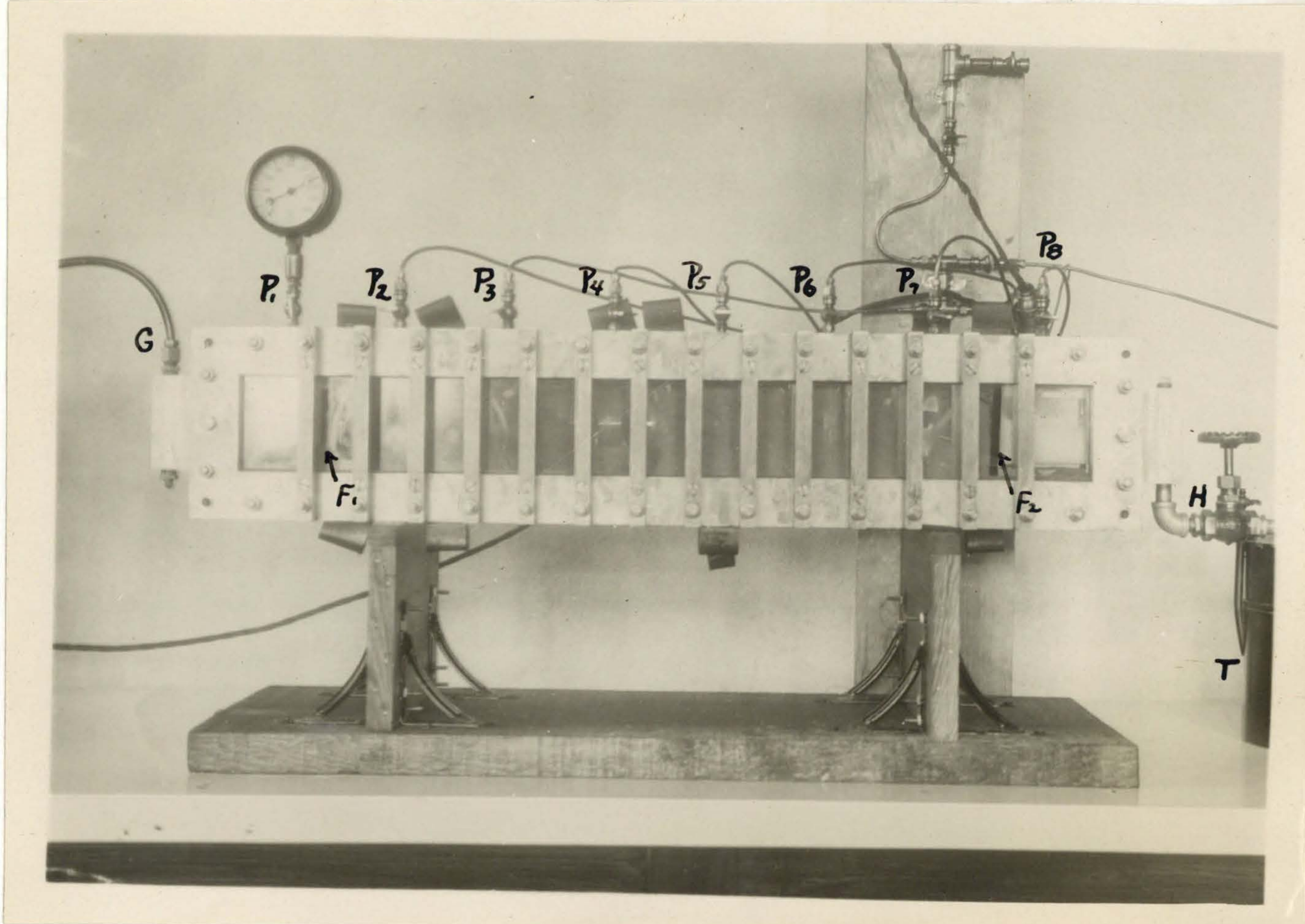
O. Manometer.

Q. Gas line from CO_2 cylinder.

R. Water bath.

S. Electric heater.

T. Gas meter.



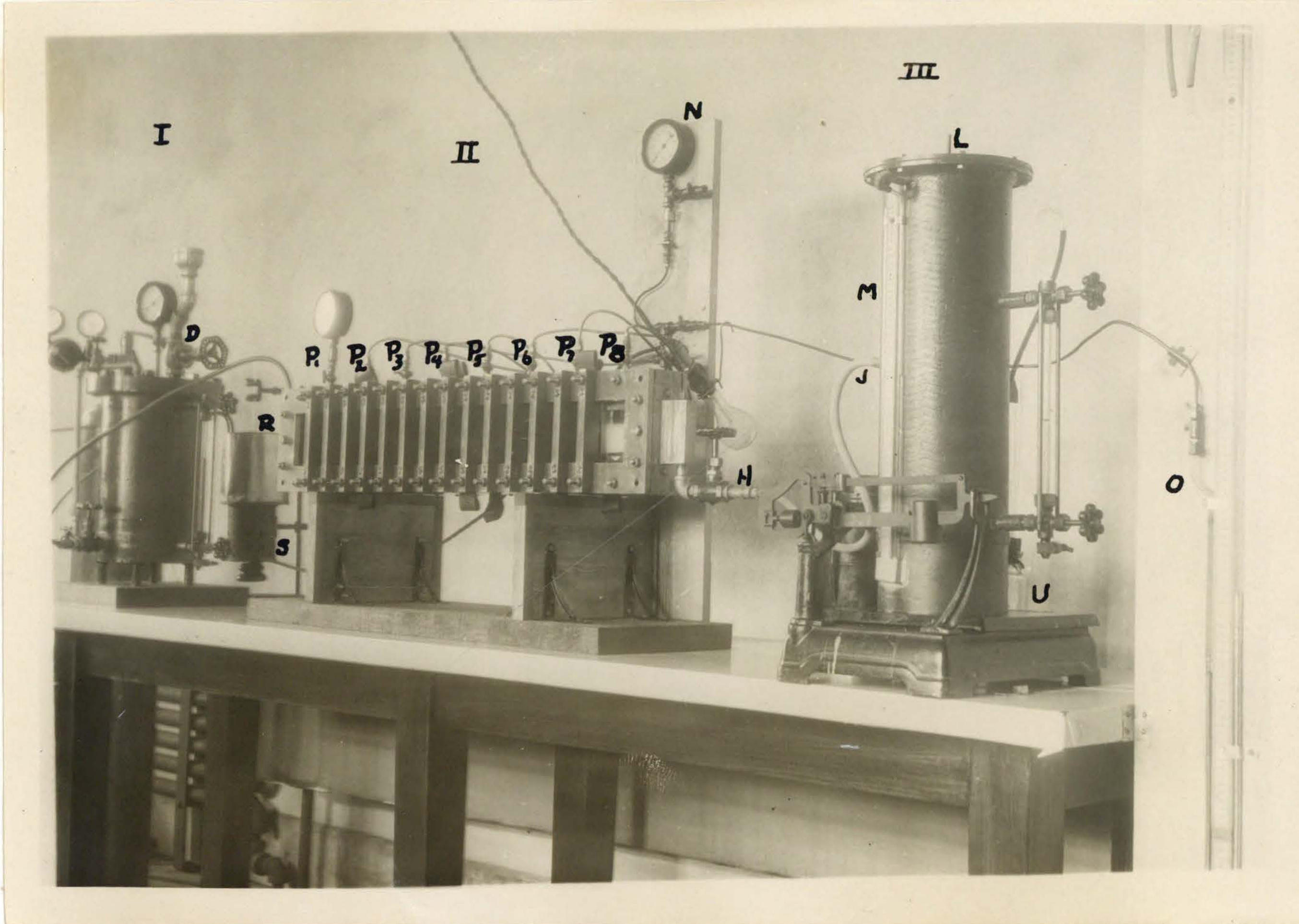
FLOW TUBE.

G. Inlet to flow tube.

F_1 and F_2 . Screens.

P_1 , P_2, P_3, etc. Outlets for pressure readings.

H. Outlet from flow tube.



D. Oil inlet.

H. Outlet from flow tube.

J. Inlet to separating chamber.

L. Gas exit from separating chamber to flow tube.

M. Water manometer.

N. Gauge.

O. Mercury manometer.

P_1, P_2, P_3, etc. Outlets for pressure readings.

R. Water bath.

S. Electric heater.

U. Gas trap.

heated by the electric heater S.

The oil used was Union Crystal Oil of a specific gravity of 0.850 or 35° A.P.I. This oil was used because it has approximately the same general properties as a crude and has the advantage of being clear and thus facilitating observation through the glass.

The gas used was CO_2 and was selected because of its large solubility in oil thus emphasizing the effects of the gas bubbles and also because of its safety.

White washed Monterey Beach sand was used. Sand No. 1 was from 14-20 mesh. Sand No. 2 was from 150-200 mesh.

Run No. 1 - Sand No. 1 - No Gas.

Run	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	Gal/Min
a	10	9.5	8.0	5.75	4.5	2.75	1.6	.75	.0437
b	15	14.1	11.6	9.25	6.7	4.3	2.5	1.3	.0620
c	20	18.7	14.4	11.7	8.7	5.6	3.3	1.75	.0638
d	25	22.5	17.7	14.3	10.8	7.2	4.2	2.25	.1005
e	30	27.5	23.0	17.9	13.4	8.7	5.3	2.7	.1195
f	35	31.0	27.5	22.0	16.0	10.4	5.7	3.3	.1410
g	40	37.0	30.5	24.0	18.0	12.0	6.5	3.6	.1762
h	45	41.0	34.0	27.5	20.0	13.5	7.7	4.2	.1837
i	50	45.0	37.0	30.5	22.5	14.75	8.6	4.7	.2113

Run No. 2 - Sand No. 1 - Saturated at P_1 with CO_2.

Run	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	Gal/Min	Gas/Oil
*a	10	9.0	7.4	5.75	4.3	2.7	1.6	.75	.0378	------
*b	10								.0352	------
*c	20	17.7	14.9	12.1					.0705	.02405
*d	30	27.5	22.5	18.0	14.5	10.0	5.0	3.0	.1410	.1280
*e	40	37.5	32.0	25.0	18.2			4.0	.2113	.0358
*f	40						6.7		.1878	.1432
*g	40	38.0	33.0	27.0	19.2	12.7	7.2	4.7	.1793	.1297
*h	40	39.0	35.0	28.0	23.0	18.0	12.25	7.25	.1832	.5110
*i	20	18.0	15.2	13.0	10.3	7.3	4.7	2.2	.0563	.1500
j	40	37.5	32.0	27.0	22.0	16.3	11.0	7.3	.1538	.2670
*k	50	46.0	39.0	33.0	27.0	18.0			.2290	.2592
*l	30	27.5	23.0	18.2	14.5	10.75	6.8	4.0	.1330	.1442
m	20	17.7	15.0	13.0	10.6	7.4	4.4	2.2	.0668	.1265
*n	50	47.0	39.0	32.0	24.0	16.0	10.7	6.7	.2352	.2350
o	30	27.5	23.0	19.2	15.3	11.2	7.0	3.8	.1174	.1730
p	50								.2253	.3470
q	45	42.0	37.0	30.0	24.0	18.0	12.2	7.3	.1878	.2860
r	10	9.3		7.4		4.5		1.2	.0282	.0635
s	25	22.5	19.0	16.7	13.3	10.0	6.0	3.5	.0977	.1522
t	35				20.5			5.0	.1210	.2792
*u	35							5.0	.1645	.2204
v	35							4.5	.1300	.1740
w	35							4.7	.1565	.2005
x	35							5.2	.1365	.2762

* Results discarded for reason set forth in description of runs.

Ratio of Pressure Gradients of Run No. 2 to Run No. 1 between various points (corrected to equal flows).

Pressure	$P_1 - P_2$	$P_2 - P_3$	$P_3 - P_4$	$P_4 - P_5$	$P_5 - P_6$	$P_6 - P_7$	$P_7 - P_8$
20	1.685	.600	.708	.763	.988	1.245	1.345
25	1.030	.750	.698	1.000	.944	1.370	1.318
30	1.015	1.020	.563	.882	.890	1.255	1.252
40	.956	.970	.882	.956	1.090	1.108	1.500
45	.733	.700	1.052	.782	.902	.727	1.370
Average	1.082	.810	.780	.878	.962	1.14	1.38

Run No. 3 - Sand No. 2 - No Gas.

Run	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	Gal/Min x 10^3
a	50	44	35	28	18	11.3	6	0.3	.948
b	75	66	51	41		17.7	10.8	0.5	1.565
c	100		73		40			0.5	2.025
d	125		93		62			0.4	2.412
e	150		112					0.6	2.767

Run No. 4 - Sand No. 2 - Saturated with CO_2 at P_1.

Run	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	Gal/min. x 10^3	Gas/oil
a	50		38		27	15	11.2	0.7	.672	#
b	75		57					0.8	1.070	#
c	100		81					1.5	1.505	#
*d	125		104					1.3	1.895	0.66
*e	125		104					0.7	1.582	1.136
*f	150		124					1.0	2.178	1.010
g	150							1.0	2.09	1.117
h	125							0.7	1.785	0.922
*i	125							0.7	1.680	0.965

Run No. 5 - Sand No. 2 - Saturated with CO_2 at P_8.

Run	P_1	P_8	Gal/min. x 10^3	
a	150	100	.753	(73 F. temp.)
b	100	50	.940	
c	150	100	1.130	
d	100	50	1.420	

No gas-oil ratio was obtainable due to a slip in the gas meter at such low rates.

Description of Runs.

The temperature of the room was kept at approximately 80° F for all of the runs. The screens used for sand No. 1 were made up of slots of 0.04 inch width and placed 0.085 inch apart. The screens used for sand No. 2 were made up of slots of 0.008 inch width placed 0.042 inch apart. It was found necessary to put a thin layer of 65 mesh sand next to the exit slot to prevent sand from passing through.

Two runs were made with each sand. First the flow was measured for oil without dissolved gas and then the flow of the oil saturated with gas was taken. Run No. 1 was made by using the CO_2 for pressure only by introducing it over the oil through B. Sub-runs (designated by letters in the tables) were made with the pressure varying from 10 to 50 pounds per square inch. The time and weights were recorded at the beginning and end of the run. The gallons per minute were then calculated by the formula:

$$\text{Gallons/Minute} = \frac{0.1410W}{T}$$

where W is the weight in pounds, T is the time in minutes and 0.1410 a conversion factor from pounds to gallons.

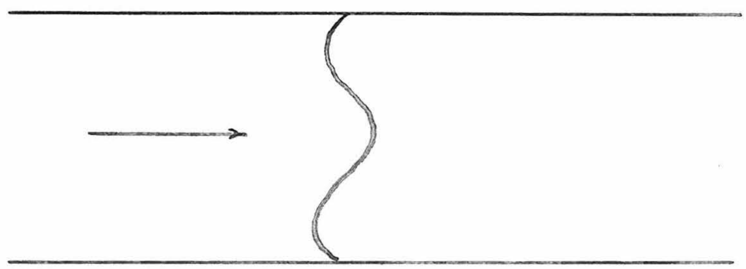
In Run No. 2 the oil was first saturated with gas by allowing the CO_2 to enter through C and bubble through the oil. The valve at D was opened slightly to allow a steady bubbling of the gas through the oil at the required pressure. Some difficulty was experienced in completely saturating the gas in this manner. The sub-runs were made in the same way as those for Run No. 1 with the addition that the initial and final readings of the gas meter were recorded. The gas-oil ratio was then computed by means of the formula:

$$\text{Gas/Oil} = \frac{V - 0.01885\ W}{0.1410\ W}$$

where V is the volume of gas passing through the meter in cubic feet, W is the weight of oil in pounds and 0.01885 is a conversion factor from pounds to cubic feet. This formula takes into account the volume of the oil displacing gas. The gas-oil ratio obtained in this manner is in cubic feet per gallon. It is known that the solubility of a gas in an oil plotted against the pressure of saturation is very nearly a straight line. The runs were therefore plotted with the gas-oil ratio against the pressure of saturation. The first few runs did not agree at all and it was finally found necessary to bubble the gas through the oil for about one and one half hours to insure saturation. The cooling caused by the evaporation of the CO_2 increased the solubility of the gas to such an extent that it was found necessary to install the water bath R in order to heat the gas as it came from the cylinder. After the correct solubility curve was obtained all runs were discarded which did not agree with the curve. The formation of bubbles could be seen very clearly through the glass sides of the flow tube. They were found to form at a point midway in the sand compartment.

In Runs No. 3 and No. 4 a very fine sand from 150-200 mesh was used. In Run No. 3 the gas was again used only as a source of pressure. It was found that the fine sand plugged up the pressure tubes after a short time, and for this reason few of the intermediate pressures could be read.

Run No. 4 was similar to Run No. 2. In this case it was found that the gas formed at a distance of about 2/5 of the length of the sand compartment from the entrance. The formation took place at slightly different distances in the top, center and bottom of the flow tube. The curve below illustrates the line of appearance of the bubbles in the sand. The arrow indicates the direction of the flow.



The bubbles in this case had about the same size as those formed in Run No. 3. However, they were very greatly deformed while passing through the sand, while in No. 3 they were able to pass through with great ease while retaining their spherical shape. The bubbles did not increase in size more than the amount that would be predicted by their expansion due to the decrease in pressure. In other words, the bubbles did not combine with the newly formed ones as they flowed through the chamber.

The results of these runs were plotted as in the curves that follow. In order to reproduce graphically the effect of the gas dissolved in the oil, the ratio of the pressure gradients at different points of Run No. 2 to those of Run No. 1

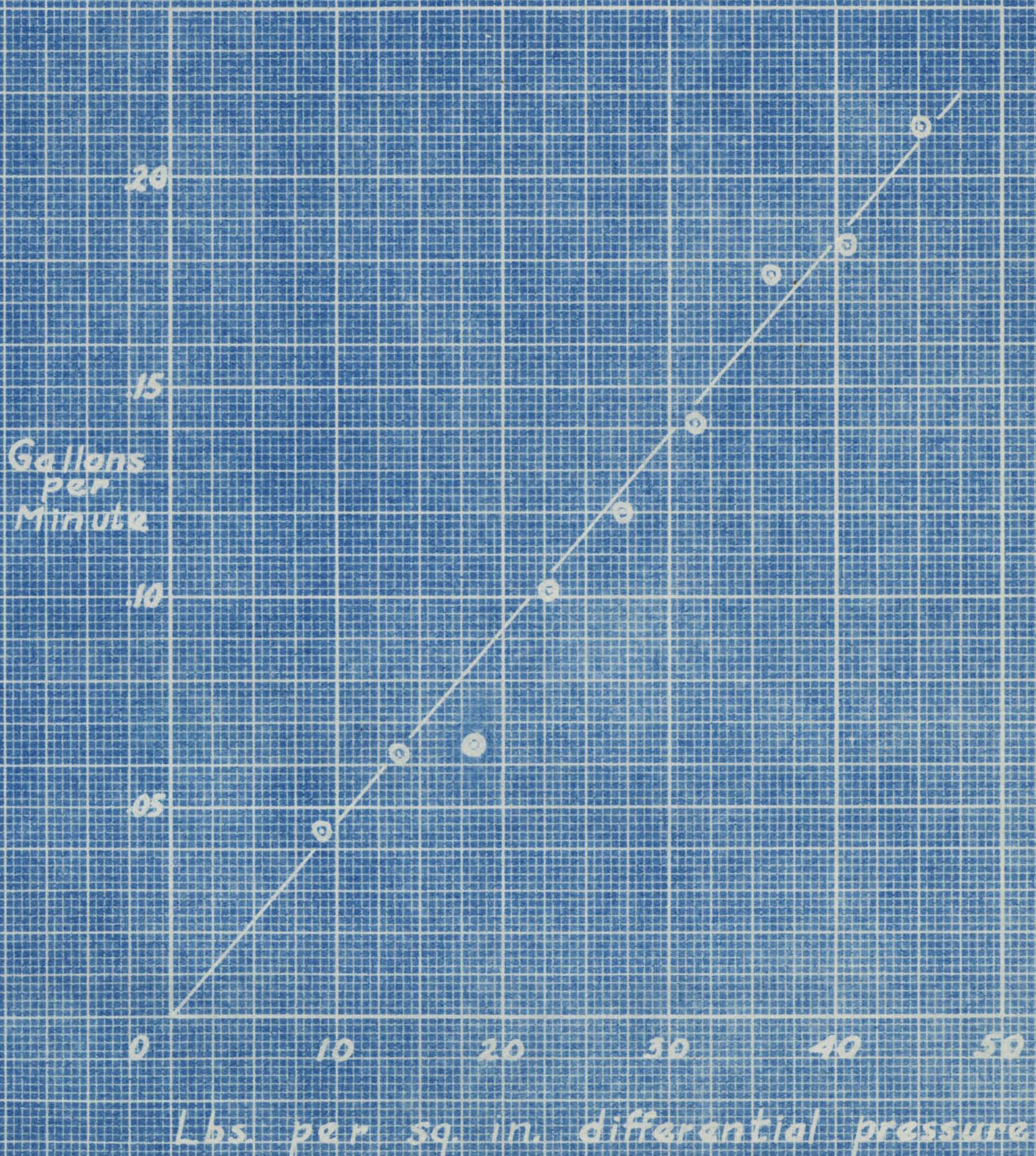
were calculated as already shown in a preceding table. The average of this ratio was then found for each one of the points and the results plotted. The resulting averages were found to make a smooth curve except for the average ratio of the pressure gradient between the first screen and the point P_2. The explanation for this discrepancy is that during the course of the runs there was at times a distance of one half inch to one inch in the upper corner in which there was no sand, due to compression. This fact made the pressure gradient between the first screen and the point P_2 unreliable.

Run No. 5 was made by saturating the oil with gas at a given pressure and then putting a gas pressure over the oil of 50 pounds per square inch greater then the saturation pressure. By manipulating the valve at H, a back pressure was maintained equal to the pressure of saturation. As heat was not available sub-run (a) was made at 73° F and consequently gave a lower rate of flow. The balance of the sub-runs were made at 80° F. This series of runs do not check. The reason for discrepancies may be the difficulty in maintaining the temperature of the room at a constant value. However, since the flow of oil without dissolved gas at 50 pounds differential pressure is 0.00948 gallons per minute (by Run No. 3), the results seem in general to indicate an increased flow caused by the decrease in viscosity due to the dissolved gas. Due to the limited time available, a check of this run was impossible.

RUN NO. 1.

Sand 14-20 mesh

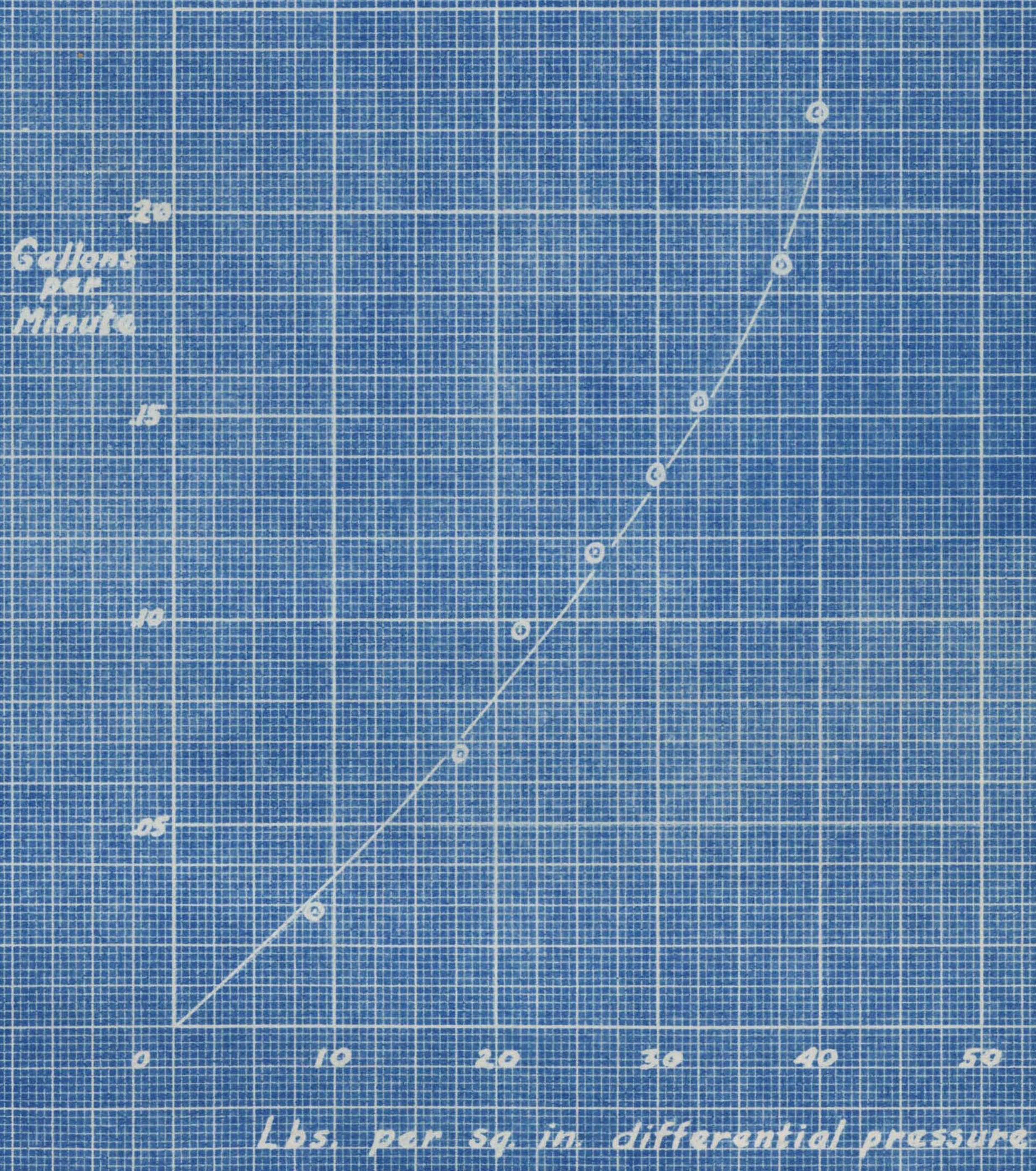
No gas



RUN NO 2.

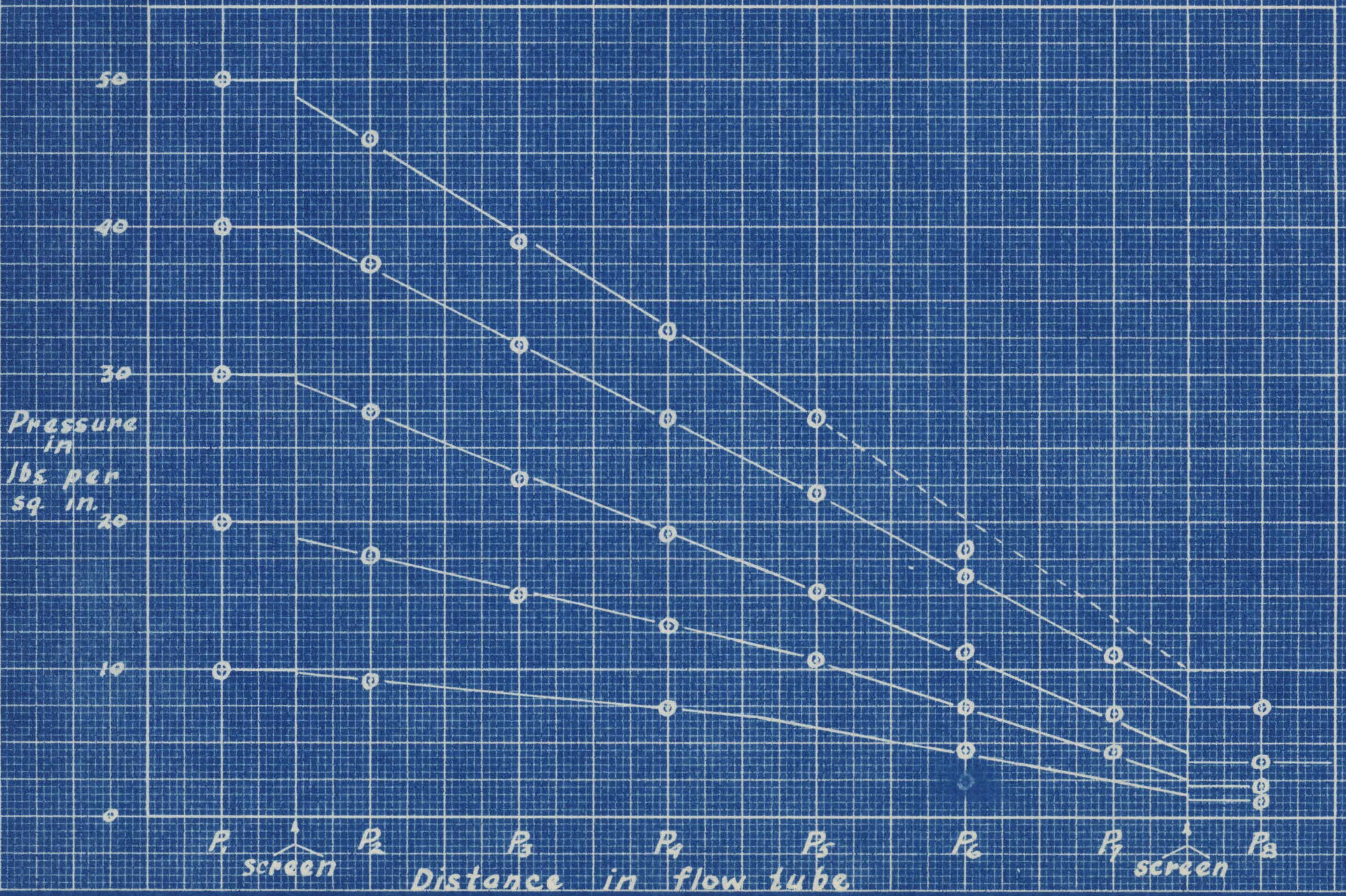
Sand 14-20 mesh

Saturated with CO_2 at P_1



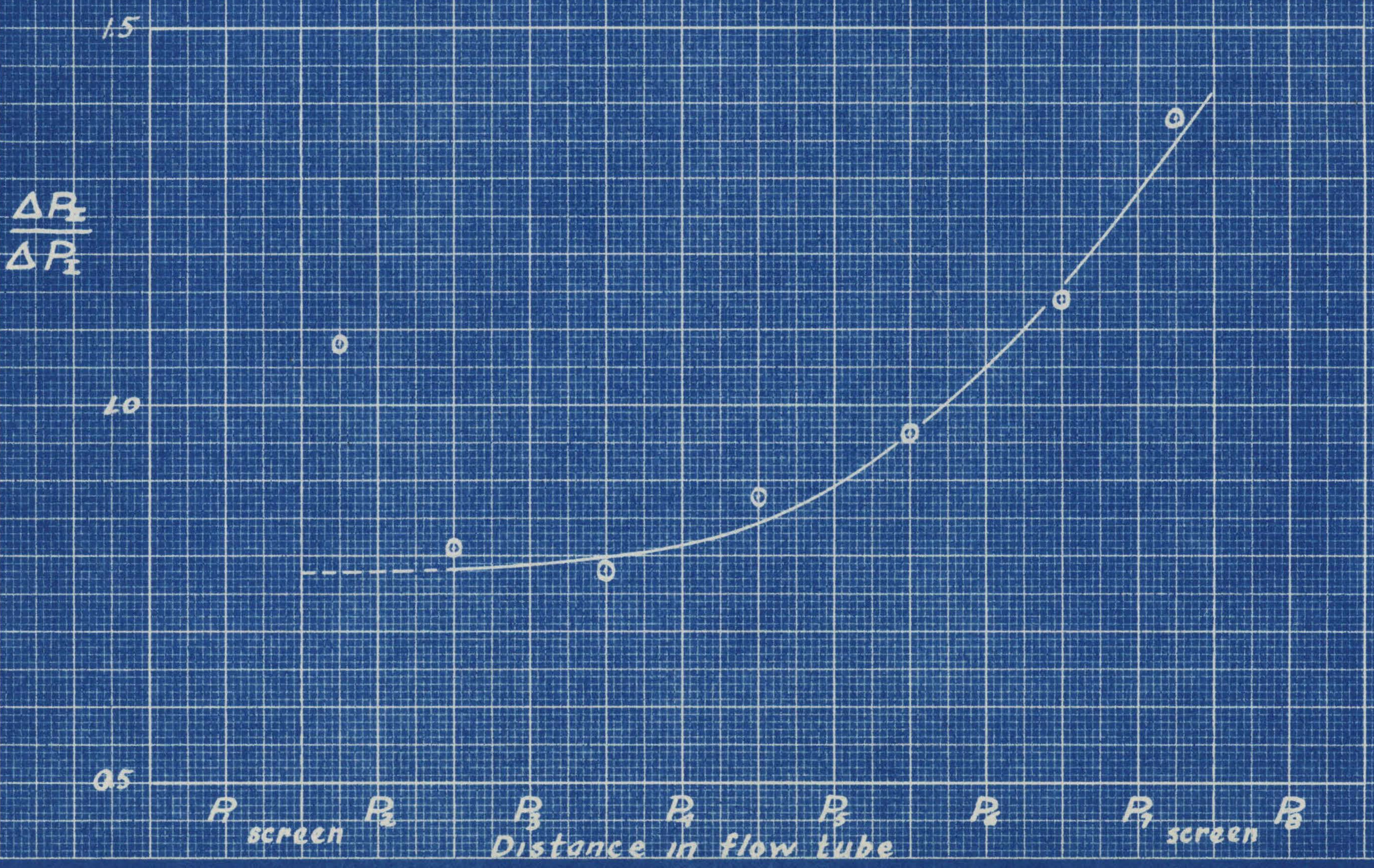
RUN NO. 2.

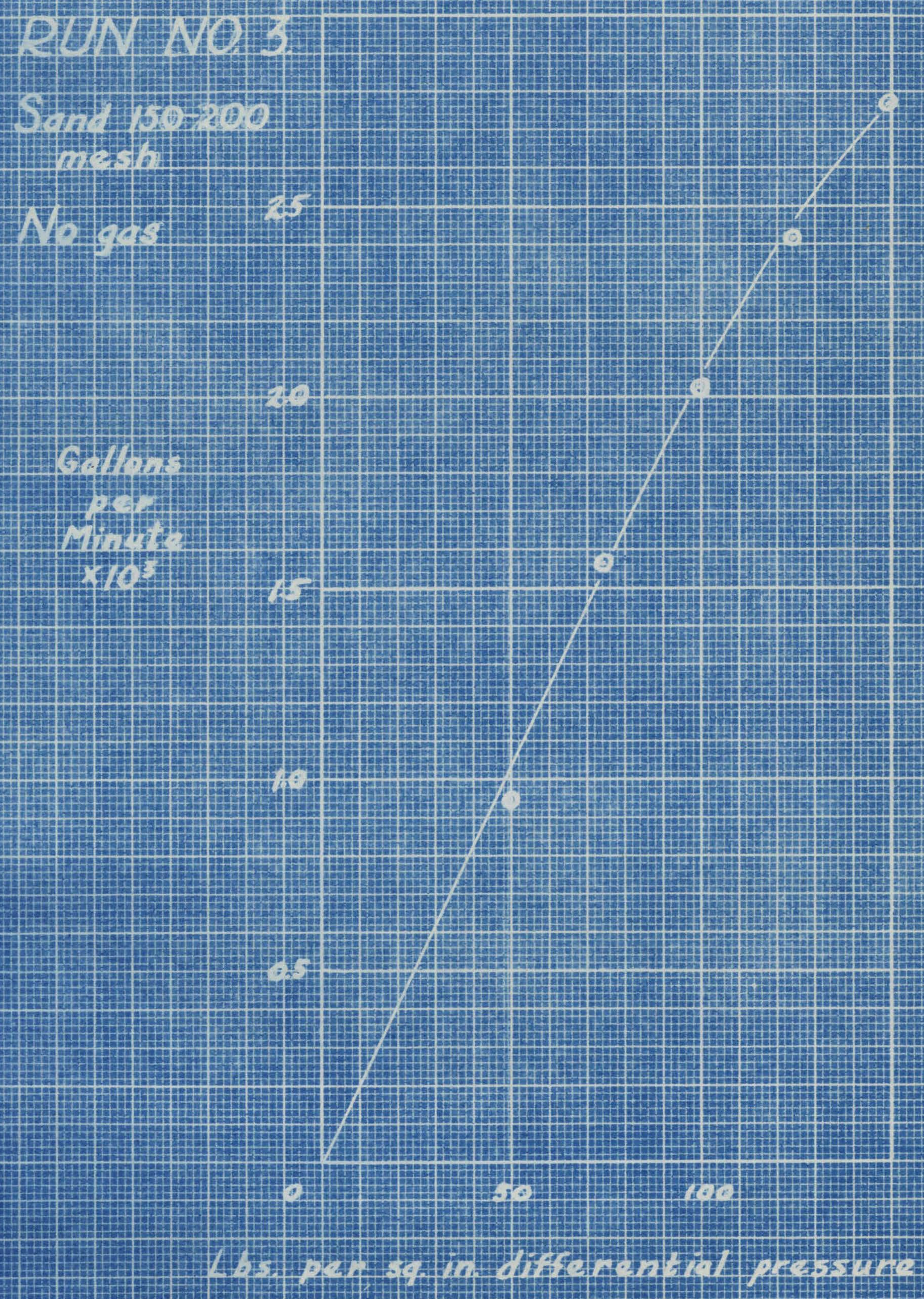
Sand 14-20 mesh. Saturated with CO_2 at P_1

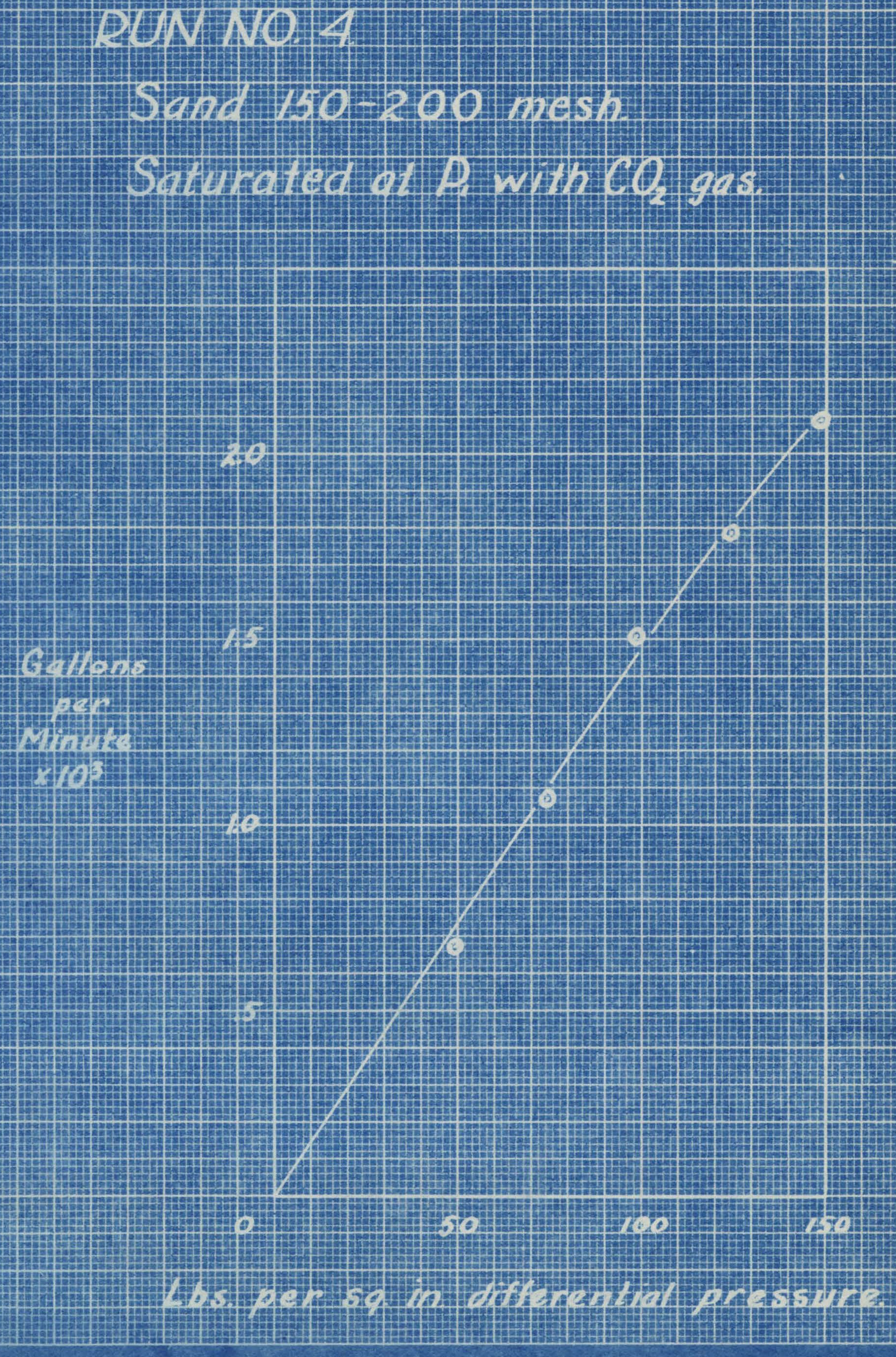


RATIO OF AVERAGE PRESSURE GRADIENTS

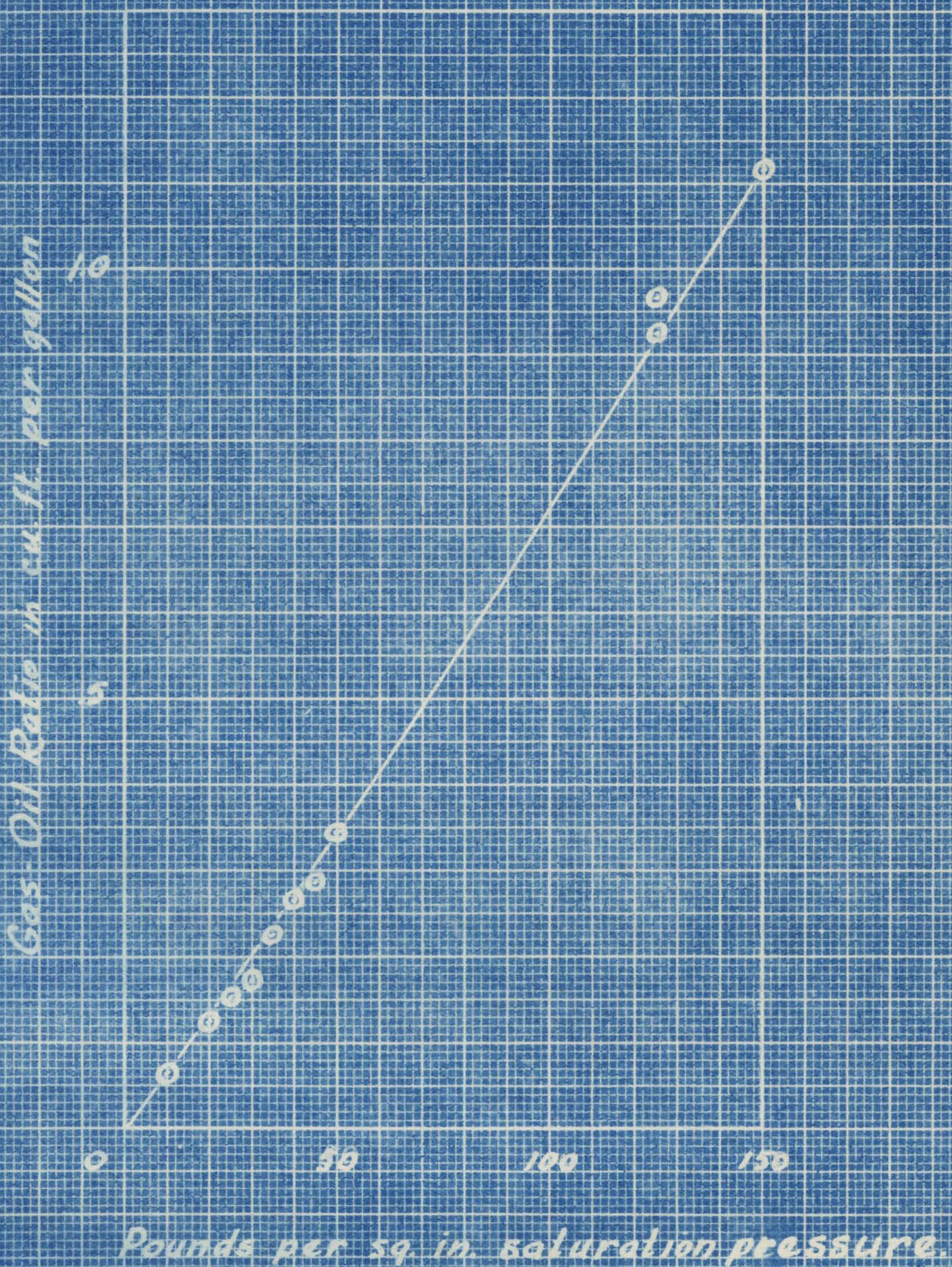
Run No. 2 to Run No. 1 at various points.




RUN NO. 3.
Sand 150-200 mesh
No gas
Gallons per Minute x10³
2.5
2.0
1.5
1.0
0.5
0
50
100
Lbs. per sq. in. differential pressure


RUN NO. 4
Sand 150-200 mesh.
Saturated at P_1 with CO_2 gas.
2.0
1.5
1.0
.5
0
50
100
150
Gallons per Minute x10³
Lbs. per sq. in. differential pressure.

Gas-Oil Ratio vs. Saturation Pressure



Conclusions.

1. It was found, as would be expected, that the pressure varies directly as the distance from the exit screen when oil without gas flows through sand.

2. When gas is present in the oil, the pressure gradient increases as the gas is expelled in the form of bubbles. This is caused first because the viscosity of the oil increases when dissolved gas is expelled and secondly because the bubbles, when flowing through the sand, must be deformed thus causing a resistance due to the increase in surface of the gas-oil interface. The latter is what has been considered in this paper as the Jamin effect.

3. The Jamin effect is not pronounced when the sand is coarse because the interstices in the sand are of such dimensions that the deformation of the bubbles is slight. However, in a fine sand this effect is very pronounced.

4. Equilibrium is not reached immediately between the oil and its dissolved gas when flowing through the sand. The oil retains the gas in a supersaturated condition for a certain distance. Although this distance is less in a case of the fine sand where the flow was slow than in the coarse sand where the flow was rapid, the time of supersaturation was greater in the fine sand. This is probably due to the fact that the turbulence is a great deal less.

5. The bubbles did not combine or flow in separate channels from the oil. They were evenly distributed from top to bottom of the flow chamber, increasing in number rather

than in size as the pressure decreased.

6. A run was made to determine how much the flow would be increased by using a back pressure equal to the pressure of saturation and using a 50 pound per square inch greater driving pressure, but due to limited time the run could not be sufficiently checked.

Acknowledgements.

Appreciation should be expressed to C. J. Coberly of Kobe, Inc., who very kindly built and loaned the apparatus used and who assisted with many helpful suggestions. Messrs. C. F. Hansen and E. S. Croasdale, members of his staff, also helped in the design of the apparatus and gave other valuable assistance. The flow tube itself was designed entirely by Mr. Coberly and his staff.

Appreciation is due Dr. W. N. Lacey, under whose direction this work was done, for many constructive ideas, his interest and co-operation, and his critical perusal of this thesis.

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